Hydrodynamic and Environmental Modelling in the Vicinity of Scott Reef

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Abstract

The proposed Browse Liquid Natural Gas (LNG) Development* includes three offshore gas-condensate fields in the Browse Basin located 290 km from the Kimberley coast and 425 km north of Broome. As a basis for the environmental impact assessment process for the upstream development a suite of models has been set-up based on the MIKE 3 modelling package. The basic model describes the physical oceanography (hydrodynamics), while routine and non-routine discharges are simulated in separate models. The development area includes the coral atoll Scott Reef, which is located in 500 m water depth on the edge of the continental shelf. Modelling the hydrodynamics in this area is challenging not least because of the steep gradients in the bathymetry. The MIKE 3 model was calibrated and validated with water level, current and temperature measurements collected over 12 months.

1 Introduction

Whenever a large offshore development is being planned an important tool for answering the "what if's" with respect to the possible environment impact is a suite of hydrodynamic and environmental models. The Browse Liquid Natural Gas (LNG) Development, which includes three gas-condensate fields, Torosa, Brecknock and Calliance (see Figure 1), is located almost 300 km from the Australian mainland but close to the coral atoll, Scott Reef. This proximity to Scott Reef puts extra focus on the suite of models which are applied in the environmental impact assessment process.

This paper describes the models selected to describe the physical oceanography and the dispersion of routine discharges (drill cuttings) and non-routine discharge (spills) within the development area. The main focus is on the oceanographic processes, how they have been included in the hydrodynamic model, and how well the model results compare to the substantial amount of measurements available from the area.

2 Modelling on the Shelf Edge

Scott Reef is located in water depths of about 500 m on the edge of the continental shelf with water depths quickly dropping to several thousands of metres to the north-west. Towards the coast to the south-east the sea bed gently slopes upwards. Scott Reef itself rises from the sea floor with almost vertical sides (Figure 2). From an oceanographic point of view the location represents a number of challenges for hydrodynamic modelling including the presence of large tidal variations, thermal stratification, upwelling and internal waves.

Before starting any hydrodynamic modelling a thorough analysis and understanding of the meteorological and oceanographic mechanisms experienced in the area is imperative. Of these the mechanisms of importance for the ensuing modelling tasks, in this case the environmental dispersion modelling, must be identified to ensure that they are included and reproduced in the hydrodynamic model. The results of this analysis for the Browse Basin including Scott Reef are shown in Table 1 and discussed in Section 3.

Figure 1 Location of Browse LNG fields (shown in red) and Scott Reef

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* The participants in the Browse LNG Development are: BP Developments Australia Pty Ltd., BHP Billiton (North West Shelf) Pty Ltd., Chevron Australia Pty Ltd., Shell Development Australia Pty Ltd. and Woodside Energy Ltd (Operator).

Table 1. Physical mechanisms in oceanographic (hydrodynamic) modelling, their timescales and their importance as forcing functions in oceanographic modelling, which is to be used for subsequent environmental modelling studies in the Browse Basin.

Physical Phenomena	**Driver**	**Typically observed phenomena**	**Typical time-scale of variation**	**Period required to capture most variations**	**Importance for oceanographic modelling[3]**	**Importance for environmental dispersion studies**
Wind	Atmos-pheric pressure gradients	Monsoonal winds	Months to weeks	One year[1]	High	High
		Cyclones	Hours to days	Many years	High[2] (if present)	High[2] (if present)
		Land Sea Breeze	Hours	One year	High, but only in coastal areas	High, but only in coastal areas
Waves	Wind	Monsoonal winds	Months to weeks	One year[1]	Low except locally in the breaking zone	High
		Cyclones	Hours to days	Many years	High[2] (if present)	High[2] (if present)
		Land Sea Breeze	Hours	One year	Low except locally in the breaking zone	High, but only in coastal areas
Currents (in top 50 m)	Wind	Monsoonal winds	Months to weeks	One year[1]	High	High
		Cyclones	Hours to days	Many years	High[2] (if present)	High[2] (if present)
		Land Sea Breeze	Hours	One year	High, but only in coastal areas	High, but only in coastal areas
Currents (all depths)	Gravitational pull of moon and sun	Barotropic (depth-averaged) tide	Hours to a fortnight	A fortnight to a year[4]	High	High
		Baroclinic (internal) tide	Hours to a fortnight	A fortnight to a year[4]	Medium	Medium
		Solitons	Minutes to hours	A fortnight to years	Low[5] (if present)	Low (if present)
	Oceano-graphic pressure gradients	Oceano-graphic Drift (large scale currents)	Months	Many years	Low (if present)	Low (if present)
		Large scale eddies	Days to weeks	Many years	Low (if present)	Low (if present)

[1] Within one year the two monsoon wind patterns are covered. However, the start and finish of the two monsoon seasons vary from year to year.

[2] Modelling of cyclones has not yet been considered in the study based on the assessment that there is a small statistical probability of a cyclone occurring at a given location combined with the small probability of discharge/spill occurring concurrently yields a small probability of occurrence.

[3] When used as a basis for environmental dispersion modelling.

[4] 18.6 years is required to capture all tidal variations.

[5] Solitons are important when determining design conditions for structures such as pipelines, but are not considered important for environmental modelling.

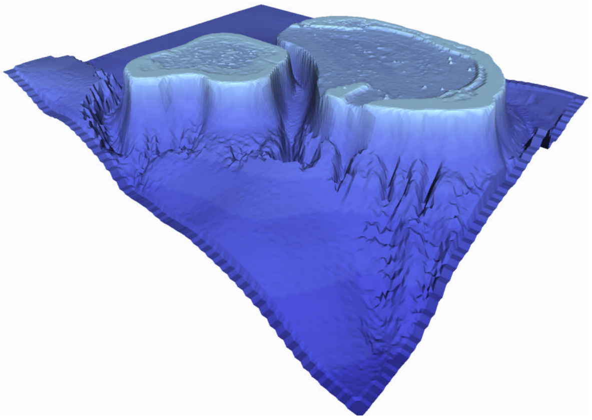

Figure 2 Perspective view of Scott Reef from the west. Note the deep channel with steep sides between the two reefs.

The metocean data collection program for the Browse region, on which the modelling described in this paper is based, is detailed in section 4.

Based on the analysis the appropriate hydrodynamic model was selected and set-up as described in section 5. In section 6 the model calibration and validation are described, while examples of the environmental dispersion modelling are included in section 7.

3 Oceanographic Processes of Importance for the Scott Reef Area

The physical phenomena in oceanographic (hydrodynamic) modelling, their timescales and their importance for a hydrodynamic model for the Scott Reef area are listed in Table 1. Basically, the atmospheric pressure gradients drive the wind, which in turn drive the waves and the currents in the top part of the water column. The gravitational force from the moon and the sun drive the tide, while the density differences in the oceans drive the oceanographic currents. And each of these drivers has different time scales and level of importance.

3.1 Wind Driven Currents

The area has a typical monsoonal wind pattern with a north-west monsoon in the summer (typically from October to February), a south-east monsoon in the winter (typically from May to July) and two transition periods in between. The monsoonal winds have a high level of importance for the oceanographic modelling. Cyclones are also experienced in the area although they do not reach Scott Reef on a yearly basis. In view of their low probability of occurrence they have not been included in the modelling at present, but may be at a later stage.

3.2 Oceanographic Currents and Eddies

Figure 3 shows the oceanographic currents affecting the north-western part of Australia (from DEWHA, 2008). The Indonesian Throughflow is located north of the area of interest and has not been identified in measurements in the vicinity of Scott Reef (see section 4). Large scale eddies shed off from the Indonesian Throughflow have, however, possibly been identified but may only have a minor influence on the overall current pattern in the Scott Reef area (see also Section 6.1).

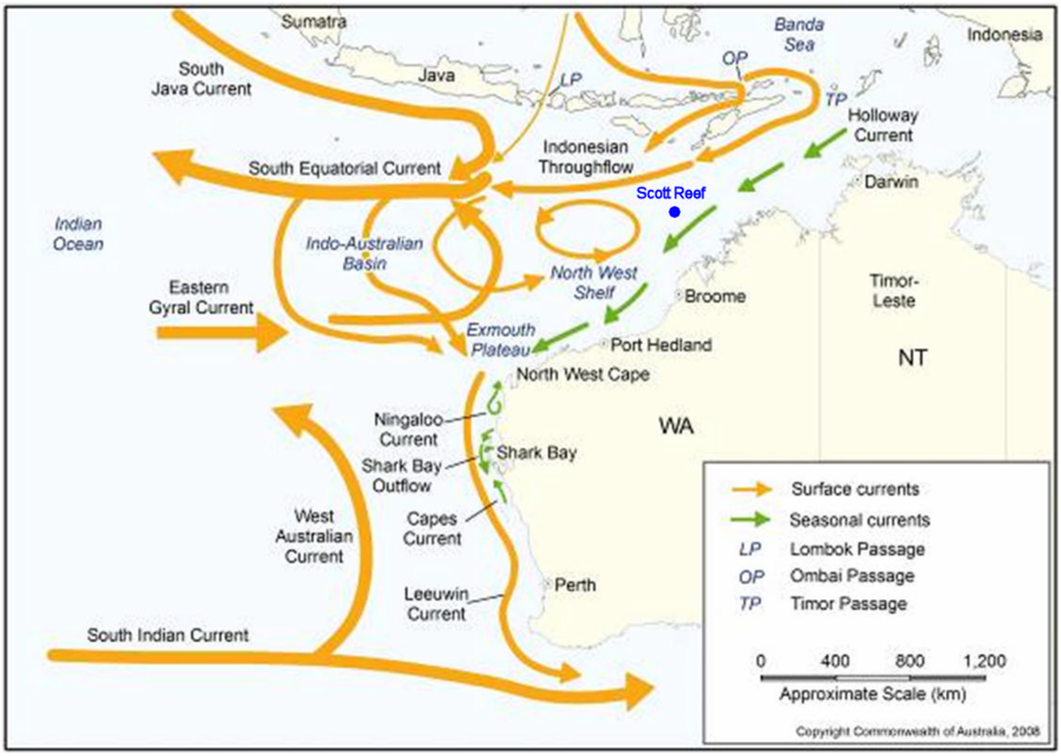

Figure 3. Oceanographic currents (subsurface) affecting north-western Australia (from DEWHA, 2008).

The Holloway Current (Holloway, 1995) is a relatively weak seasonal current, which is yet to be described in detail. It has not been identified in the measurements in the vicinity of Scott Reef and is not considered to be of importance for the modelling of the Scott Reef area.

3.3 Internal Tides and Solitons

"Internal waves" is a very generic term, which covers all types of waves within the ocean. Internal waves are generated by disturbances to a stratified ocean by barotropic tides, varying winds and waves, and often in combination with variations in depth like a shelf break, an island or a sea mount. Some internal waves occur on a regular basis like internal (baroclinic) tides, while others only occur now and then like single solitary waves (called solitons).

The internal tide is of significant importance for the modelling at Scott Reef, while solitons are not important for dispersion modelling.

4 Browse Measurement Program

Column 4 and 5 in Table 1 describe respectively the typical time scale for the variation of each phenomena and the period required to capture most variations. For example, monsoonal winds are relatively constant during each of the two main seasons lasting several months, so that variations are captured within one year.

It was concluded that one year of data was sufficient to describe the main physical phenomena except for cyclones, oceanographic current and large scale eddies. As discussed in Section 3 cyclones have not been considered at the present stage, while the variability of oceanographic currents and associated eddies requires measurements covering many years, and will thus have to be accounted for in other ways than through a field measurement program.

An extensive 12 months metocean measurement campaign in and around Scott Reef with more than 70 instruments was undertaken by Woodside with details for the key moorings for the present project shown in Figure 4 and given in Table 2 and Table 3. Additionally, a meteorological station was set-up within the South Reef and a number of drifter buoy tracks were collected.

Table 2. Water level station

Name	**Depth [m MSL]**
A2 Browse WL	40

Table 3. Current and Temperature moorings

Name	**Depth [m MSL]**	**Number of current metres**	**Number of temperature sensors**
B2 Brecknock	550	8	20
C1 North Scott Reef	475	3	3
G2 Shelf Crossing	197	5	11
H2 South Scott Reef	300	5	15
I1 Channel	447	5	5

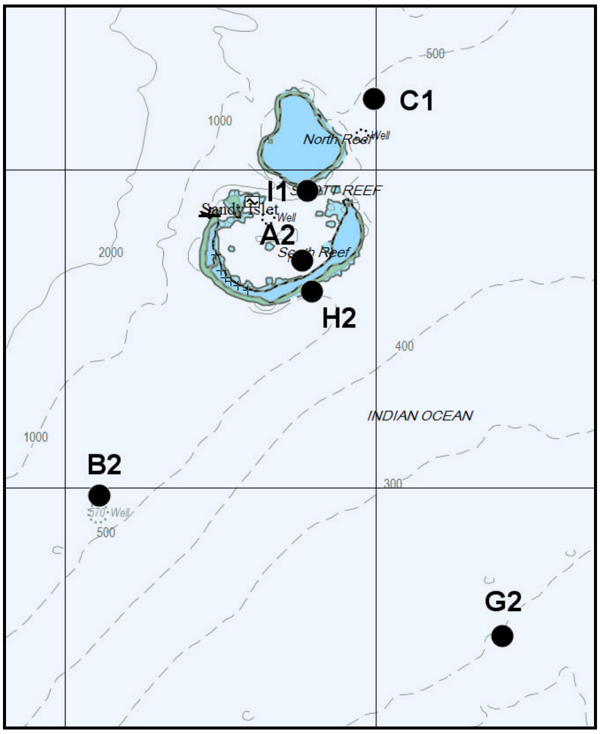

Figure 4 Metocean locations in and around Scott Reef

The measurement program covered the period September 2006 to September 2007 with a high data return.

5 3-D Hydrodynamic Model Set-up

Simulating current and temperature variations through the water column requires a baroclinic 3-dimensional model. A number of different models exist, the main differences found in solution method (eg finite-difference or finite-volume), vertical discretisation (contant z-layer height or constant number of sigma-layers) and whether or not vertical accelerations are included (non-hydrostatic models versus hydrostatic models). After some testing the MIKE 3 finite-difference non-hydrostatic model was selected (Abbott, 1979 and DHI, 2008).

A nested computational grid with resolutions varying from 8100m to 300m around Scott Reef was set-up as shown in Figure 5.

In the vertical 25 layers were applied with a resolution of 20 m except for the top layer being 1½ times the standard resolution (ie. 30 m) and the bottom layer being bottom fitted for depths of 490 m and more. This yielded a total of 1,110,700 computational points.

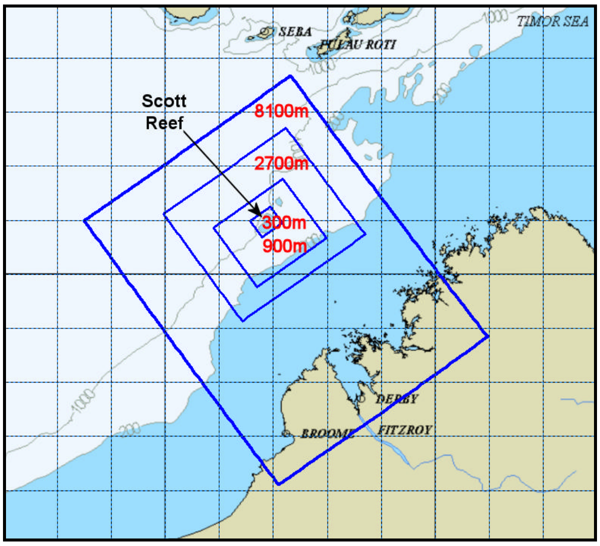

Figure 5 Model area for 3-D hydrodynamic model (in blue) with horizontal grid resolution.

5.1 Open Boundary Conditions

Along the three open boundaries of the model half-hourly tidal variations based on the 8 major tidal constituents taken from a global model (see Andersen, 1995) were applied. Additionally, daily temperature profiles calculated from the measurements at Brecknock were applied at the open boundaries. The tidal signal (already being applied at the boundary) was removed from the temperature measurements by applying a 60 hour low-pass filter (Figure 6).

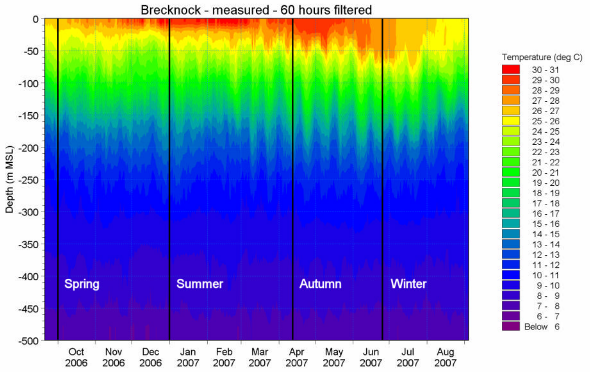

Figure 6 Temperature profile at Brecknock. Vertical lines indicate the four selected calibration and validation periods.

Alternatively the temperature variations could have been taken from a large ocean model like BLUElink developed by Bureau of Meteorology, Royal Australian Navy and CSIRO. However, this model was not yet available for a commercial project like the one presented in this paper.
Measurements of the salinity showed no major variations within the area. The salinity was therefore kept constant at 34.6 psu through all simulations.

5.2 Meteorological Forcings

A detailed and calibrated wind field data set was available from another Browse study component (SatOcean Services, 2008) covering the period November 2002 to November 2007 with a horizontal resolution of 0.0625° by 0.0625° and at 3 hourly intervals. This was supplemented by atmospheric pressure, air temperature, cloudiness and relative humidity from the GFS (Global Forecast System) model (with a resolution of 1° by 1° and 3 hour time interval) run by National Centers for Environmental Prediction (NCEP) in the US. The air temperature, cloudiness and relative humidity were required for the heat balance calculations.

6 Model Calibration and Validation

One period during the spring/transition period was selected for model calibration while three periods, one for each of the three other seasons (summer, transition/autumn and winter) were selected for model validation. Each period covered a 14 day neap-spring tidal cycle plus 1 day and 16 hours for warm-up of the model. The four periods are listed in Table 4.

Table 4. Calibration period (spring) and validation periods (summer, autumn and winter). Time in UTC+8 hours.

Season	Period
Spring	2006-10-01 08:00 - 2006-10-17 00:00
Summer	2006-12-30 08:00 - 2007-01-15 00:00
Autumn	2007-04-11 08:00 - 2007-04-27 00:00
Winter	2007-06-25 08:00 - 2007-07-11 00:00

The main calibration factors applied included the turbulence scheme (where the k-ε scheme was selected), the compressibility (where a value of 668 m/s was applied in the three outer grids and a value varying with depth of 10 – 668 m/s in the 300 m grid), and the wind stress (where the wind stress factor varied from 0.0016 at 0 m/s to 0.0026 at 24 m/s). A bottom roughness of 0.05 m was applied, but was of minor importance for the model calibration. Heat exchange calculations were also included, but without any adjustments.

Comparisons of measurements and model results for the four periods were carried out for all stations as listed in Table 2 and Table 3 as time history plots, quantile-quantile (Q-Q) plots and frequency plots. Additionally, bias and root-mean-square values were calculated for water levels and depth-averaged currents and compared to performance parameters as defined by

Foundation for Water Research, 1993. Examples of comparisons and performance parameters are shown in Figure 7, Figure 8 and Table 5, while an illustration of the basic model results are shown in Figure 9.

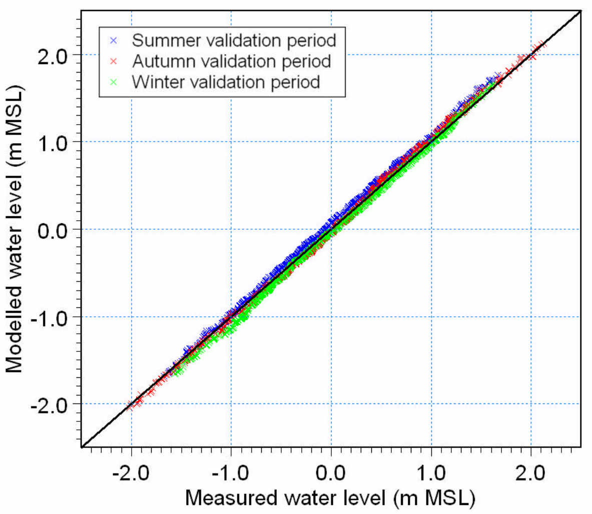

Figure 7 Q-Q plots for water levels at A2.

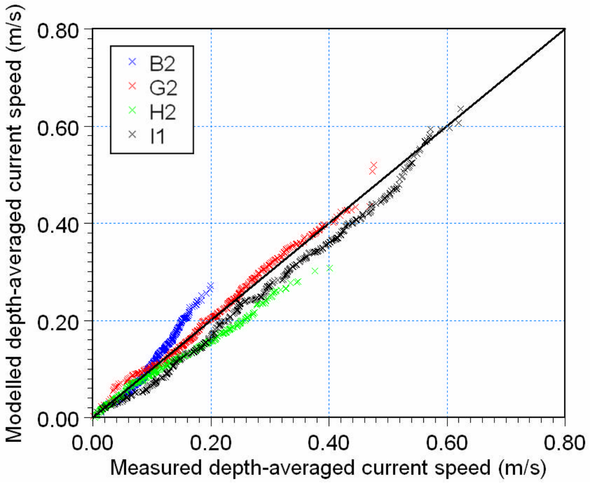

Figure 8 Q-Q plots for depth-averaged currents during summer validation period.

Table 5. Statistical performance parameters for depth-averaged current speed during spring calibration period (G1 not available for spring period).

Station	Bias [m/s]	RMS Error [m/s]	Peak value [m/s]	RMS Error [%]
B2	0.02	0.04	0.23	15
H2	-0.01	0.06	0.43	14
I1	-0.03	0.10	0.74	14

Both Q-Q plots above show a good agreement. Likewise for the performance parameters in Table 5 as these are below the recommended 10 - 20% on RMS error (in % of the peak value). In general a satisfactory agreement for all four periods between the large number of measurements and the model was achieved.

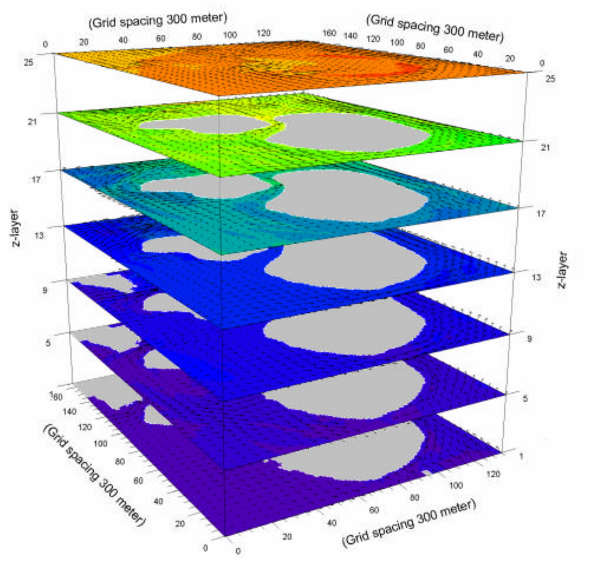

Figure 9 Illustration of basic model results with every 4th layer shown in the 300m grid. Colours indicate temperature.

6.1 Sensitivity Test for Large Scale Eddies

A test for possible inclusion of the large scale eddies shed off from the Indonesian Throughflow was carried out by including sea surface anomalies from satellite measurements along the open water level boundaries of the model. However, the relatively small width of the satellite footprints combined with the fact that they do not overfly the same location very often (e.g. every 10 days) did not provide sufficient data for this approach to succeed. Boundary data extracted from BLUElink may include the eddies, so this may be a possible solution once BLUElink becomes commercially available. However, with the model comparing well to the measurements without the inclusion of large scale eddies it was decided not to pursue this further.

7 Environmental Dispersion Modelling

Two examples of environmental modelling based on the hydrodynamic model described above are given below. The first example (Figure 10) shows how a possible oil spill of 8m^3 diesel from the Brecknock-4 location would spread. In this case a larger number of spill scenarios (>100) covering statistically independent combinations of wind and tidal conditions were selected, and simulation of oil spill for each scenario carried out using the Lagrangian MIKE 3 Spill Analysis (SA) model driven by the underlying hydrodynamic model. Based on these simulations maps showing probability of exceeding 0.1 g/m^2 oil after 6, 12, 24, 72 and 120 hours were produced (among others).

In the second example dispersion of drill cuttings during the drilling of the Brecknock-4 well was simulated using the Lagrangian MIKE 3 Particle Analysis (PA) model. Modelling of the suspended

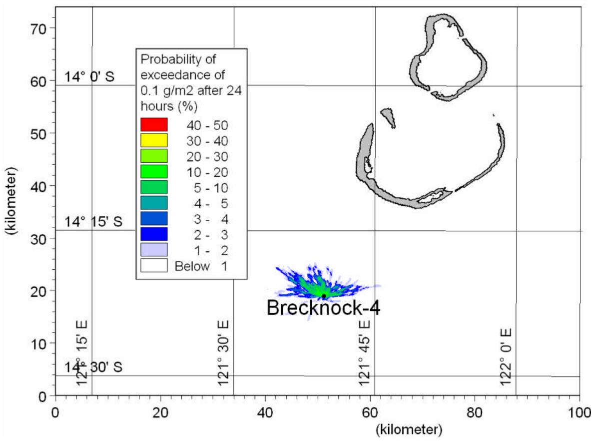

Figure 10 Probability of oil spill exceeding 0.1 g/m^2 24 hours after simulated oil spill at Brecknock-4 southwest of Scott Reef

sediment plume and seabed sedimentation was required. These processes are illustrated in Figure 11. An example of a sedimentation footprint from the drilling of the 8½" hole section during spring tide is shown in Figure 12.

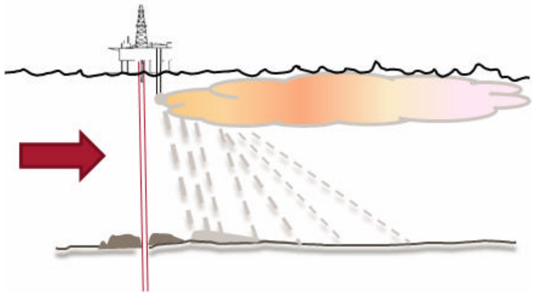

Figure 11 Schematic presentation of plume and sedimentation from drill cutting discharge.

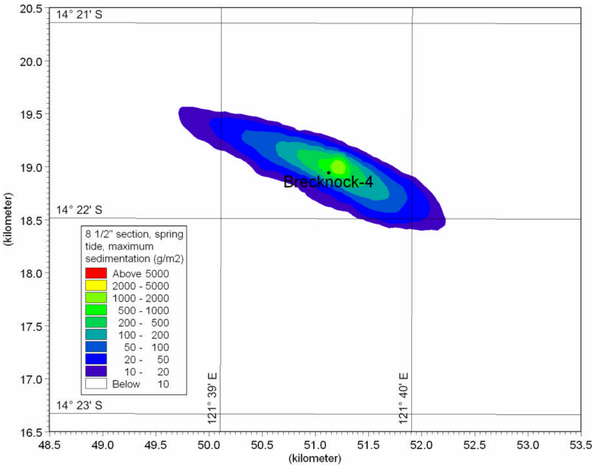

Figure 12 Maximum sedimentation (g/m^2) from drilling of 8½" hole section (spring tide).

8 Summary

A thorough analysis of the oceanographic processes, which are of importance for describing the hydrodynamics, and which are necessary for environmental modelling for the Browse LNG Development was carried out. Based on this a 3-D baroclinic hydrodynamic model was set-up and validated against a substantial amount of in field measurements which demonstrated that it was able to satisfactorily reproduce the hydrodynamic conditions in the area. Two environmental modelling examples were then presented to demonstrate the applicability of the model suite.

9 Acknowledgements

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