APPENDIX 3.2

CUTTINGS AND OIL SPILL MODELLING

Consulting Port and Coastal Engineers

PROPOSED EXPLORATION DRILLING IN THE ORANGE BASIN DEEP WATER LICENCE AREA OFF THE WEST COAST OF SOUTH AFRICA

Drill Cuttings and Oil Spill Modelling Specialist Study

Report 1133/01 Rev. 03

06 December 2013

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Prepared for the Environmental Assessment Practitioner:

CCA Environmental (Pty) Ltd

On behalf of the Applicant:

Shell South Africa Upstream B.V.

PRDW
Consulting Port and Coastal Engineers

PROPOSED EXPLORATION DRILLING IN THE ORANGE BASIN DEEP WATER LICENCE AREA OFF THE WEST COAST OF SOUTH AFRICA

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Impact Assessment

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EXECUTIVE SUMMARY

Shell South Africa Upstream B.V. has obtained an exploration right for the Orange Basin Deep Water Licence Area. The eastern border of the Licence Area is located between approximately 150 km and 300 km off the West Coast of South Africa approximately between Saldanha Bay and Kleinzee with water depths ranging from 500 m to 3 500 m. Shell proposes to drill one or possibly two exploration wells in an area of interest located in the northern portion of the licence area, which is 900 km^2 in extent with water depths ranging between 1 500 m and 2 100 m.

This study describes the Drill Cuttings and Oil Spill Modelling Specialist Study which forms part of the Impact Assessment for the project. The scope of this study is as follows:

- Model the transport, dispersion and bottom deposition of drill cuttings discharged during drilling operations;
- Model the trajectory and fate of oil due to a small operational spill on the water surface at the drill vessel; and
- Model the trajectory and fate of oil due to a large blowout spill at the wellhead on the seafloor.

The drill cuttings model results show that the large depths at the well site (1 800 to 2 040 m) combined with the moderate to strong current speeds (at 200 m depth the median speed is 0.12 m/s and the maximum 0.56 m/s) and relatively low mass of cuttings discharged (1 042 t) result in the drill cuttings being spread over a large area, with relatively low deposition thicknesses of less than 1 mm predicted for distances greater than about 150 m from the location of the well. The footprint where the deposition thickness exceeds 0.001 mm is predicted to be less than 33 km^2 and occurs within a distance of 50 km from the well.

The 1 t (7.4 bbl) spill of hydraulic fluid scenario is predicted to remain on the water surface for a maximum of 2 days during which it will travel up to 150 km from the source, predominantly in a north-westerly direction. There is no probability of the oil reaching the shoreline.

The 10 t (74 bbl) spill of diesel scenario is predicted to remain on the water surface for a maximum of 1.5 days during which it will travel up to 110 km from the source, predominantly in a north-westerly direction. There is no probability of the oil reaching the shoreline.

The 5-day and 20-day large blowout oil spill scenarios are predicted to result in extensive areas of oiling of the subsurface and particularly at the water surface. Once the oil surfaces it tends to be transported in a north-westerly direction due to the prevailing near-surface currents and winds which reduces but does not eliminate the probability of shoreline oiling. For the medium weathering scenario the 20-day blowout in summer results in a 600 km long by 50 km wide area where the probability of oiling exceeds 90%.

The probability of shoreline oiling depends on spill duration, the season and weathering scenario. If drilling is confined to summer, as planned, then for the medium weathering scenario no shoreline oiling is predicted by the model for either blowout scenario. For the worst case slow weathering scenario during summer the 5-day blowout scenario is predicted to have no probability of shoreline oiling and the 20-day blowout scenario has less than 10% probability of shoreline oiling. The model results show that drilling during winter would significantly increase the probability of shoreline oiling compared to the probabilities for summer as described above, due to the stronger prevailing north-westerly winds in winter.

The model results will be provided to the Marine Faunal and the Fisheries Specialists to enable the associated ecological impacts to be assessed..

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EXPERTISE AND DECLARATION OF INDEPENDENCE

This report was prepared by Stephen Luger of Prestedge Retief Dresner Wijnberg (Pty) Ltd (PRDW). Stephen is a Registered Professional Engineer and holds an MSc in Engineering from the University of Cape Town. He was employed by the Council for Scientific and Industrial Research (CSIR) for sixteen years as a coastal modelling specialist. For the past seven years he has been employed by PRDW Consulting Port and Coastal Engineers as a coastal modelling specialist and currently holds the post of Technical Director.

He has twenty-two years of experience in the application of numerical models in the fields of waves, hydrodynamics, tsunamis, sediment transport, water quality, oil spills, harbour layout, vessel motions, marinas and dredging. These modelling studies have been conducted for feasibility studies, environmental impact studies, nuclear safety studies and detailed engineering design. The countries where the studies have been conducted include South Africa, Namibia, Gabon, Nigeria, Kenya, Mauritius, Mozambique, Cameroon, Angola, Egypt, Bahrain, Qatar, Jordan, Israel, Ireland, Chile, Peru, Australia, East Timor and the Seychelles. He has undertaken drill cuttings and/or oil spill studies in South Africa and Mozambique for Anadarko, PetroSA, Vale and Sasol.

He is the author or co-author of over 20 articles in scientific journals, chapters in books and conference proceedings, over 60 technical reports for external contract clients, and has presented over 20 papers at local and international conferences.

This specialist report was compiled for CCA Environmental (Pty) Ltd on behalf of Shell South Africa Upstream B.V. for their use in compiling a Basic Assessment Report and Environmental Management Programme Addendum for the proposed exploration drilling programme in the Orange Basin Deep Water Licence Area off the West Coast of South Africa. I do hereby declare that PRDW is financially and otherwise independent of the Applicants and CCA Environmental.

Allan Wijnberg (Chief Executive Officer)

Stephen Luger (Project Director)

1. INTRODUCTION

1.1 Background

Shell South Africa Upstream B.V. (hereafter referred to as 'Shell') has obtained an exploration right for the Orange Basin Deep Water Licence Area. The eastern border of the Licence Area is located between approximately 150 km and 300 km off the West Coast of South Africa approximately between Saldanha Bay and Kleinzee with water depths ranging from 500 m to 3 500 m.

Based on analysis of seismic data, Shell proposes to drill one or possibly two exploration wells in an area of interest located in the northern portion of the licence area (see Figure 1-1). Exploration drilling is undertaken to determine whether geological structures or 'prospects', identified by studying the data from seismic surveys, contain oil or gas in potentially commercial extractable amounts.

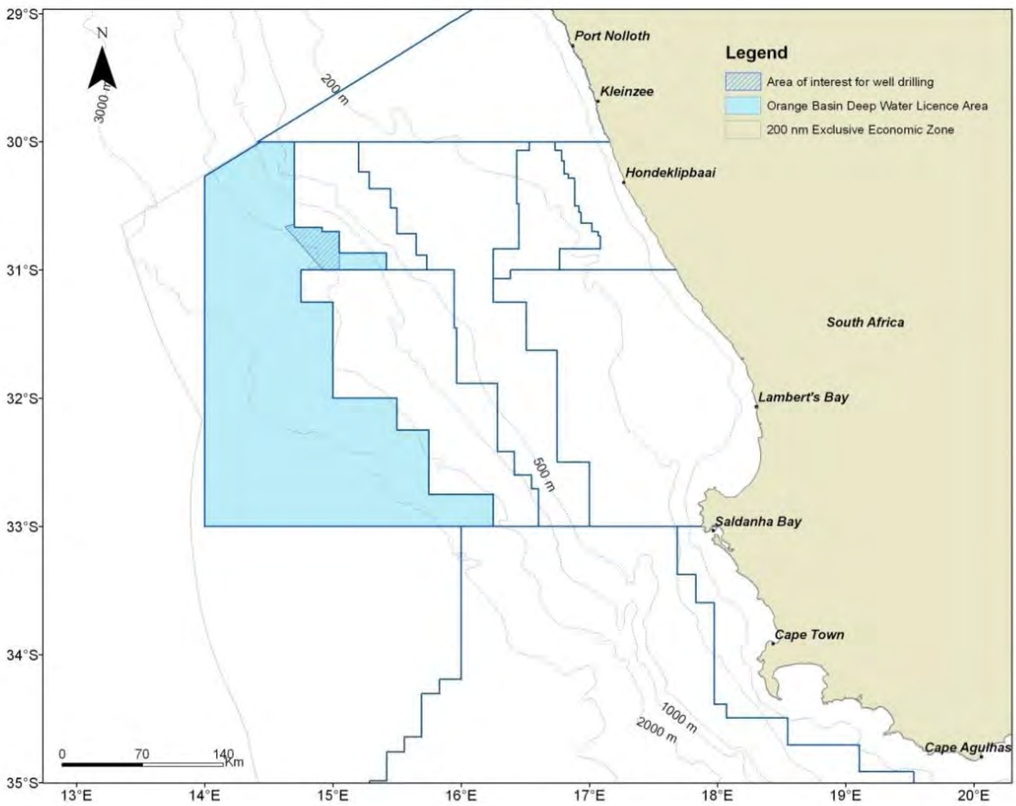


Figure 1-1: *Locality of the Orange Basin Deep Water License Area and the area of interest for well drilling*

CCA Environmental (Pty) Ltd has been appointed by Shell to undertake a Basic Assessment process and amend their existing approved Environmental Management Programme (EMPr) for the proposed exploration drilling. CCA has appointed PRDW to undertake the Drill Cuttings and Oil Spill Modelling Specialist Study which forms part of the study process.

1.2 Project Description

1.2.1 Well Location and Drilling Programme

Shell proposes to drill one or possibly two wells in the northern portion of the licence area. At this stage an area of interest has been defined for the drilling locations (see Figure 1-1), which is 900 km^2 in extent with water depths ranging between 1 500 m and 2 100 m. The final well location will be based on a number of factors, including further analysis of the 3D seismic data, the geological target and seafloor location obstacles. The expected final depth of the well is between 2 700 m and 3 000 m below the seafloor and is expected to take in the order of three months to complete. For operational reasons, drilling is expected to take place in a future summer window period between November to April.

Depending on the success of the first well, a second well may be drilled to establish the quantity and potential flow rate of the resource. The appraisal well would be drilled in a location and to a depth determined by the results of the first well. It is anticipated that the appraisal well would be drilled at least one year after completion of the first well in order to allow sufficient time for data analysis and planning.

1.2.2 Drilling Methodology

Various types of drilling technology can be used depending on, inter alia, the water depth and marine operating conditions experienced at the well site. Shell is currently considering two alternative drilling units, either a semi-submersible drilling vessel (rig) or a drill-ship.

The drilling unit would move onto location over the proposed drill site. The 36 inch (91 cm) diameter structural conductor pipe would either be drilled and cemented or jetted into place depending on the shallow seabed properties. The conductor pipe would be approximately 75 m deep.

Below the conductor pipe, a 26 inch (66 cm) diameter hole would be drilled for a 20 inch (51 cm) surface casing, which would extend to approximately 1 000 m below the seabed. The surface casing would be secured into place by pumping cement through the casing at the bottom of the hole and back up into the space between the casing and the borehole wall (annulus).

These first two hole sections would be drilled using seawater with viscous sweeps and water-based mud (WBM). The rotating drill string causes the drill bit to crush the rock into small particles called cuttings. All cuttings and WBM from this initial drilling stage would be discharged directly onto the seafloor.

Following the initial drilling stage described above, a blowout preventer (BOP) and marine riser, which isolates the drilling fluid and cuttings from the environment, is run and installed on the wellhead. The BOP contains high pressure safety valves designed to seal the well and prevent the uncontrolled release of fluids from the well (a 'blowout') in the event that the primary well barrier (normally over balanced drilling fluid) is lost. Drilling is continued by lowering the drill string, with a smaller bit, through the riser to the 20 inch diameter casing shoe and rotating the drill string, causing the drill bit to crush the rock. This stage of drilling would be undertaken using a synthetic-based mud (SBM).

While drilling is in progress, drilling fluid is continuously pumped down the inside of the hollow drill string. The fluid emerges through ports in the drill bit and then rises (carrying the rock cuttings with it) up the annular space between the sides of the hole (the casing and riser pipe) and the drill string, to the drilling unit. The returned drill mud is treated to remove solids and drilled cuttings from the re-circulating mud stream. The cuttings are treated and discharged overboard. The hole diameter decreases in steps with depth as progressively smaller diameter casings are inserted into the hole at various stages and cemented into place. During the drilling of a well, the primary discharge from the drilling vessel is the drilling cuttings.

Cuttings range in size from clay to coarse gravel. The composition of the rock particles reflects the types of sedimentary rocks penetrated by the drill bit. Although most of the drilling fluids are mechanically separated from the drilling cuttings, the discharged cuttings would contain some residual SBM. Prior to discharge to sea, the drill cuttings would be treated to reduce their oil content to less than 6.9% of dry cuttings weight. Bulk volumes of SBM remaining at the end of well drilling, would either be shipped for onshore treatment and disposal through an approved waste disposal company or re-used during the drilling of the subsequent well.

If the exploration well encounters hydrocarbons, an appraisal well would be drilled, which would be flow-tested to determine the economic potential of the discovery before the well is either abandoned or suspended for later re-entry and completion. If flow testing is required, hydrocarbons would be burned at the well site. A high-efficiency flare is used to maximise combustion of the hydrocarbons.

Based on the results of the drilling, logging and possible testing of the well, a decision would be made as to whether to suspend or abandon the well.

1.2.3 Support vessels

The drilling operations would be supported by at least three vessels, which would facilitate equipment and material transport between the drilling unit and port. The standby vessels would also provide support for fire fighting, oil containment/recovery, rescue and any equipment that may be required in case of an emergency.

1.3 Scope of this Study

The scope of this specialist study is as follows:

- Model the transport, dispersion and bottom deposition of drill cuttings discharged during drilling operations;
- Model the trajectory and fate of oil due to a small operational spill on the water surface at the drill vessel; and
- Model the trajectory and fate of oil due to a large blowout spill at the wellhead on the seafloor.

The model results will be provided to the Marine Faunal and the Fisheries Specialists to enable the impacts to be assessed.

1.4 Layout of Report

The environmental data required for both the drill cuttings and oil spill modelling is described in Section 2, followed by the drill cuttings modelling in Section 3 and the oil spill modelling in Section 4. Conclusions follow in Section 5.

2. ENVIRONMENTAL DATA

2.1 Bathymetry

The baseline bathymetry for the study was obtained from the following sources:

- MIKE C-MAP electronic hydrographic charts (DHI, 2012a)
- Survey of the area of interest for well drilling, provided by the client.

2.2 Wind

The advection of oil on the sea surface due to wind was modelled using space and time varying operational hindcast wind fields obtained from the National Centers for Environmental Prediction (NCEP, 2012). The data comprises wind speed and direction on a 0.5° geographical grid at three-hourly intervals from February 2005 to May 2013.

2.2.1 Validation of Wind Data

No offshore measured wind data was available for the validation of the NCEP hindcast wind data, however 32 years (1979 – 2010 inclusive) of GROW (Grow Reanalysis of Ocean Waves) hindcast wind data was provided by the client at coordinates 15˚E, 31˚S. The NCEP and GROW hindcast wind roses and wind speed histograms at this location are compared in Figure 2-1 and Figure 2-2 respectively (note that wind direction is defined as the direction from which the wind is coming). The comparison shows the wind roses to be in excellent agreement, with the data indicating a predominantly south-easterly wind direction. The NCEP wind speeds are on average about 5% weaker than the GROW wind speeds. In the absence of any in-situ wind measurements, the good agreement of the two hindcast datasets provides some confidence in the use of the NCEP wind fields for this study.

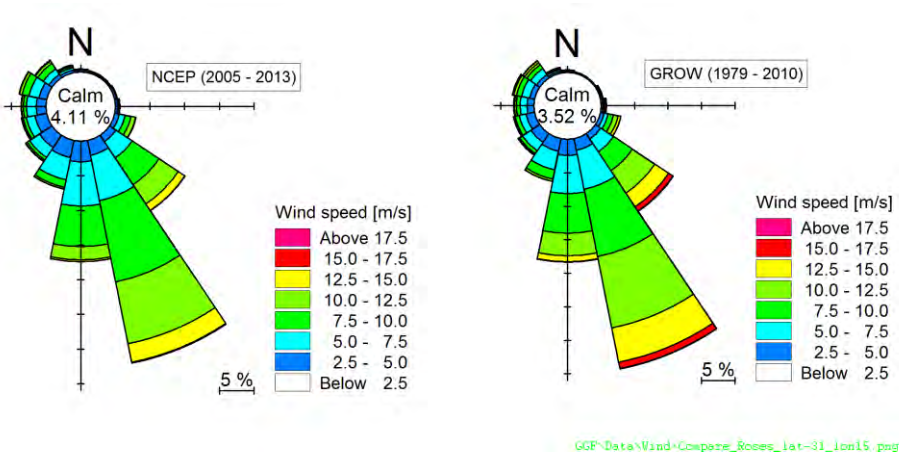
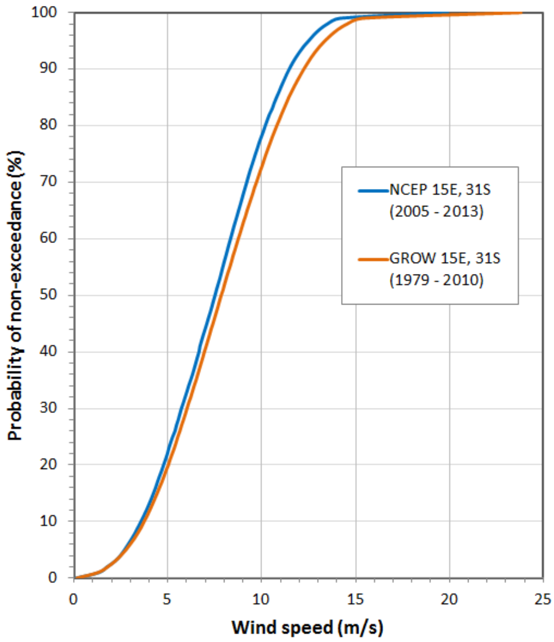


Figure 2-1: *Comparison of wind roses for GROW and NCEP hindcast data at location 15°E, 31°S.*

GGF\Data\Wind\Compare_Exceedance_lat-31_lon15.xlsx

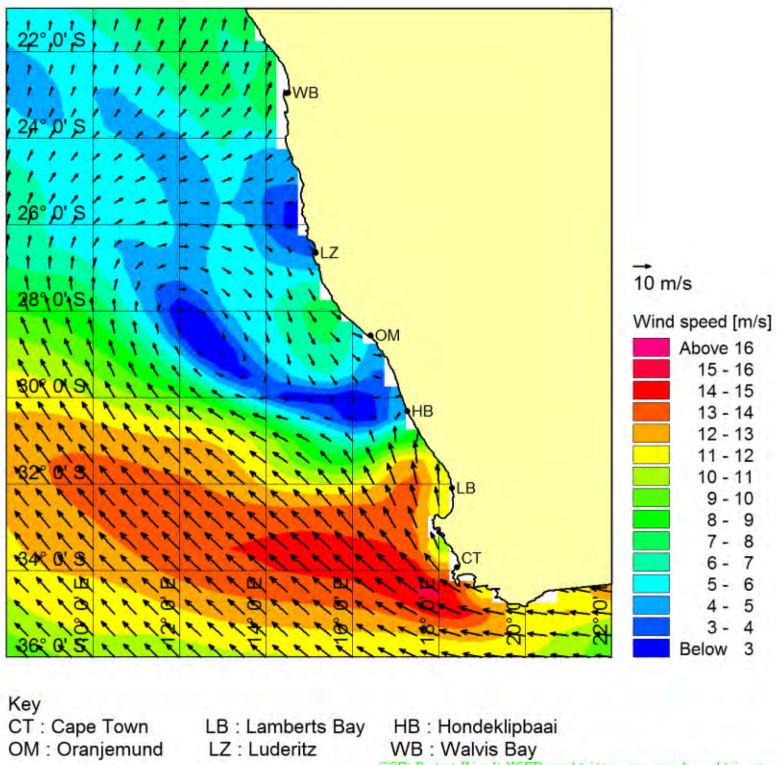


Probability of non-exceedance (%)	Wind speed (m/s)	
	NCEP 15E, 31S (2005 - 2013)	GROW 15E, 31S (1979 - 2010)
0	0.11	0.14
30	5.72	6.02
50	7.51	7.84
60	8.34	8.75
70	9.20	9.72
80	10.19	10.80
90	11.46	12.24
95	12.50	13.36
99	14.19	15.36
100	19.89	23.81

Figure 2-2: *Comparison of wind speed histograms for GROW and NCEP hindcast data at location 15°E, 31°S.*

2.2.2 Spatial Variation of Wind

Wind speed and direction have the potential to vary significantly over domain of the study area. This is highlighted in Figure 2-3, which provides an example of a NCEP wind field at an instance in time.



GGF\Data\Wind\NCEP_multi\ncep_wind_multi.png

Figure 2-3: *Example of a NCEP hindcast wind field, highlighting the potential for spatial variation of winds at an instance in time.*

Figure 2-4 presents annual wind roses at selected locations over the domain of the study area. The south-easterly dominant wind direction is a characteristic over the entire study are. The data displays a general trend for wind speeds to increase toward the shoreline, with the exception of 17°E, 31°S (likely due to the influence of St Helena Bay to the south). The occurrence of westerly and north-westerly winds, responsible for blowing oil toward the shoreline, increase toward the south, as the effects of frontal systems become more pronounced during the austral winter. The presented spatial variation in the wind climate serves to highlight the importance of modelling space-varying wind fields.

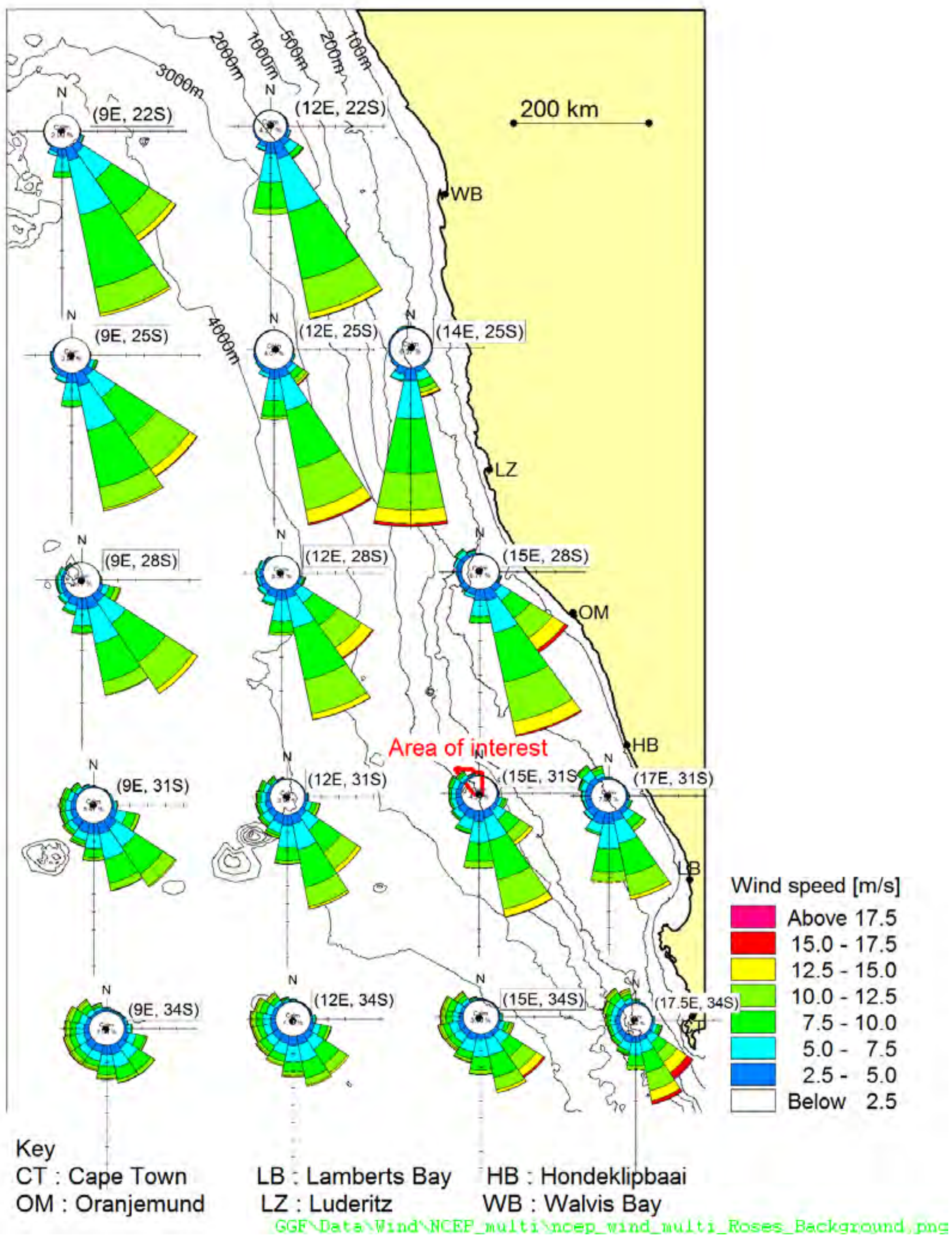


Figure 2-4: *NCEP hindcast wind roses at selected locations over the domain of the study area, highlighting the spatial variation in the annual wind climate.*

2.2.3 Seasonal Variation of Wind

Only two seasons have been considered for this study, namely austral summer and winter. Summer is defined as the months of October through to March, while winter is defined as the months of April through to September. Figure 2-5 presents the seasonal wind roses for the NCEP wind hindcast data at location 15°E, 31°S. The data indicates a distinct seasonality, with a considerably more pronounced north-westerly component during winter, due to passing frontal systems over this period of the year.

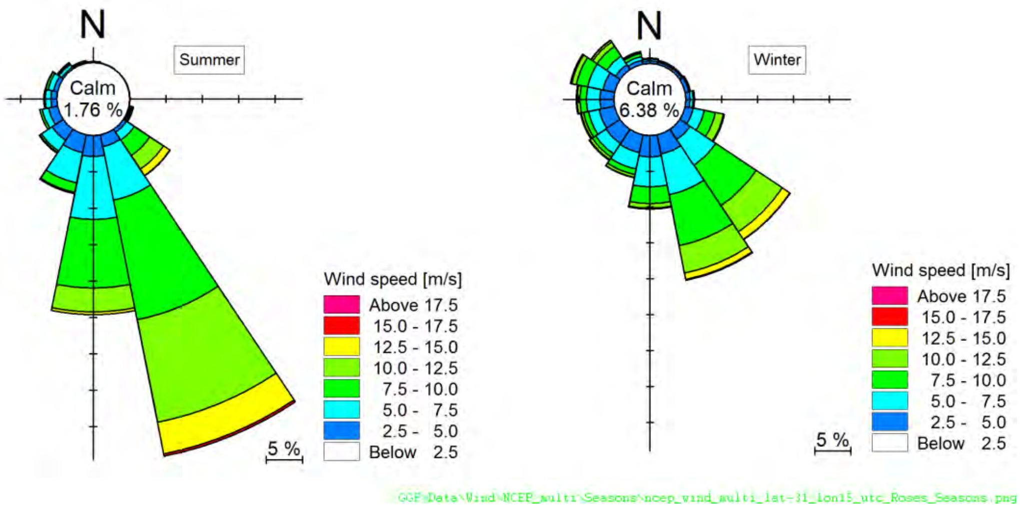


Figure 2-5: *Seasonal wind roses for NCEP hindcast data at location 15°E, 31°S.*

2.3 Currents

The advection of oil and drill cuttings through the water column due to oceanic currents was modelled using space and time varying hindcast current fields obtained from HYCOM (Hybrid Coordinate Ocean Model) (HYCOM, 2013). The data provides daily current speed and direction on a geographical grid of approximately 1/12°. The data includes 32 vertical levels, with the resolution of each layer varying with depth (10 m resolution near the surface down to 500 m resolution for depths greater than 2000 m). Four years of data (2009 to 2012 inclusive) were downloaded for use as input to both the oil spill and drill cuttings models.

2.3.1 Validation of Current Data

The validation of the HYCOM hindcast currents was aided through a comparison with measured currents obtained from the Benguela Source and Transport (BEST) experiment 1, forming part of the World Ocean Circulation Experiment (WOCE) (BEST, 2013). The data provides hourly measurements of current speed and direction from 18 June 1992 to 26 October 1993 at coordinates 14.7088˚E, 30.4442˚S (approximately 25 km north of the area of interest for well drilling). Measurements are available at two depths, namely 215 m and 520 m.

In addition to the measured currents, SAT-OCEAN hindcast currents were provided by the client for further comparison and validation. The SAT-OCEAN data provides current speed and direction at 19 vertical levels on a 1/32° spatial grid at 3 hourly intervals from 2003 to 2012. Data at coordinates 15°E, 31°S were made available for this study.

As neither of the two hindcast datasets (HYCOM nor SAT-OCEAN) overlap the available measurements, only a comparison of the annual statistics could be carried out. Figure 2-6 and Figure 2-7 compare the WOCE BEST 1 measured current roses at 215 m and 520 m depths with those of the HYCOM and SAT-OCEAN data at depths of 200 m and 500 m respectively (note that current direction is defined as the direction toward which the current is flowing). Figure 2-8 provides a comparison of the current speed histograms. It is noted that the presented HYCOM currents have been increased by a factor of 1.25 to bring them more in line with the measurements. This factor has been applied as a constant over all depths in the HYCOM hindcast data for this study.

The comparison indicates that of the two hindcast datasets, the scaled HYCOM currents provide a more representative dataset when compared to the measured currents.

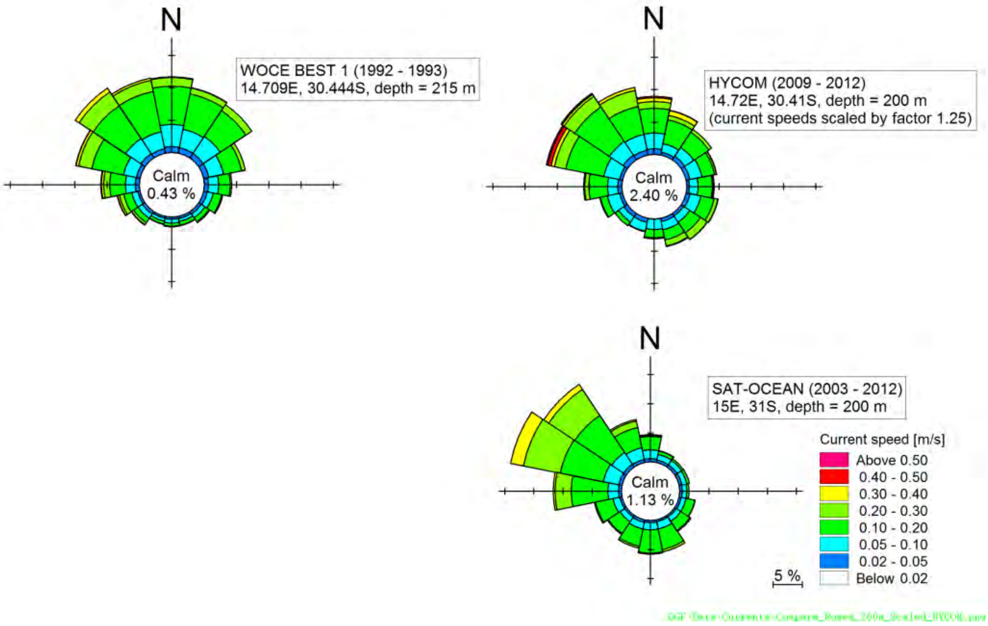


Figure 2-6: *Comparison of HYCOM and SAT-OCEAN hindcast data with WOCE BEST 1 measured currents. Current roses at water depth of approximately 200 m.*

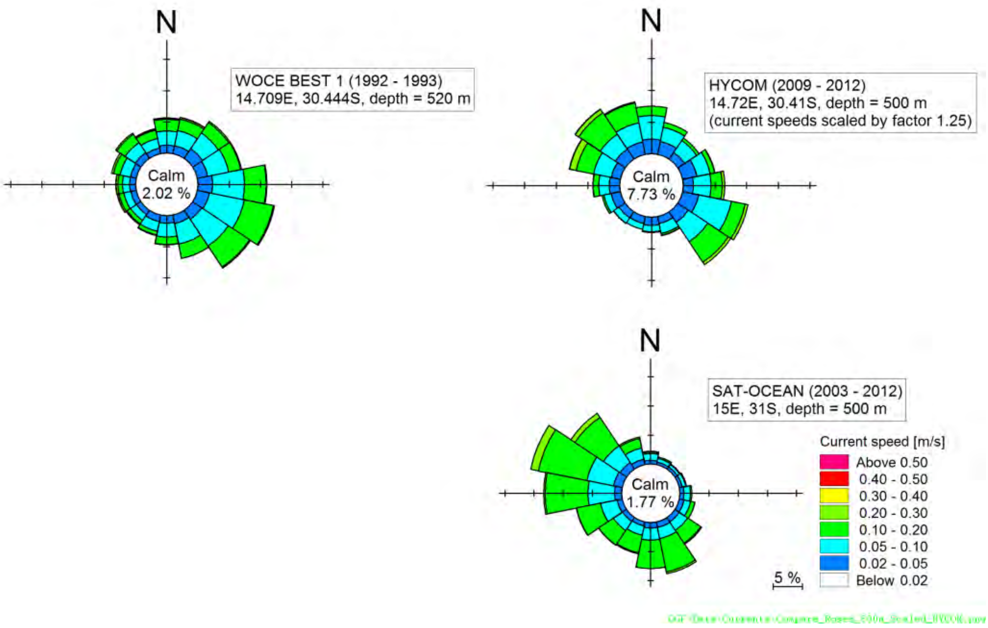


Figure 2-7: *Comparison of HYCOM and SAT-OCEAN hindcast data with WOCE BEST 1 measured currents. Current roses at water depth of approximately 500 m.*

Probability of non-exceedance (%)	Current speed (m/s)					
	Measured 215 m	HYCOM 200 m	SAT-OCEAN 200 m	Measured 520 m	HYCOM 500 m	SAT-OCEAN 500 m
0	0.01	0.00	0.00	0.01	0.00	0.00
30	0.09	0.09	0.09	0.06	0.04	0.07
50	0.12	0.12	0.13	0.08	0.06	0.10
70	0.16	0.16	0.17	0.10	0.10	0.13
80	0.19	0.19	0.20	0.12	0.11	0.15
90	0.23	0.24	0.25	0.15	0.14	0.17
95	0.27	0.29	0.28	0.18	0.18	0.19
99	0.35	0.42	0.33	0.25	0.25	0.22
100	0.48	0.56	0.41	0.39	0.33	0.28

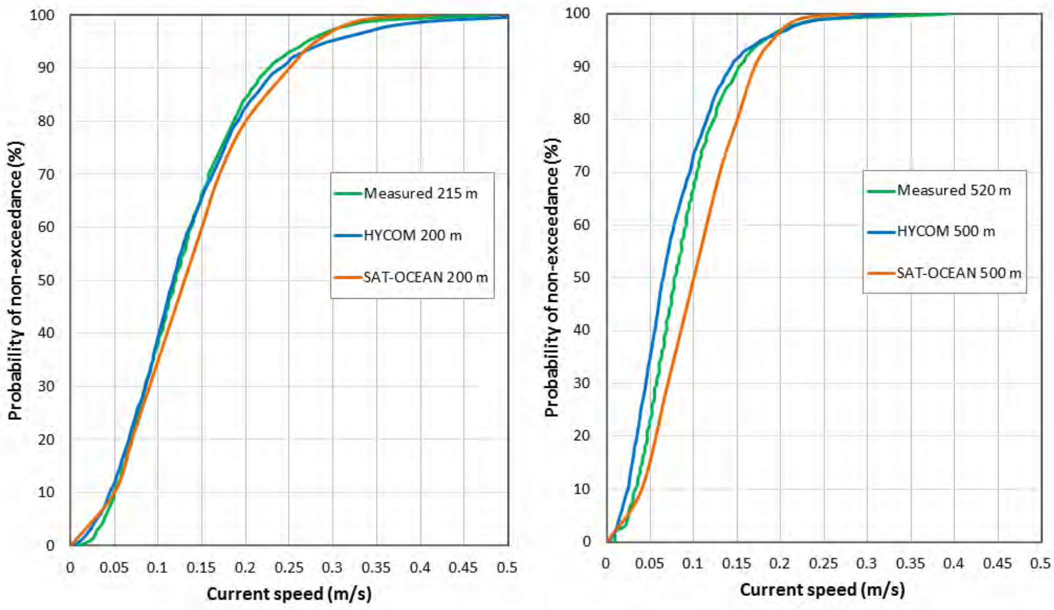


Figure 2-8: *Comparison of HYCOM and SAT-OCEAN hindcast data with WOCE BEST 1 measured currents. Current speed histograms at water depths of approximately 200 m and 500 m.*

It must be noted that the HYCOM data is provided at 24 hourly intervals, which is at sufficient resolution to resolve the background flow (the Benguela current), but it cannot resolve any daily fluctuations in the current fields. Analysis of the WOCE BEST 1 measurements does indeed indicate diurnal rotary currents, superimposed on the background flow. Inspection of the SAT-OCEAN hindcast data shows that although the data is at a temporal resolution of 3 hours, the strong diurnal signal observed in the measurements is not evident in this dataset either.

These diurnal rotary currents manifest themselves as small rotary deviations along the strong advection due to the background flow. An example of this concept is shown in Figure 2-9, which provides tracks of drifter buoys released in the Southern Atlantic Ocean (Pazos, et al., 2006). Although not within the study area, the tracks serve to indicate the large scale advection due to the background flow (including the mesoscale eddies, which are resolved in the hindcast current fields), as well as the small rotary deviations off the large scale advection, representing the diurnal rotary currents.

Molecular diffusion due to unresolved turbulence or eddies is typically modelled as dispersion. As the diurnal rotary currents result in relatively small deviations from the advection due to the background flow, this unresolved process has been assumed to be included in the modelled dispersion for this study.

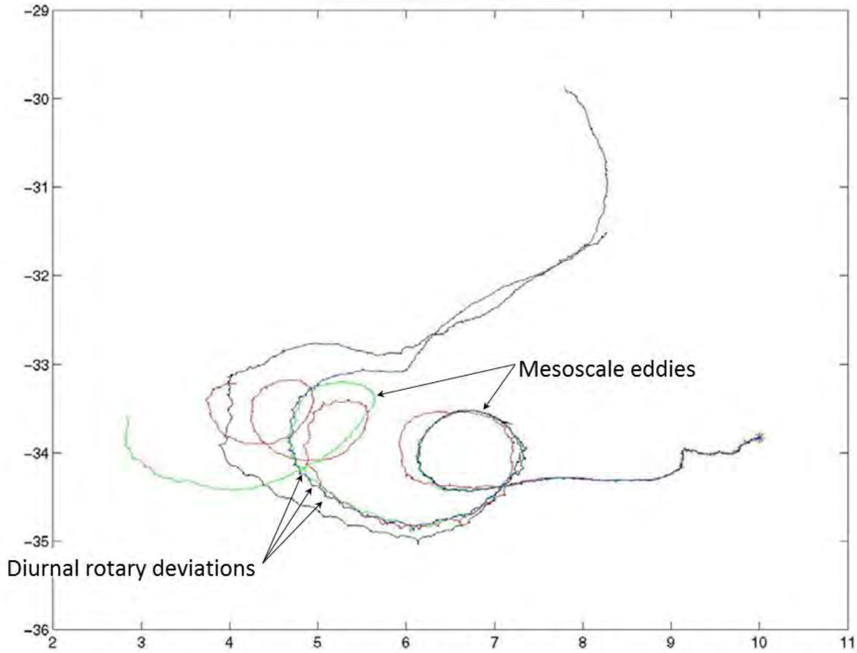


Figure 2-9: *Example of drifter tracks in the Southern Atlantic Ocean from 18 July 2006 to mid-September 2006* ***(Pazos, et al., 2006)****. The horizontal and vertical axes indicate degrees longitude and latitude respectively.*

Given the favourable comparison of the overall statistics of the scaled HYCOM data with the WOCE BEST 1 current measurements, and the ability to model the diurnal rotary currents not resolved in the hindcast data as a dispersive process, the scaled HYCOM currents were accepted for use as input for the oil spill and drill cuttings modelling for this study.

2.3.2 Spatial Variation of Currents

Figure 2-10 provides an example of a HYCOM current field at 10 m water depth at an instance in time. The presented example indicates a number of mesoscale eddies, resulting in considerable variation in current speed and direction over the domain.

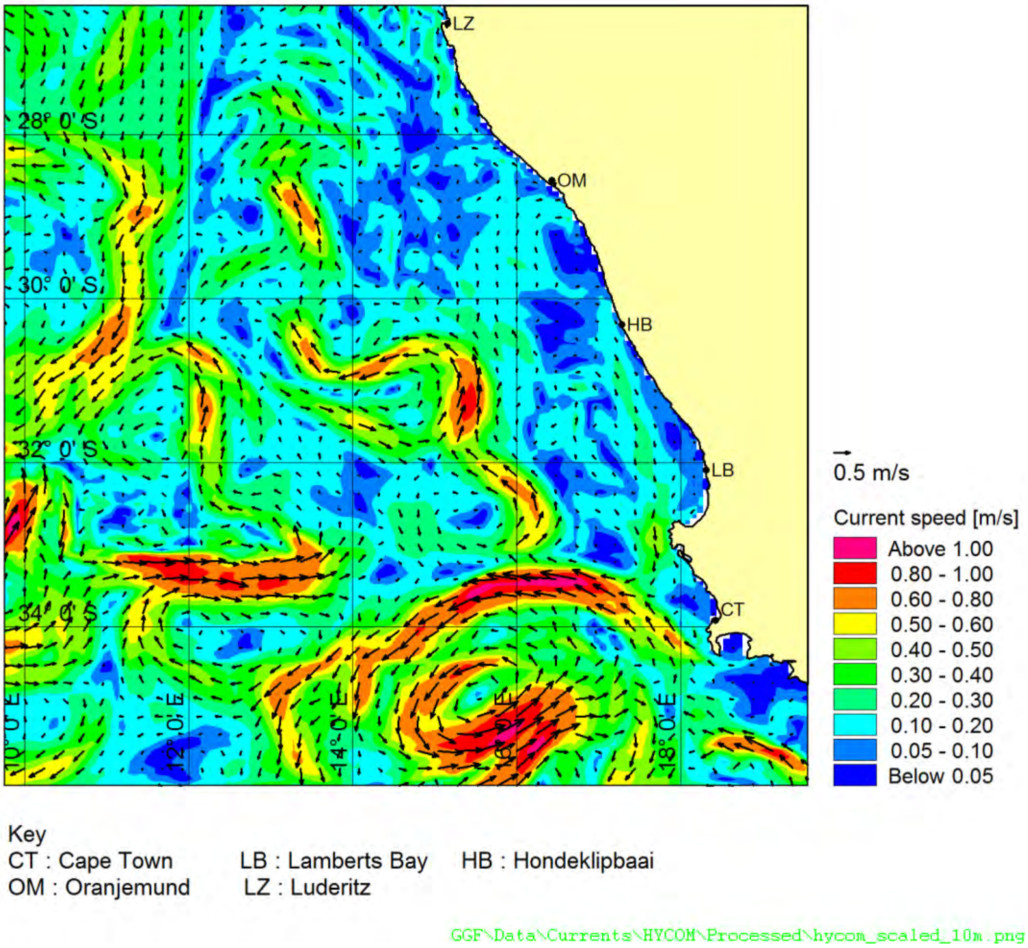


Figure 2-10: *Example of a scaled HYCOM current field at 10 m water depth, highlighting the potential for spatial variation of currents at an instance in time.*

Figure 2-11 presents annual current roses at 10 m water depth at selected locations over the domain of the study area. There is some evidence of wind induced currents at this level, resulting in north-westerly current directions, although the current speeds and directions are highly variable over the considered area. The spatial variation in the hindcast currents highlights the importance of modelling space and time varying current fields, rather than seasonally averaged currents.

Figure 2-12 presents scaled HYCOM current roses at coordinates 15°E, 31°S for selected depths. The data indicates considerable variation in both current speed and direction with depth. Current speeds tend to decrease with depth, while directions rotate from predominantly north-westerly directions at the surface to south-easterly directions near the seabed.

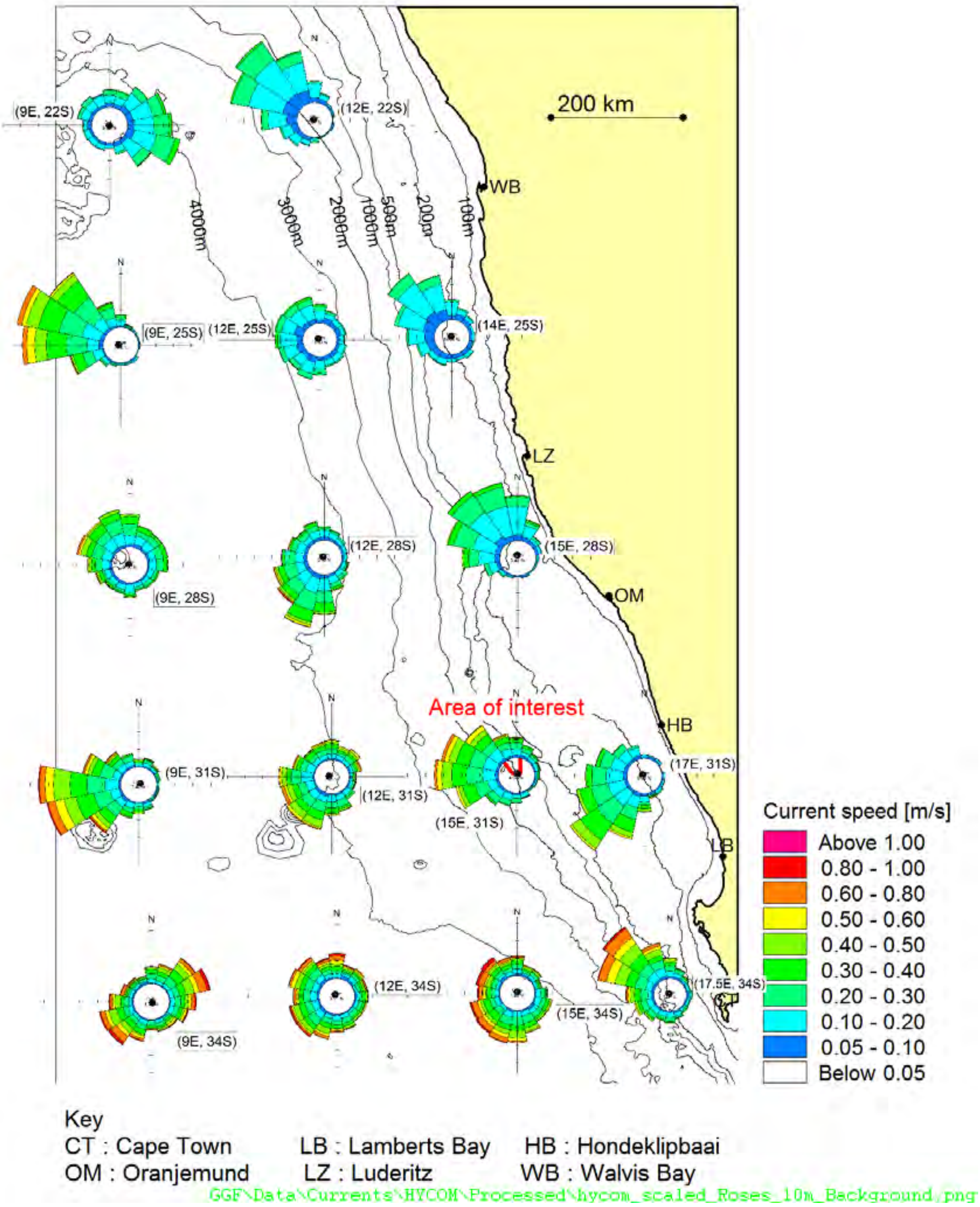


Figure 2-11: *Scaled HYCOM current roses at 10 m water depth over the domain of the study area, highlighting the spatial variation in the annual current climate.*

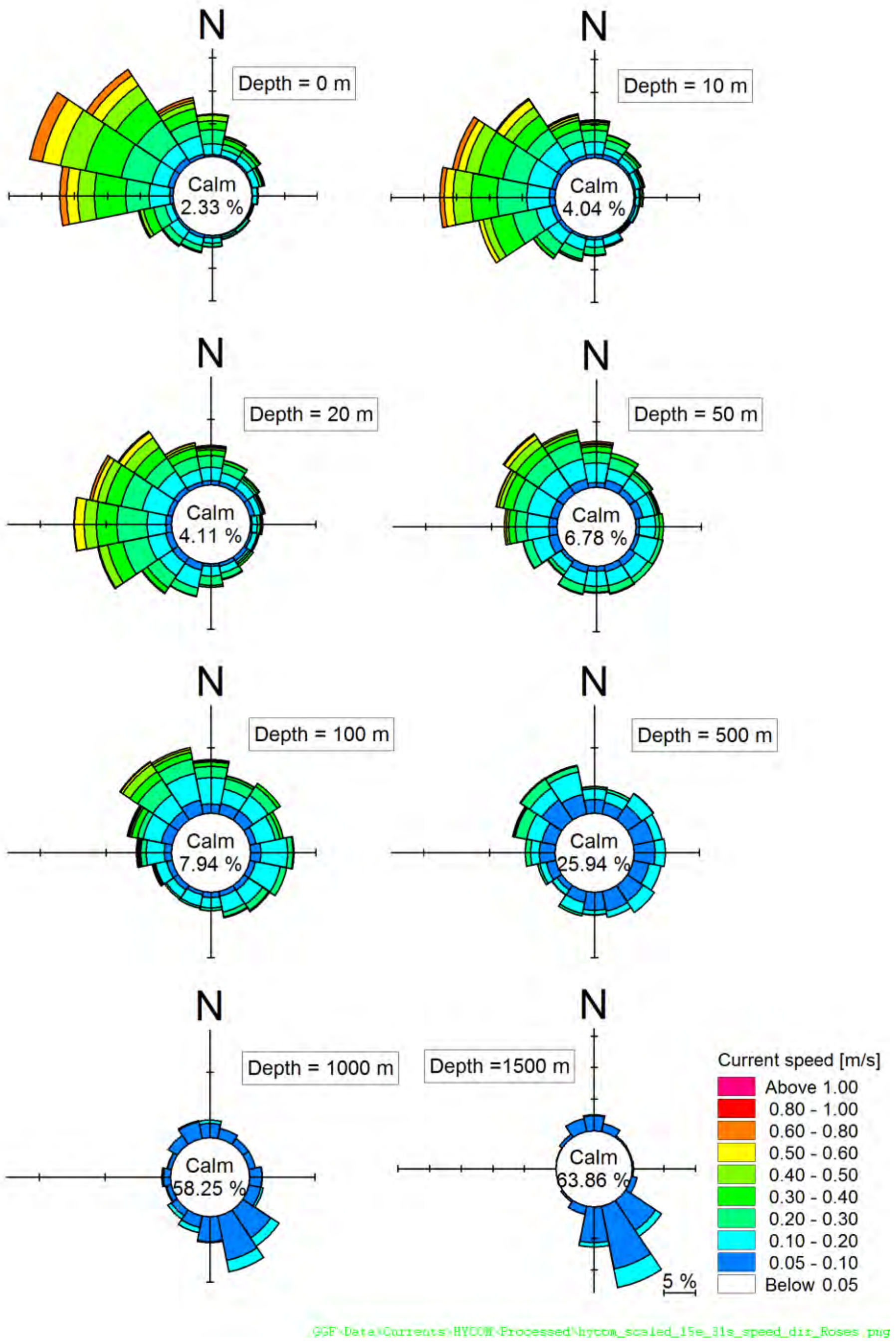


Figure 2-12: *Variation of scaled HYCOM current roses with depth at location 15E, 31S.*

2.3.3 Seasonal Variation of Currents

Only two seasons have been considered for this study, namely austral summer and winter. Summer is defined as the months of October through to March, while winter is defined as the months of April through to September. Figure 2-13 presents the seasonal current roses for the scaled HYCOM hindcast data at location 15°E, 31°S, at two selected depths. The data indicates some seasonality, with more pronounced westerly currents near the surface during summer, due to stronger south-easterly winds over this time of the year (Figure 2-5). The seasonality in currents becomes less pronounced with depth.

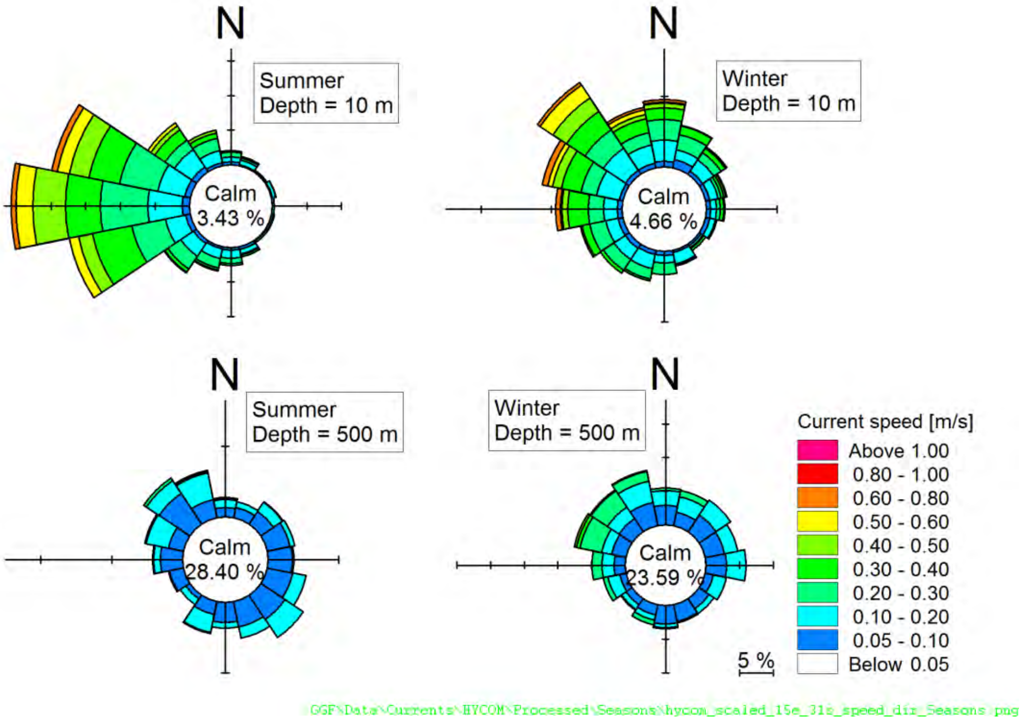


Figure 2-13: *Seasonal current roses for HYCOM hindcast data at location 15°E, 31°S.*

3. DRILL CUTTINGS

3.1 Background

The term 'drill cuttings' refers to the sediment removed from below the seabed as a result of drilling operations required to access the oil reservoir. Drilling is undertaken in a number of sections, with the drill diameter decreasing for deeper sections. The sediment removed from the drilling of the initial section is discharged directly onto the seabed, in the vicinity of the drilling location. Drilling of subsequent sections requires the cuttings to be brought to the surface through the drilling pipe. Once at the surface, the cuttings must first be separated from the drilling mud. The drilling mud is re-used, while the treated drill cuttings are discharged at the sea surface.

This section of the report presents the modelling undertaken to simulate the advection and dispersion of drill cuttings from release at the surface to deposition on the seabed. The aim of the drill cuttings modelling is to determine the thickness and extent of the deposited sediment on the seabed. The accidental release of drilling muds at the surface has not been considered as part of this study.

As described in Section 1.2.1, should the exploration well encounter hydrocarbons, an appraisal well would be drilled at least one year later. In this section the cuttings from one well has been modelled. Should a second well be drilled close to the first well then the impact in terms of cuttings deposited on the seabed can conservatively be assumed to be cumulative, although over time the deposited cuttings may sink into the seabed or be redistributed during episodic strong current events.

3.2 Model Description

The drill cuttings modelling was undertaken using the MIKE 3 Particle Tracking Model. The model is part of the 'MIKE by DHI' coupled modelling system developed by DHI in Denmark. The application of the model is described in the User Manual (DHI, 2012b).

The model uses the Lagrangian discrete parcel method on a regular rectangular three-dimensional numerical domain. Space and time-varying currents are specified from a pre-defined current database. Particles are released into the water column at a specified location, with each particle having a specified settling velocity and associated mass of sediment, dependent on the defined discharge rate. Once the particles are released in the water body, their discrete path due to advection by the currents and random walk dispersion is followed and recorded as a function of time relative to the reference grid system fixed in space. The density distribution of the ensemble can be interpreted as the concentration of the particles. The primary model output is the deposition thickness on the seabed. Re-suspension of deposited sediment from the seabed is included in the model, but was not used in this study, due to the generally low seabed currents in the vicinity of the proposed well locations.

3.3 Model Setup

3.3.1 Computational Mesh

The MIKE 3 Particle Tracking Model requires input hydrodynamics on a three dimensional regular grid. The horizontal grid resolution of the model for this study is 1 500 m, which is considered adequate to reasonably resolve the bathymetry in the area of interest. As the raw HYCOM current fields are on a 1/12˚ horizontal grid (roughly 8000 m), HYCOM currents were mapped to the input hydrodynamic file using an inverse weighting algorithm. The vertical grid resolution of the input hydrodynamics is 100 m. As the HYCOM data includes a number of layers in the top 100 m in the water column, the data was analysed to determine the layer most representative of the top 100 m, as it is desirable for a falling particle to be advected by the average current over this depth. As such, the HYCOM data at 20 m was chosen as the surface layer of the input hydrodynamic file (Figure 2-12). For depths greater than 100 m, HYCOM data at corresponding depths were mapped to the input hydrodynamic file. As discussed in Section 2.3.1, all raw HYCOM current speeds have been scaled by a factor of 1.25, to bring the hindcast current speeds more in line with the observed measurements.

The model allows for the output to be recorded on a finer grid than the input hydrodynamics and bathymetry. The model output of bed thickness presented herein has been recorded on a 300 m horizontal grid.

3.3.2 Dispersion Parameters

The model parameters governing the molecular diffusion due to unresolved turbulence, eddies and diurnal rotary currents (i.e. dispersion) need to be included in the drill cuttings model. As there is some uncertainty regarding these parameters, three dispersion settings were modelled, representing 'low', 'medium' and 'high' dispersion respectively. The modelled dispersion settings are presented in Table 3-1.

Table 3-1: *Modelled dispersion parameters*

Parameter	Low	Medium	High
Horizontal dispersion coefficient (m^2/s)	0.5	5	10
Vertical dispersion coefficient (m^2/s)	5×10^{-5}	5×10^{-4}	1×10^{-3}

3.3.3 Location of Well

The location of the proposed oil well is limited to the area of interest for well drilling, introduced in Figure 1-1. Two locations within this area have been considered for the modelling of drill cuttings in this study, namely a 'shallow well' and a 'deep well'. The coordinates of these locations are detailed in Table 3-2, and shown in Figure 3-1.

Table 3-2: *Modelled well locations*

Description	Geographical		WGS84 UTM 33S		Depth
	Longitude (deg)	Latitude (deg)	X (m)	Y (m)	(m)
Shallow well	15.000 E	30.750 S	500000.0	6598103.8	1 800
Deep well	14.850 E	30.850 S	485657.7	6587012.0	2 040

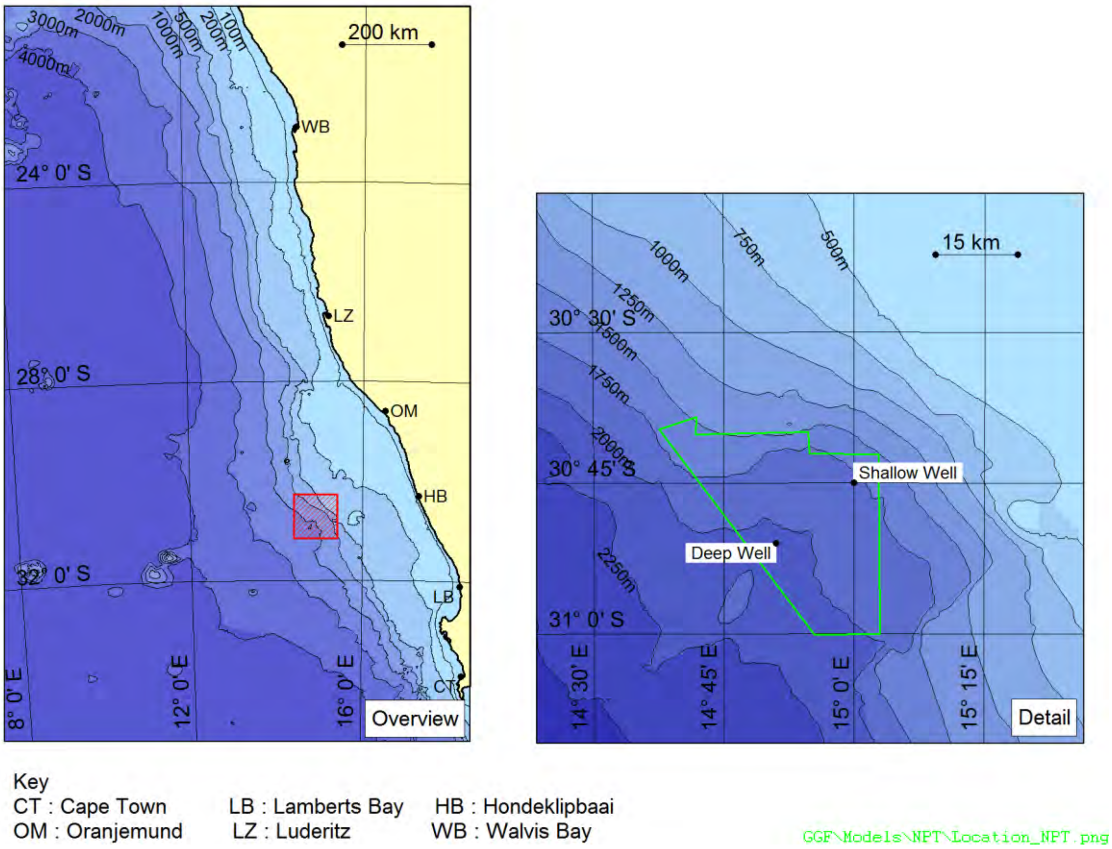


***Figure 3-1:** Locality plan. Red square shows the cuttings model output area. The detailed view of the red square (right) shows the area of interest for well drilling in green with the modelled shallow and deep well locations indicated.*

3.4 Discharge Scenario

The modelling of the release of drill cuttings requires an estimation of the rate of discharge for each drilling section, and the duration over which the discharge is released. Table 3-3 presents the modelled discharge scenario, provided by the client.

***Table 3-3:** Modelled drilling program (provided by client)*

Section	Drill diameter (in)	Depth of section (m)	Volume (m^3)	In-situ porosity (%)	Sediment density (kg/m^3)	Mass (kg)	Drilling duration (days)	Cuttings load (kg/s)	Discharge location
1	26	1000	342.5	25	2650	680 787	2	3.94	Seabed
2	17.25	800	120.6	20	2650	255 718	4	0.74	Surface
3	12.25	450	34.2	20	2650	72 540	4	0.21	Surface
4	8.5	400	14.6	15	2650	32 985	8	0.04	Surface

Note that the drilling durations in Table 3-3 are the durations that drilling is actually occurring and when cuttings are discharged. It thus excludes downtime and well testing time.

Table 3-4 provides the modelled grain size distribution for the drill cuttings, assumed to be constant for each drill section. The modelled grading distribution was adapted from those originally provided by the client, to include a grain size of 0.2 mm. This was done to provide a smoother deposition pattern on the seabed. The grain size distribution applies to the drill cuttings from the main hole, i.e. the risered section for which the cuttings are released at the water surface.

Table 3-4: *Modelled grading distribution (adapted from those provided by client), and associated settling velocities*

Grain size (mm)	Volume (%)	Settling Velocity (m/s)	Time to fall 1800 m (hours)
0.1	17	0.0065	77.1
0.2	16	0.0216	23.1
0.5	17	0.0616	8.1
1	25	0.1010	5.0
5	20	0.2449	2.0
10	5	0.3464	1.4

Settling velocities (v_s) have been calculated as a function of the diameter of the grain size (d), as well as the densities of the sediment (ρ_s = 2650 kg/m^3) and sea water (ρ_w = 1025 kg/m^3). For 0.1 mm <= d <= 1 mm, the Budryck equation is used:

$$v_s = \frac{8.925}{d}\left[\sqrt{1 + 95\frac{\rho_s - \rho_w}{\rho_w}d^3} - 1\right]$$

while for d > 1 mm the Rittinger equation is used:

$$v_s = \frac{8.925}{d}\left[\sqrt{1 + 95\frac{\rho_s - \rho_w}{\rho_w}d^3} - 1\right]$$

The discharge scenario described above was modelled a sufficient number of times to adequately sample the statistical variability of the environmental data, i.e. the current speeds and directions. To this end, each model setup has been simulated 180 times, with the starting date incrementing 8 days with each simulation. This ensured the complete sampling of the four year HYCOM current database (2009 to 2012 inclusive). Statistics over all simulations could then be calculated.

3.5 Results

The model results presented herein have been subdivided into results for the shallow and deep well locations. The effect of the modelled dispersion settings and season in which discharge takes place is provided for each well location. The effect of the season on the model results was assessed by considering only the model results where the majority of the discharge occurred in the season of interest. As described in Section 2.2.3, summer is defined as the months of October through to March, while winter is defined as the months of April through to September.

The raw model output from the particle tracking model is the concentration of sediment (kg/m^2) on the seabed in each grid cell. The modelled bed concentrations have been converted into bed thickness assuming a sediment density of 2650 kg/m^3, and a deposited sediment porosity of 0.4 (i.e. a dry bulk density of 2650x(1-0.4) = 1590 kg/m^3).

It has been assumed that for the cuttings discharged at the seabed from the top holes (drill section 1 in Table 4-1), *"will all settle within a 120 m radius around the bore hole",* based on information provided by the client. As the output grid size is 300 m, the modelled deposition of sediment from drill section 1 was evenly distributed within one grid cell of the well location for all simulations (resulting in an average thickness of 4.8 mm). In reality, the deposition pattern would be approximately conical around the drill location. Assuming a radius of 120 m, the estimated mass of sediment from Table 3-3 would hypothetically result in a cone of height 28.4 mm.

The locality plan of the area used to display the drill cuttings model results corresponds to the red square shown in Figure 3-1.

3.5.1 Shallow Well Location

Figure 3-2 provides an example of the modelled deposition thickness from one of the 180 individual simulations, and presents the sensitivity of the model results due to the three considered dispersion settings (Table 3-1). Finer grain sizes take longer to settle out than larger grain sizes (Table 3-4), and therefore tend to be deposited further from the location of the drill well. The isolated zones of deposition evident in Figure 3-2 reflect the discrete grain size classes used in the model.

The longer settling time of the finer fractions also makes them more sensitive to the model dispersion settings, with higher dispersion coefficients resulting in cuttings being spread over a larger area. Figure 3-2 indicates that, for the finer grain sizes, the 'high' dispersion setting can lead to deposition thicknesses lower than the minimum considered threshold of 0.001 mm, and consequently a smaller observed footprint further from the site.

Figure 3-3 provides plots of the maximum modelled deposition thickness for each grid cell, calculated over all 88 summer and all 92 winter simulations, and shows the sensitivity of the results to dispersion, as well as the season in which discharge takes place. As the plots show the maximum modelled deposition thickness calculated over all relevant simulations, the deposition footprint is much larger than would be expected due to an individual simulation. The plots do however quantify the limiting region within which cuttings may be deposited. The roughly north-west to south-east orientation of the modelled depositions reflects the observed current directions through the water column (Figure 2-12). The results are not particularly sensitive to the season in which discharge takes place, owing to the observed lack of seasonality over much of the water column (Figure 2-13). The apparent reduction in the deposition footprint with increased dispersion is as a result of the modelled deposition thicknesses falling below the 0.001 mm threshold for smaller grain sizes, which tend to settle out further from the well location.

Table 3-5 quantifies the modelled extent of the deposition footprint for a number of threshold thicknesses. The mean and maximum footprint areas for an individual simulation were calculated over all 88 summer and all 92 winter simulations. Only threshold thicknesses up to 1 mm are referenced, as the modelled deposition thickness is less than this value for all model results in all grid cells other than the grid cell containing the well location (a deposition footprint of 0.09 km^2 corresponds to an area of 300 m x 300 m i.e. one grid cell). As discussed in Section 3.5 the it has been assumed that the cuttings discharged at the seabed from the top holes will all settle within a 120 m radius (area of 0.07 km^2) around the bore hole; however 0.09 km^2 is the minimum area resolved by the model and thus the minimum area reported in Table 3-5 and Table 3-6 is 0.09 km^2. The reason is that the focus of the modelling was to simulate the deposition of cuttings released at the water surface rather than from the top holes.

Table 3-5: *Modelled extent of deposition footprint for the shallow well location for any individual simulation.*

Deposition thickness (mm)	Extent of deposition footprint (km^2)											
	Low dispersion				Medium dispersion				High dispersion			
	Summer		Winter		Summer		Winter		Summer		Winter	
	Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean
> 0.001	27.09	21.48	32.4	21.64	25.92	21.43	30.33	22.44	28.62	23.74	29.34	24.34
> 0.002	14.31	10.87	17.19	11.51	14.76	12.36	17.37	12.69	15.39	13.55	18.63	13.7
> 0.005	6.93	4.79	7.56	5.22	7.56	5.68	9.27	6.07	8.73	7.08	9.72	7.38
> 0.01	4.14	2.64	4.77	2.90	4.95	3.76	5.04	3.92	4.86	4.43	5.22	4.52
> 0.02	2.34	1.63	2.52	1.74	2.61	2.27	2.7	2.26	2.79	2.44	2.79	2.30
> 0.05	1.17	0.88	1.17	0.86	1.17	0.88	1.17	0.78	0.90	0.65	0.90	0.54
> 0.1	0.72	0.49	0.81	0.45	0.45	0.27	0.45	0.22	0.09	0.09	0.09	0.09
> 0.2	0.36	0.23	0.45	0.21	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09
> 0.5	0.18	0.09	0.18	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09
> 1	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09

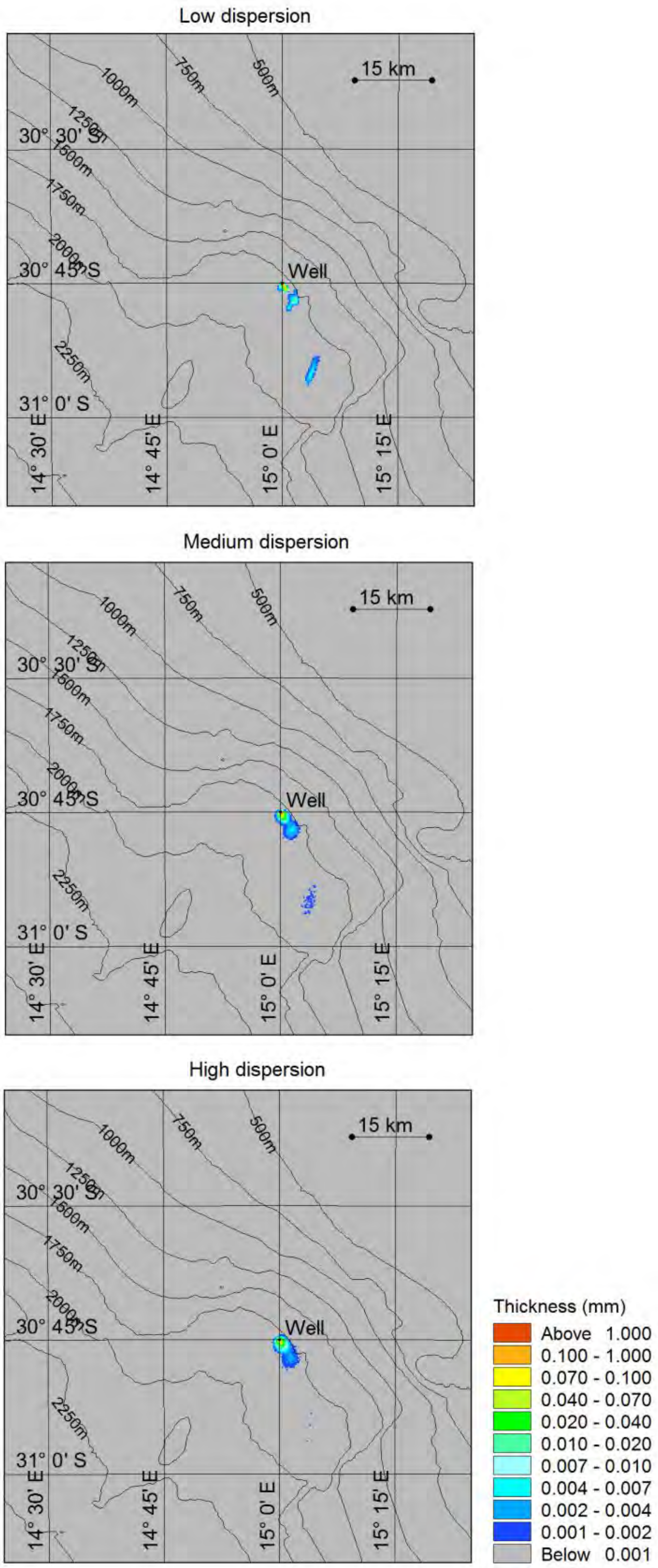


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Figure 3-2: *Example of modelled deposition thickness due to an individual simulation for the shallow well location. Plot shows the effect of dispersion settings on the model results. The locality plan of the area used to display the model results is shown in Figure 3-1.*

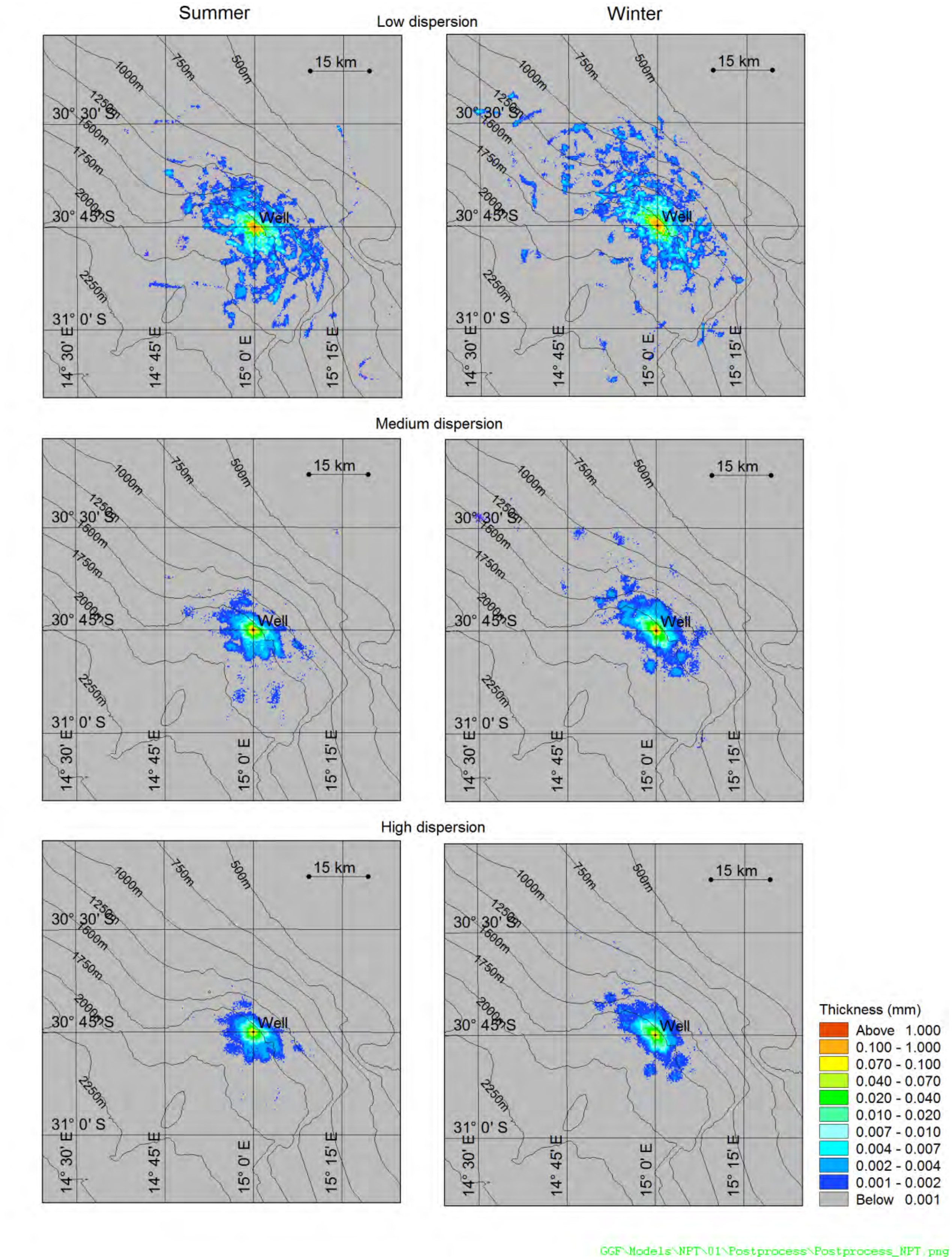

Figure 3-3: *Maximum modelled deposition thickness in each grid cell over all simulations for the shallow well location. Plot shows the effect of both the season and dispersion settings on the model results. The locality plan of the area used to display the model results is shown in Figure 3-1.*

3.5.2 Deep Well Location

Figure 3-4, Figure 3-5 and Table 3-6 present model results for the deep well location, and are analogous to those presented for the shallow well location above. The results are relatively insensitive to the location of the drilling works, although the deeper location has the same effect as slightly higher dispersion, as particles are able to 'spread out' further as they fall deeper through the water column. The general comments regarding the shallow well location model results apply equally to the deep well location model results, and are thus not repeated here.

Table 3-6: *Modelled extent of deposition footprint for the deep well location for any individual simulation.*

Deposition thickness (mm)	Extent of deposition footprint (km^2)											
	Low dispersion				Medium dispersion				High dispersion			
	Summer		Winter		Summer		Winter		Summer		Winter	
	Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean
> 0.001	29.07	22.08	31.32	22.07	29.79	22.87	33.3	23.33	29.43	25.13	32.49	25.28
> 0.002	17.82	11.46	17.19	11.66	16.29	12.77	18.72	13.06	17.28	13.75	20.43	14.11
> 0.005	7.11	4.93	8.28	5.28	8.55	6.14	9.45	6.5	9.09	7.57	9.54	7.73
> 0.01	4.23	2.77	4.41	2.98	4.95	4	5.04	4.04	5.22	4.59	5.04	4.54
> 0.02	2.34	1.74	2.61	1.81	2.7	2.32	2.61	2.19	2.7	2.33	2.7	2.12
> 0.05	1.17	0.86	1.26	0.85	1.17	0.78	1.08	0.68	0.9	0.49	0.99	0.42
> 0.1	0.72	0.44	0.72	0.42	0.45	0.2	0.36	0.17	0.09	0.09	0.09	0.09
> 0.2	0.36	0.19	0.36	0.18	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09
> 0.5	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09
> 1	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09

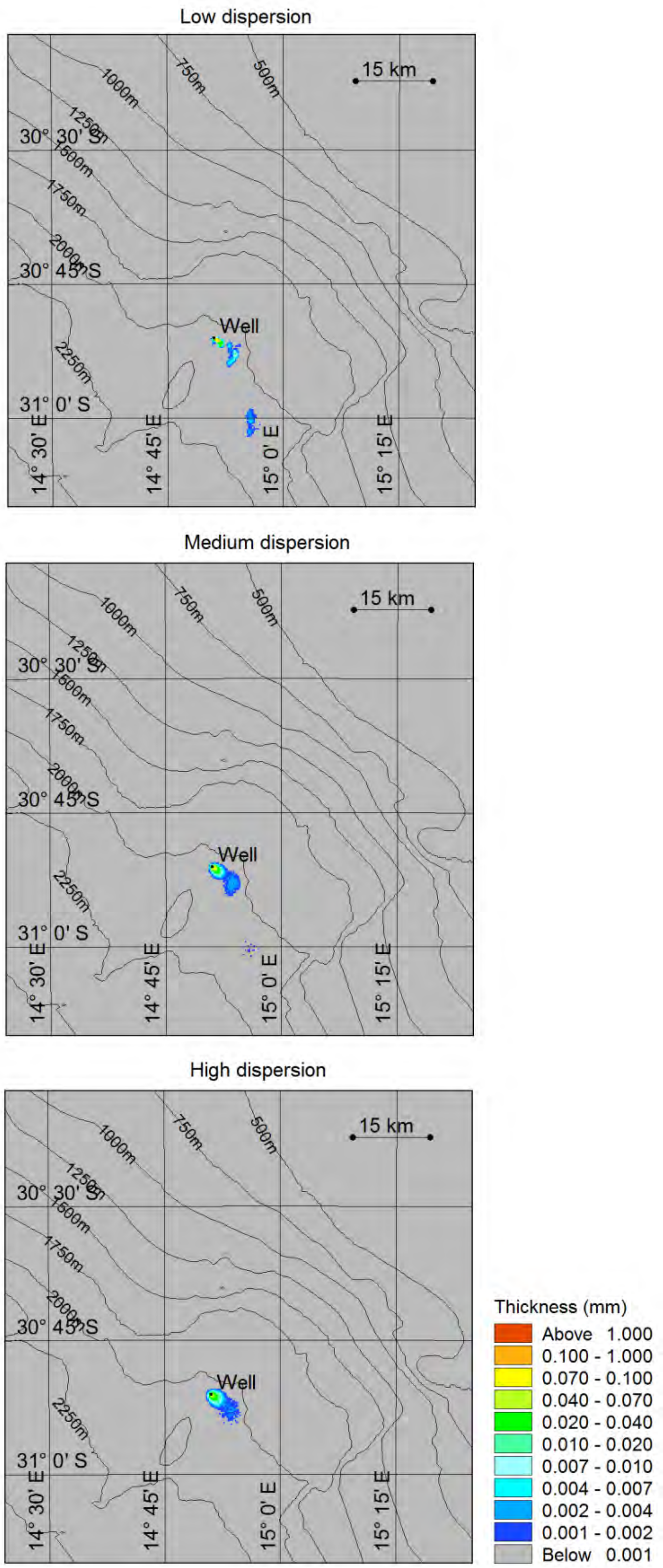

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Figure 3-4: *Example of modelled deposition thickness due to an individual simulation for the deep well location. Plot shows the effect of dispersion settings on the model results. The locality plan of the area used to display the model results is shown in Figure 3-1.*

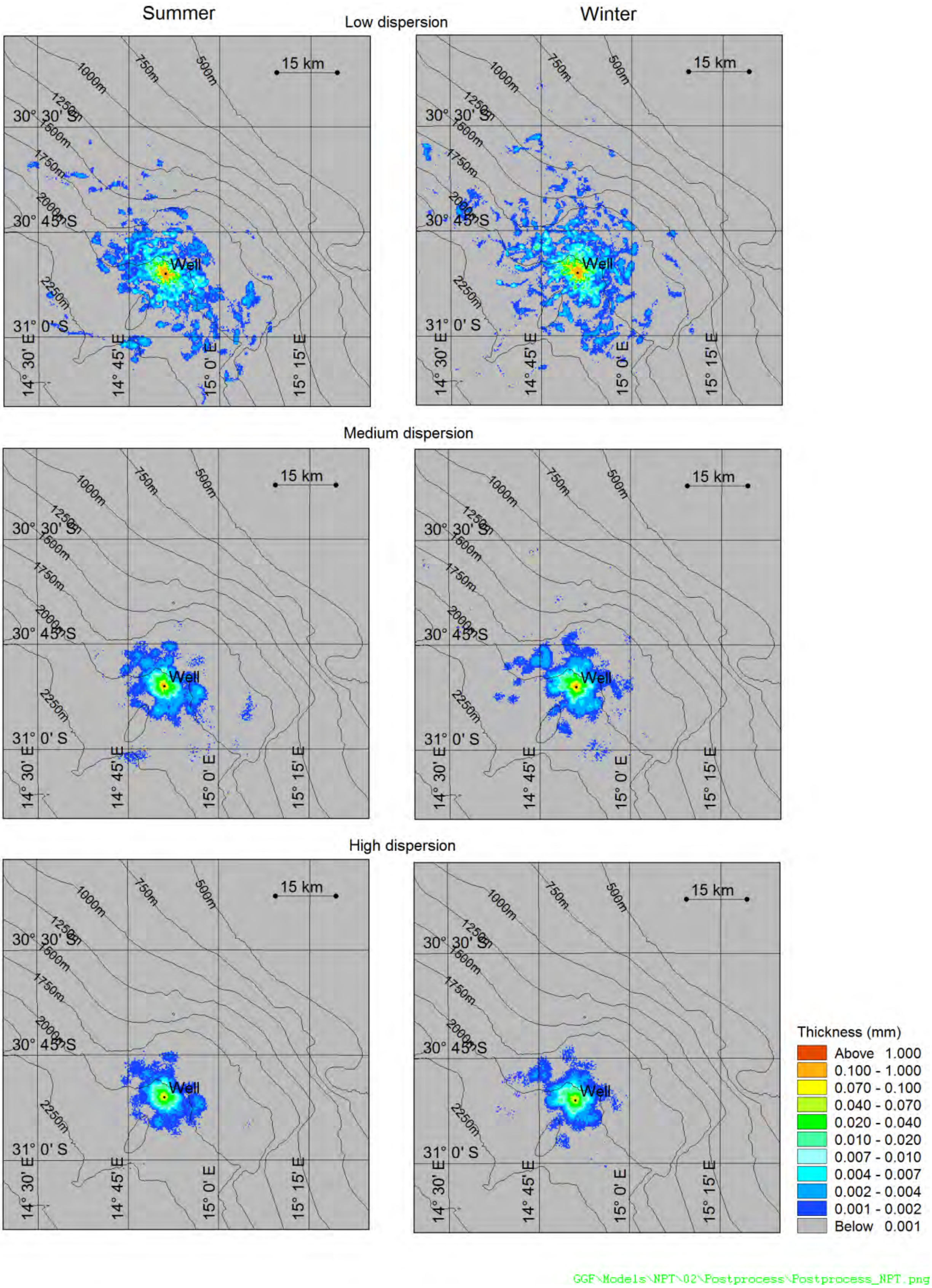


Figure 3-5: *Maximum modelled deposition thickness in each grid cell over all simulations for the deep well location. Plot shows the effect of both the season and dispersion settings on the model results. The locality plan of the area used to display the model results is shown in Figure 3-1.*

3.6 Discussion

The drill cuttings model results show that the large depths at the well site (1 800 to 2 040 m) combined with the moderate to strong current speeds (at 200 m depth the median speed is 0.12 m/s and the maximum 0.56 m/s) and relatively low mass of cuttings discharged (1 042 t) result in the drill cuttings being spread over a large area, with relatively low deposition thicknesses of less than 1 mm predicted for distances greater than about 150 m from the location of the well. The footprint where the deposition thickness exceeds 0.001 mm is predicted to be less than 33 km^2 and occurs within a distance of 50 km from the well.

The expected deposition pattern and thickness is relatively insensitive to the choice of location of the well (shallow vs. deep), as well as to the season in which the drilling takes place.

The results of the drill cuttings modelling presented herein are intended to inform an estimate of the environmental impact of the proposed drilling works, addressed in a separate study. The results corresponding to 'medium' dispersion settings provide the best estimate model results. A conservative approach would be to consider the model results due to 'low' and 'high' dispersion settings as well, and use the results which have the largest environmental impact.

Should a second well be drilled close to the first well then the impact in terms of cuttings deposited on the seabed can conservatively be assumed to be cumulative, although over time the deposited cuttings may sink into the seabed or be redistributed during episodic strong current events.

4. OIL SPILLS

4.1 Background

Two small operational and two large oil spill scenarios have been modelled in order to predict the trajectory and fate of the oil. The inputs to the model include the bathymetry, currents and winds described in Section 2, and the oil spill scenarios described below. The model outputs include the probability of oiling of the sea surface, the subsurface (in the case of blowouts at the seabed) and the shoreline, as well at the minimum time to oiling.

4.2 Oil Spill Scenarios

Small operational oil spills may occur at the drill vessel, for example during fuel transfer or due to the rupture of hydraulic lines. Large oil spills may occur due to a blowout at the wellhead on the seabed.

Although the probability of a well blowout is extremely low, it nonetheless provides the greatest environmental concern during drilling operations. A blowout can be caused by the uncontrolled flow of reservoir fluids into the wellbore, which results in a release of hydrocarbons to the sea. The primary safeguard against a blowout is the drilling fluid. The density of the fluid can be controlled to balance any abnormal formation pressures. Abnormal formation pressures are detected by primary well control equipment. The likelihood of a blowout is further minimised by employing a BOP, which is a secondary control system. The BOP is installed on the wellhead and is designed to close in the well if flow from the wellbore is detected. It can usually be operated from a number of stations on the drilling unit. This equipment is thoroughly inspected prior to installation and subsequently pressure and function tested on a regular basis. Advanced well intervention and capping equipment is available in Saldanha Bay for deployment in the event of a subsea well control incident. This unique piece of equipment is only stored in four international locations, namely Norway, Brazil, South Africa and Singapore and is maintained ready for immediate mobilisation in the event of an incident. The subsea well intervention system includes four capping stacks to shut-in an uncontrolled subsea well and two hardware kits to clear debris and apply subsea dispersant at a wellhead.

The following four oil spill scenarios were provided by the client and have been modelled in this study:

Table 4-1: *Modelled oil spill scenarios (provided by client)*

Oil spill number	Description	Oil type	Vertical position of spill	Location of spill	Duration of spill	Rate of oil release	Total oil discharged
1	Operational spill of hydraulic fluid, e.g. due to rupture of a hydraulic line on the drill vessel.	Hydraulic fluid	On water surface at drill vessel	15.000 E, 30.750 S	Instantaneous	Instantaneous	7.4 bbl = 1 t
2	Operational spill of diesel, e.g. due to hose rupture during fuel transfer from support vessel to drill vessel.	Diesel fuel oil	On water surface at drill vessel	15.000 E, 30.750 S	Instantaneous	Instantaneous	74 bbl = 10 t
3	Large blowout at seabed capped after 5 days	Light to medium Crude	At wellhead on seabed	15.000 E, 30.750 S	5 days	80 000 bbl/day = 10 811 t/day	0.4 million bbl = 54 055 t
4	Large blowout at seabed capped after 20 days	Light to medium Crude	At wellhead on seabed	15.000 E, 30.750 S	20 days	80 000 bbl/day = 10 811 t/day	1.6 million bbl = 216 223 t

To place the blowout spill scenarios in context, the Deepwater Horizon/Macondo blowout in the Gulf of Mexico in 2010 flowed for 87 days and the total oil discharge has been estimated at 4.9 million barrels

(National Response Team, 2011). Subsequent to the Macondo blowout the oil and gas industry invested in the construction of four sets of advanced well intervention and capping equipment. Considering the availability of this well capping equipment in Saldanha Bay, a 20-day blowout spill with a total oil discharge of 1.6 million barrels assessed in this study can be considered a worst case scenario.

The location of the proposed oil well is limited to the area of interest for well drilling, as shown in Figure 3-1. One location in the landward corner of this area has been assumed for the oil spill release, since this location will result in the largest probability of shoreline oiling. The location is at 15.000 E, 30.750 S in a water depth of 1 800 m and is labelled as 'shallow well' in Figure 3-1.

As described in Section 1.2.1, should the exploration well encounter hydrocarbons, an appraisal well would be drilled at least one year later. The oil spills described above could occur during the drilling of either the exploration or the appraisal well.

No spill response actions are included in the oil spill modelling, e.g. the use of dispersants, skimming, or burning.

4.3 Model Description

The oil spill modelling was performed using the MIKE 21/3 Oil Spill Model developed by DHI in Denmark. The application of the model is described in the User Manual (DHI, 2012c), while full details of the physical processes being simulated and the numerical solution techniques are described in the Scientific Documentation (DHI, 2012d).

The MIKE 21/3 Oil Spill Model is used for modelling the fate of oil discharged or accidentally spilled in lakes, estuaries, and coastal areas or to the open sea. The model describes the total amount of spilled oil as an assemblage of smaller oil amounts represented by individual oil track particles. These Lagrangian particles are advected by a pre-defined three-dimensional current field with an additional wind drift component in the case of oil at the water surface. Vertical oil movement is driven by differences in oil density and water density in both the upward and downward direction and is based on Stokes Law. Horizontal and vertical dispersion due to unresolved turbulence is modelled using the random walk method.

The following weathering processes can be included in the model: spreading, evaporation, dissolution, vertical oil dispersion, settling, biodegradation, dissolution and photo-oxidation. These weathering processes are illustrated in Figure 4-1, while the relative importance of these processes over time is schematised in Figure 4-2. Note that oil dispersion refers to the mixing of oil droplets into the water column and is a different process to the dispersion resulting from unresolved turbulence as described in the previous paragraph.

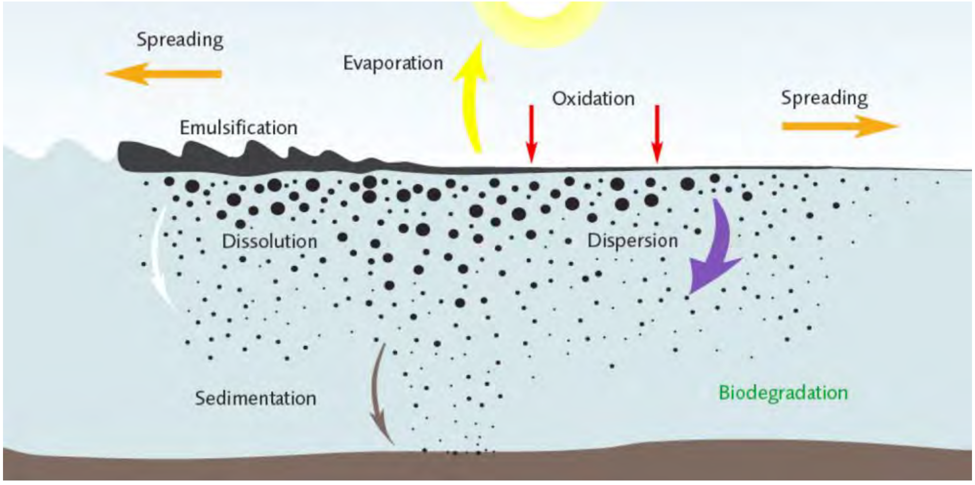


Figure 4-1: *Oil weathering processes* ***(ITOPF, 2002)***

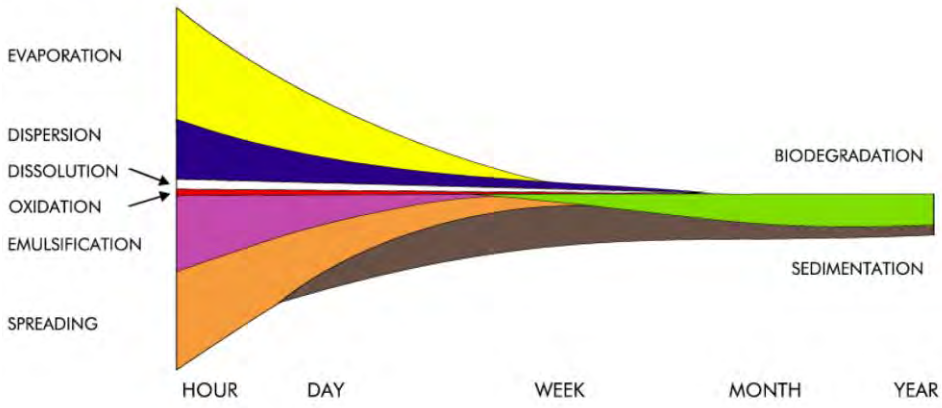


Figure 4-2: *A schematic representation of the fate of a crude oil spill showing changes in the relative importance of weathering processes with time - the width of each band indicates the importance of the process* ***(ITOPF, 2002)***

The model output comprises both particle tracks and concentration maps where the particles are mapped onto a three-dimensional grid as oil concentrations.

4.4 Model Setup

4.4.1 Oil Characterisation

In the model the oil is divided into two main fractions: a light volatile fraction of aromatics and other oil components with a molecular weight less than approximately 160 g/mol and a boiling point well below 300°C; and a heavy fraction (> 160 g/mol) with a boiling point above 250°C - 300°C. The volatile fraction is subject to all the weathering processes described in Section 4.3, whilst the heavy fraction is subject to all the weathering processes except evaporation. The model has detailed formulations for all the weathering processes, although in this study a parameterised approach was applied, as described below.

In the case of the small spill of hydraulic fluid, the dominant weathering process will be oil dispersion. This was modelled as a first order decay process, as detailed in Table 4-2.

In the case of the small spill of diesel, the dominant weathering process will be evaporation and oil dispersion. Evaporation was modelled according to the 'Model of Reed' (DHI, 2012d), where the evaporation rate is a function of vapour pressure, slick area, wind speed and particle diameter. The primary model input parameter for evaporation was the proportion of volatile oil fractions and the vapour pressure. The oil dispersion was modelled as a first order decay process, as detailed in Table 4-2.

In the case of the large blowout of crude oil at the seabed, all the weathering processes described in Section 4.3 will occur to some extent over the duration of the spill. As the blowout plume leaves the well on the seabed the momentum of the discharge as well as the buoyancy of the oil/gas mixture is anticipated to result in a rapid rise of the near-field plume. Gas hydrate formation and the entrainment of ambient water is however likely to result in the near-field plume being trapped in the order of 60 m above the seabed (Spaulding, et al., 2000). Thereafter the oil particles will rise towards the surface as a function of oil droplet diameter and the differences in oil and water density as determined by Stokes law. Due to the anticipated range of droplet sizes, six different oil droplet diameters have been applied in the model. Once the oil surfaces the volatile fraction will undergo evaporation, which was modelled according to the 'Model of Reed' (DHI, 2012d). The remaining processes of oil dispersion, dissolution, biodegradation, photo-oxidation and settling have been parameterised as a first order decay process. Due the uncertainty in the crude oil characteristics at the site, as well as uncertainties in the weathering behaviour of oil from a deepwater blowout (rather than a surface spill) and also uncertainties regarding the long-term (weeks to months) weathering due to oil dispersion, dissolution, biodegradation, photo-oxidation and settling, three different weathering rates have been modelled: fast, medium and slow weathering. Details are provided in Table 4-2.

Table 4-2: *Oil characterisation*

Parameter	Hydraulic fluid	Diesel fuel oil	Crude oil
API (1)	28.1	37.6	35.0
Oil density (kg/m^3)	887	837	850
Proportion volatile oil fractions (2) (%)	0	100	60
Proportion heavy oil fractions (3) (%)	100	0	40
Density volatile oil fractions (kg/m^3)	-	837	796
Density heavy oil fractions (kg/m^3)	887	-	931
Evaporation vapour pressure (atm) (4)	-	$2x10^{-5}$	$2x10^{-5}$
Rate of oil dispersion (half-life in days) (5)	2.0 (6)	0.6 (7)	-
Rate of oil dispersion/dissolution/biodegradation/photo-oxidation/settling – fast weathering scenario (half-life in days)	-	-	4 (8)
Rate of oil dispersion/dissolution/biodegradation/photo-oxidation/settling – medium weathering scenario (half-life in days)	-	-	10 (9)
Rate of oil dispersion/dissolution/biodegradation/photo-oxidation/settling – slow weathering scenario (half-life in days)	-	-	30 (10)
Droplet diameter for faction number 1/2/3/4/5/6 (um) (11)	-	-	50/80/150/250/500/1000
Rise speed for fraction number 1/2/3/4/5/6 (m/s) (12)	-	-	0.25/0.61/2.12/6.10/23.02/80.56
Time to surface for fraction number 1/2/3/4/5/6 (days) (13)	-	-	80/33/9.5/3.3/0.9/0.3

Notes:

(1) The American Petroleum Institute gravity scale, $API = \frac{141.5}{specific\ gravity} - 131.5$.

(2) Light volatile oil fraction with molecular weight less than approximately 160 g/mol and a boiling point well below 300°C.

(3) Heavy oil fraction (> 160 g/mol) with a boiling point above 250°C - 300°C.

(4) For a 10 m/s wind this results in approximately 90% of the volatile oil fraction evaporating within 2 days.

(5) The rate is expressed as the half-life, which is the time needed for 50% of the oil to disappear from the sea surface. After six half-lives have passed, about 1% of the oil will remain.

(6) Based on the dispersion rate of hydraulic oil with an API of 28.1 and a viscosity of 46.0 cSt at 40°C predicted by the ADIOS weathering model (NOAA, 2009).

(7) Based on dispersion rate of diesel fuel oil with an API of 37.6 predicted by the ADIOS weathering model (NOAA, 2009).

(8) Based on the half-life of a Group 3 oil (ITOPF, 2002).

(9) Based on previous oil spill modelling results in this region showing 18% of Bonny Light Crude remaining on the water surface 11 days after the end of the release (ASA, 2005).

(10) Based on the longest half-life reported in literature for microbial decay of the Deepwater Horizon oil spill (Reddy, 2012), i.e. non-evaporative weathering is assumed to be dominated by biodegradation. Note that in all cases the non-evaporative weathering is applied to both the subsurface as well as the surface oil.

(11) Based on droplet diameters modelled for an Ekofisk oil blowout (Spaulding, et al., 2000) and the Deepwater Horizon blowout (North, 2011). The four larger fractions will reach the surface rapidly (within 0.3 to 3.3 days) whilst the two smaller fractions will take longer than 30 days. This is consistent with the assumption used by (North, 2011) that for the Deepwater Horizon oil spill up to two thirds of the oil was either captured or found on the surface within a relatively narrow radius of the source.

(12) Based on Stokes law.

(13) Based on release depth of 1740 m, i.e. water depth of 1800 m less the 60 m near-field rise of the plume.

4.4.2 Environmental Data

The MIKE 21/3 Oil Spill Model requires input winds and currents on a two or three dimensional regular grid. The applied wind and current data are described in Section 2.

For the small surface spills a two dimensional grid with a grid size of 5 km was used. The model allows for the output to be mapped onto a finer grid and the output grid was set to 200 m for the small spills. The location of the grid is shown in Figure 4-3.

For the large blowout spills a three dimensional grid with a horizontal grid size of 20 km and a vertical grid size of 100 m was used both for defining the winds and currents as well as for output. The location of the grid is shown in Figure 4-3. As the HYCOM data includes a number of layers in the top 100 m of the water column, the data was analysed to determine the layer to be used in the oil spill model, recalling that the wind drift is added to the advection of the surface oil. To avoid double counting of the wind drift, the HYCOM data at 10 m depth rather than at the surface was chosen as the surface layer of the applied current field. For depths greater than 100 m, HYCOM data at corresponding depths were mapped to the input current file.

The wind drift was set to 3% of the wind speed and the wind drift angle due to the Coriolis force was 10° to the left. The horizontal dispersion (due to non-resolved turbulence) was set to 5 m^2/s.

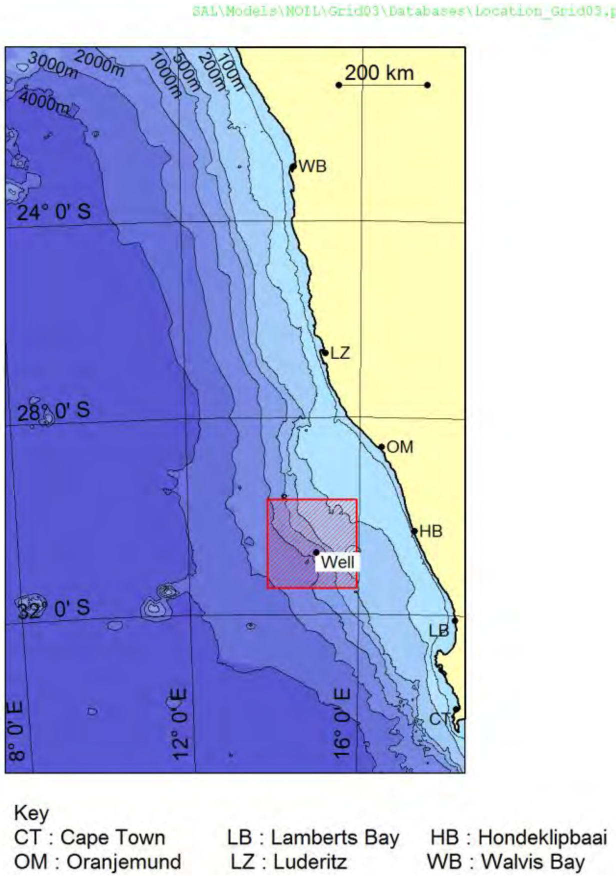


Figure 4-3: *Model grids: the area shown is the grid area for the large blowout spills, while the red square is the grid area for the small surface spills*

4.4.3 Simulations

A number of stochastic model simulations were performed for each spill in order to model the probability of oiling over the range of expected environmental conditions. Details of the model simulations for each spill are provided in Table 4-3. In the case of the large blow-out spills (spill numbers 3 to 4) the simulation was continued for 60 days after the end of the spill to allow time for the oil to reach the surface and subsequently spread and weather. The simulations cover the four years of current and wind data described in Section 2. Note that there is little benefit in setting the time offset between simulations longer than the duration of the spill, as this will simply repeat part of the release under the same hydrodynamic conditions. For this reason only 70 different simulations were performed for spill 4 which has a release duration of 20 days.

Table 4-3: *Details of oil model simulations*

	Oil spill number			
	1	2	3	4
Duration of spill (days)	Instantaneous	Instantaneous	5	20
Duration of simulation (days)	3	3	65	80
Time offset between simulations (days)	3	3	10	20
Number of simulations	485	485	140	70

4.4.4 Postprocessing

The output from each simulation included the oil mass mapped onto each grid cell at each time step as well as the maximum mass in each grid cell occurring at any time during the simulation. The model distinguishes between surface oil and subsurface oil. The following thresholds were applied to indicate the presence of oil:

- For floating oil an average thickness over the cell of 0.3 µm. This oil thickness can be described as a 'bright colours sheen' (NOAA, 2009).
- For subsurface oil an average concentration in the cell of 10 parts per billion (ppb) (French, 1999). Note that in the oil spill model used in this study the subsurface oil refers to the oil rising from the blowout at the seabed to the surface. Oil that is dispersed or dissolved into the water column is included in the first order decay parameterisation and is thus not included in the subsurface oil concentration.

Each simulation was assigned to either summer or winter depending on the month in the middle of the spill release. The results were then presented as the probability of oil exceeding the relevant thresholds in a particular grid cell for all spills occurring in either winter or summer, i.e. given that a spill occurs in a particular season, the results show the probability that the currents and winds will result in oiling at a particular location for this single spill event. Note that the oil may only be present at a particular location for a few hours in order for this location to be considered as having being oiled.

The minimum time to oiling was also estimated.

4.5 Results

Figures showing the modelled probability of oiling for both summer and winter for each of the four oil spill scenarios are included in Sections 4.5.1 to 4.5.4 below. In addition, a full set of model results for each of the four oil spills are included in Annexures A to E. The full set of results includes examples of the instantaneous oil patch and the area swept by oil during one selected spill event. Also shown is the mass balance over time of the following oil states: released, on surface, subsurface, ashore, evaporated, dispersed/dissolved/biodegraded/photo-oxidised/settled, and lost through the model boundary.

4.5.1 Oil Spill 1 (1 t of Hydraulic Fluid)

The modelled probability of surface oiling for the 1 t spill of hydraulic fluid for spill events in summer and winter are shown in Figure 4-4 and Figure 4-5, respectively. The area shown in these figures is indicated in Figure 4-3. The full set of results is included in Annexure A.

The oil remains on the water surface for a maximum of 2 days before a combination of oil dispersion and spreading reduce the oil thickness below the threshold of 0.3 µm (see Figure A—2, Figure A—5 and Figure A—6). The oil dispersed into the water column is not tracked by the model, but is likely to be located below the area of surface oiling and within 25 m of the water surface.

During the maximum of 2 days that the oil remains on the water surface the oil travels up to 150 km from the source predominantly in a north-westerly direction. There is no probability of the oil reaching the shoreline. Due to the instantaneous nature of the release the oil sweeps a narrow trajectory (see for example Figure A—1), which results in a low probability of oiling at any one location.

SAL\Models\NOIL\Grid03\Scenario01aa\Postprocess\Postprocess_NOIL_Summer_0.3um_10ppb_Probability.png

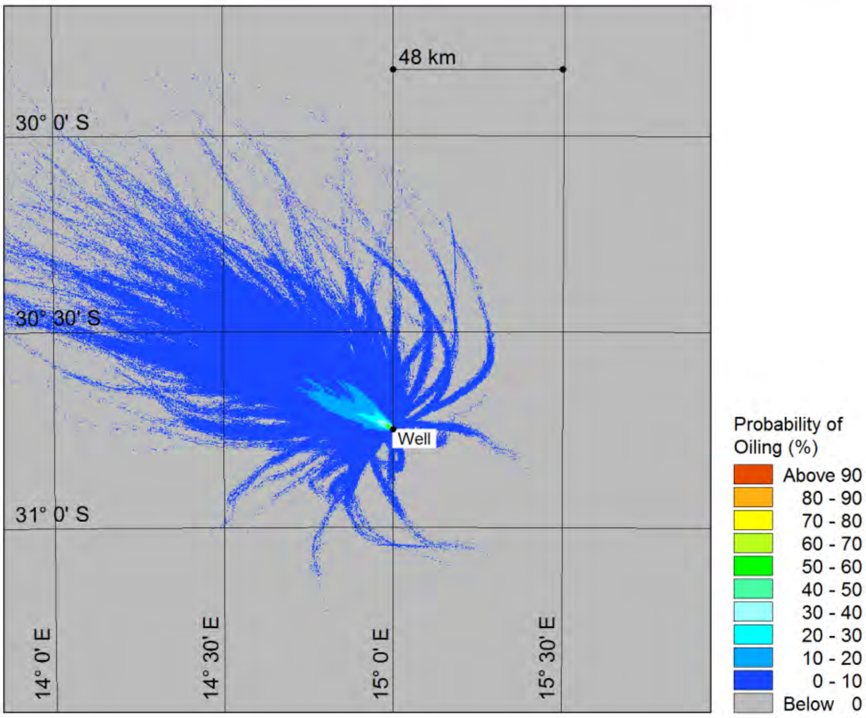


Figure 4-4: *Oil spill 1 (1 t of hydraulic fluid). Probability of surface oiling for a spill event in summer.*

SAL\Models\NOIL\Grid03\Scenario01aa\Postprocess\Postprocess_NOIL_Winter_0.3um_10ppb_Probability.png

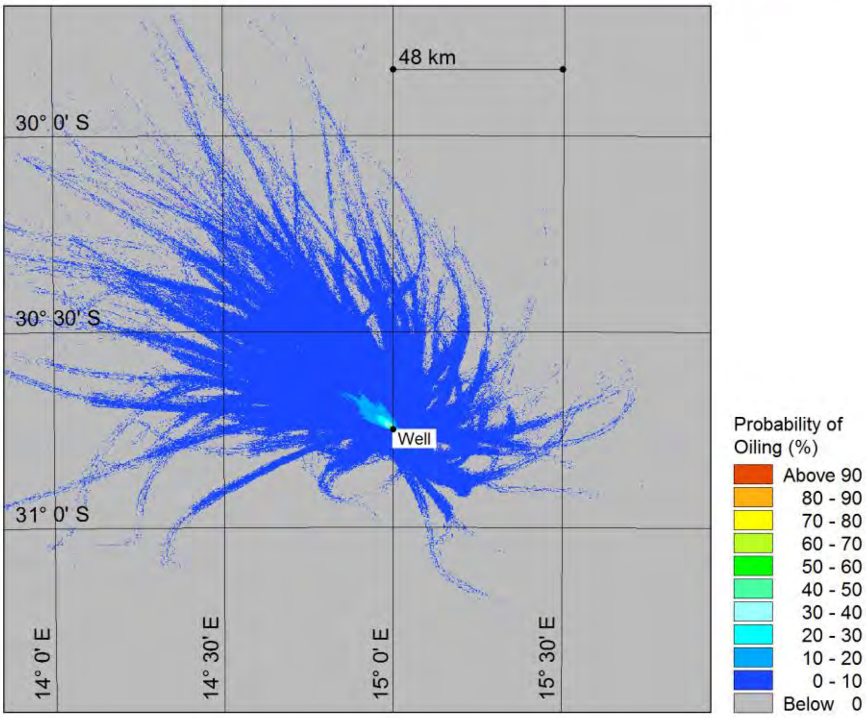


Figure 4-5: *Oil spill 1 (1 t of hydraulic fluid). Probability of surface oiling for a spill event in winter.*

4.5.2 Oil Spill 2 (10 t of Diesel)

The modelled probability of surface oiling for the 10 t spill of diesel for spill events in summer and winter are shown in Figure 4-6 and Figure 4-7, respectively. The area shown in these figures is indicated in Figure 4-3. The full set of results is included in Annexure B.

The oil remains on the water surface for a maximum of 1.5 days before a combination of evaporation, oil dispersion and spreading reduce the oil thickness below the threshold of 0.3 µm (see Figure B—2, Figure B—5 and Figure B—6). The oil dispersed into the water column is not tracked by the model, but is likely to be located below the area of surface oiling and within 25 m of the water surface.

During the maximum of 1.5 days that the oil remains on the water surface the oil travels up to 110 km from the source predominantly in a north-westerly direction. There is no probability of the oil reaching the shoreline. Due to the instantaneous nature of the release the oil sweeps a narrow trajectory (see for example Figure B—1), which results in a low probability of oiling at any one location.

Although the diesel spill is ten times larger than the hydraulic oil spill, the area oiled is smaller due to evaporation and the more rapid dispersion of the diesel.

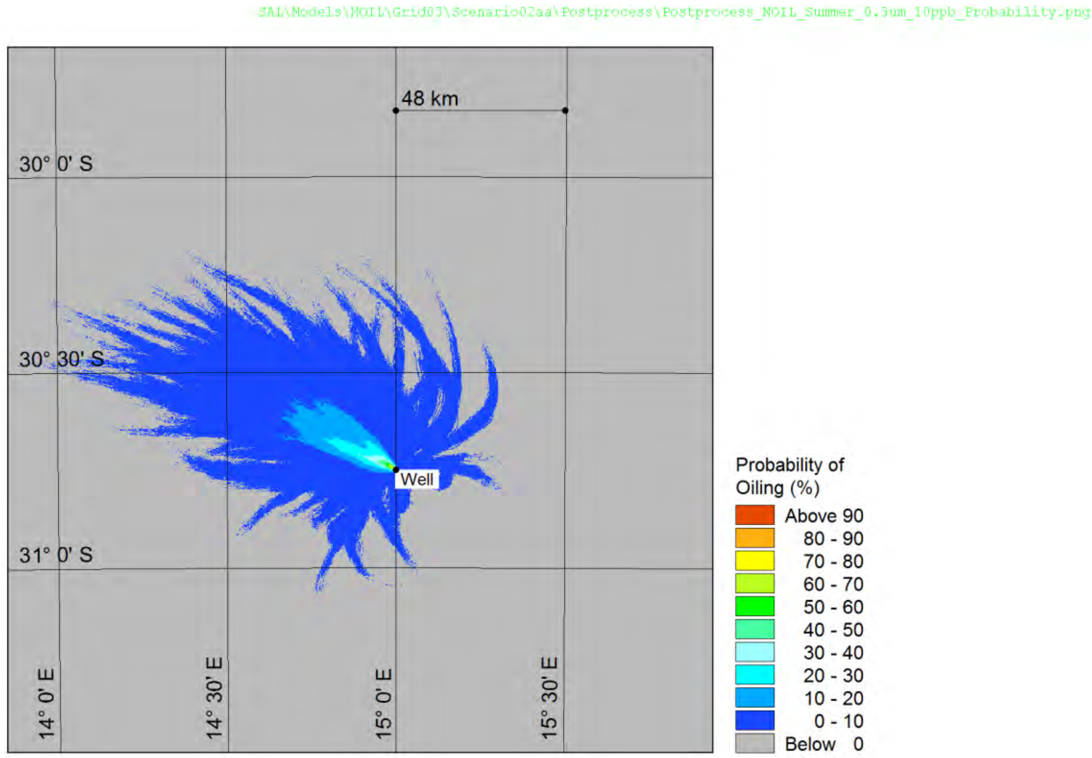


Figure 4-6: *Oil spill 2 (10 t of diesel). Probability of surface oiling for a spill event in summer.*

SAL\Models\NOIL\Grid03\Scenario02aa\Postprocess\Postprocess_NOIL_Winter_0.3um_10ppb_Probability.png

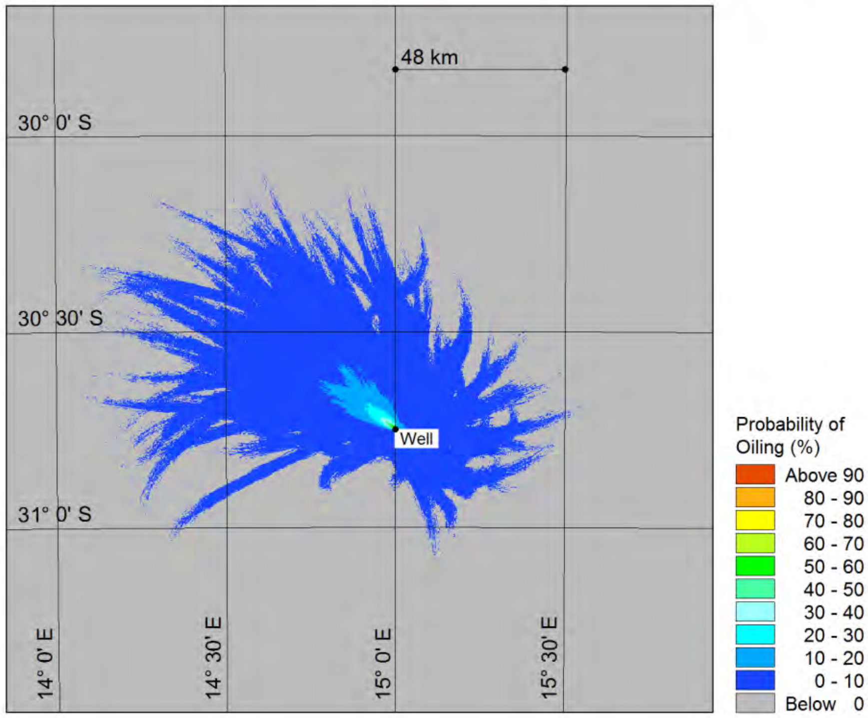


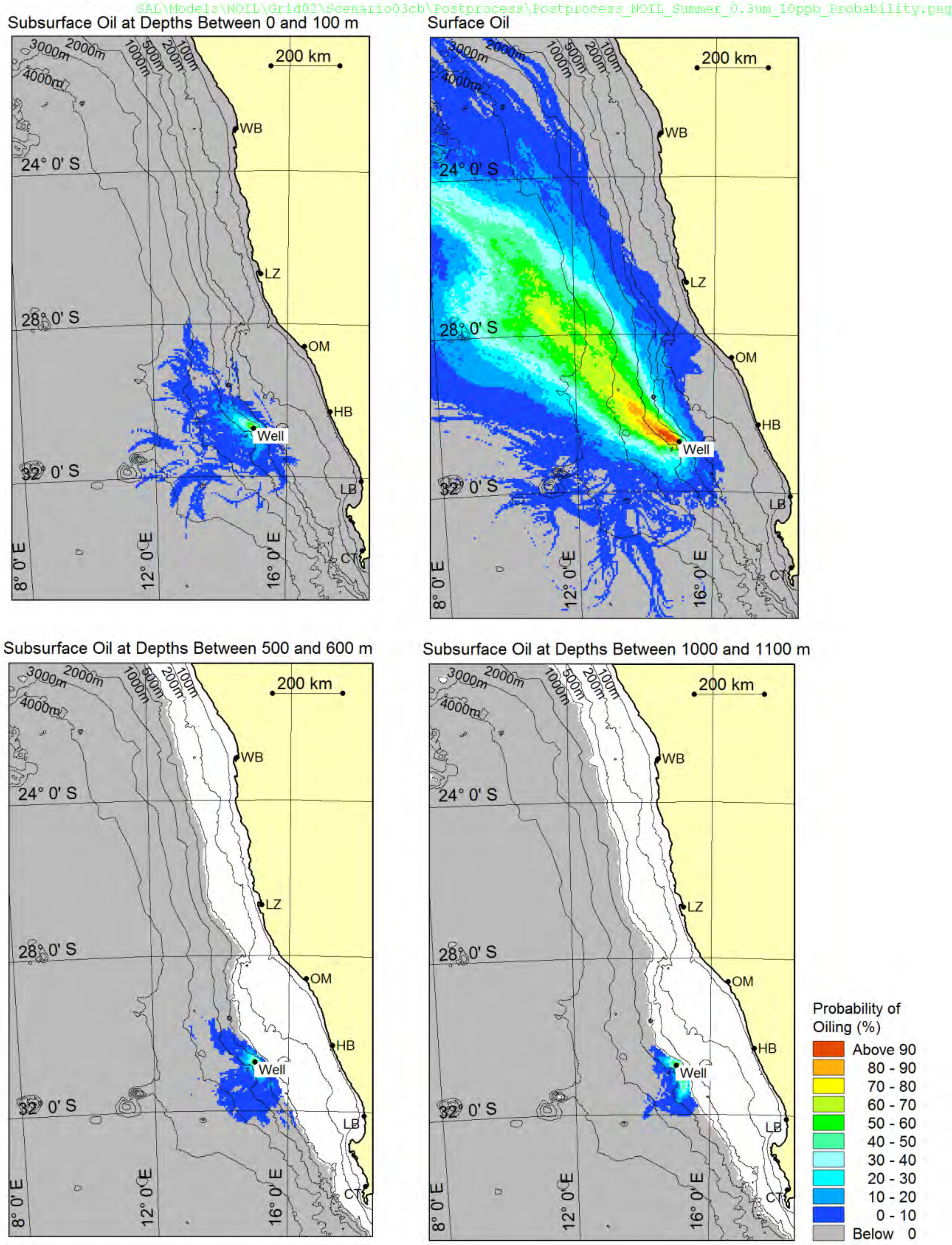
Figure 4-7: *Oil spill 2 (10 t of diesel). Probability of surface oiling for a spill event in winter.*

4.5.3 Oil Spill 3 (5-day Blowout)

The modelled probability of surface oiling for the 5-day blowout for spill events in summer and winter are shown in Figure 4-8 and Figure 4-9, respectively. The simulation duration was 65 days (5 days of spill plus 60 days thereafter). As discussed in Section 4.4.1, due the uncertainty in the crude oil characteristics at the site as well as uncertainties in the long-term weathering behaviour of the oil, three different weathering rates have been modelled: fast, medium and slow weathering. The figures below show results for the medium weathering scenario, which can be considered to be the most likely scenario. Results for the fast weathering scenario (which results in a smaller area of impact) and the slow weathering scenario (which results in a larger area of impact) are included in Annexure C.

The figures below show how the oil rises through the water column whilst being transported horizontally by the three-dimensional current field. Once the oil surfaces it tends to be transported in a north-westerly direction due to the prevailing near-surface currents and winds. During summer the strong south-easterly winds tend to transport the oil away from the shoreline, whilst the weaker winds in winter increase the probability of shoreline oiling. For the 5-day blowout and the medium weathering scenario the oil is not predicted to reach the shoreline, although it does come within approximately 50 km of the shoreline. The probability of shoreline impacts for all spills and all weathering scenarios are discussed in Section 4.6. The surface oiling to the south of the well is generally caused by the slower-rising oil fractions being transported by southward moving subsurface currents.

At any one time the surface oil patch covers a relatively small area (see for example Figure C—8). The oil however sweeps a large area as a result of the 5-day duration of the discharge, the differing surfacing times of the six oil fractions and the spatial and temporal variability in the current and wind fields (see for example Figure C—10). For the medium weathering scenario the oil is present on the water surface for more than 40 days after the start of the spill (see Figure C—9, Figure C—13 and Figure C—14). This assumes no mitigation in terms of an oil spill management plan.



Key

CT : Cape Town LB : Lamberts Bay HB : Hondeklipbaai

OM : Oranjemund LZ : Luderitz WB : Walvis Bay

Figure 4-8: *Oil spill 3 (5-day blowout) medium weathering scenario. Probability of surface and subsurface oiling for a spill event in summer.*

SAL\Models\NOIL\Grid02\Scenario03cb\Postprocess\Postprocess_NOIL_Winter_0.3um_10ppb_Probability.png

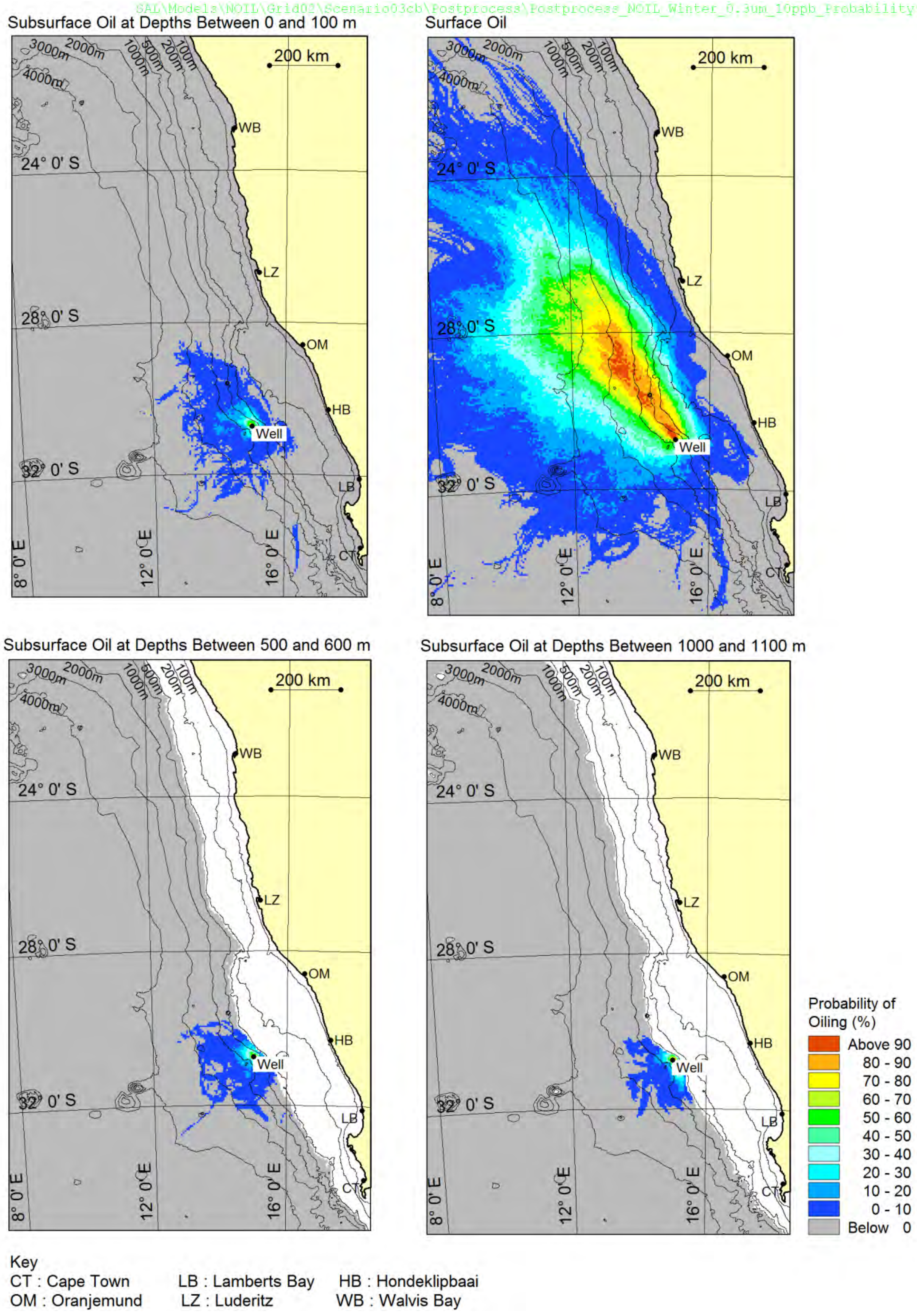


Figure 4-9: *Oil spill 3 (5-day blowout) medium weathering scenario. Probability of surface and subsurface oiling for a spill event in winter.*

4.5.4 Oil Spill 4 (20-day Blowout)

The modelled probability of surface oiling for the 20-day blowout for the medium weathering scenario for spill events in summer and winter are shown in Figure 4-10 and Figure 4-11, respectively. The simulation duration was 80 days (20 days of spill plus 60 days thereafter). The full set of results is included in Annexure D.

The results are qualitatively similar to those for the 5-day blowout as described in Section 4.5.3 above. The difference is that the longer release increases the duration that oil is present on the water surface and thus increases the probability of oiling, particularly in the area north-west of the well, where for the medium weathering scenario in summer there is a 600 km long by 50 km wide area where the probability of oiling exceeds 90%.

For the 20-day blowout and the medium weathering scenario there is a less than 10% probability of oiling of the shoreline between Luderitz to Oranjemund for spills occurring during winter. No oiling of the shoreline is predicted during summer. A detailed analysis of the shoreline oiling is provided in Section 4.6.

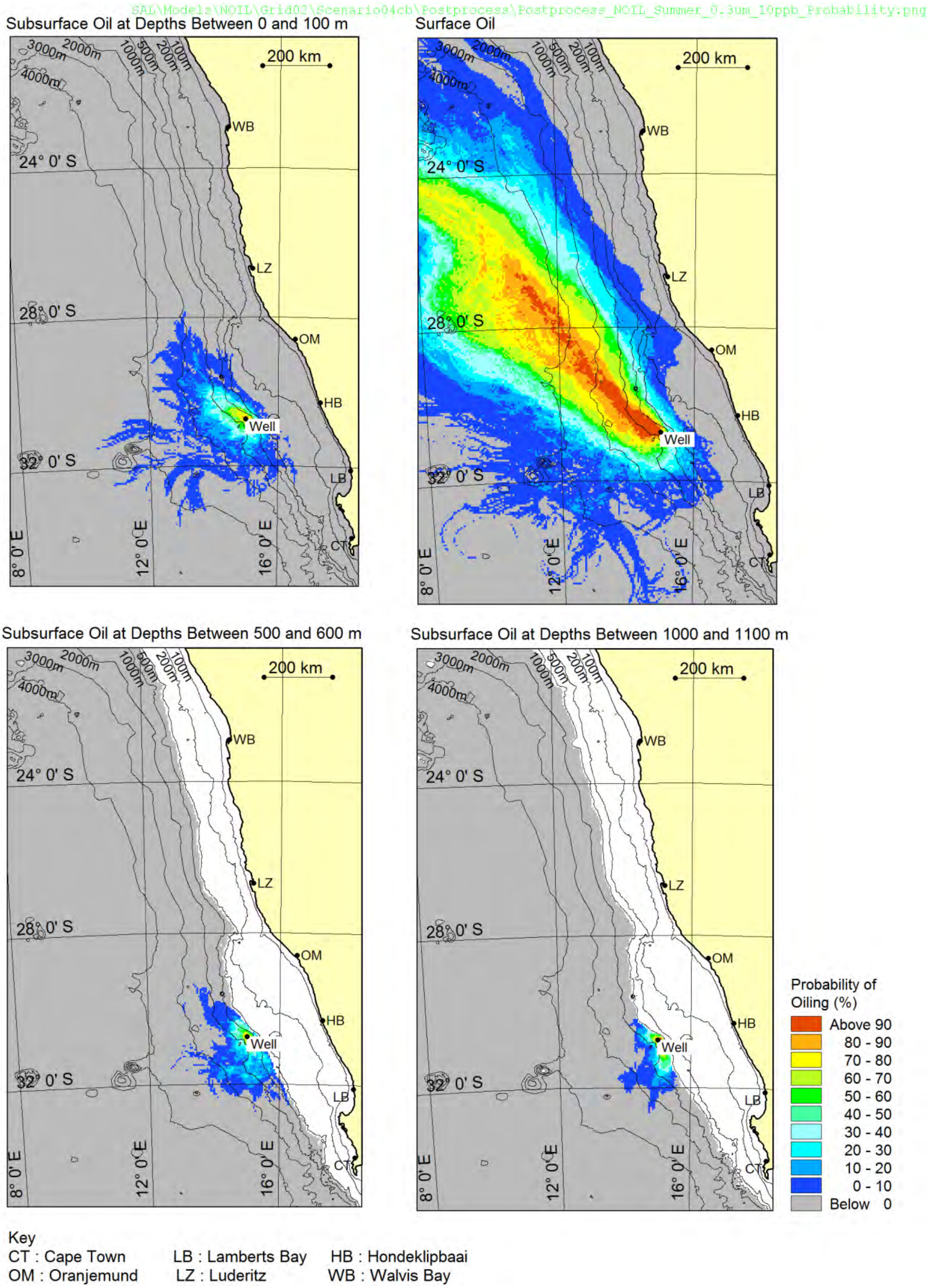


Figure 4-10: *Oil spill 4 (20-day blowout) medium weathering scenario. Probability of surface and subsurface oiling for a spill event in summer.*

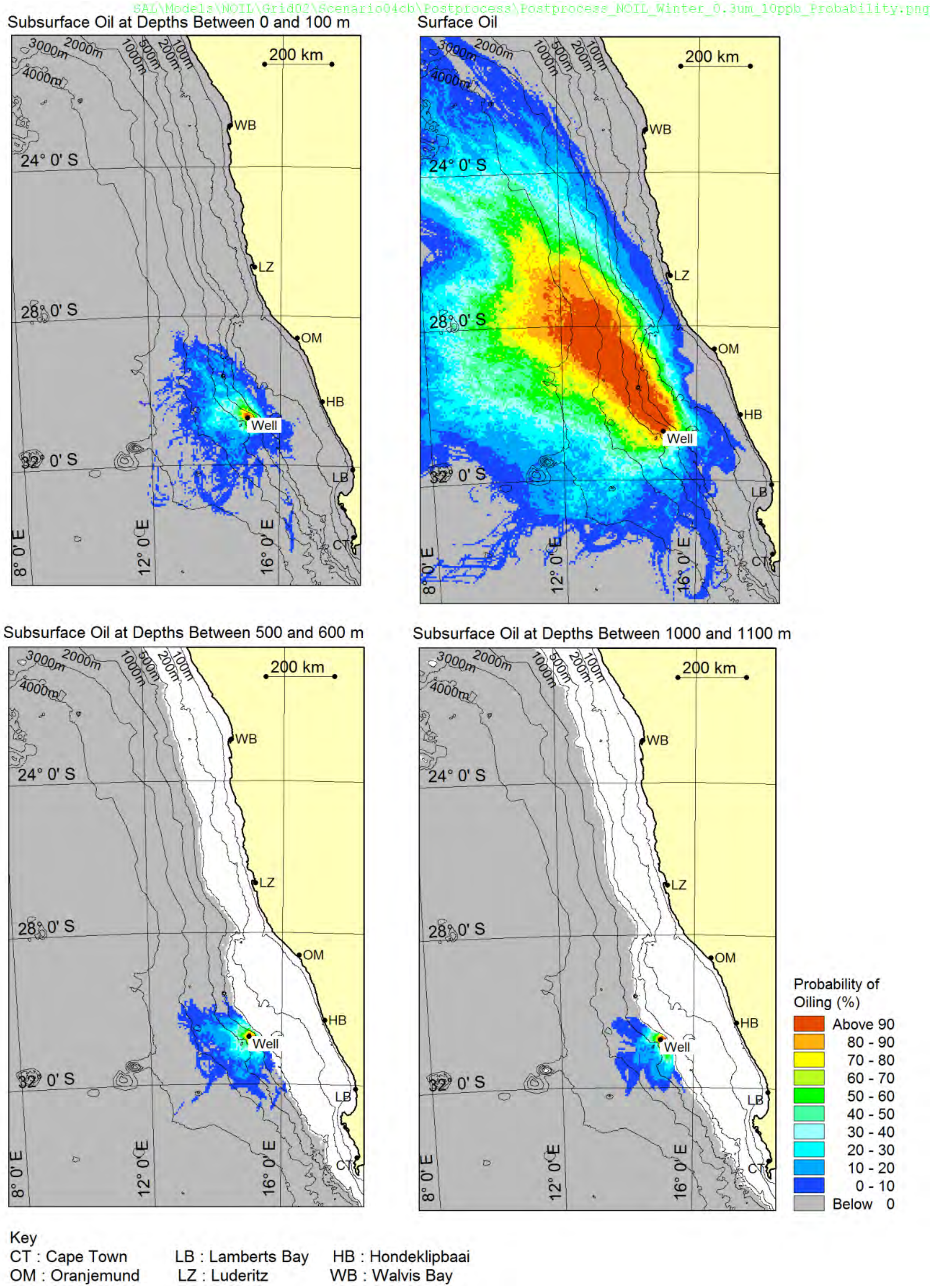


Figure 4-11: *Oil spill 4 (20-day blowout) medium weathering scenario. Probability of surface and subsurface oiling for a spill event in winter.*

4.6 Discussion

The 1 t spill of hydraulic fluid and the 10 t spill of diesel are relatively short-lived on the water surface (< 2 days) and there is no probability of the oil reaching the shoreline.

The large blowout spills result in extensive areas of oiling of the subsurface and particularly at the water surface. Once the oil surfaces it tends to be transported in a north-westerly direction due to the prevailing near-surface currents and winds which reduces the probability of shoreline oiling. However, the stochastic model results show that shoreline oiling may occur, particularly for the longer duration blowouts during winter and for the slow oil weathering scenario, as shown in Table 4-4 and Table 4-5 for summer and winter respectively. The probabilities shown in Table 4-4 and Table 4-5 refer to the highest probability of oiling for any location along the particular section of shoreline. The specific locations of oiling can be seen in the probability plots, e.g. Figure D-19. To account for local onshore sea breezes and wave drift, which are not resolved by the model, cases where the oil came within one grid cell (20 km) of the shoreline were counted as shoreline oiling.

Table 4-4: *Probability of shoreline oiling for a spill event in summer*

Section of shoreline	5-day blowout			20-day blowout		
	Fast weathering	Medium weathering	Slow weathering	Fast weathering	Medium weathering	Slow weathering
North of Walvis Bay	0	0	0	0	0	0
Walvis Bay to Luderitz	0	0	0	0	0	0
Luderitz to Oranjemund	0	0	0	0	0	0
Oranjemund to Hondeklipbaai	0	0	0	0	0	<10%
Hondeklipbaai to Lamberts Bay	0	0	0	0	0	<10%
Lamberts Bay to Cape Town	0	0	0	0	0	<10%

Table 4-5: *Probability of shoreline oiling for a spill event in winter*

Section of shoreline	5-day blowout			20-day blowout		
	Fast weathering	Medium weathering	Slow weathering	Fast weathering	Medium weathering	Slow weathering
North of Walvis Bay	0	0	0	0	0	0
Walvis Bay to Luderitz	0	0	0	0	0	<10%
Luderitz to Oranjemund	0	0	<10%	0	<10%	<10%
Oranjemund to Hondeklipbaai	0	0	<10%	0	0	<10%
Hondeklipbaai to Lamberts Bay	0	0	0	0	0	<10%
Lamberts Bay to Cape Town	0	0	<10%	0	0	<10%

Although the medium weathering scenario can be considered to be the most likely scenario, the uncertainties associated with the crude oil characteristics at the site as well as uncertainties in the long-term weathering behaviour of the oil mean that the slow weathering scenario should also be included in the environmental assessment.

The results show that drilling during summer rather than winter significantly reduces the risk of shoreline oiling, which is mainly related to stronger prevailing north-westerly winds in winter.

5. CONCLUSIONS

The drill cuttings model results show that the large depths at the well site (1 800 to 2 040 m) combined with the moderate to strong current speeds (at 200 m depth the median speed is 0.12 m/s and the maximum 0.56 m/s) and relatively low mass of cuttings discharged (1 042 t) result in the drill cuttings being spread over a large area, with relatively low deposition thicknesses of less than 1 mm predicted for distances greater than about 150 m from the location of the well. The footprint where the deposition thickness exceeds 0.001 mm is predicted to be less than 33 km^2 and occurs within a distance of 50 km from the well.

The 1 t (7.4 bbl) spill of hydraulic fluid scenario is predicted to remain on the water surface for a maximum of 2 days during which it will travel up to 150 km from the source, predominantly in a north-westerly direction. There is no probability of the oil reaching the shoreline.

The 10 t (74 bbl) spill of diesel scenario is predicted to remain on the water surface for a maximum of 1.5 days during which it will travel up to 110 km from the source, predominantly in a north-westerly direction. There is no probability of the oil reaching the shoreline.

The 5-day and 20-day large blowout oil spill scenarios are predicted to result in extensive areas of oiling of the subsurface and particularly at the water surface. Once the oil surfaces it tends to be transported in a north-westerly direction due to the prevailing near-surface currents and winds which reduces but does not eliminate the probability of shoreline oiling. For the medium weathering scenario the 20-day blowout in summer results in a 600 km long by 50 km wide area where the probability of oiling exceeds 90%.

The probability of shoreline oiling depends on spill duration, the season and weathering scenario. If drilling is confined to summer, as planned, then for the medium weathering scenario no shoreline oiling is predicted by the model for either blowout scenario. For the worst case slow weathering scenario during summer the 5-day blowout scenario is predicted to have no probability of shoreline oiling and the 20-day blowout scenario has less than 10% probability of shoreline oiling. The model results show that drilling during winter would significantly increase the probability of shoreline oiling compared to the probabilities for summer as described above, due to the stronger prevailing north-westerly winds in winter.

The model results will be provided to the Marine Faunal and the Fisheries Specialists to enable the associated ecological impacts to be assessed.

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ANNEXURE A | FULL SET OF MODEL RESULTS FOR OIL SPILL 1 (1 T OF HYDRAULIC FLUID)

FIGURES (ANNEXURE A)	Page N°

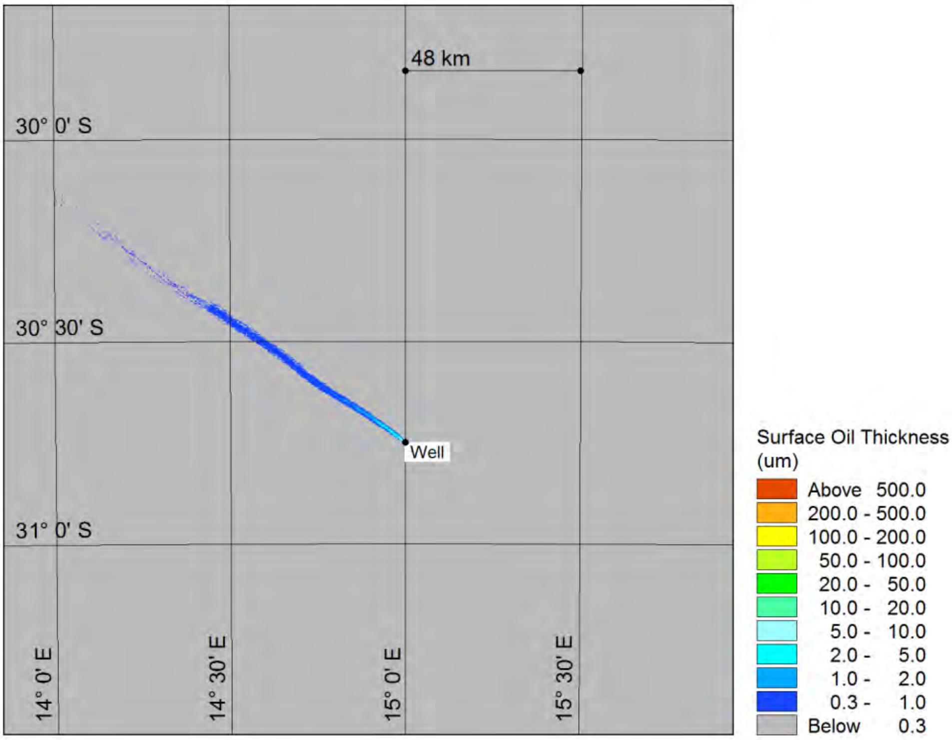

Figure A—1: *Oil spill 1 (1 t of hydraulic fluid). Predicted oil trajectory for one spill case. Plot shows the maximum oil thickness on the water surface at any time during the spill, i.e. the area swept by oil.*

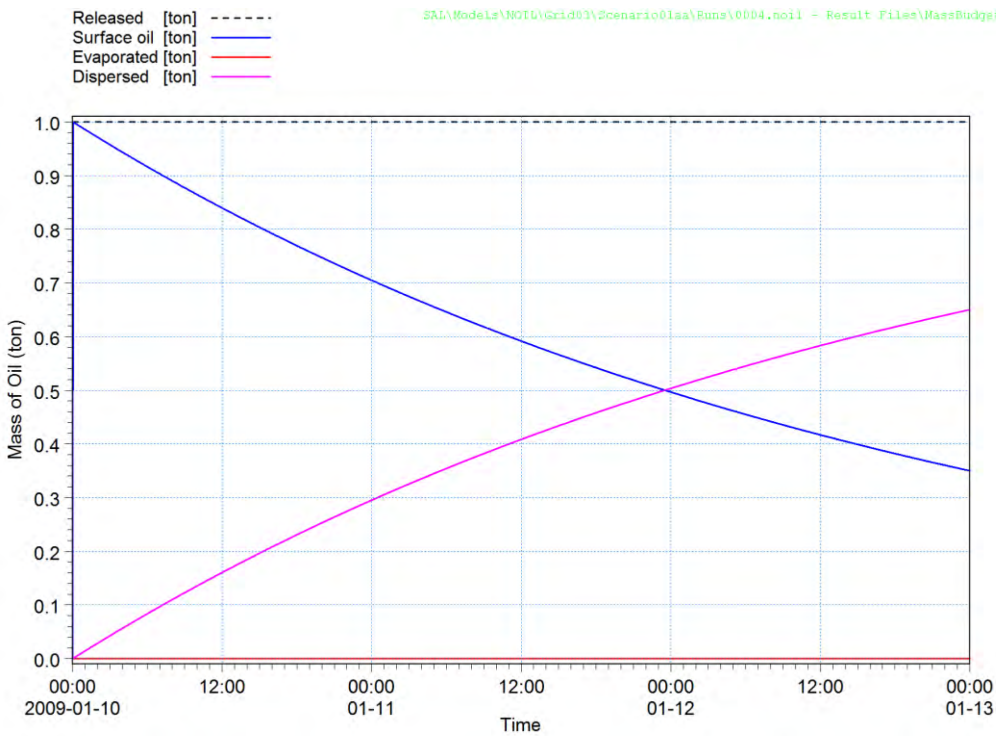

Figure A—2: *Oil spill 1 (1 t of hydraulic fluid). Oil mass balance for one spill case.*

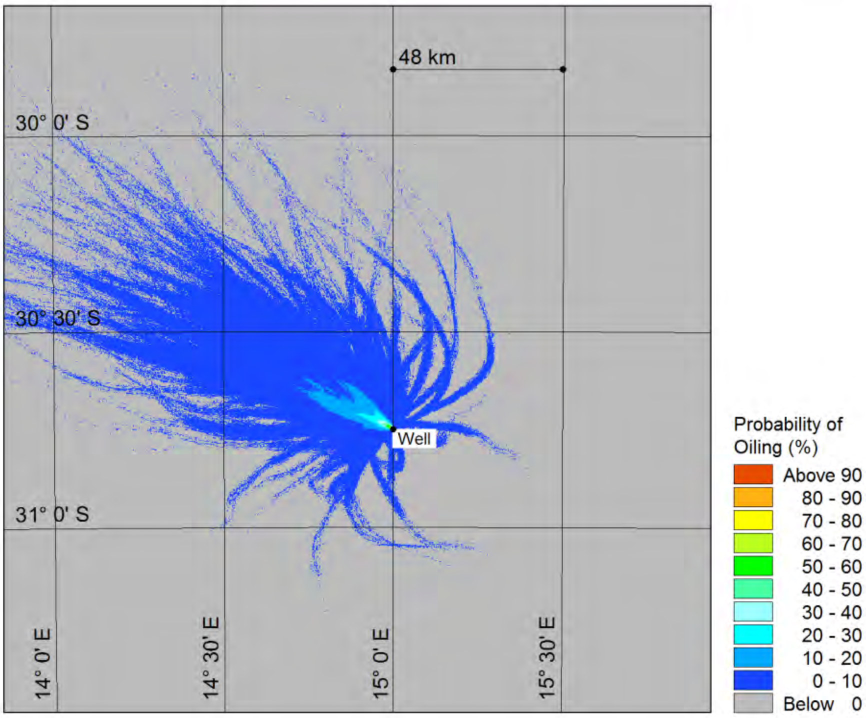

Figure A—3: *Oil spill 1 (1 t of hydraulic fluid). Probability of surface oiling for a spill event in summer.*

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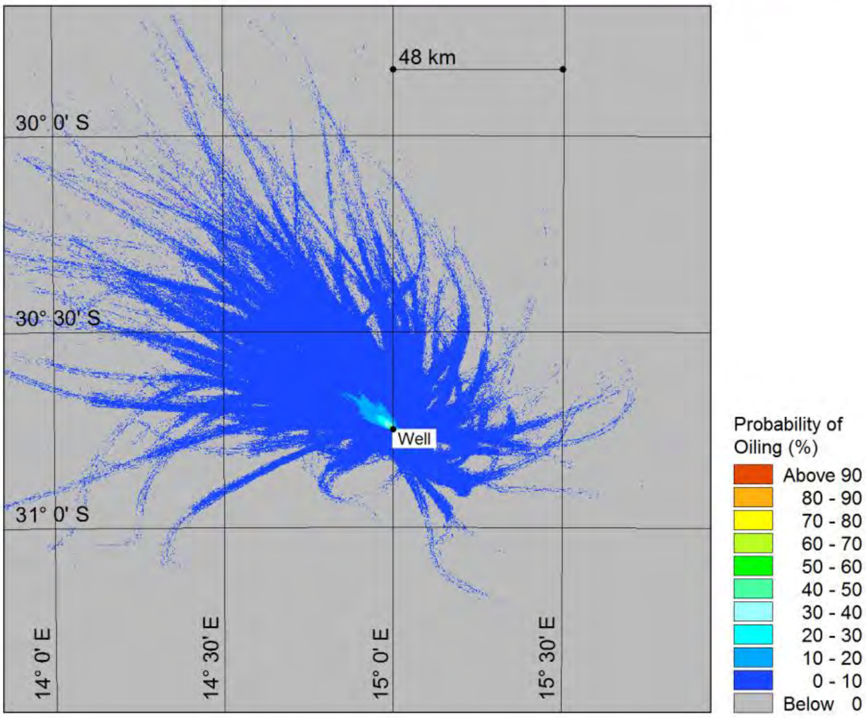

Figure A—4: *Oil spill 1 (1 t of hydraulic fluid). Probability of surface oiling for a spill event in winter.*

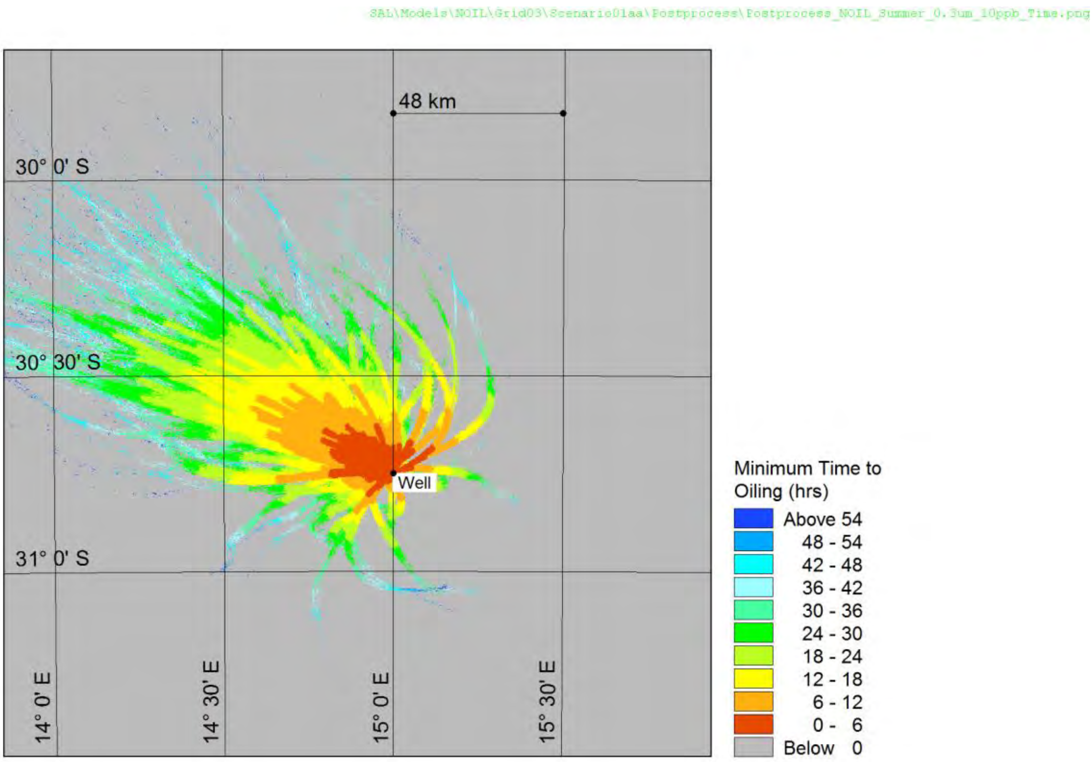

Figure A—5: *Oil spill 1 (1 t of hydraulic fluid). Minimum time to oiling for a spill event in summer.*

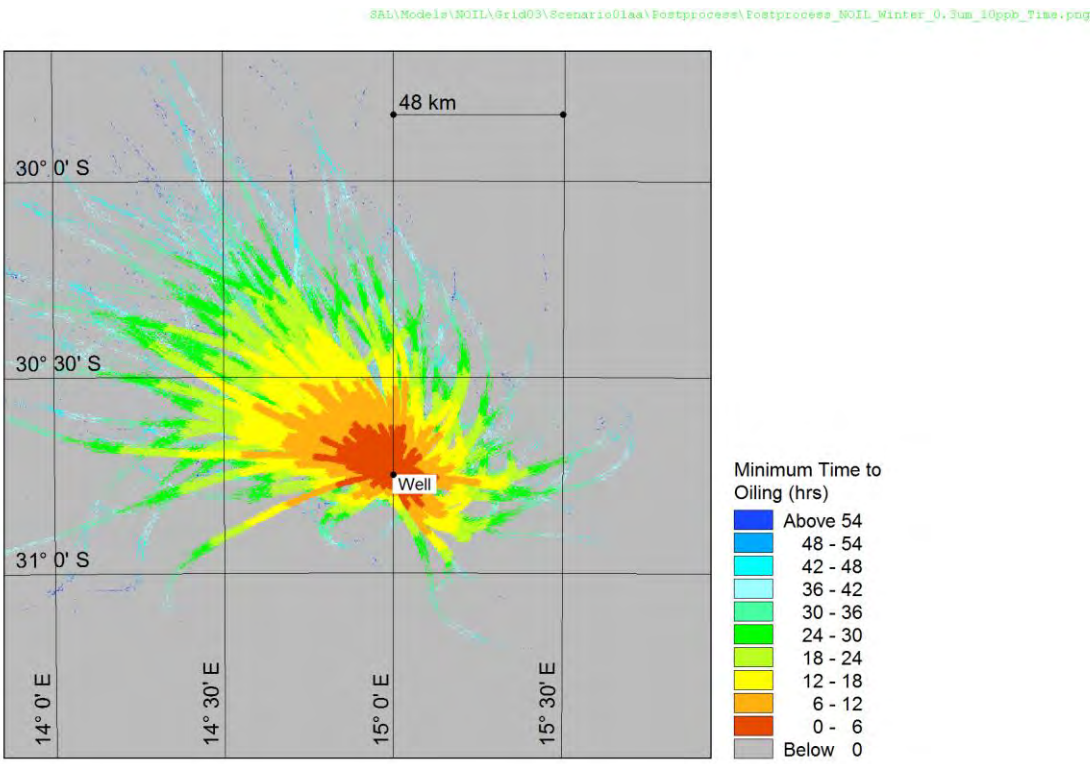

Figure A—6: *Oil spill 1 (1 t of hydraulic fluid). Minimum time to oiling for a spill event in winter.*

ANNEXURE B | FULL SET OF MODEL RESULTS FOR OIL SPILL 2 (10 T OF DIESEL)

FIGURES (ANNEXURE B)	Page N°

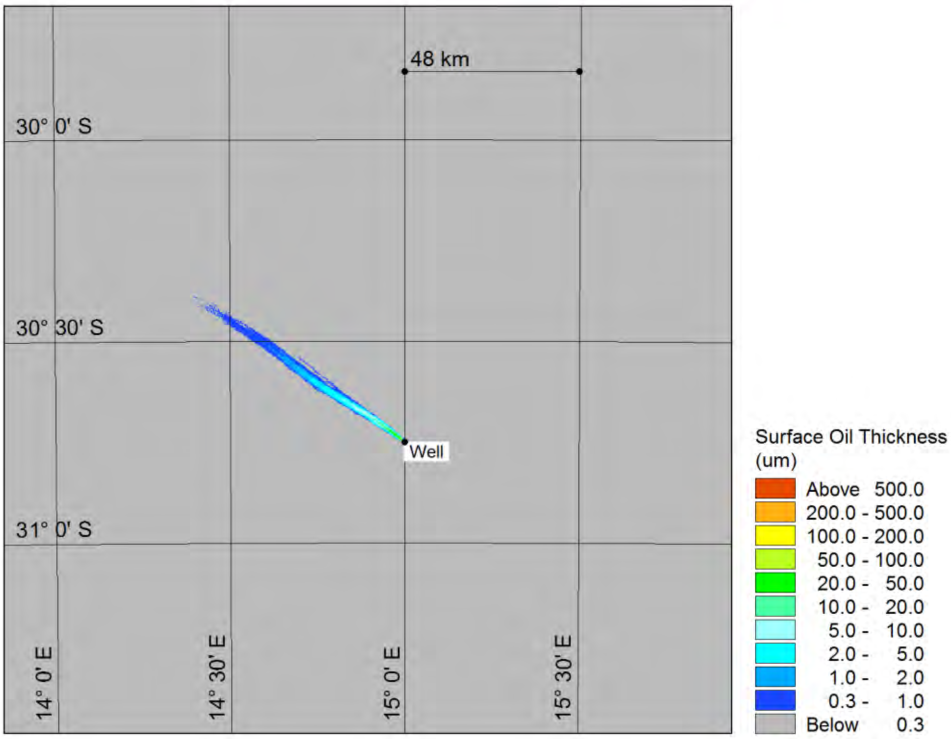

Figure B—1: *Oil spill 2 (10 t of diesel). Predicted oil trajectory for one spill case. Plot shows the maximum oil thickness on the water surface at any time during the spill, i.e. the area swept by oil.*

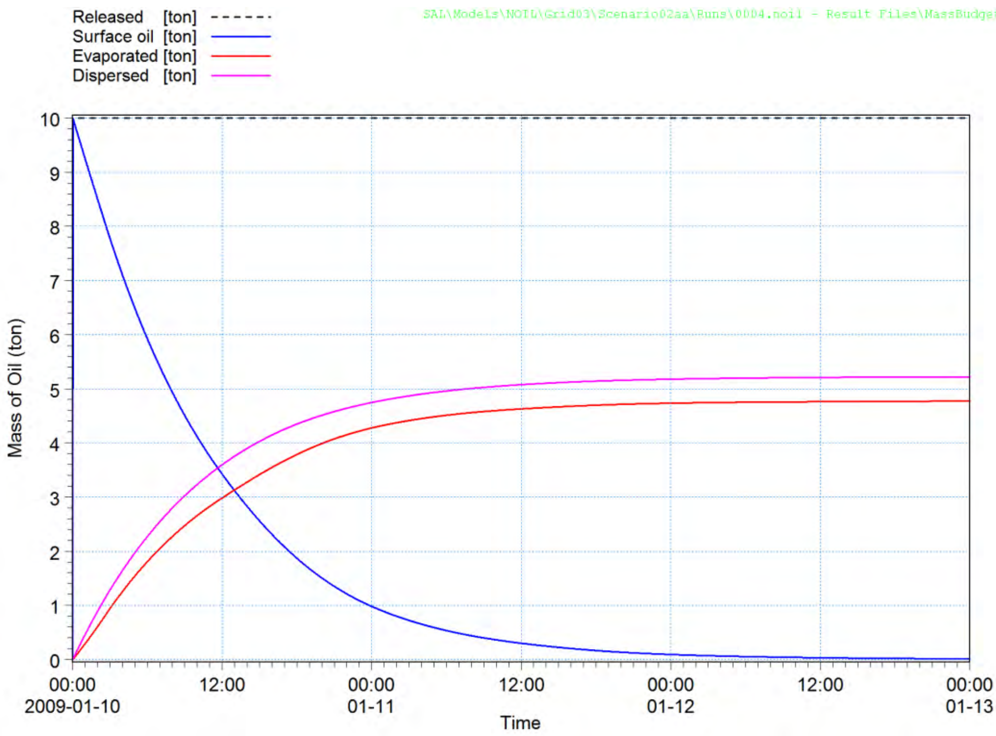

Figure B—2: *Oil spill 2 (10 t of diesel). Oil mass balance for one spill case.*

SAL\Models\NOIL\Grid03\Scenario02aa\Postprocess\Postprocess_NOIL_Summer_0.3um_10ppb_Probability.png

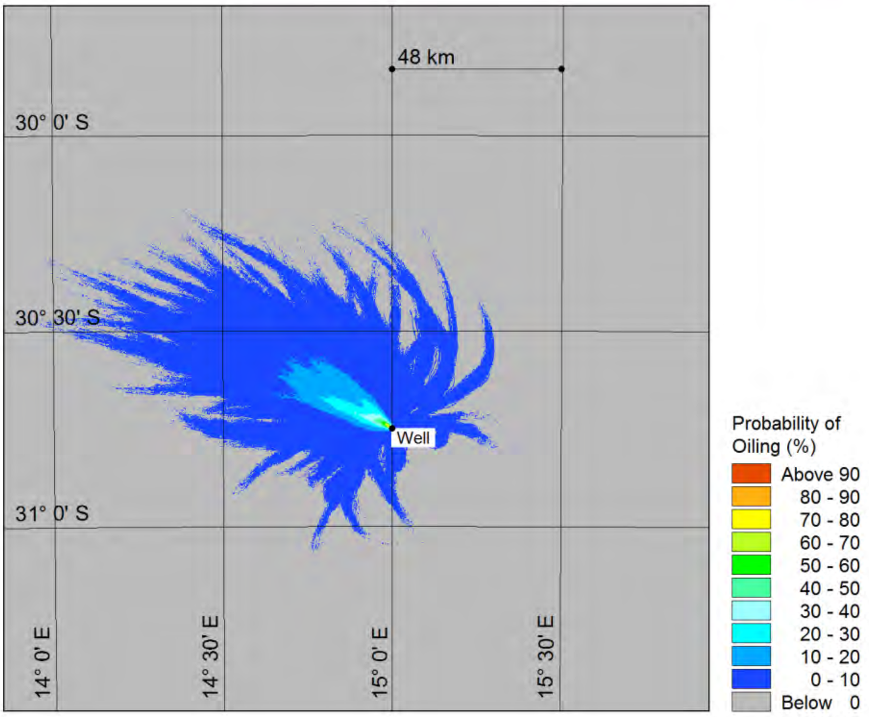

Figure B—3: *Oil spill 2 (10 t of diesel). Probability of surface oiling for a spill event in summer.*

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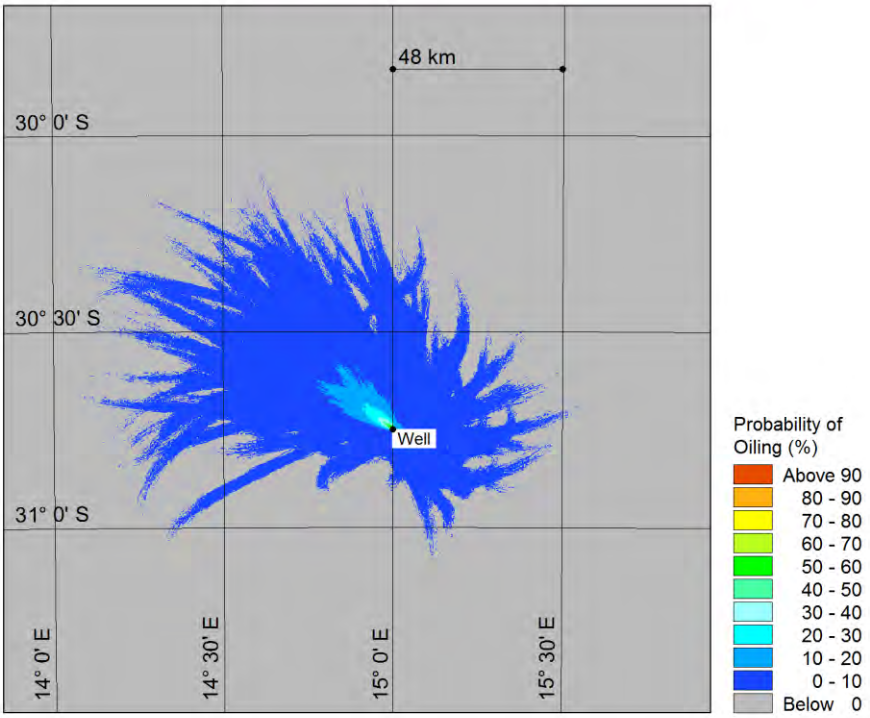


Figure B—4: *Oil spill 2 (10 t of diesel). Probability of surface oiling for a spill event in winter.*

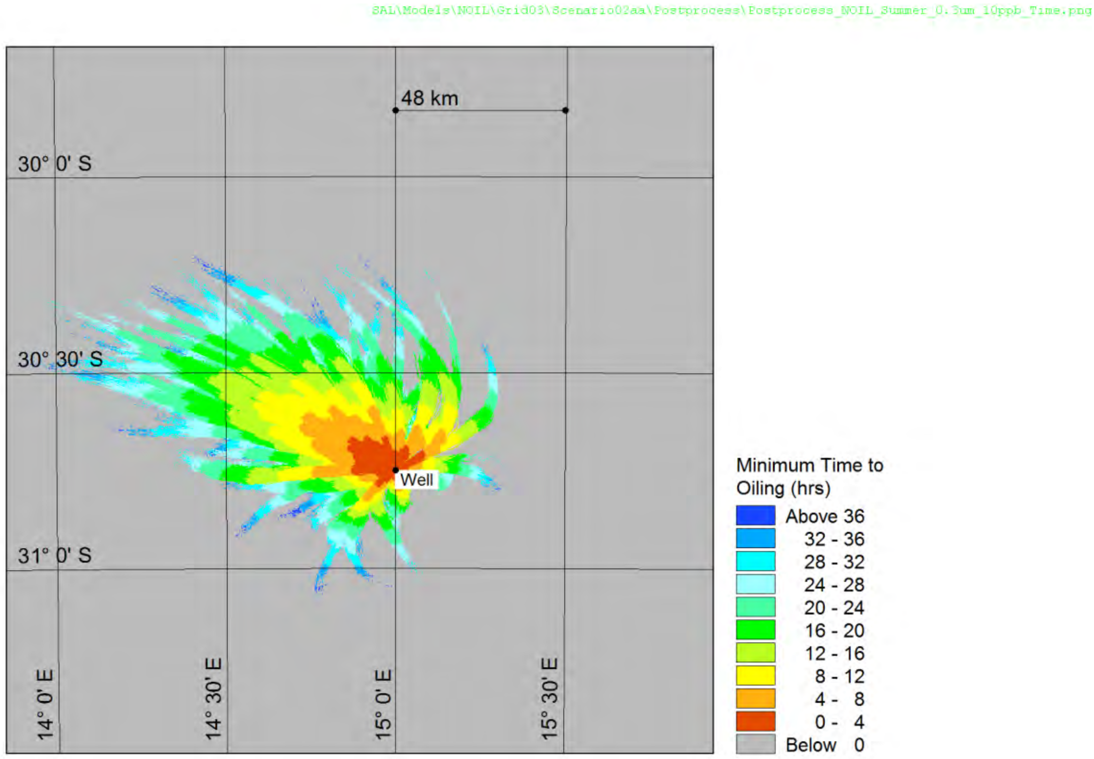


Figure B—5: *Oil spill 2 (10 t of diesel). Minimum time to oiling for a spill event in summer.*

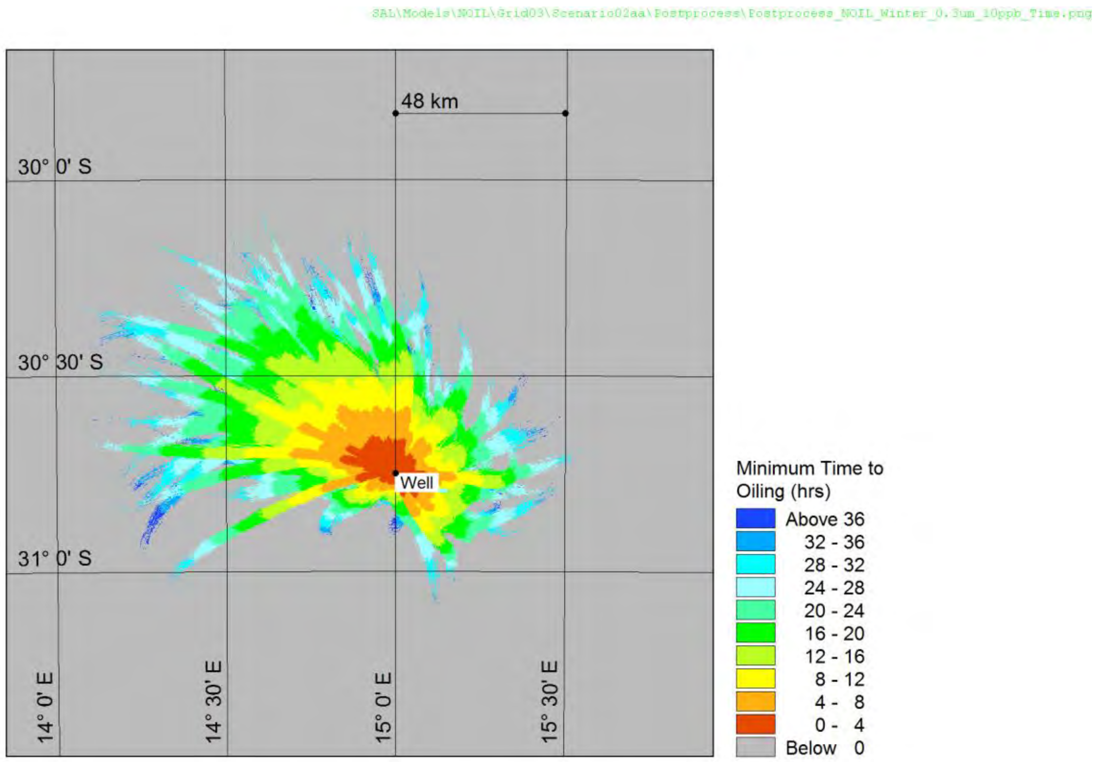


Figure B—6: *Oil spill 2 (10 t of diesel). Minimum time to oiling for a spill event in winter.*

ANNEXURE C | FULL SET OF MODEL RESULTS FOR OIL SPILL 3 (5-DAY BLOWOUT ON SEABED)

FIGURES (ANNEXURE C)

Page N°

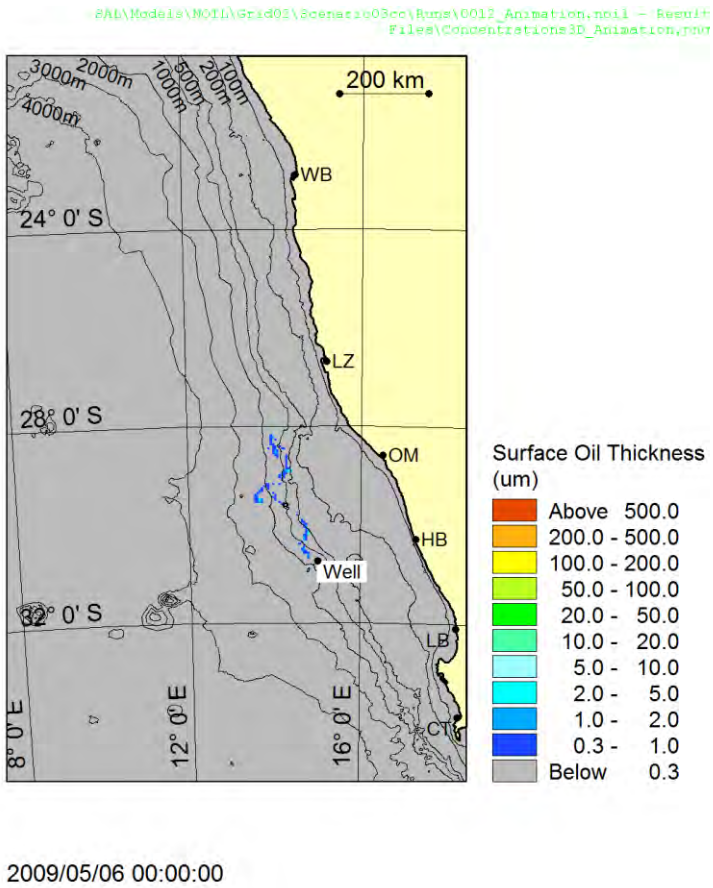


Figure C—1: *Oil spill 3 (5-day blowout) fast weathering scenario. Instantaneous surface oil patch 14 days after the start of a spill case where the oil approached the shore.*

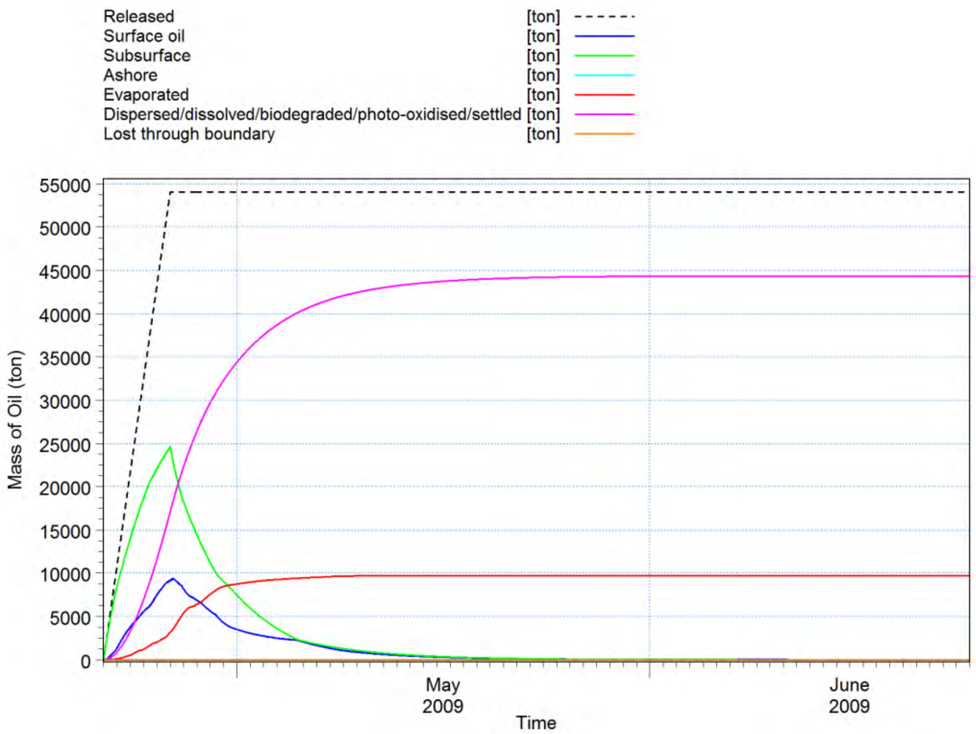


Figure C—2: *Oil spill 3 (5-day blowout) fast weathering scenario. Oil mass balance for a spill case where the oil approached the shore.*

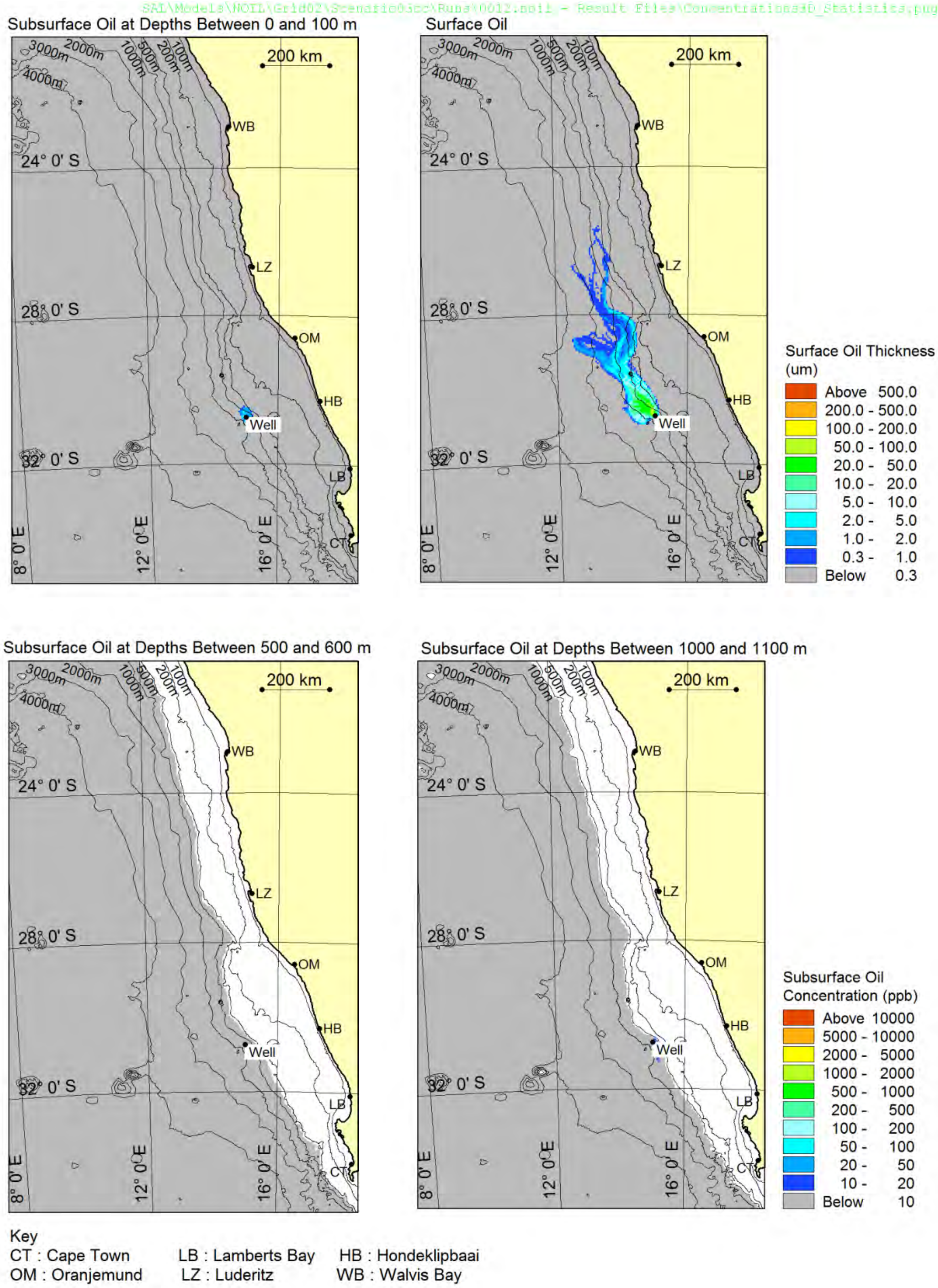


Figure C—3: *Oil spill 3 (5-day blowout) fast weathering scenario. Predicted oil trajectory for a spill case where the oil approached the shore. Plot shows the maximum oil thickness on the water surface and the maximum subsurface oil concentration at any time during the spill, i.e. the area swept by oil.*

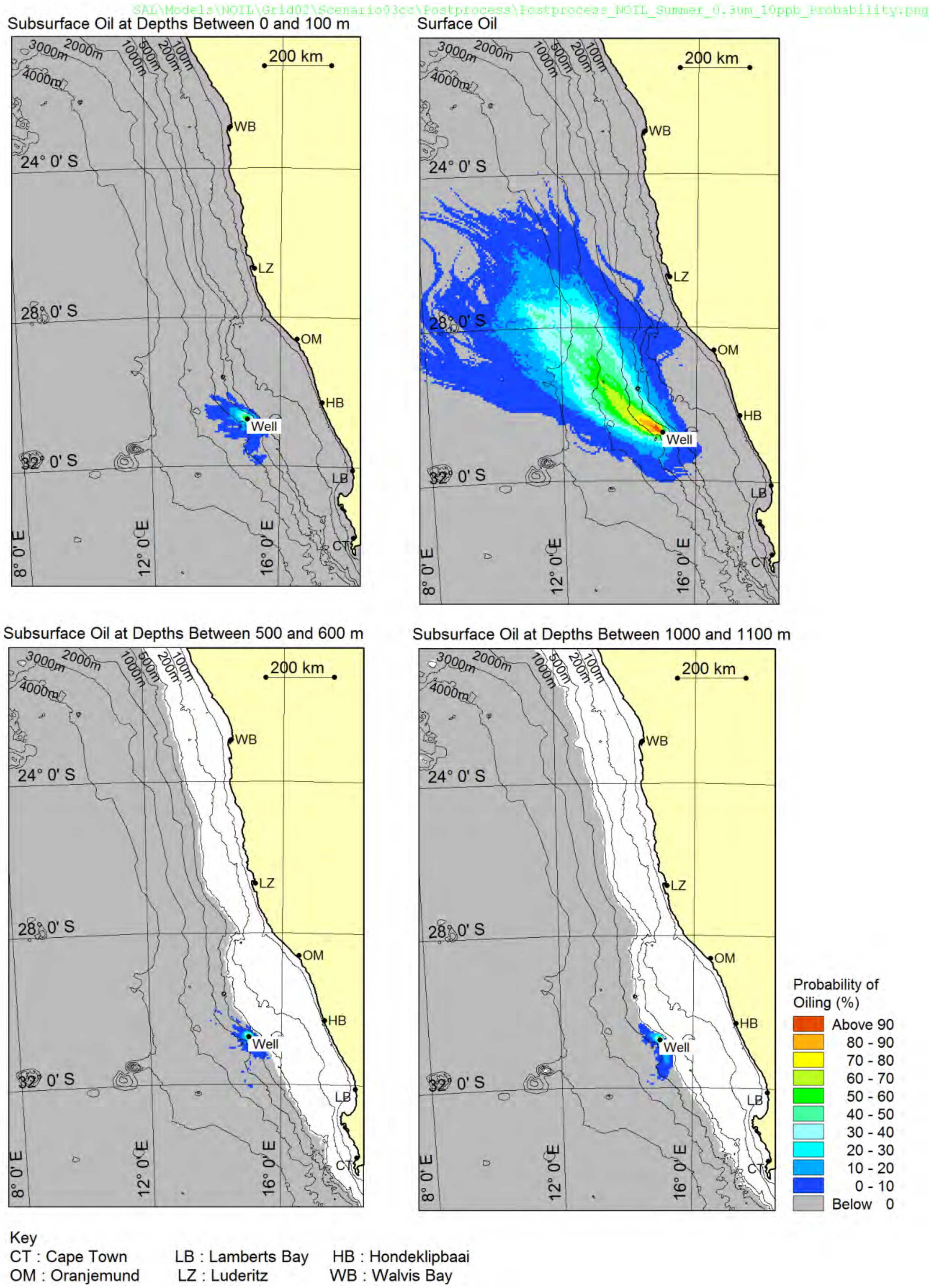


Figure C—4: *Oil spill 3 (5-day blowout) fast weathering scenario. Probability of surface and subsurface oiling for a spill event in summer.*

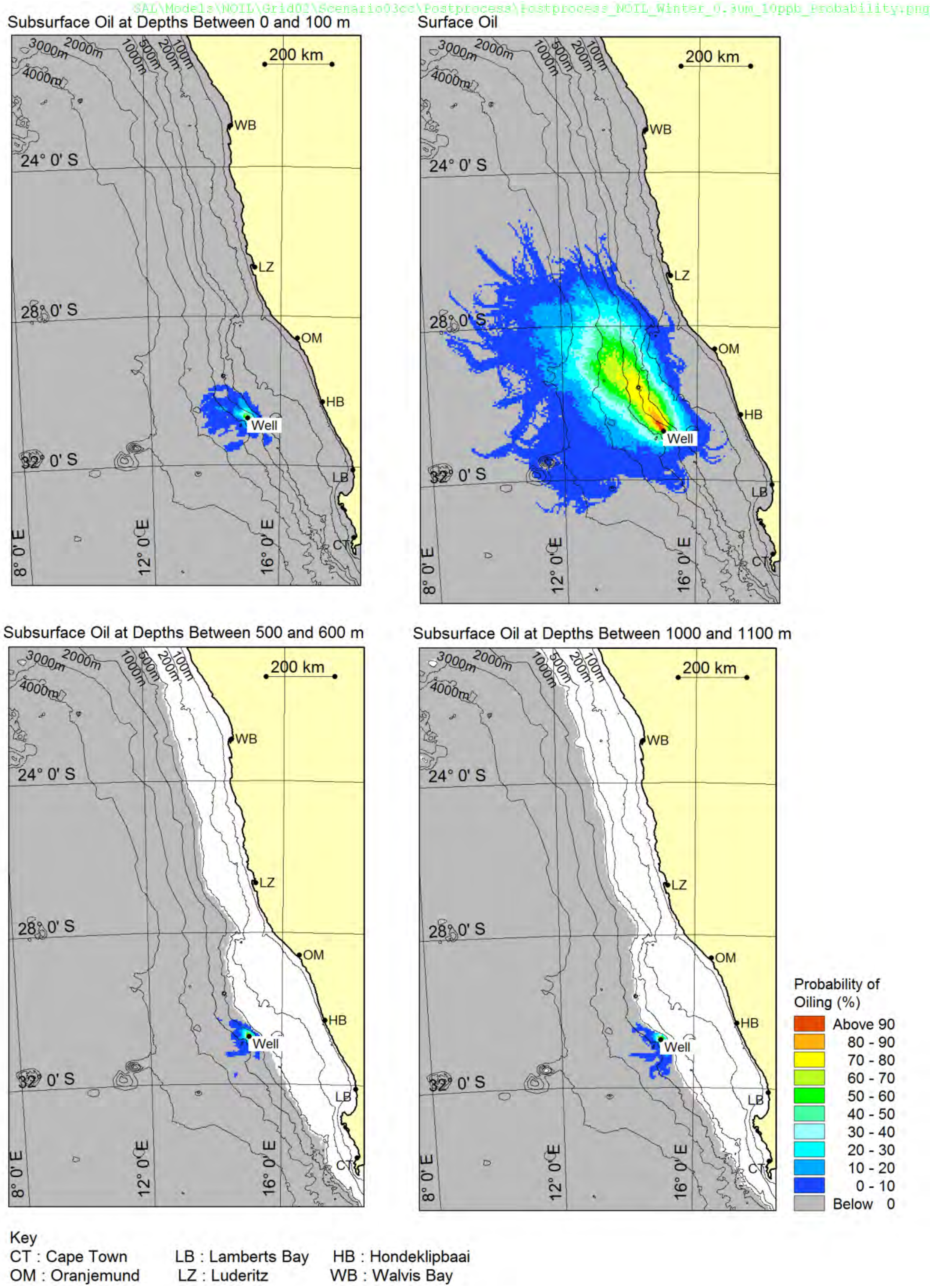


Figure C—5: *Oil spill 3 (5-day blowout) fast weathering scenario. Probability of surface and subsurface oiling for a spill event in winter.*

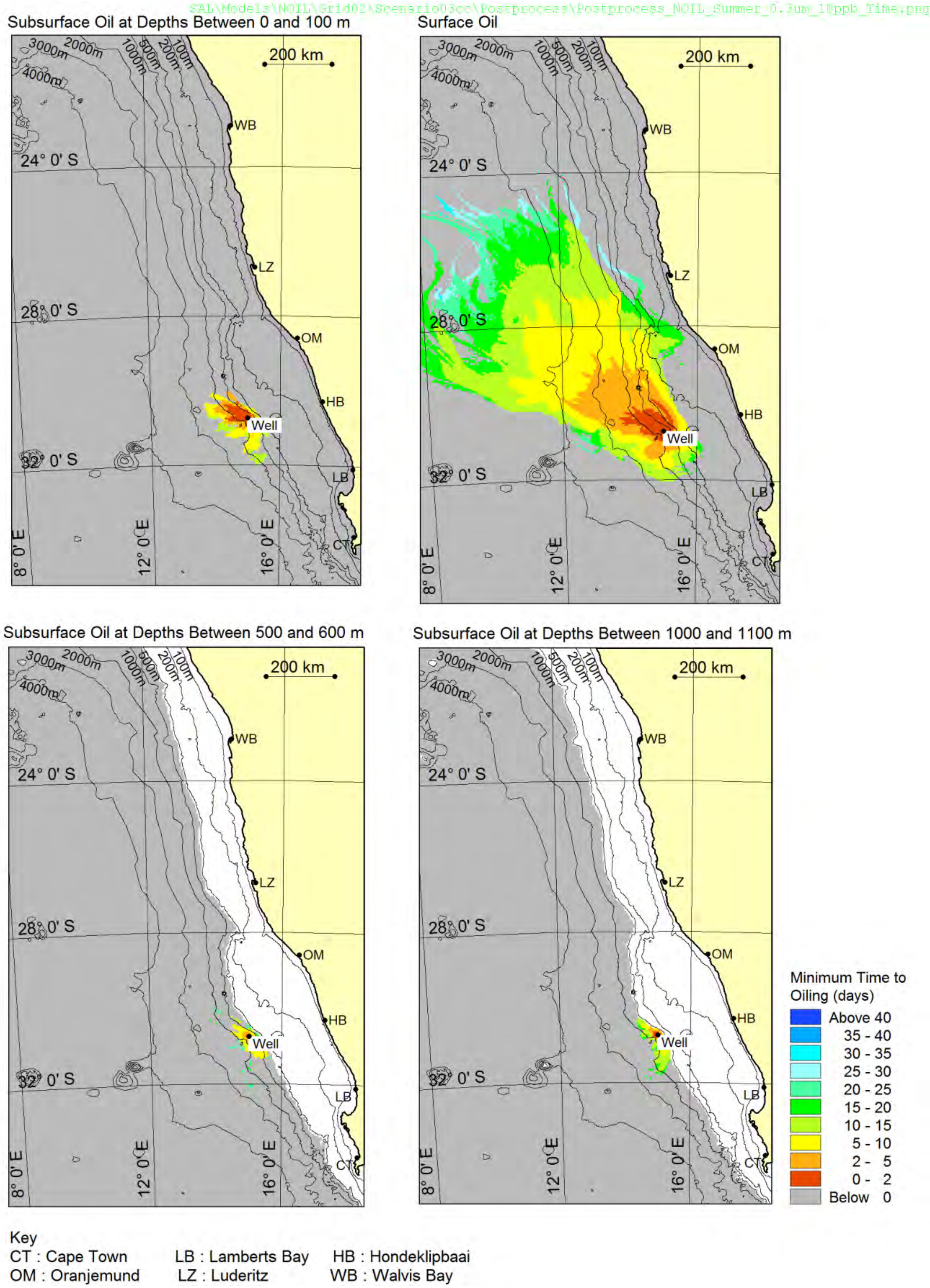


Figure C—6: *Oil spill 3 (5-day blowout) fast weathering scenario. Minimum time to oiling (from start of spill) for a spill event in summer.*

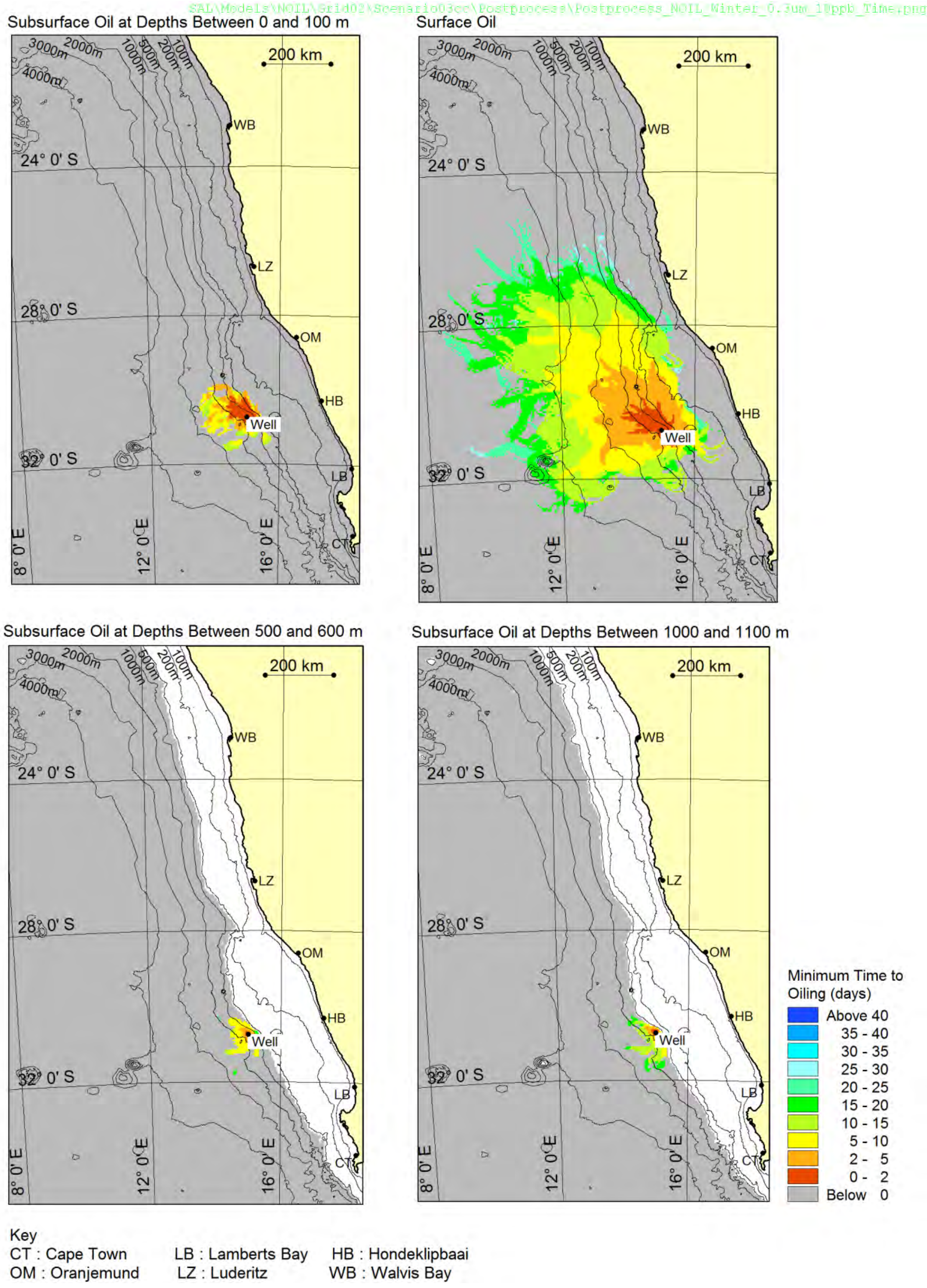


Figure C—7: *Oil spill 3 (5-day blowout) fast weathering scenario. Minimum time to oiling (from start of spill) for a spill event in winter.*

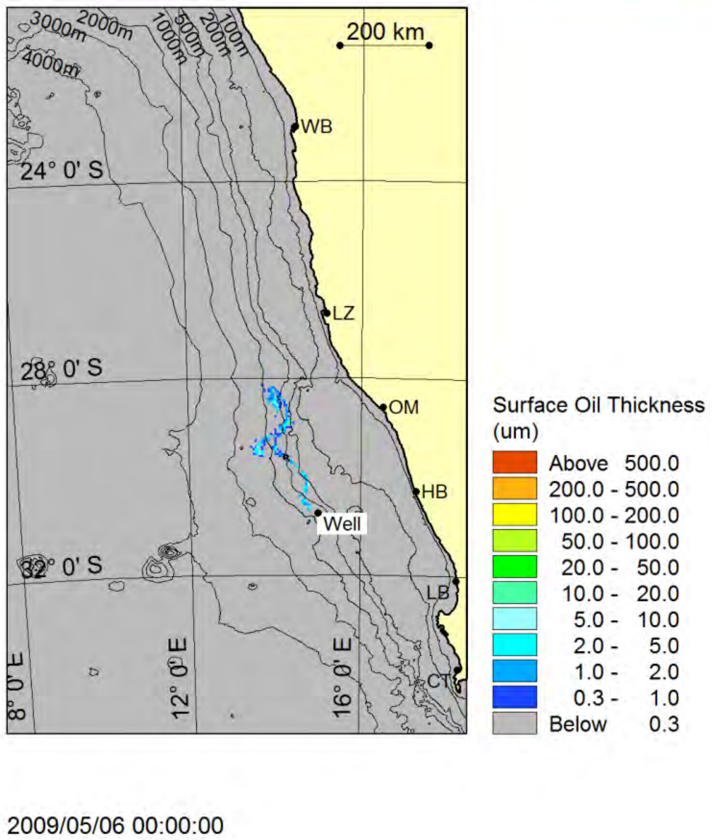


Figure C—8: *Oil spill 3 (5-day blowout) medium weathering scenario. Instantaneous surface oil patch 14 days after the start of a spill case where the oil approached the shore.*

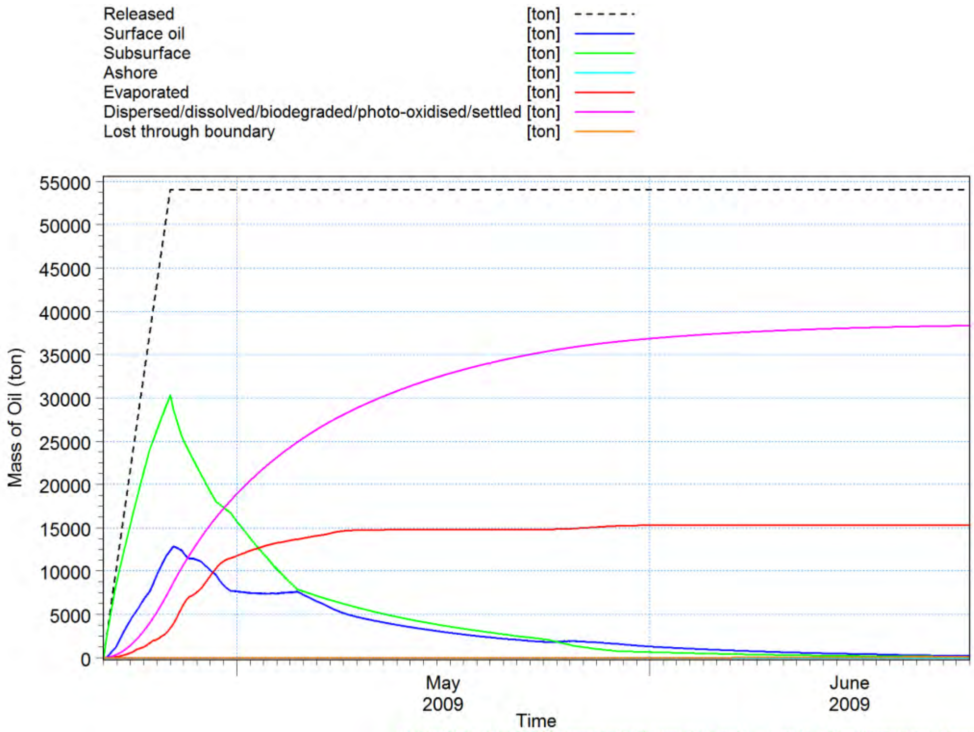


Figure C—9: *Oil spill 3 (5-day blowout) medium weathering scenario. Oil mass balance for a spill case where the oil approached the shore.*

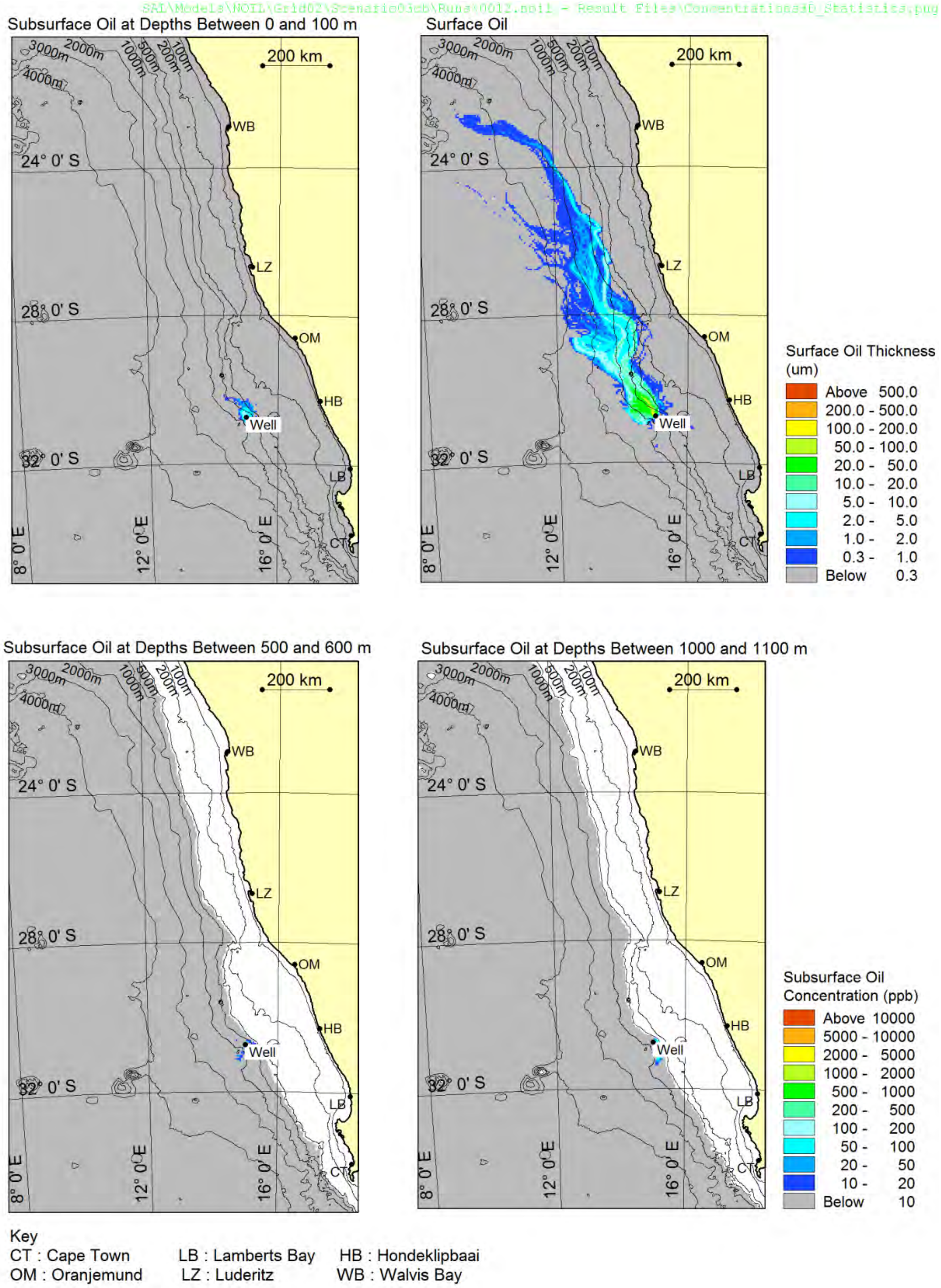
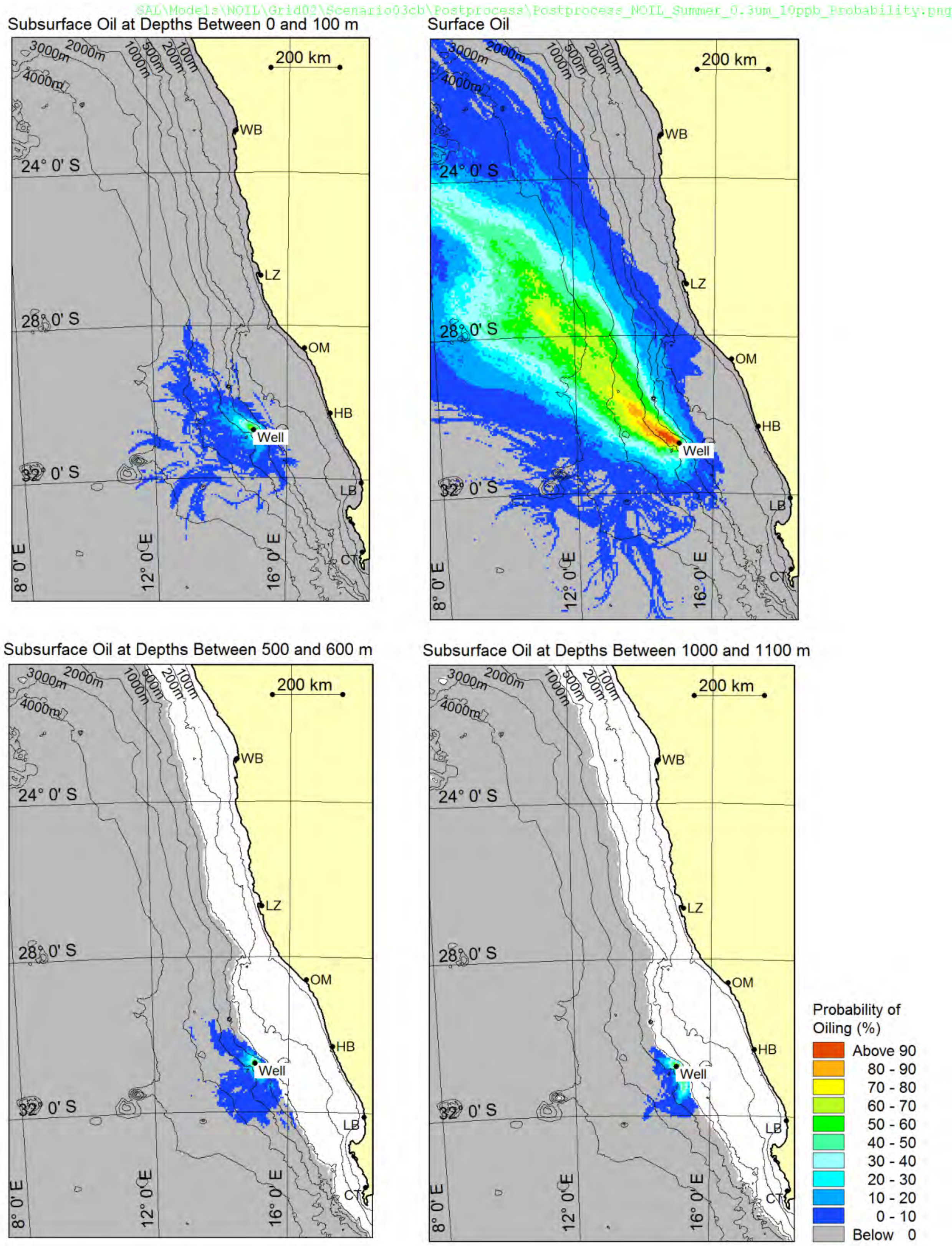
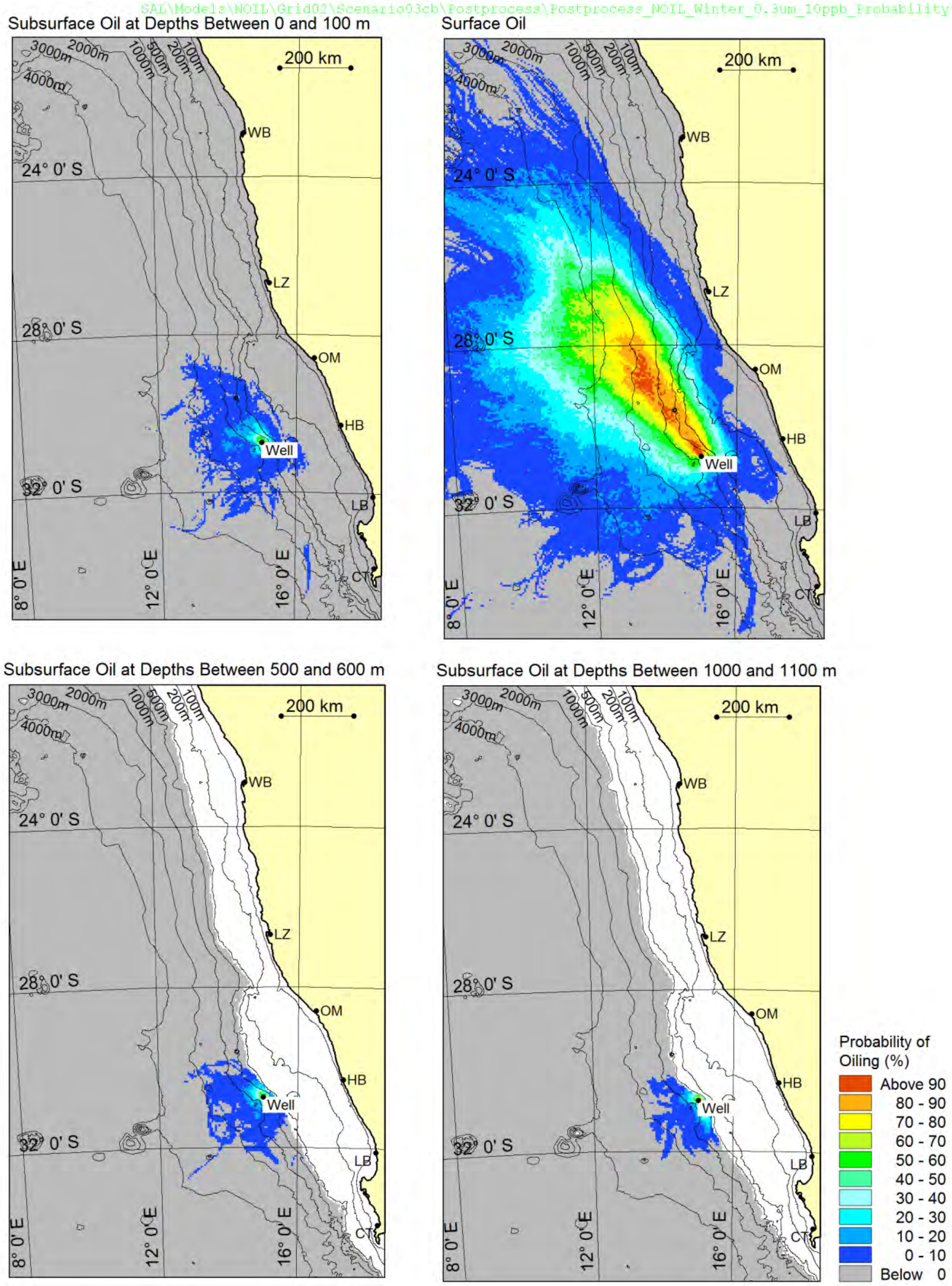


Figure C—10: *Oil spill 3 (5-day blowout) medium weathering scenario. Predicted oil trajectory for a spill case where the oil approached the shore. Plot shows the maximum oil thickness on the water surface and the maximum subsurface oil concentration at any time during the spill, i.e. the area swept by oil.*



Key
CT : Cape Town LB : Lamberts Bay HB : Hondeklipbaai
OM : Oranjemund LZ : Luderitz WB : Walvis Bay

Figure C—11: *Oil spill 3 (5-day blowout) medium weathering scenario. Probability of surface and subsurface oiling for a spill event in summer.*



Key
CT : Cape Town LB : Lamberts Bay HB : Hondeklipbaai
OM : Oranjemund LZ : Luderitz WB : Walvis Bay

Figure C—12: *Oil spill 3 (5-day blowout) medium weathering scenario. Probability of surface and subsurface oiling for a spill event in winter.*

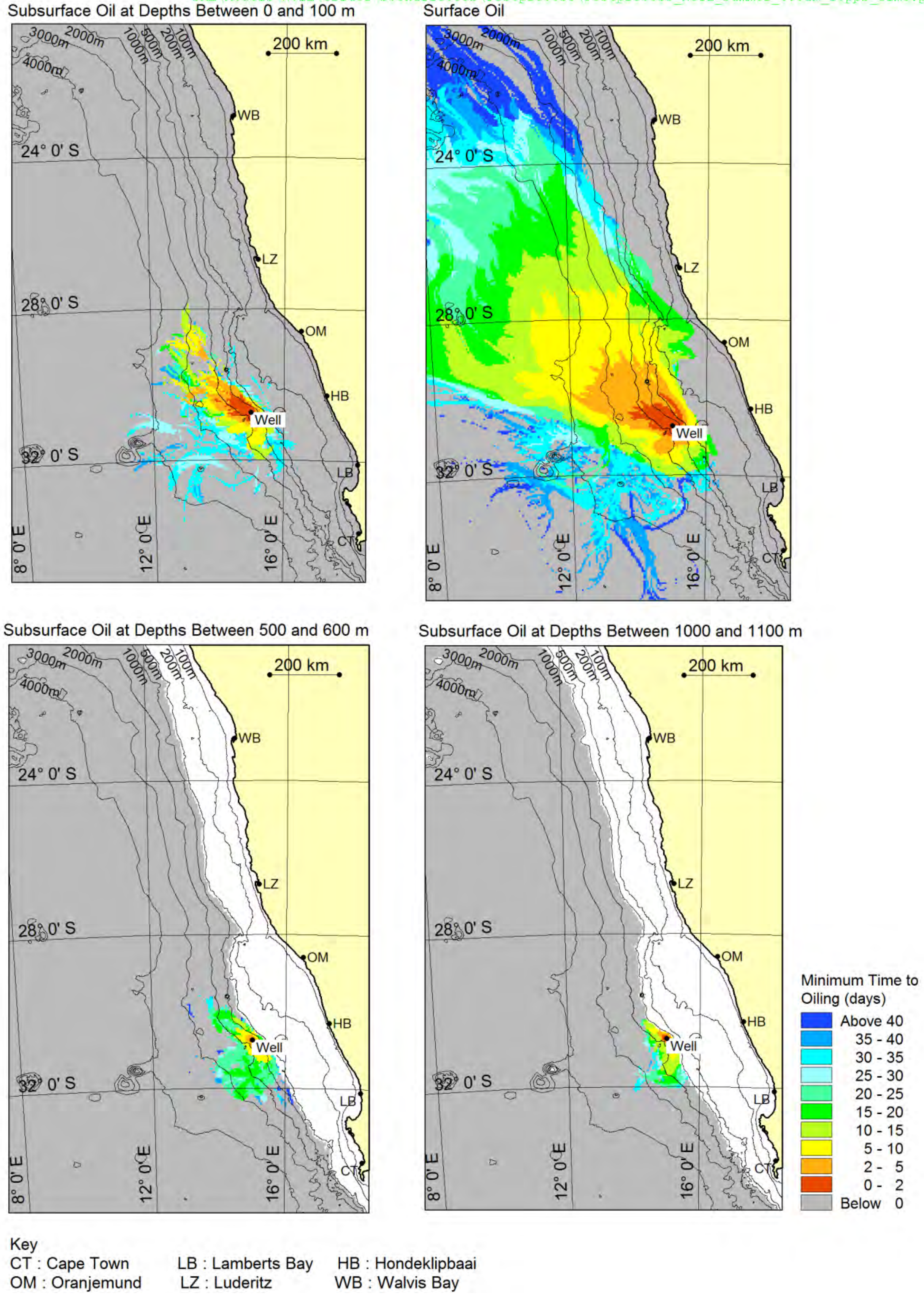


Figure C—13: *Oil spill 3 (5-day blowout) medium weathering scenario. Minimum time to oiling (from start of spill) for a spill event in summer.*

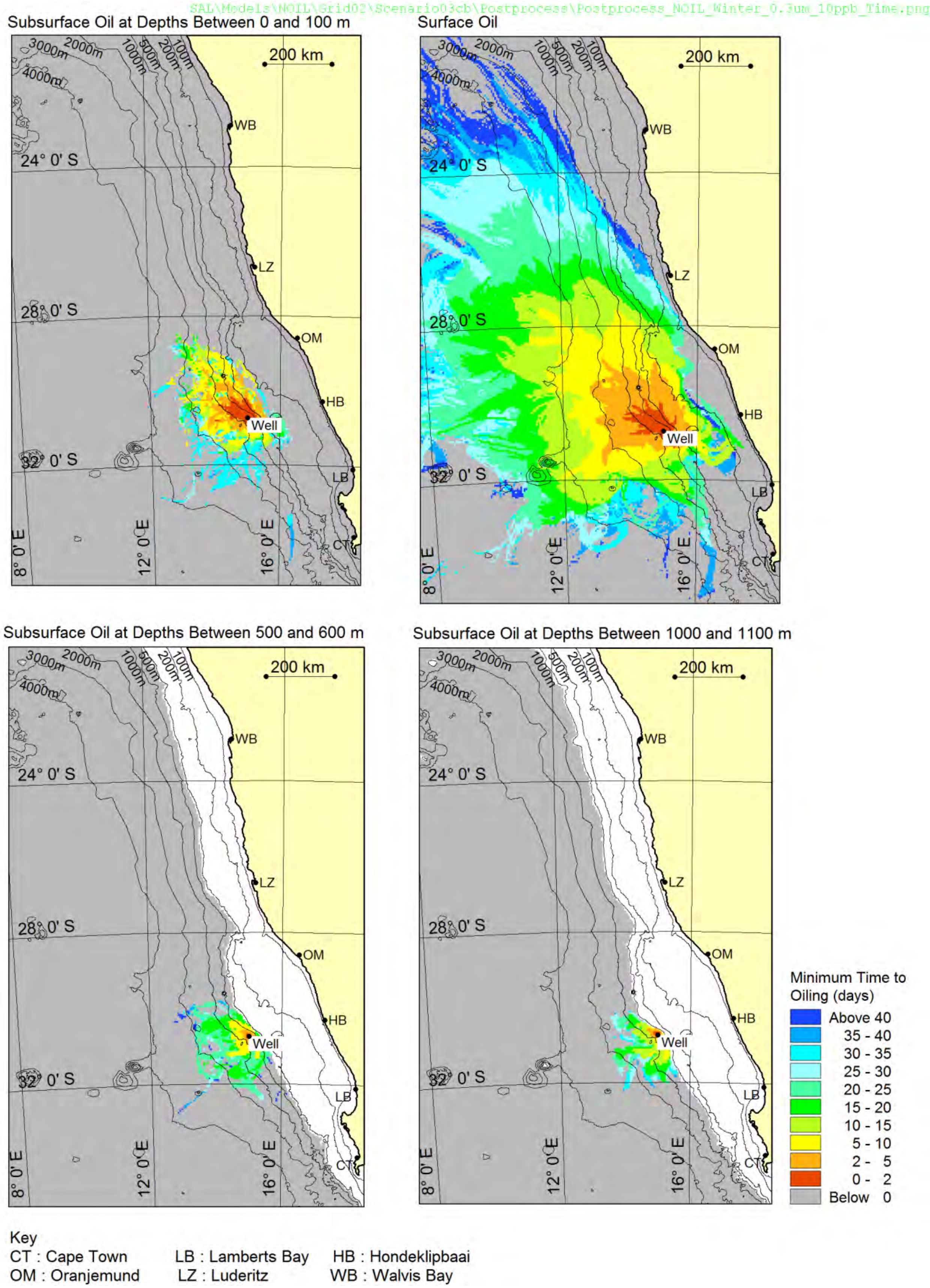


Figure C—14: *Oil spill 3 (5-day blowout) medium weathering scenario. Minimum time to oiling (from start of spill) for a spill event in winter.*

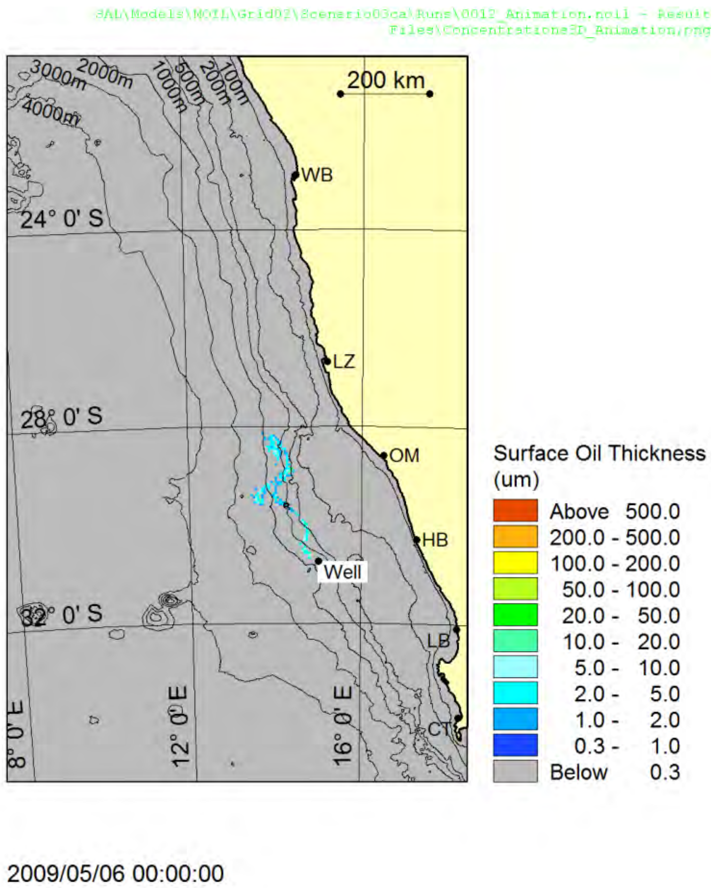


Figure C—15: *Oil spill 3 (5-day blowout) slow weathering scenario. Instantaneous surface oil patch 14 days after the start of a spill case where the oil approached the shore.*

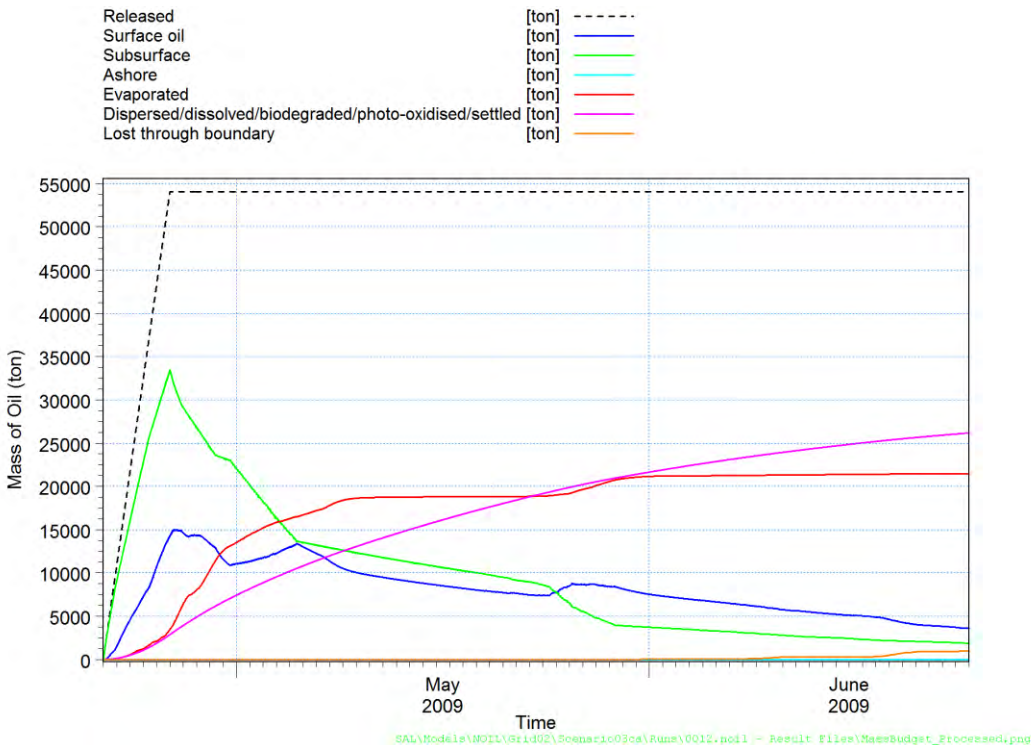
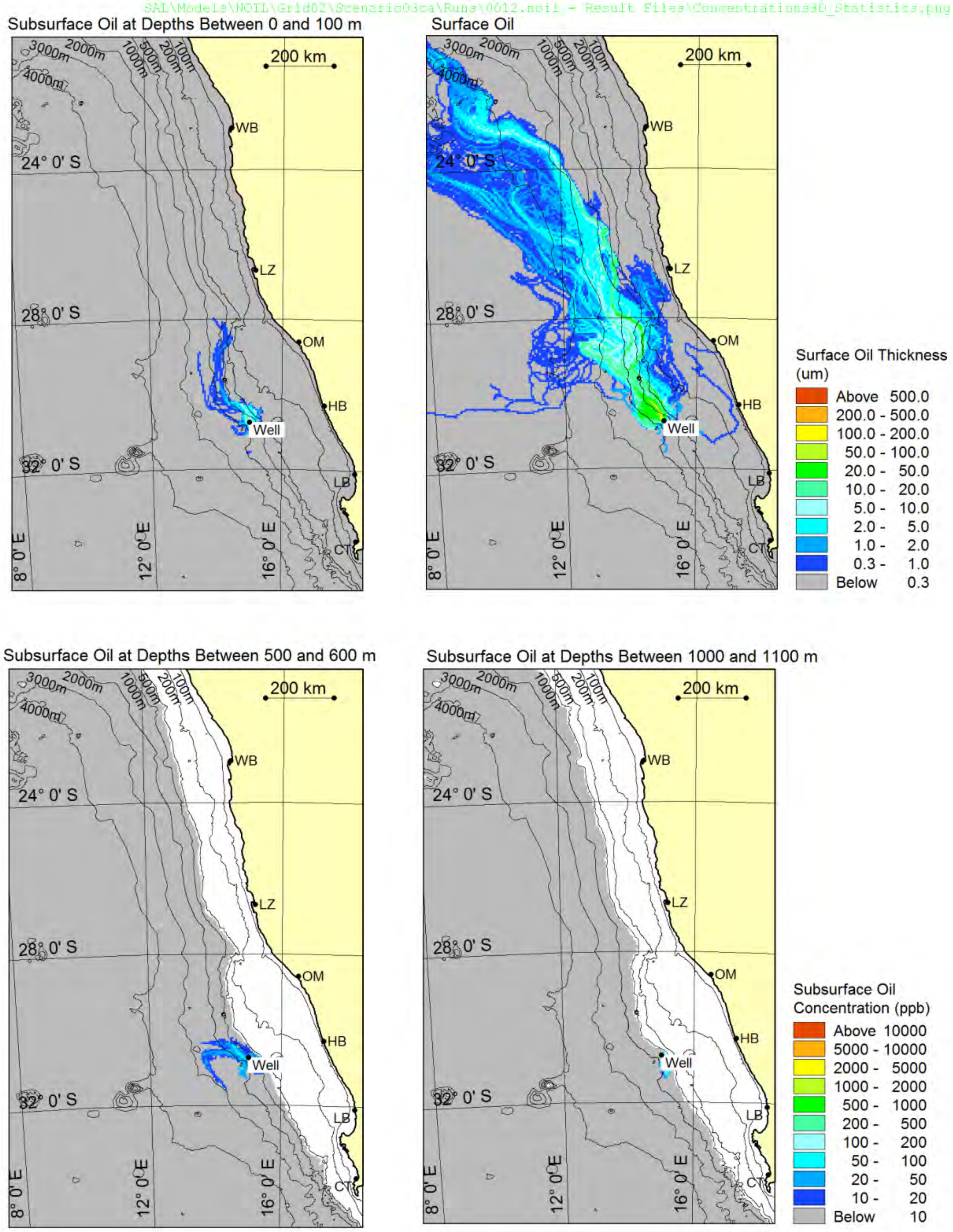


Figure C—16: *Oil spill 3 (5-day blowout) slow weathering scenario. Oil mass balance for a spill case where the oil approached the shore.*



Key
CT : Cape Town
OM : Oranjemund
LB : Lamberts Bay
LZ : Luderitz
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Figure C—17: *Oil spill 3 (5-day blowout) slow weathering scenario. Predicted oil trajectory for a spill case where the oil approached the shore. Plot shows the maximum oil thickness on the water surface and the maximum subsurface oil concentration at any time during the spill, i.e. the area swept by oil.*

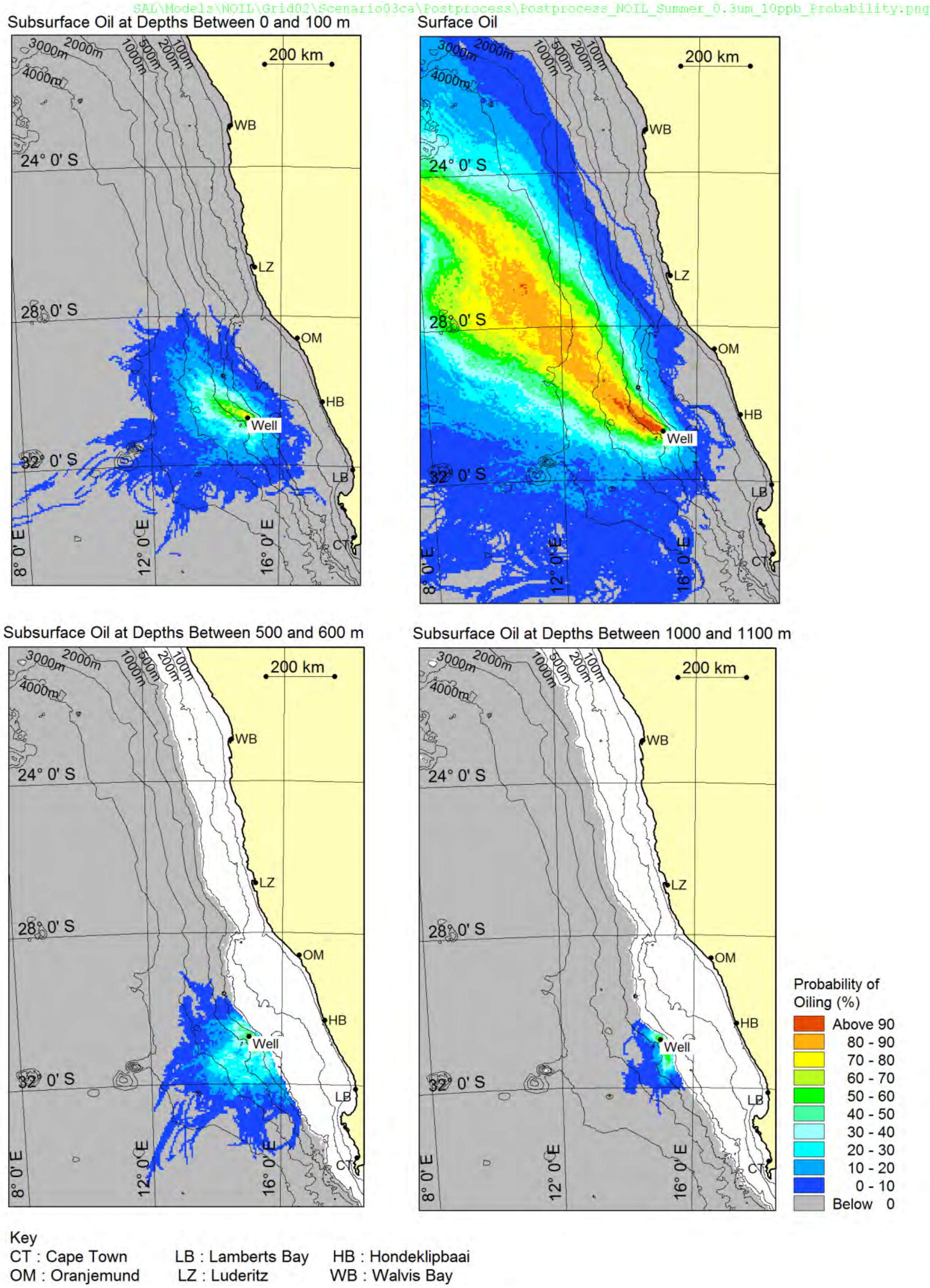


Figure C—18: *Oil spill 3 (5-day blowout) slow weathering scenario. Probability of surface and subsurface oiling for a spill event in summer.*

SAL\Models\NOIL\Grid02\Scenario03ca\Postprocess\Postprocess_NOIL_Winter_0.3um_10ppb_Probability.png

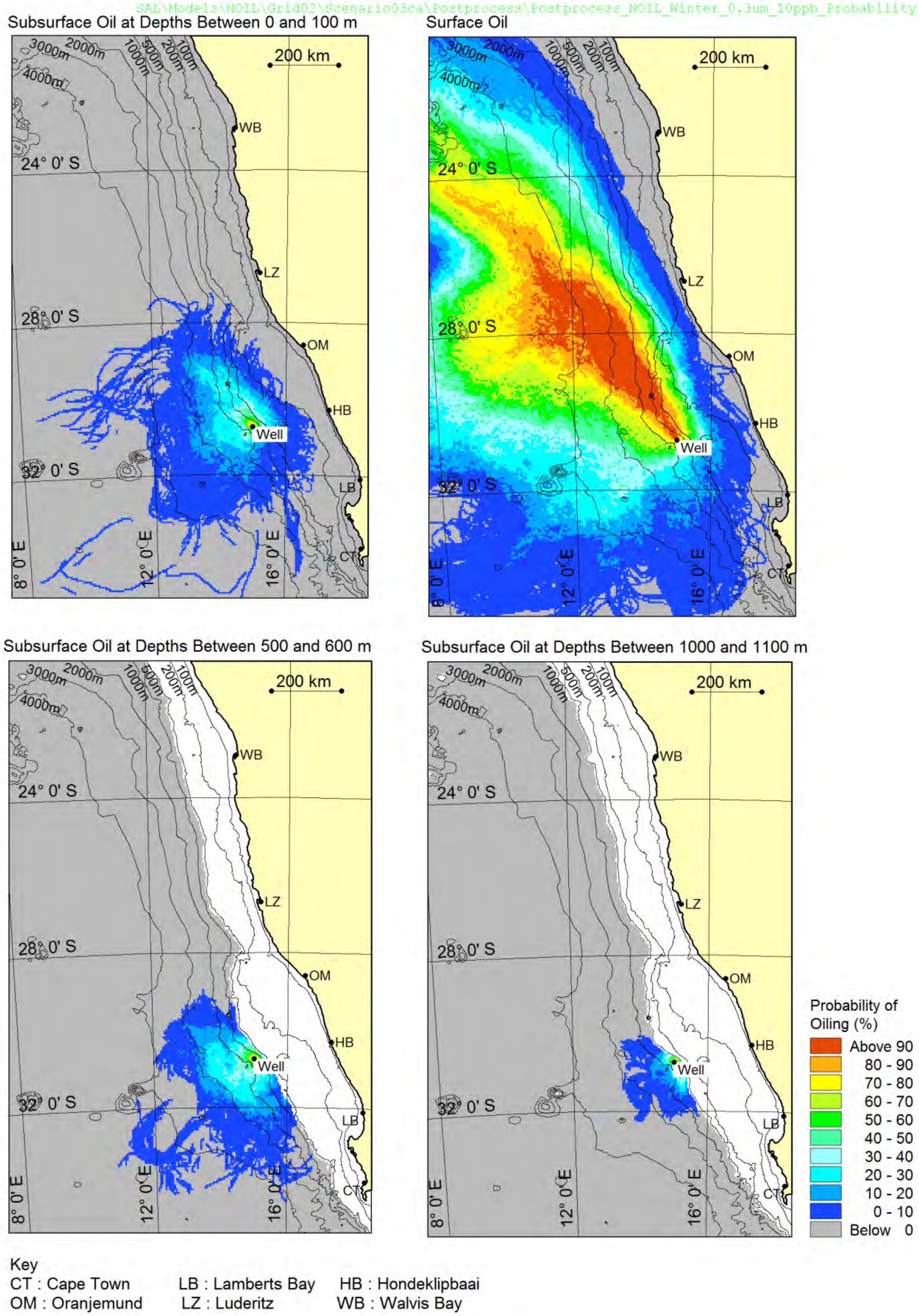


Figure C—19: *Oil spill 3 (5-day blowout) slow weathering scenario. Probability of surface and subsurface oiling for a spill event in winter.*

SAL\Models\NOIL\Grid02\Scenario03ca\Postprocess\Postprocess_NOIL_Summer_0.3um_10ppb_Time.png

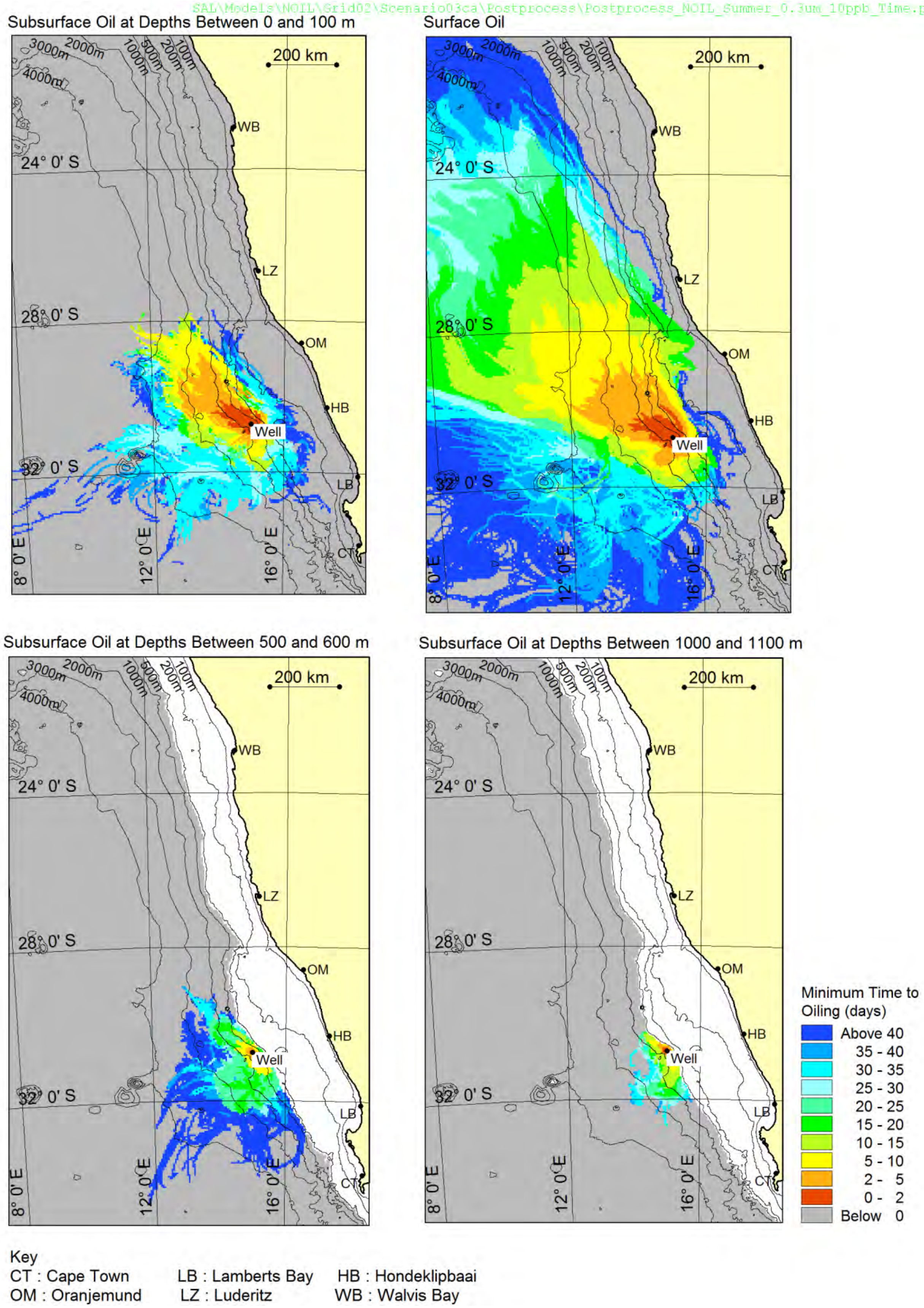


Figure C—20: *Oil spill 3 (5-day blowout) slow weathering scenario. Minimum time to oiling (from start of spill) for a spill event in summer.*

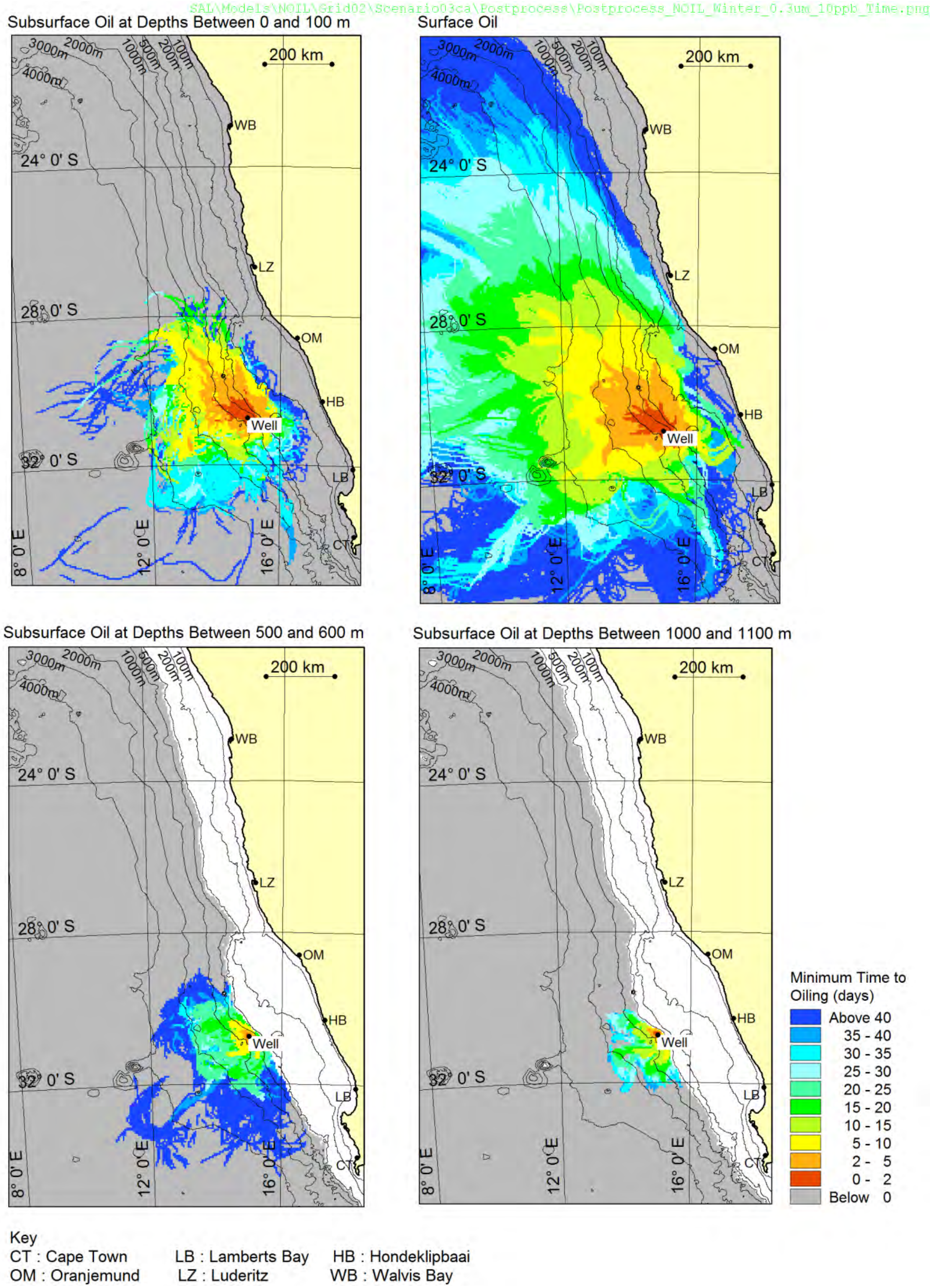


Figure C—21: *Oil spill 3 (5-day blowout) slow weathering scenario. Minimum time to oiling (from start of spill) for a spill event in winter.*

ANNEXURE D | FULL SET OF MODEL RESULTS FOR OIL SPILL 4 (20-DAY BLOWOUT ON SEABED)

FIGURES (ANNEXURE D)	Page N°

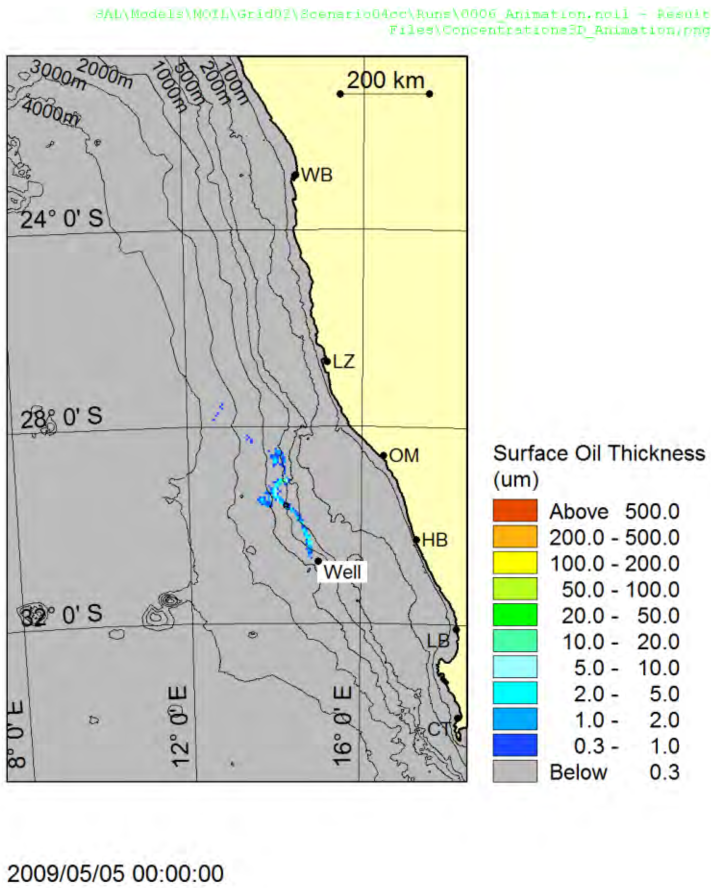


***Figure D—1:** Oil spill 4 (20-day blowout) fast weathering scenario. Instantaneous surface oil patch 14 days after the start of a spill case where the oil approached the shore.*

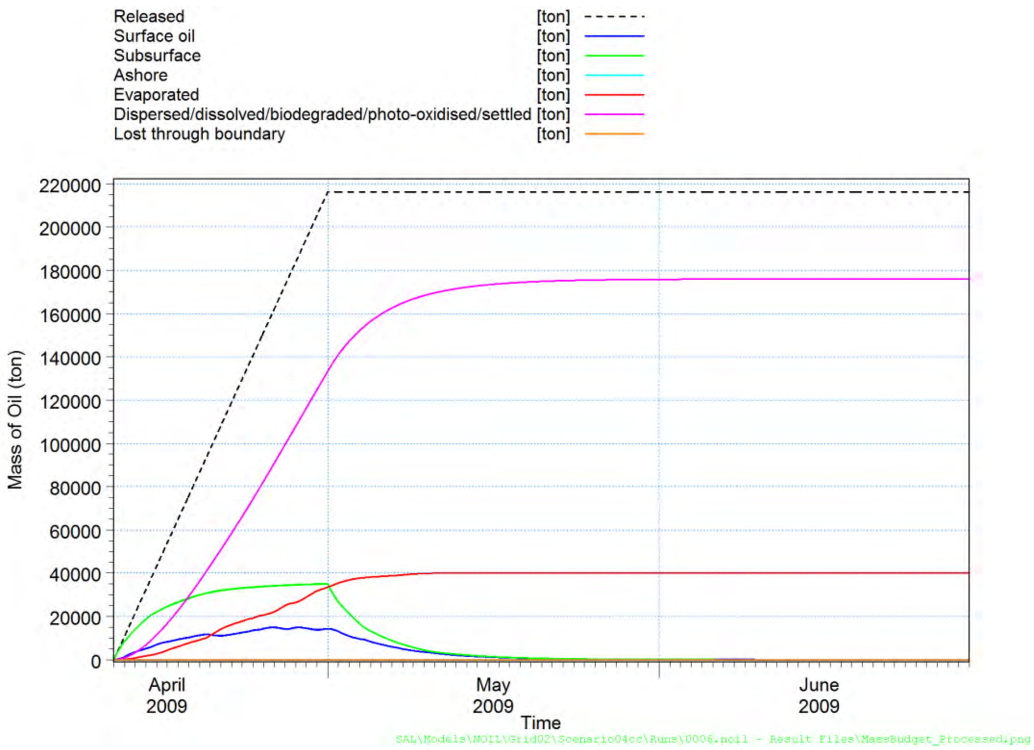


***Figure D—2:** Oil spill 4 (20-day blowout) fast weathering scenario. Oil mass balance for a spill case where the oil approached the shore.*

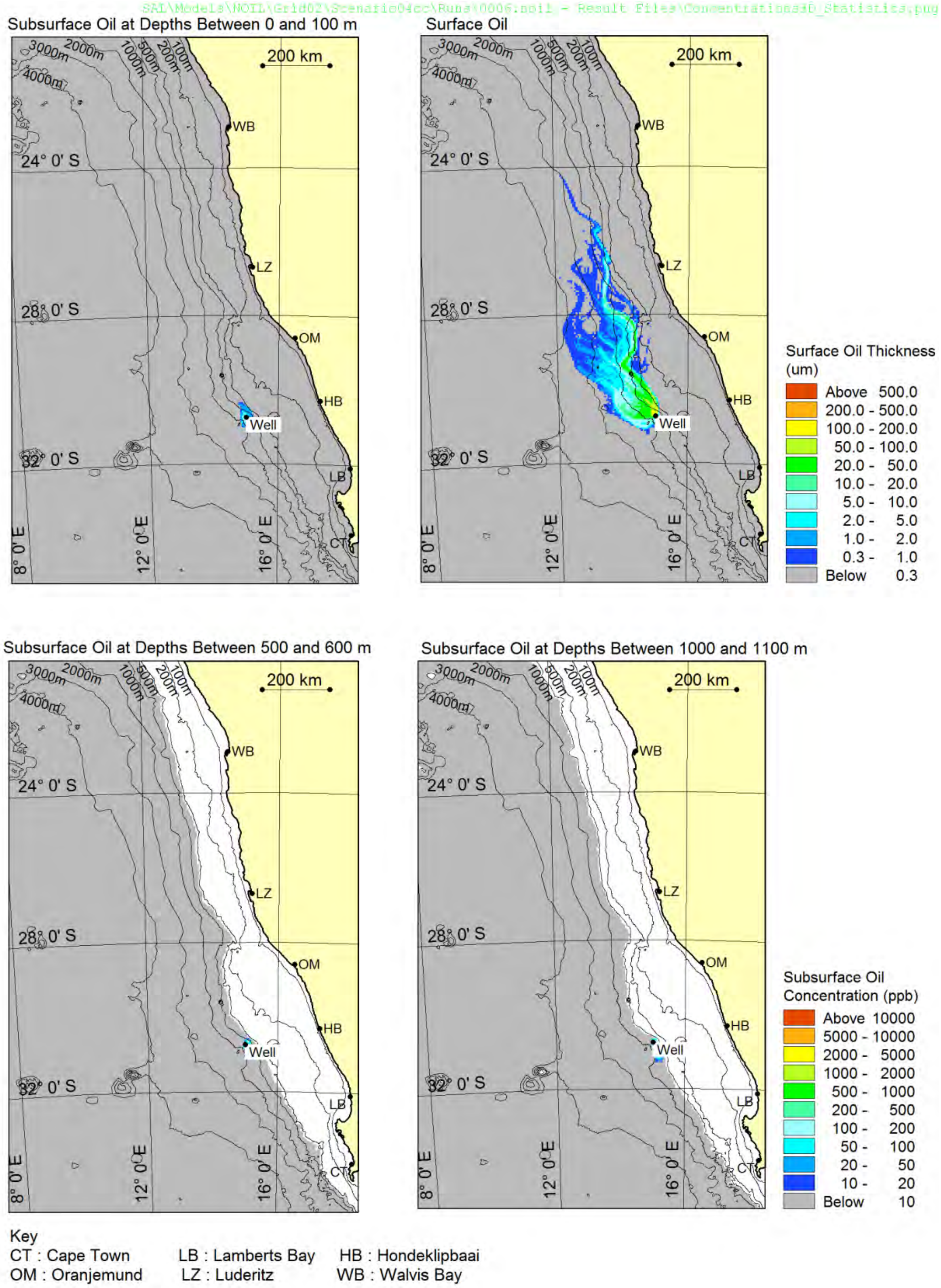
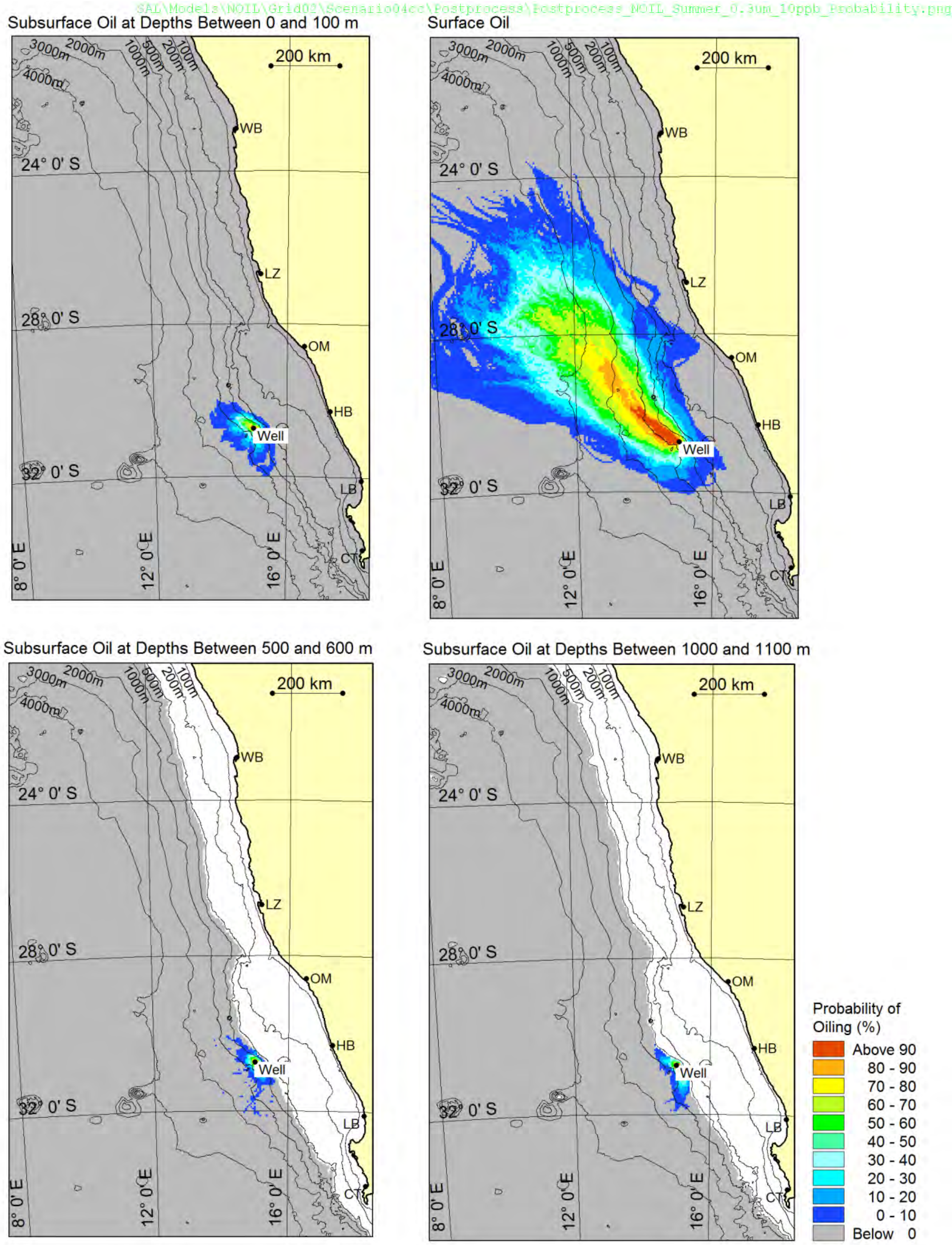


Figure D—3: *Oil spill 4 (20-day blowout) fast weathering scenario. Predicted oil trajectory for a spill case where the oil approached the shore. Plot shows the maximum oil thickness on the water surface and the maximum subsurface oil concentration at any time during the spill, i.e. the area swept by oil.*



Key

CT : Cape Town	LB : Lamberts Bay	HB : Hondeklipbaai
OM : Oranjemund	LZ : Luderitz	WB : Walvis Bay

Figure D—4: *Oil spill 4 (20-day blowout) fast weathering scenario. Probability of surface and subsurface oiling for a spill event in summer.*

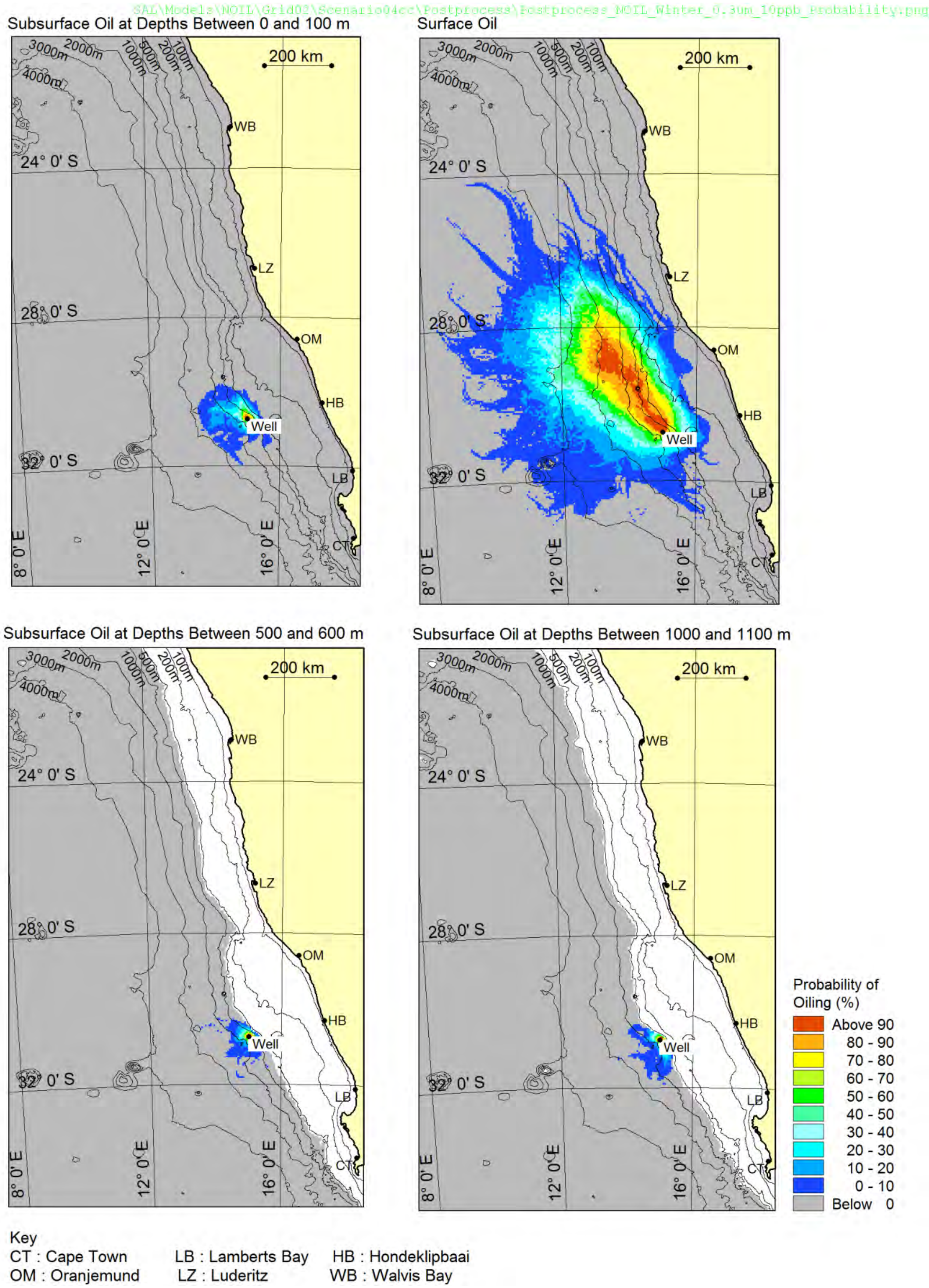


Figure D—5: *Oil spill 4 (20-day blowout) fast weathering scenario. Probability of surface and subsurface oiling for a spill event in winter.*

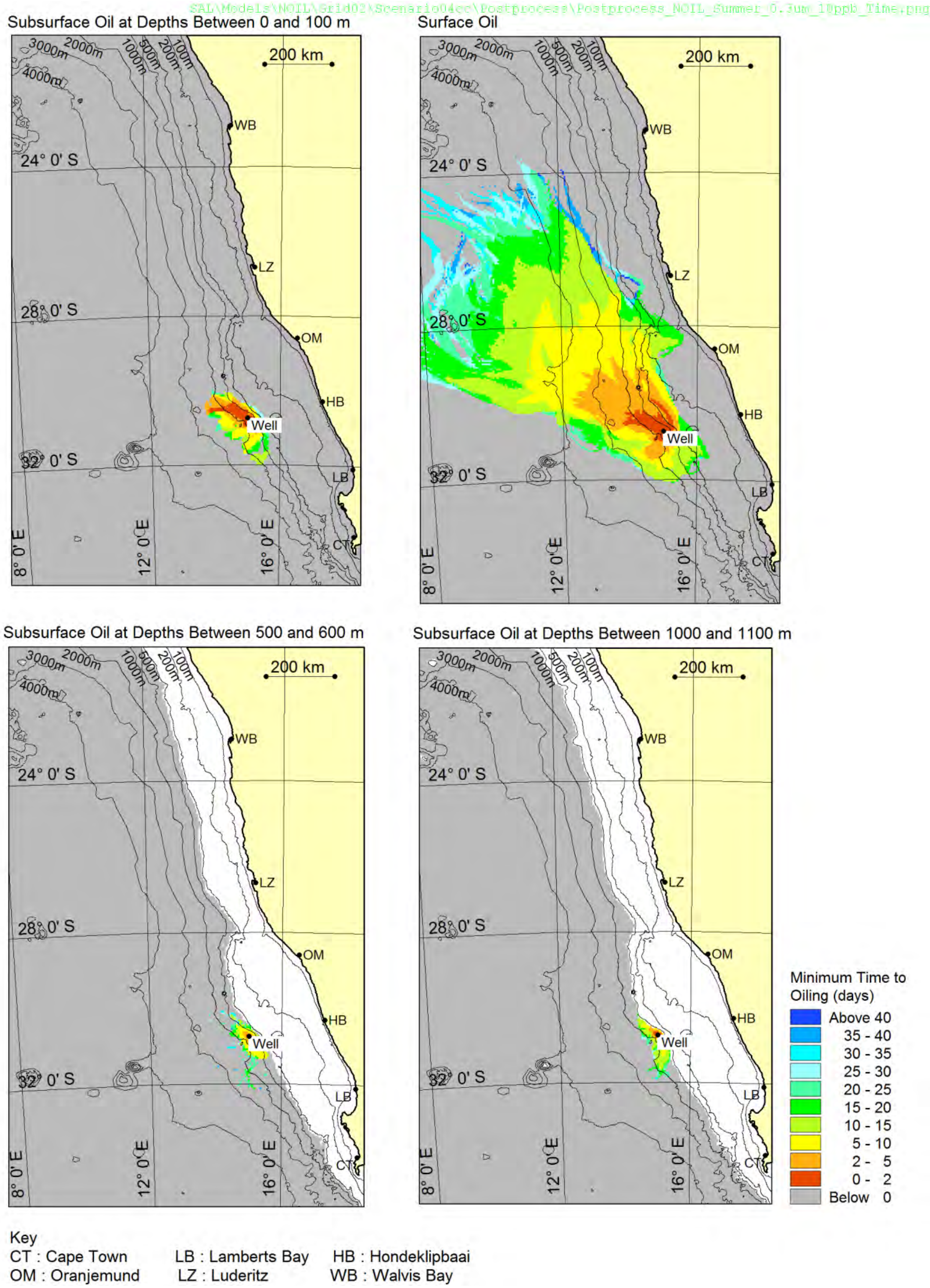
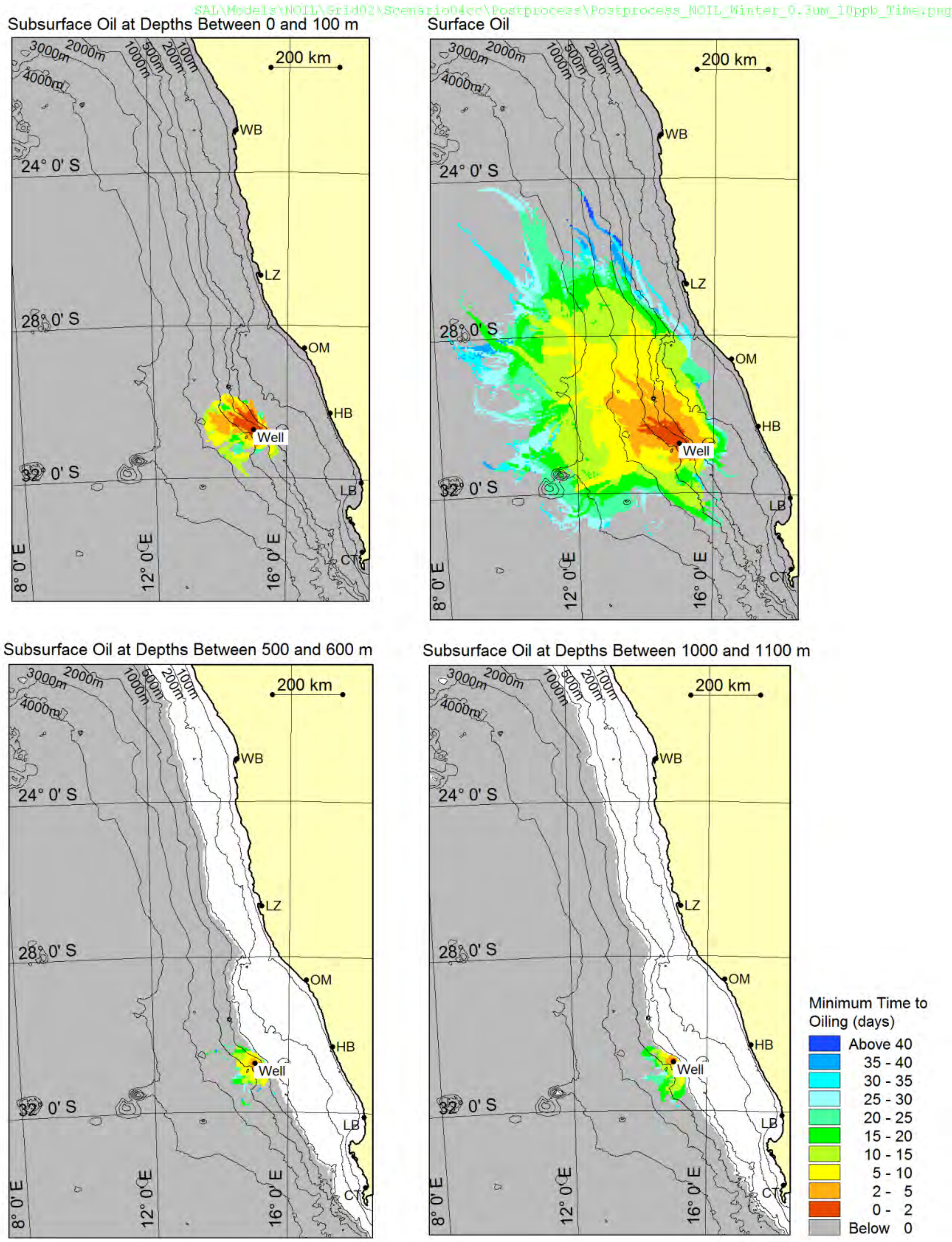


Figure D—6: *Oil spill 4 (20-day blowout) fast weathering scenario. Minimum time to oiling (from start of spill) for a spill event in summer.*



Key
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OM : Oranjemund LZ : Luderitz WB : Walvis Bay

Figure D—7: *Oil spill 4 (20-day blowout) fast weathering scenario. Minimum time to oiling (from start of spill) for a spill event in winter.*

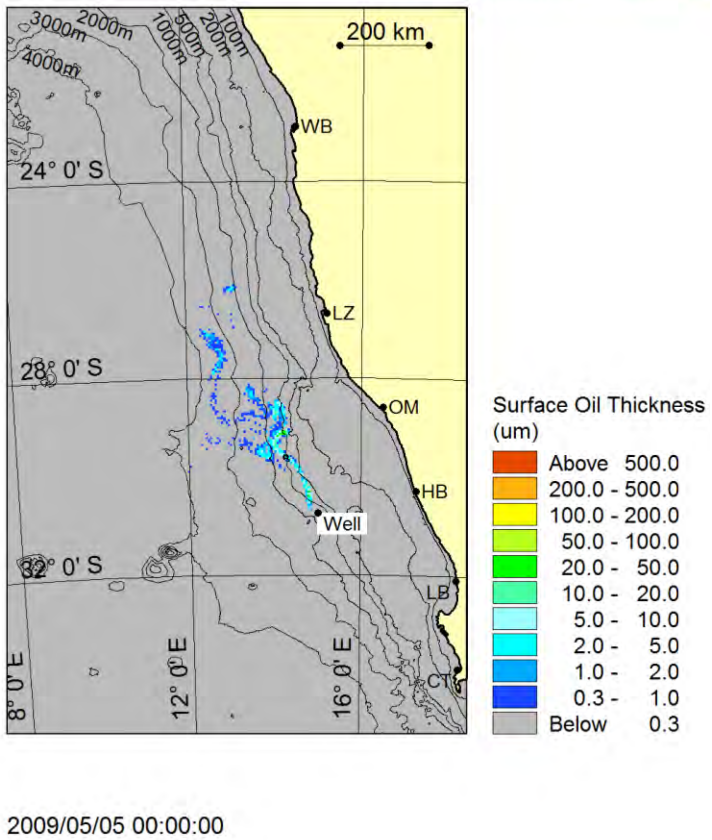


Figure D—8: *Oil spill 4 (20-day blowout) medium weathering scenario. Instantaneous surface oil patch 14 days after the start of a spill case where the oil approached the shore.*

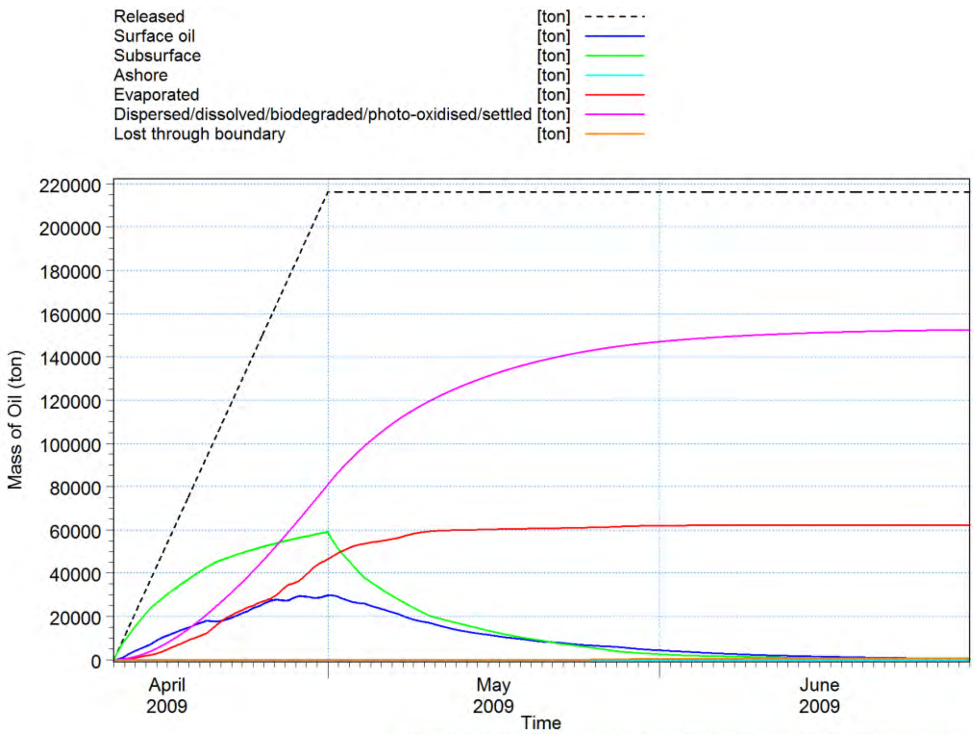


Figure D—9: *Oil spill 4 (20-day blowout) medium weathering scenario. Oil mass balance for a spill case where the oil approached the shore.*

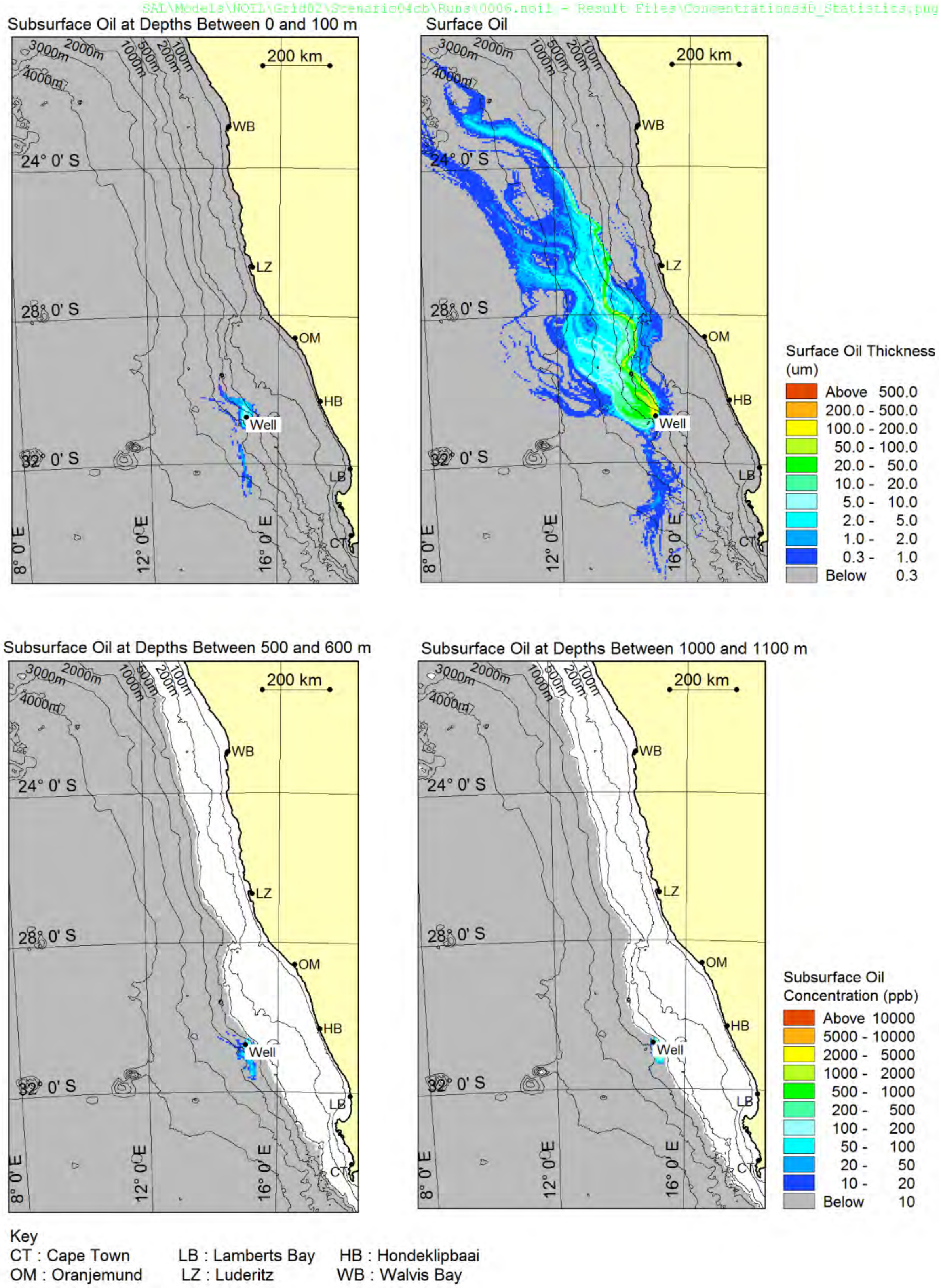
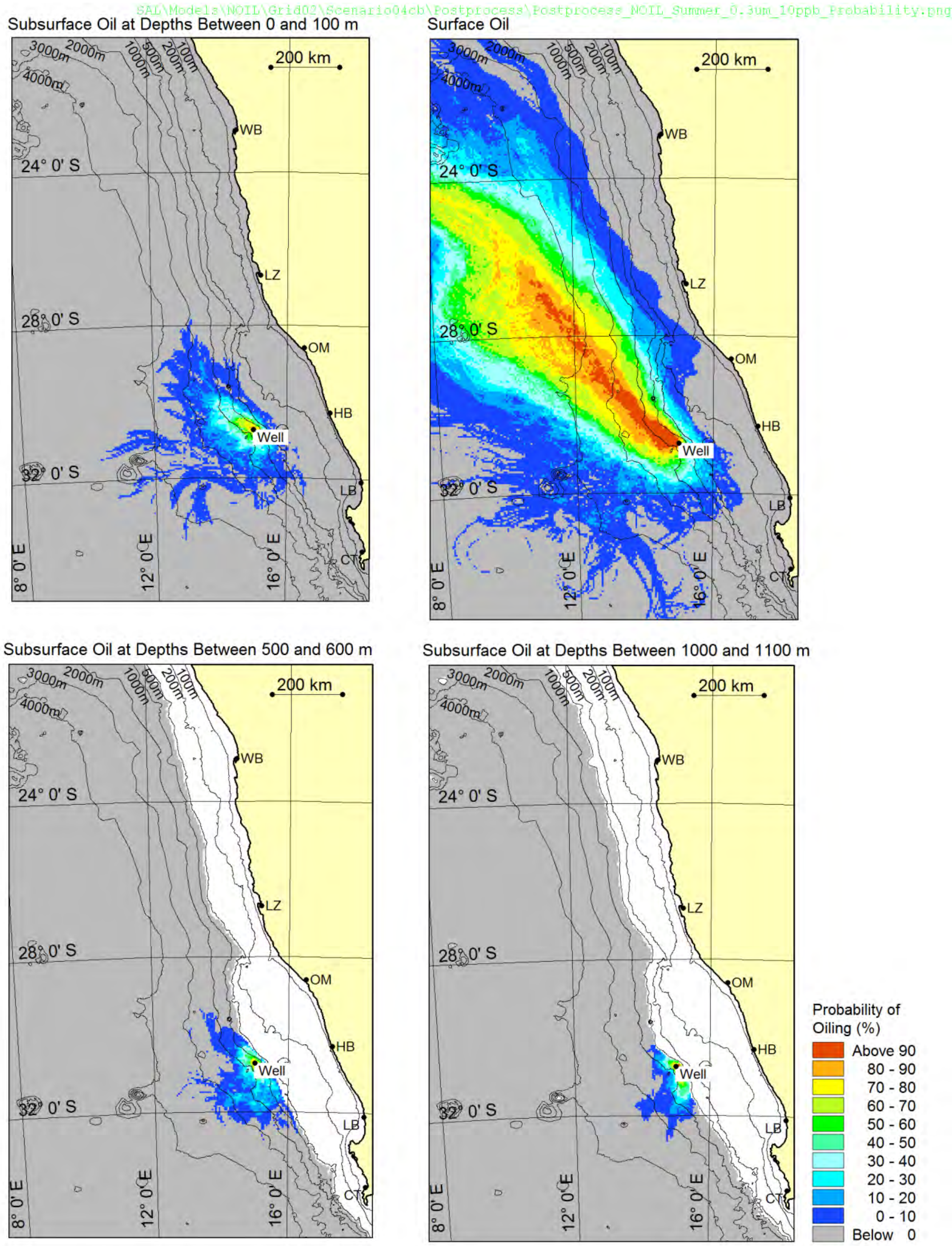


Figure D—10: *Oil spill 4 (20-day blowout) medium weathering scenario. Predicted oil trajectory for a spill case where the oil approached the shore. Plot shows the maximum oil thickness on the water surface and the maximum subsurface oil concentration at any time during the spill, i.e. the area swept by oil.*



Key
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Figure D—11: *Oil spill 4 (20-day blowout) medium weathering scenario. Probability of surface and subsurface oiling for a spill event in summer.*

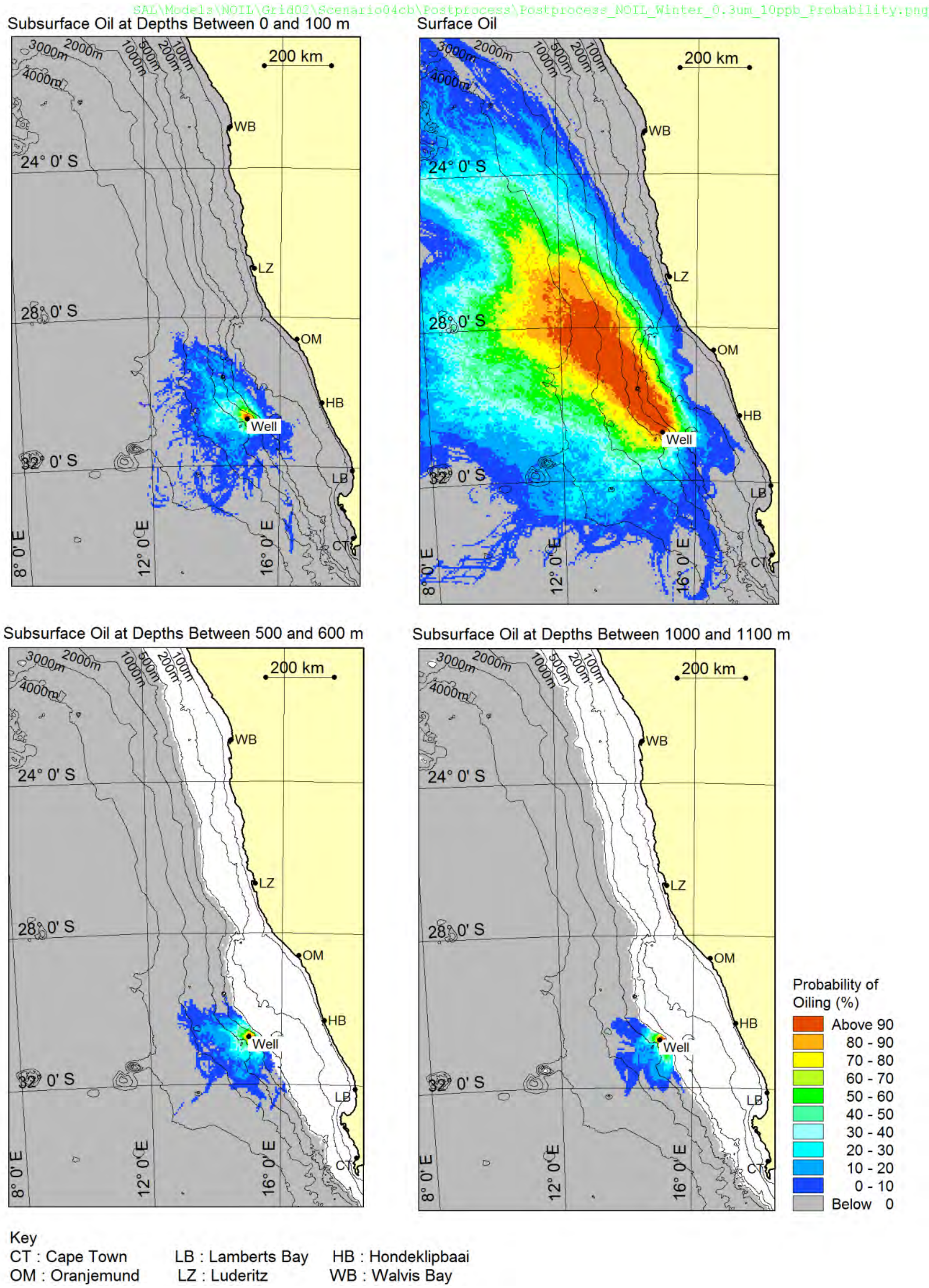
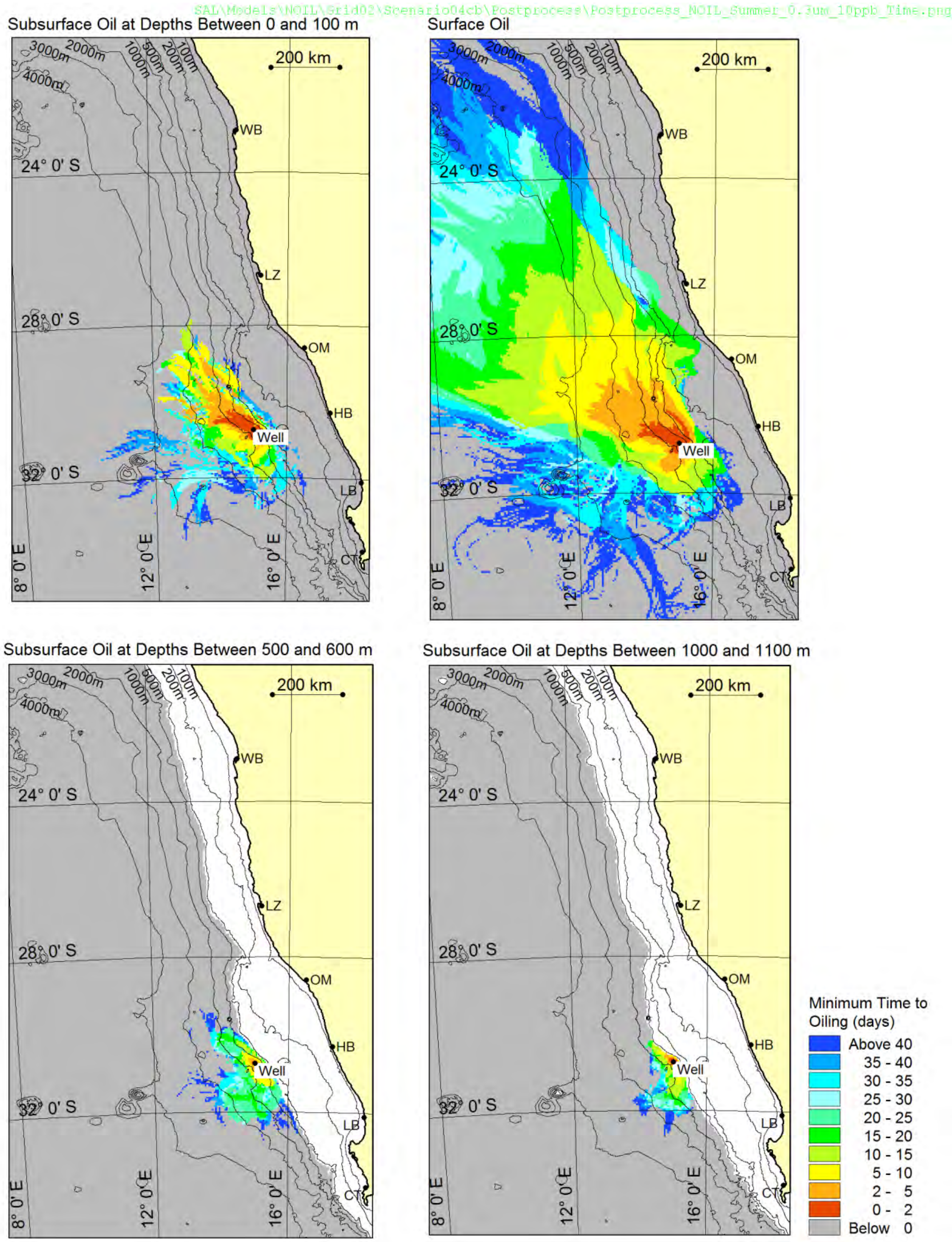


Figure D—12: *Oil spill 4 (20-day blowout) medium weathering scenario. Probability of surface and subsurface oiling for a spill event in winter.*



Key
CT : Cape Town LB : Lamberts Bay HB : Hondeklipbaai
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Figure D—13: *Oil spill 4 (20-day blowout) medium weathering scenario. Minimum time to oiling (from start of spill) for a spill event in summer.*

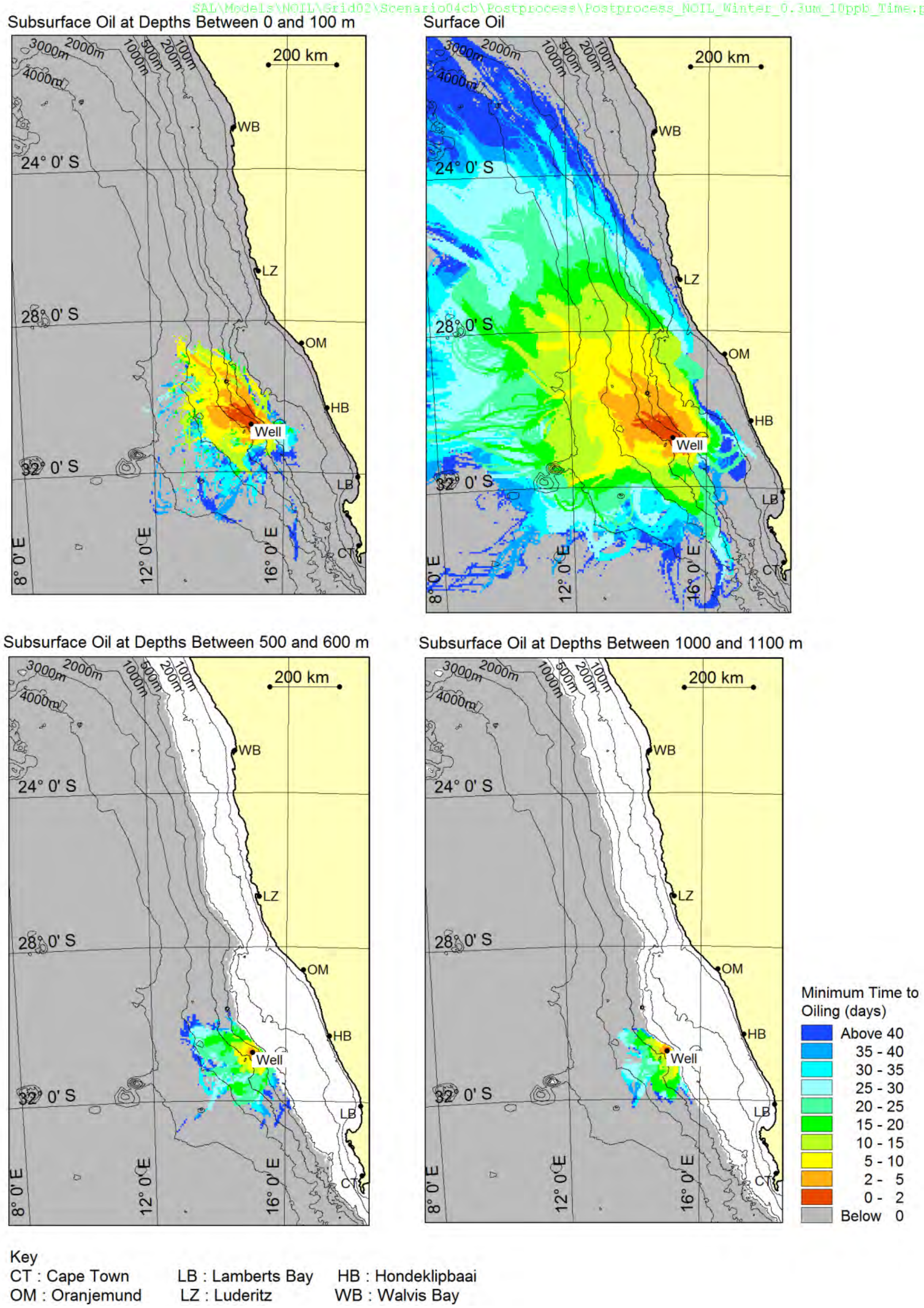


Figure D—14: *Oil spill 4 (20-day blowout) medium weathering scenario. Minimum time to oiling (from start of spill) for a spill event in winter.*

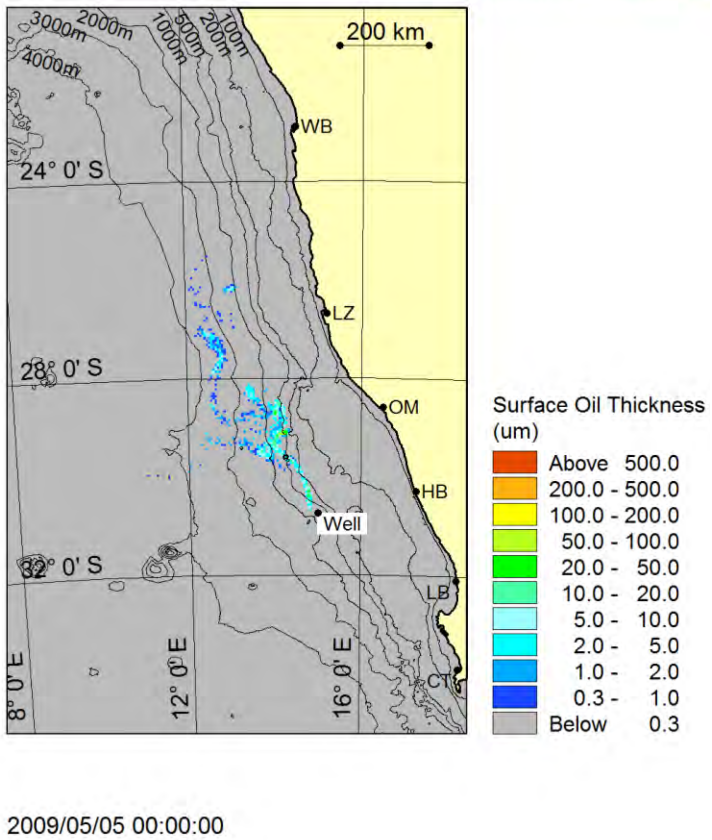


Figure D—15: *Oil spill 4 (20-day blowout) slow weathering scenario. Instantaneous surface oil patch 14 days after the start of a spill case where the oil approached the shore.*

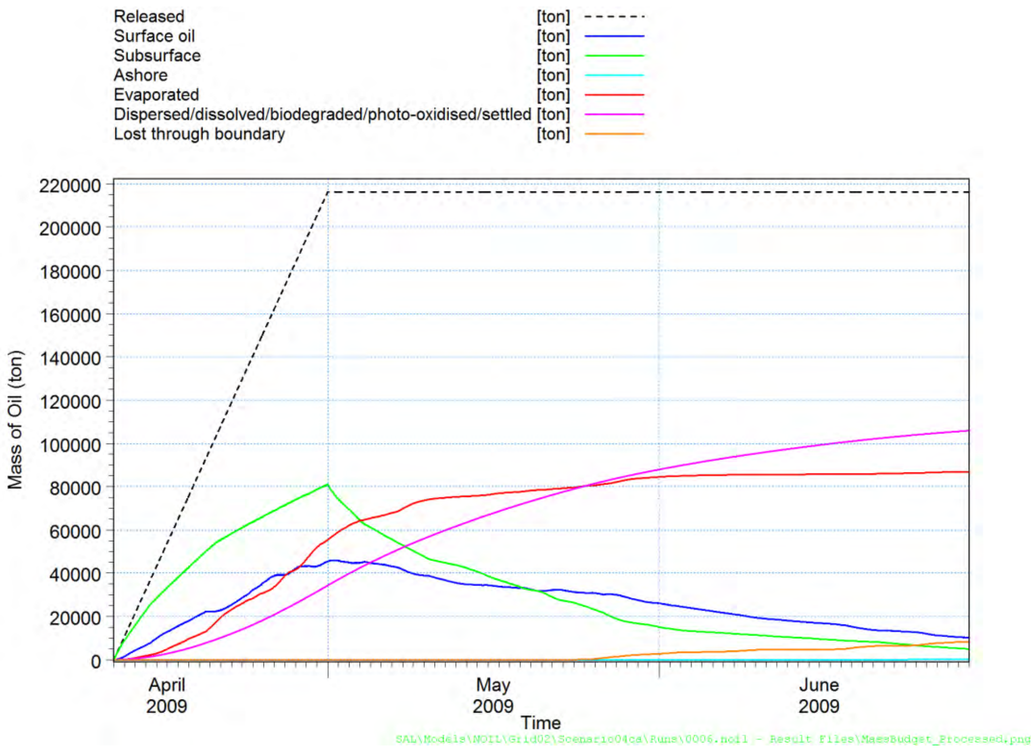


Figure D—16: *Oil spill 4 (20-day blowout) slow weathering scenario. Oil mass balance for a spill case where the oil approached the shore.*

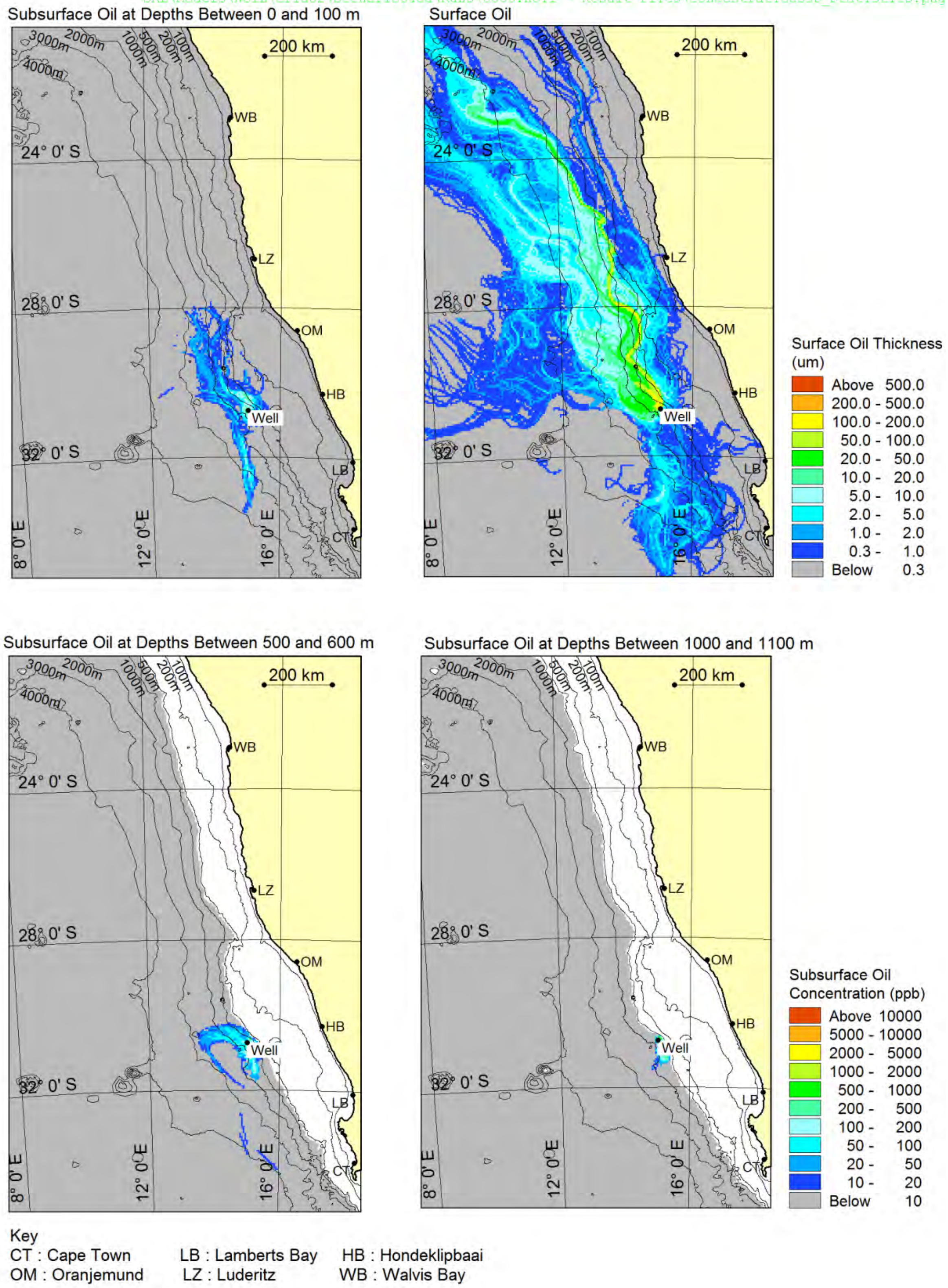
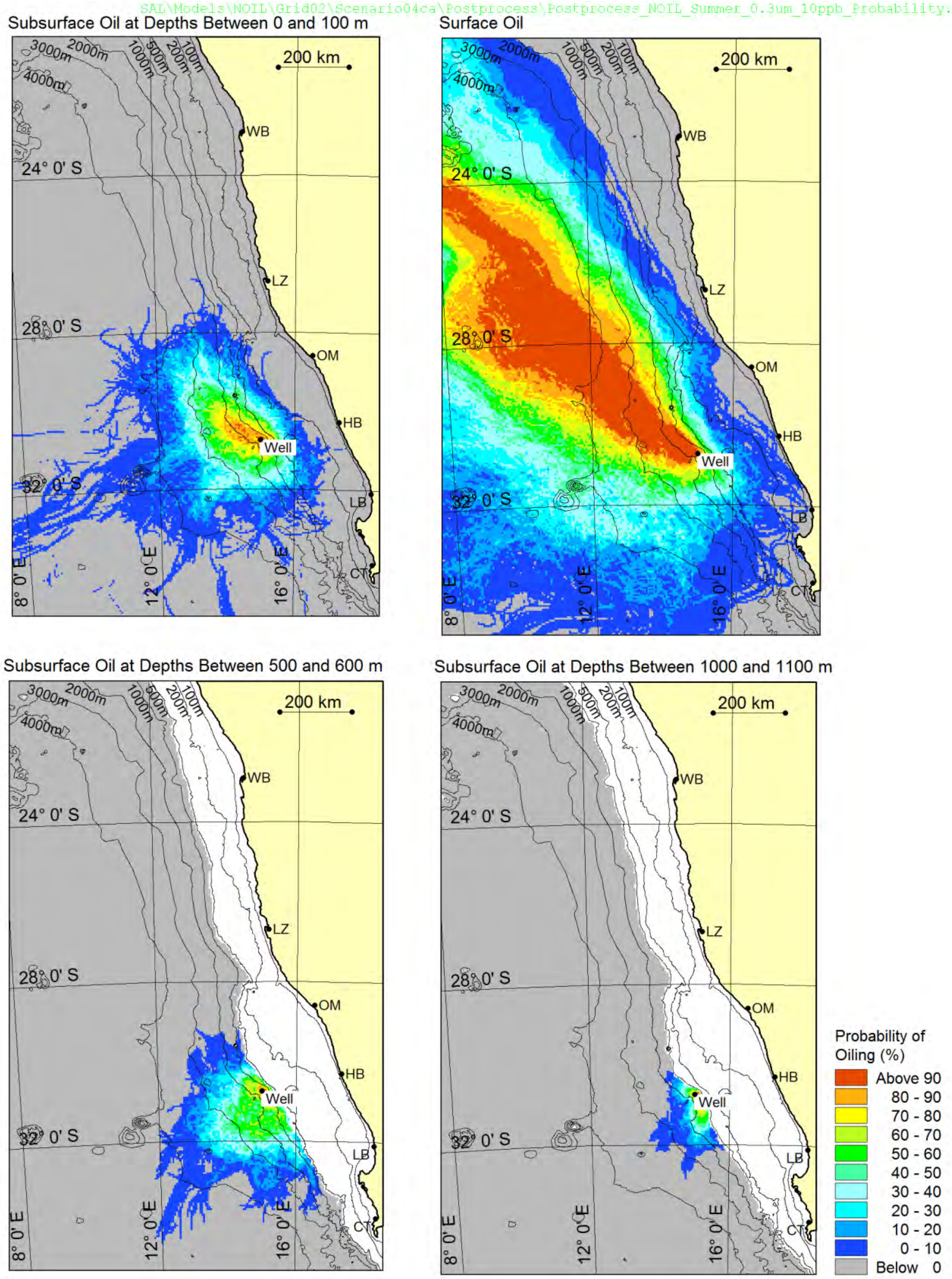


Figure D—17: *Oil spill 4 (20-day blowout) slow weathering scenario. Predicted oil trajectory for a spill case where the oil approached the shore. Plot shows the maximum oil thickness on the water surface and the maximum subsurface oil concentration at any time during the spill, i.e. the area swept by oil.*

SAL\Models\NOIL\Grid02\Scenario04ca\Postprocess\Postprocess_NOIL_Summer_0.3um_10ppb_Probability.png



Key
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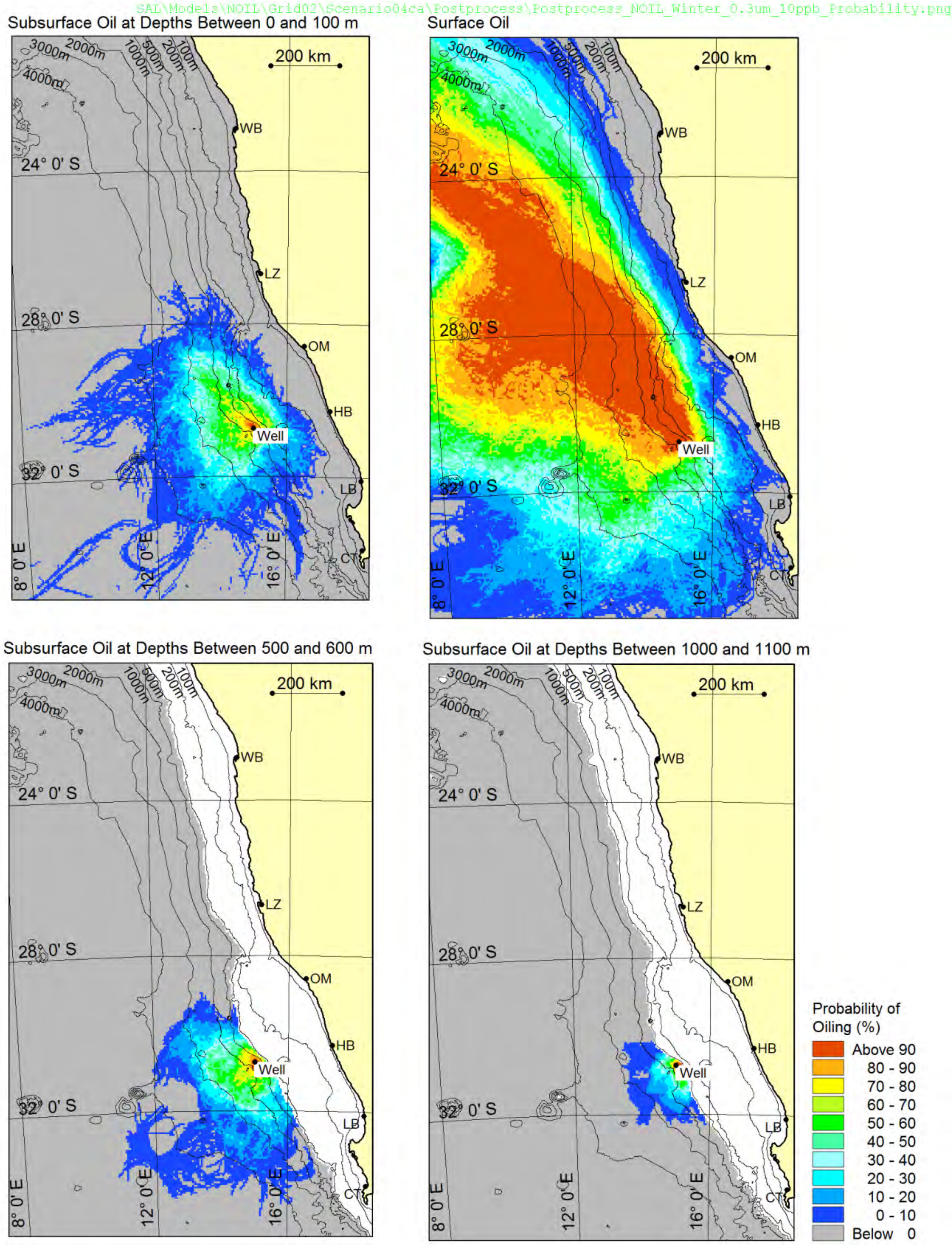
Figure D—18: *Oil spill 4 (20-day blowout) slow weathering scenario. Probability of surface and subsurface oiling for a spill event in summer.*



Key
CT : Cape Town LB : Lamberts Bay HB : Hondeklipbaai
OM : Oranjemund LZ : Luderitz WB : Walvis Bay

Figure D—19: *Oil spill 4 (20-day blowout) slow weathering scenario. Probability of surface and subsurface oiling for a spill event in winter.*

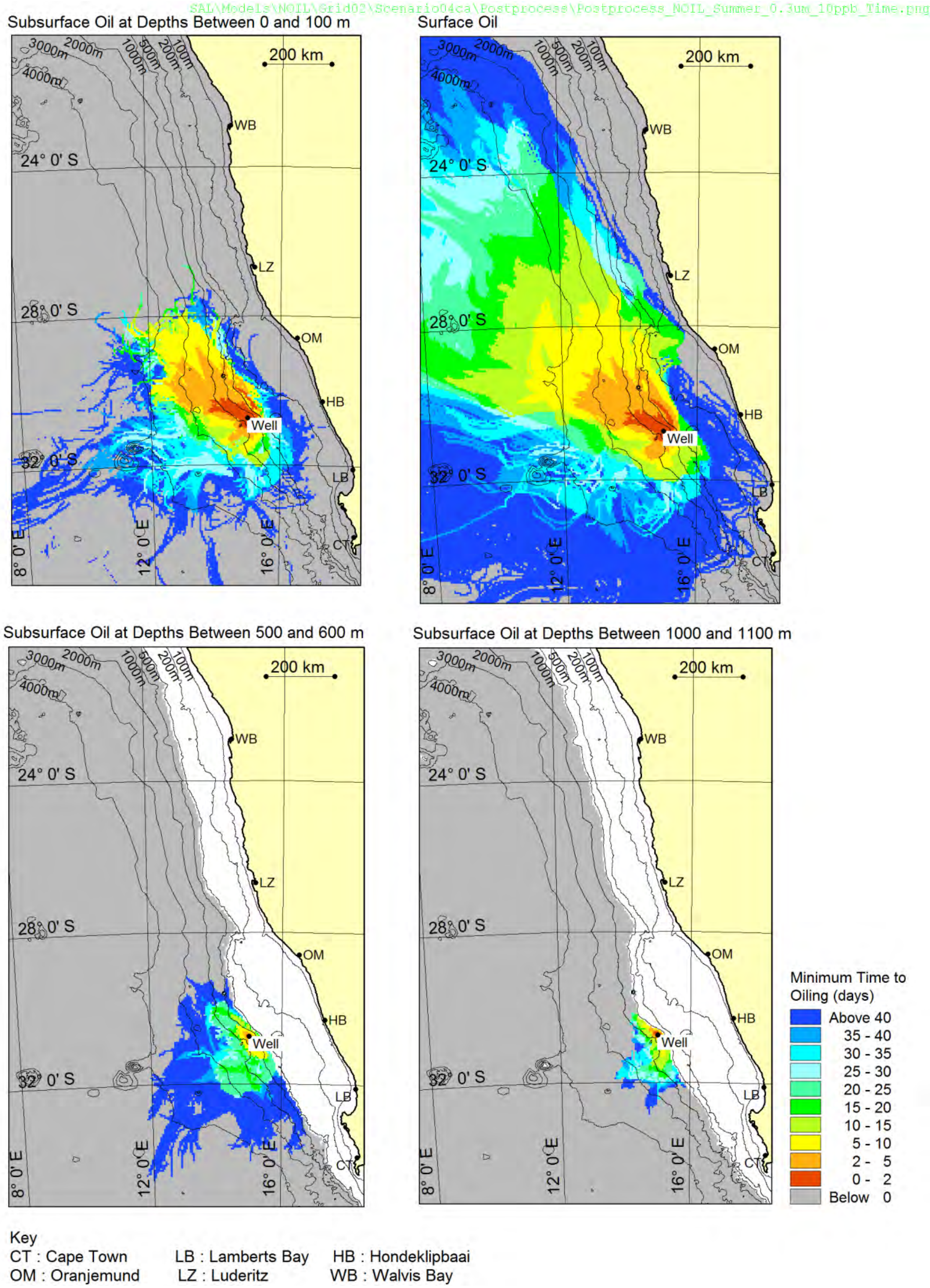


Figure D—20: *Oil spill 4 (20-day blowout) slow weathering scenario. Minimum time to oiling (from start of spill) for a spill event in summer.*

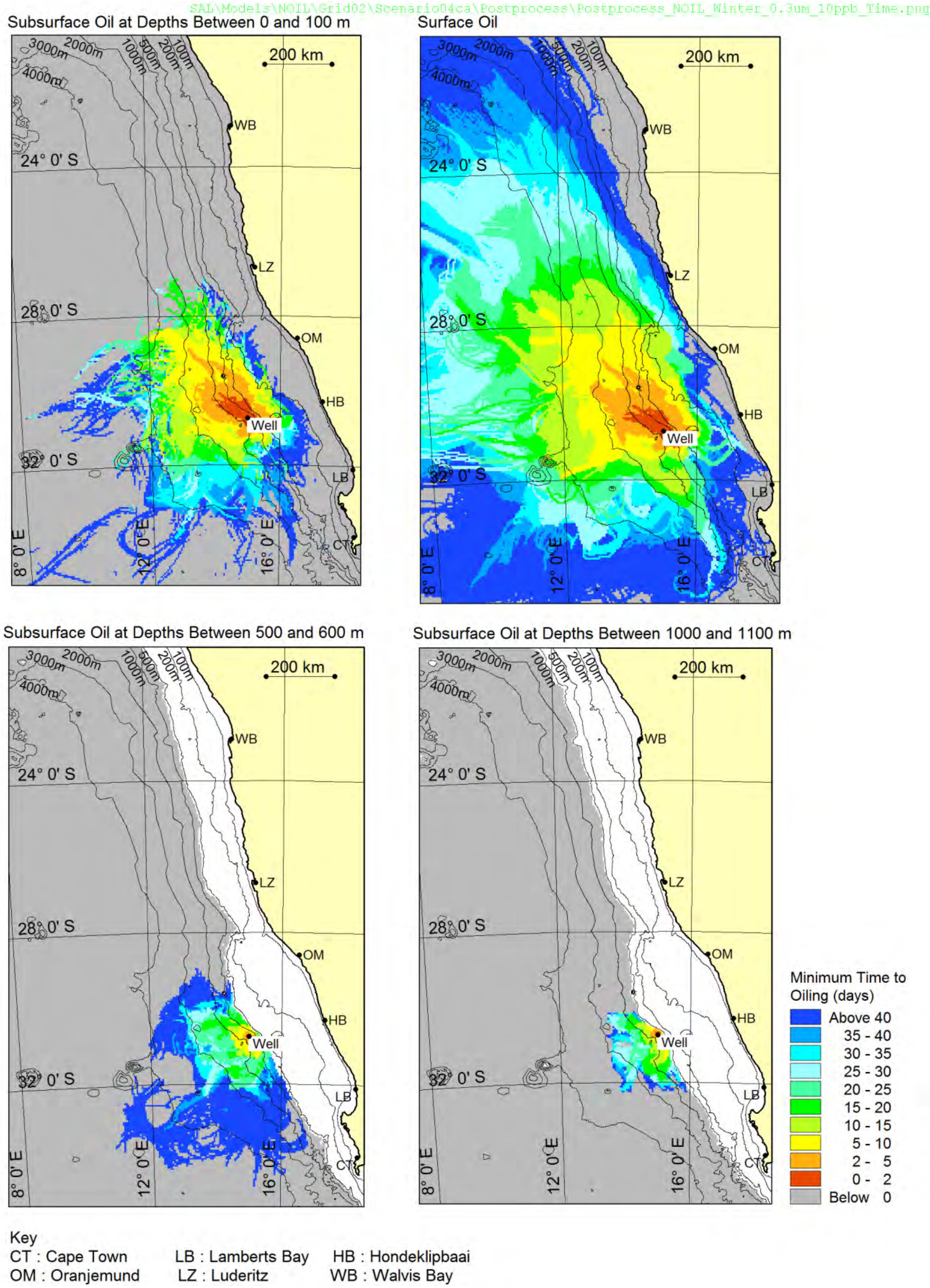


Figure D—21: *Oil spill 4 (20-day blowout) slow weathering scenario. Minimum time to oiling (from start of spill) for a spill event in winter.*