Ocean Circulation

in the Region of

Barrow Island, Varanus Island
and the
Montebello Islands

on the
Australian North West Shelf

Validation
of the
GEMS 3D Coastal Ocean Model (GCOM3D)

for
Apache Energy

July 1997

THE GEMS 3D COASTAL OCEAN MODEL

The GEMS 3D Coastal Ocean Model (GCOM3D, also referred to as OILTRAK) is a three-dimensional ocean model which has been specifically developed to study and predict ocean currents on or near the continental shelf and in harbours and estuaries (Hubbert, 1993). GCOM3D simulates the physical oceanography of the region of interest driven by winds and tides and thermodynamics (where relevant).

For oil spill modelling or search and rescue applications, the surface ocean currents from GCOM3D are used. For water quality and sediment transport studies, which often require an understanding of the vertical variation of the currents, the full three dimensional current field is used.

GCOM3D has been used by a large number of oil companies in Australia (e.g. Woodside, BHP, WAPET, Apache, Shell, MIM, Comalco, Command, Discovery, Lasmo, Teikoku) for operations on the North West Shelf, Bass Strait and in the Gulf of Carpentaria. GCOM3D has also been adopted by the Australian Maritime Safety Authority (AMSA) as part of the national oil spill and search and rescue response system. The Royal Australian Navy and the United States Navy have also purchased GCOM3D as part of their ocean prediction systems. More detailed descriptions of the model are included in Appendix 1.

Verification of GCOM3D Predictions

Ocean currents and oil spill trajectories predicted by GCOM3D have been tested against many experimental data sources in Australia and overseas. These include "mat" tracks obtained by Lasmo Oil near Exmouth Gulf and by Command Petroleum near Onslow. In Mermaid Sound, Woodside Petroleum provided current meter data for verification of the model. Apache Energy undertook a high resolution verification study around the Montebello Islands using an Acoustic Doppler Current Profiler (ADCP). GCOM3D has also been used for many applications other than for oil spill modelling such as predicting the currents near the Sydney ocean outfalls for the New South Wales EPA. As a part of this study, the model current predictions were compared with observations off Sydney and with the track of a drifting buoy released by the Australian Navy. The United States Navy has carried out detailed verification studies in the Yellow Sea.

In all of these cases, good agreement was obtained between model predictions and observations. Most of the earlier results have been reported either in the proceedings of the 1993 Australasian Coastal Engineering Conference (Hubbert, 1993a,b) or in the 1994 APEA Journal. The more recent work has been reported at conferences including IAPSO '95 (Hawaii), IAPSO '97 (Melbourne) and Australian Meteorological and Oceanographic Society conferences.

Verification near the Montebello Islands

Since the integration of GCOM3D with OILMAP for oil spill studies, Apache Energy has undertaken two verification studies of the 3D model current predictions in the vicinity of the Montebello Islands on the Australian North West Shelf. The first study compared GCOM3D predictions with data from an Acoustic Doppler Current Profiler (ADCP) at two sites near the islands. The advantage of an ADCP is that it measures vertical profiles of the currents and therefore comparisons of near surface current predictions with data can be made. The results of this work are given in a previous report prepared jointly with Apache Energy (Appendix 2). This report details the results of a new study of GCOM3D predictions against acoustic current meter data collected by WNI Science & Engineering for Apache Energy along a proposed pipeline from the Wonnich site at the Montebello Islands. Three acoustic current meter moorings were maintained from February 26 to March 12 1996 (16 days) at three sites along a proposed pipeline route from the Wonnich site (Figure 1). The depths of the current meters was different in each case, providing data at three different depths (4 metres, 16 metres and 25 metres relative to mean sea level) against which the depth-profiled predictions of the GCOM3D model can be compared.

DESCRIPTION OF THE MODEL FOR THE WONNICH AREA

Bathymetry

The bathymetry for this work was based on a 100 metre resolution grid of the North West Shelf which has been developed from data supplied primarily by Apache Energy, WAPET and BHP.

GCOM3D grid

For this work, GCOM3D was set up on a 500 metre horizontal resolution grid with 10 vertical levels to simulate ocean currents over a region from Barrow Island to the Montebello Islands (Figures 1 and 2).

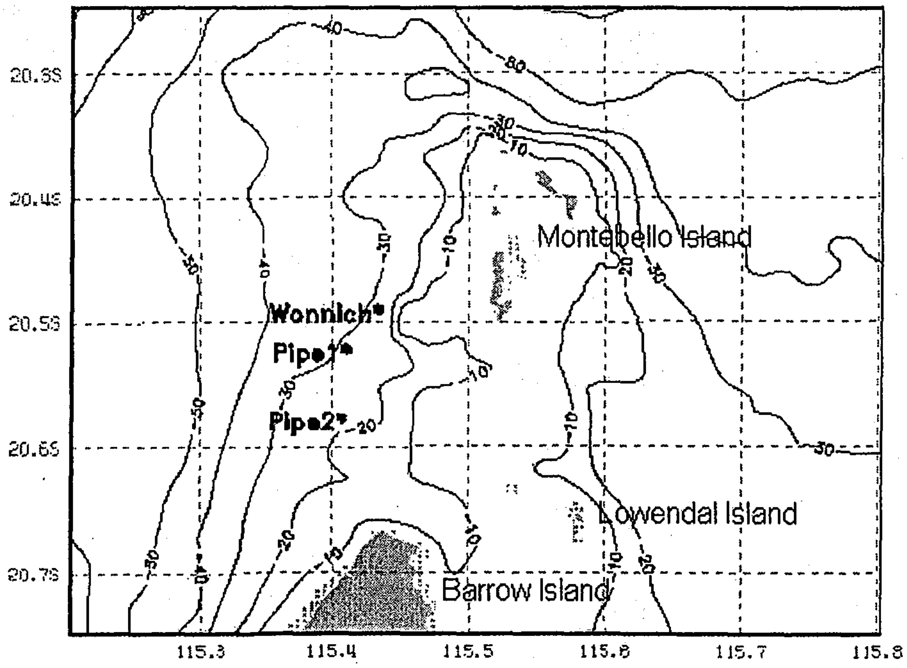

Figure 1: Two dimensional bathymetry for the model region showing the location of current measurement moorings.

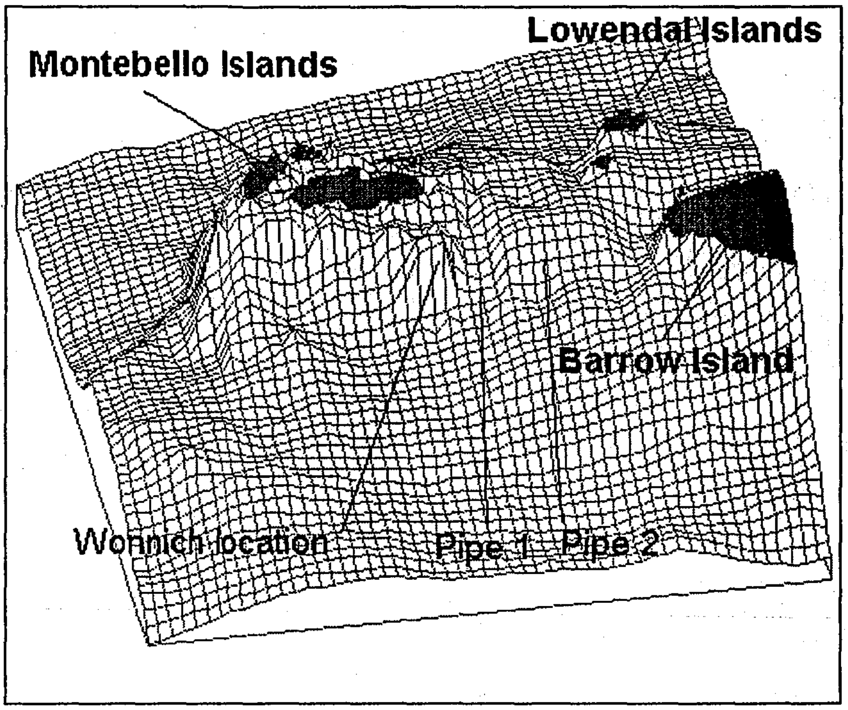

Figure 2: Three dimensional bathymetry for the model region.

Tidal forcing

Tidal constituent amplitude and phase data for eight tidal constituents (M2, S2, K2, N2, O1, K1, P1, SA) from the GEMS North West Shelf tidal model were used to drive the GCOMP3D ocean model. The tides in the region are very complex and it is important to drive the model with accurate tidal data. The GEMS data was developed from an intense modelling program of tides on the north-west shelf and verified against all the available tide gauge stations.

Wind forcing

Apache Energy maintains an anemometer at Varanus Island which recorded hourly wind observations for the period of the current meter observations. This wind data was used by the model to generate wind-induced water flows.

Model simulations

The Varanus Island winds and tides were used to drive GCOM3D on the 500 metre bathymetric grid for the period March 1 to March 12 1996 to compare current predictions with the current meter observations. The earlier period of measurement was not compared because of the poor data returned by the current meters during the period of slack water flows during the neap tide. The modelled period extends from a neap to a spring tide, and thus, both the short term (semi-diurnal tidal cycles) and longer term (neap to spring tidal cycle) phases of the predicted and observed currents can be compared. The predicted and observed currents for three separate locations were compared, providing evidence of how consistently the model performed over the model area. This is important for the credibility of the model because of the variable water flows in the area. Figures 3 and 4 provide examples of the wider tidal-current field over the modelled area for flooding and ebbing tides.

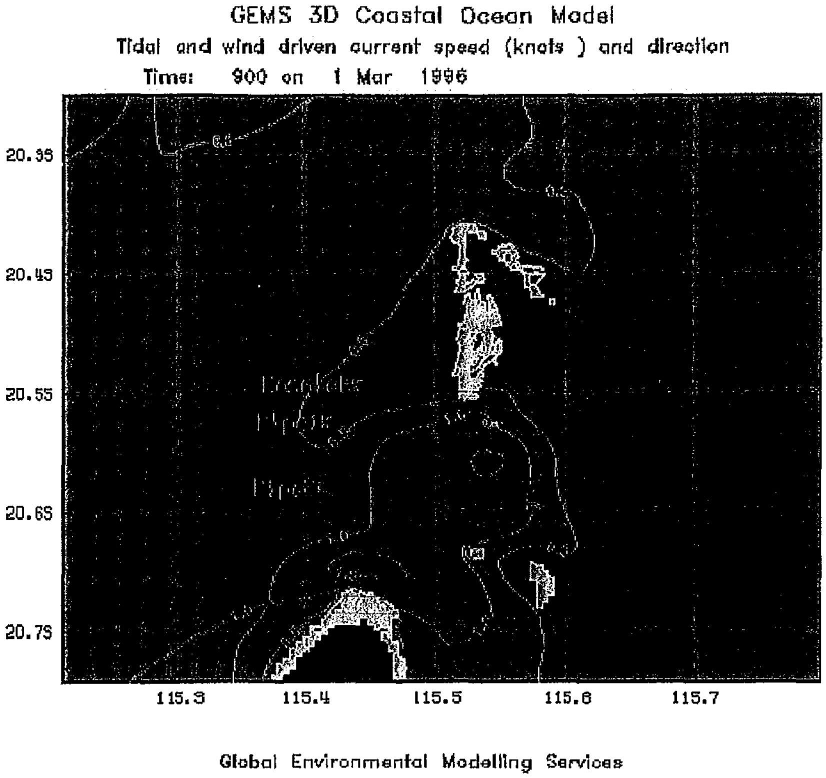

Figure 3: An example of the predicted tidal flows over the model region at 2 metres depth during a flooding tide.

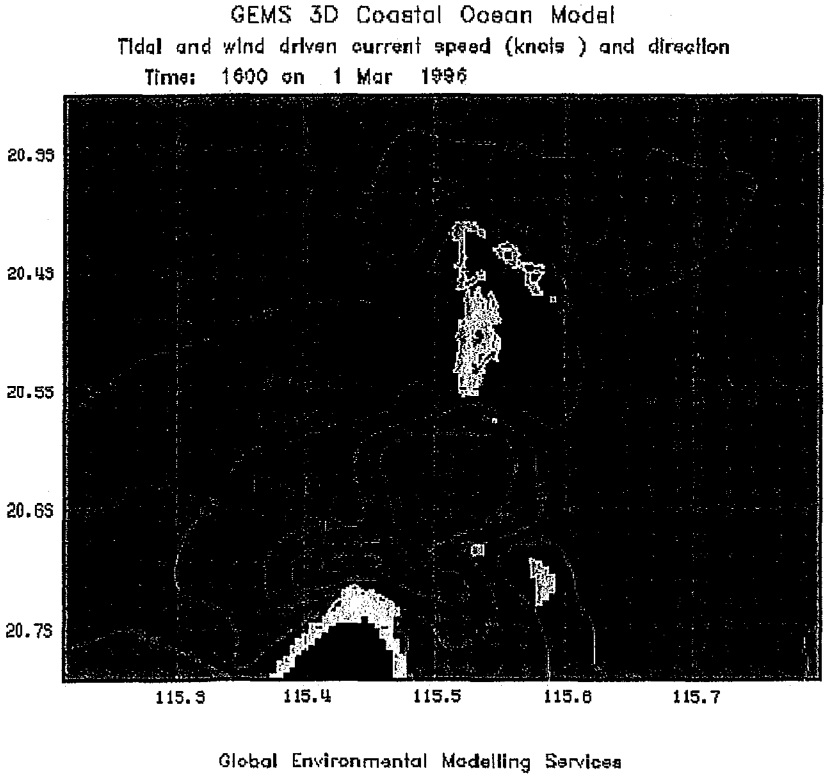

Figure 4: An example of the predicted tidal flows over the model region at 2 metres depth during an ebbing tide.

COMPARISON OF OBSERVED AND PREDICTED CURRENT FLOWS

Results at the Wonnich site

The measurements at this site were made 20 metres above the bottom (nominally 4 m below MSL) and, therefore, nearer the surface than at the other two sites. Both observed and predicted currents showed a very weak east-west flow and a much stronger north-south flow. This is consistent with the result reported during the previous study (Appendix 2) that the currents near the Wonnich site are predominantly directed north-south along the shelf of the islands by the sharply sloping bathymetry.

Figures 5 and 6 show the overlay of predicted and observed east-west (U component) and north-south (V component) currents at the Wonnich site respectively.

The predictions at the Wonnich site show very good agreement with both the phase and amplitude of the observations of the weak east-west flow (Figure 5). The predictions for the north-south flow show very good agreement with the phase of the observations but there are some discrepancies in the amplitudes (Figure 6). Variation between observed and predicted currents was not consistent in direction, however, and appear to occur during some, but not all, of the stronger wind events. The very good agreement during several of the strong wind events suggests that discrepancies resulted when winds observed at Varanus Island were lower than those over the Wonnich location and, thus, the model was not provided with sufficient wind forcing. Strong wind events over this period were predominantly from the west and south west. Varanus Island would be partially sheltered from some of these winds by Barrow Island, while the Wonnich site would be exposed.

It is important to note that predictions of oil spill risk using the model predictions applied a random sampling approach whereby 100 different spill trajectories were driven by separate time series of current flow predicted by the GCOM3D model (Appendix 2). Hence, the effect of small, occasional discrepancies would be reduced.

Results at the Pipeline 1 site

The measurements at this site were made 5 metres above the bottom and hence were less effected by wind-forcing. Both observed and predicted currents showed an east-west flow dominated by the ebb and flood of the tide south of the Montebello Islands. The north-south flow was less dominated by the tide and therefore the response to wind forcing was more evident. The north-south flow was however weaker than at the Wonnich site due to the deeper location of the observations.

Figures 7 and 8 show the overlay of predicted and observed east-west (U component) and north-south (V component) currents at the Pipeline 1 site respectively

The predictions at the Pipeline 1 site show very good agreement with both the phase and amplitude of the observations of the east-west flow (Figure 7) during the last seven days of the 12 day period. During the first five days, a period of weaker tidal flow, the phase agreement is good but the effect of the wind is somewhat under predicted. The predictions for the north-south flow also show very good agreement with the phase of the observations but again there are some discrepancies in the amplitudes (Figure 8) particularly during the period of weaker currents in the first five days.

The results at the Pipeline 1 site support the conclusion that wind forcing provided to the model was low during some, but not all, of the strong wind events. A further reason for these differences may be that the effect of the surface wind stress in the model is not being simulated near the bottom quite as well as it is near the top of the ocean.

Results at the Pipeline 2 site

The measurements at this site were also 5 metres above the bottom but were nearer to the surface than at the Pipeline 1 site due to the shallower location of the mooring. The results were similar to those at the Pipeline 1 site, with both observed and predicted currents showing a strong east-west flow dominated by the ebb and flood of the tide and weaker north-south flow forced by the wind. The response to wind forcing was more evident at this site due to its shallower location.

Figures 9 and 10 show the overlay of predicted and observed east-west (U component) and north-south (V component) currents at the Pipeline 2 site respectively.

The predictions at the Pipeline 2 site show very good agreement with both the phase and amplitude of the observations of the east-west flow (Figure 9) during most of the 12 day period. In the first two days, during the weak tidal flow, the magnitude of the southward flowing current is over predicted as for the other sites. The predictions for the north-south flow show a poorer agreement with the observations (Figure 10) than observed at the other sites.

These results again suggest that the Varanus Island winds were slightly weaker than local winds near the Wonnich site during some of the wind events. The reason for observing greater discrepancies in the north-south flow at this site than at the other sites whilst still getting good agreement with the east-west flow is not obvious. One potential explanation is an error in the model bathymetry near the Pipeline 2 site which is effecting the north-south flow but not the east-west flow.

CONCLUSIONS

Overall, the results of the verification at the three sites are very encouraging. The following appear to be the major outcomes of the study:

a) The model is predicting the tidal flow at all depths with good accuracy in both the phase and amplitude of the tidal current.
b) The model is predicting the wind driven flow near the surface with good accuracy for most events.
c) Prediction of the wind driven current near the bottom of the ocean shows less skill than near the surface.
d) Some improvements to the model bathymetry, particularly near the Pipeline 2 site, may need to be made.
e) There may be some instances when the Varanus Island wind observations are slightly lower than in the Wonnich region. This may be due to a degree of sheltering by Barrow Island for some wind directions. However, overall, the Varanus Island winds appear to provide a good approximation to the winds experienced at the Wonnich site.

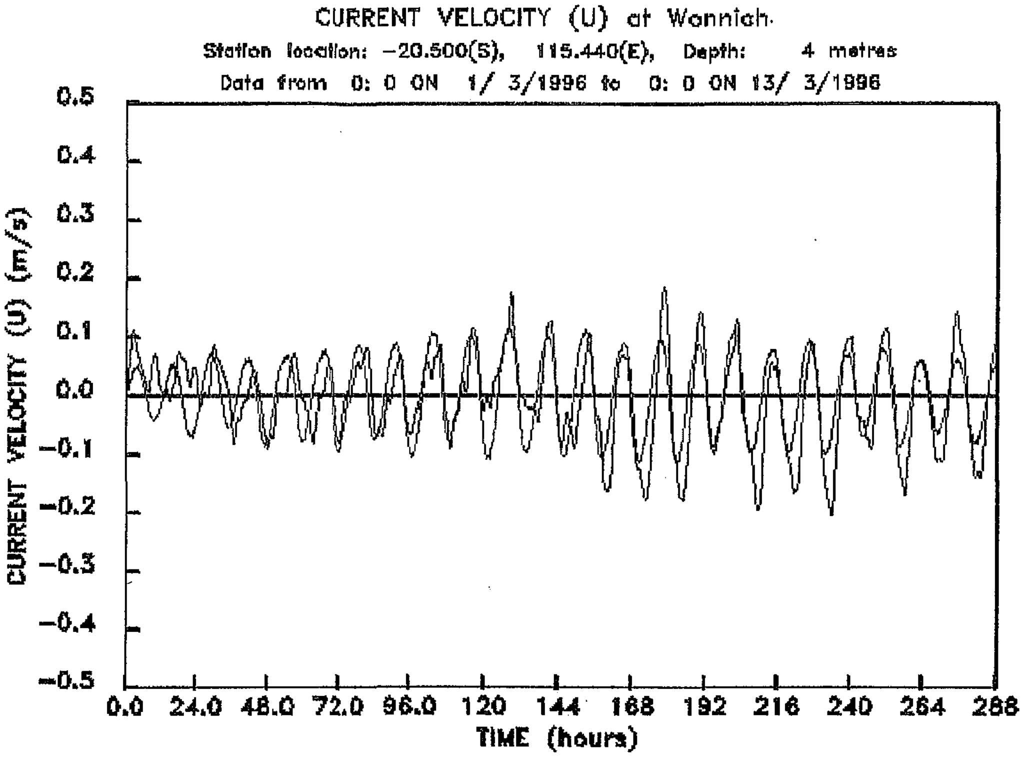

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Figure 5: Comparison of the observed (blue) and predicted (red) east-west tidal current velocity at Wonnich.

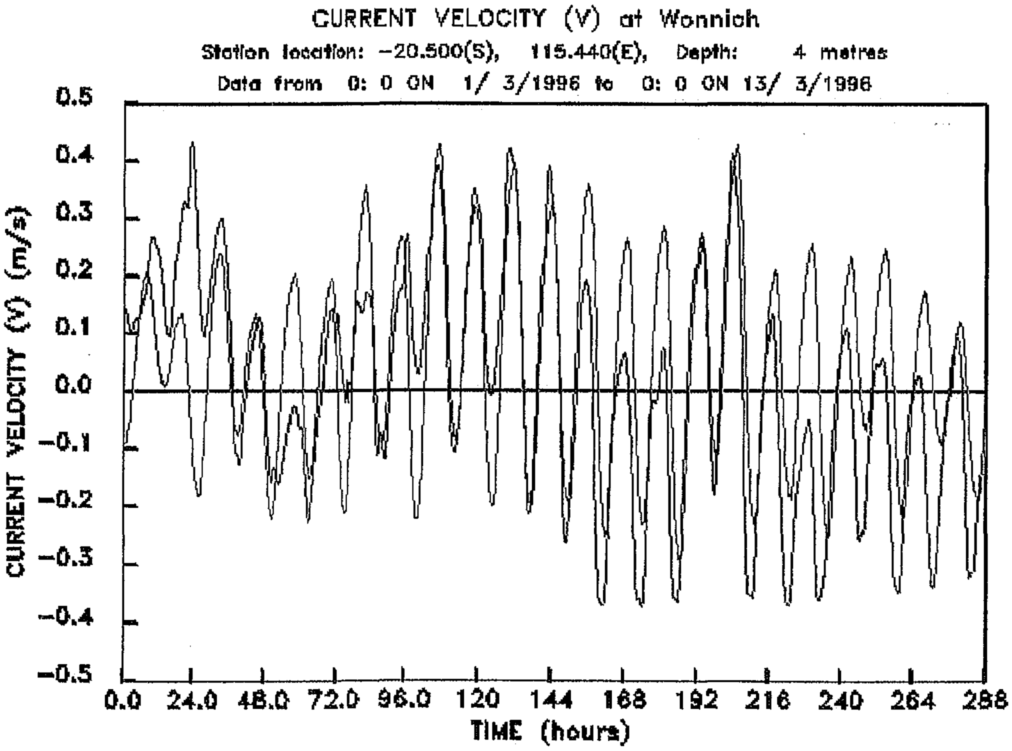

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Figure 6: Comparison of the observed (blue) and predicted (red) north-south tidal current velocity at Wonnich.

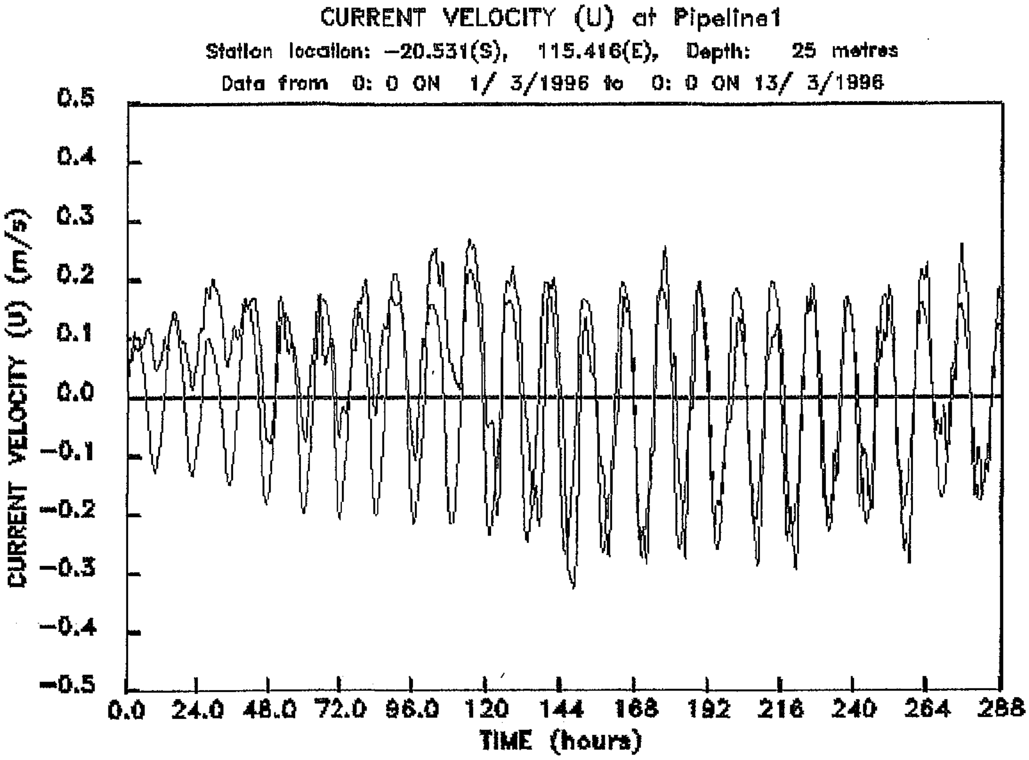

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Figure 7: Comparison of the observed (blue) and predicted (red) east-west tidal current velocity at Pipeline 1.

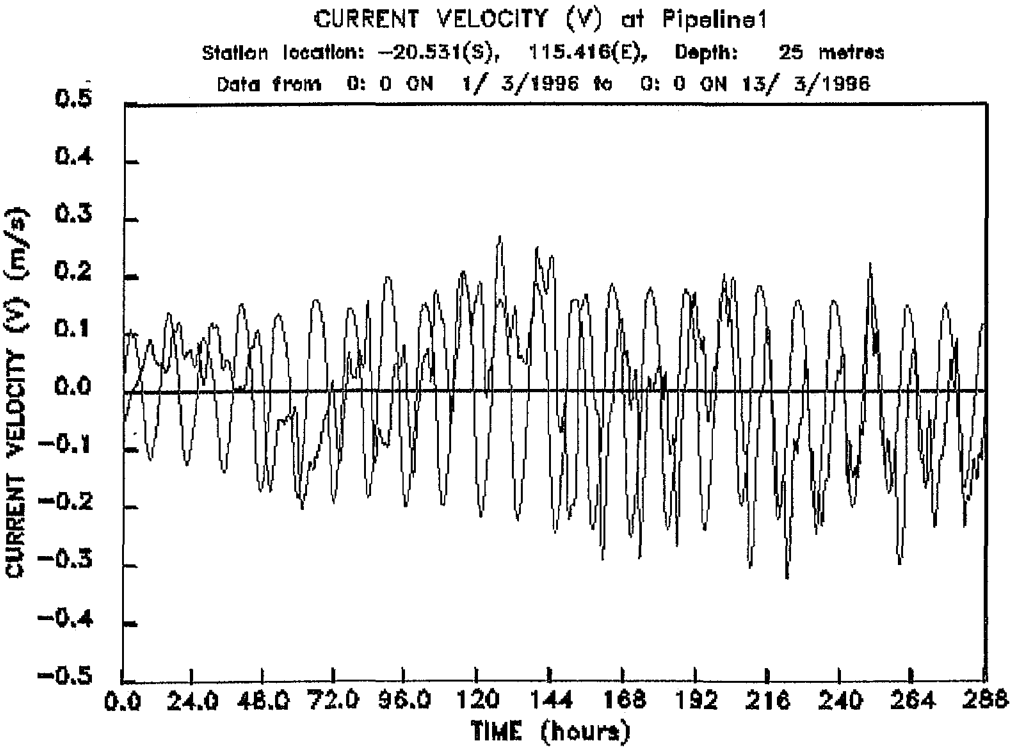

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Figure 8: Comparison of the observed (blue) and predicted (red) north-south tidal current velocity at Pipeline 1.

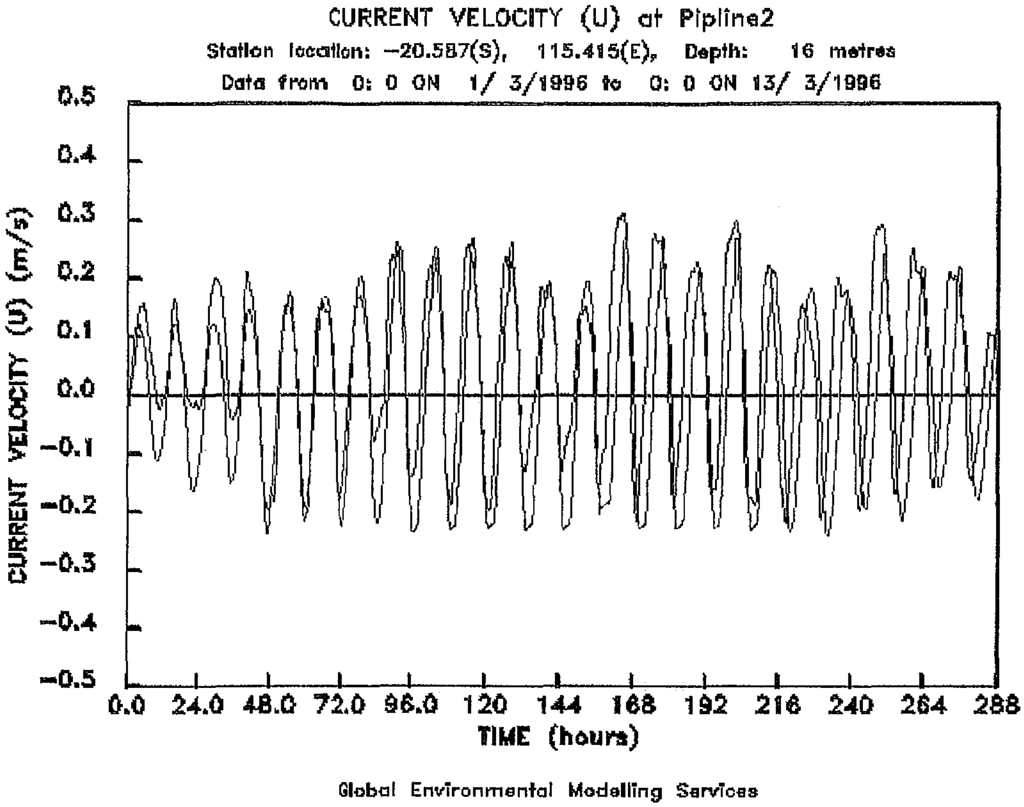

Figure 9: Comparison of the observed (blue) and predicted (red) east-west tidal current velocity at Pipeline 2.

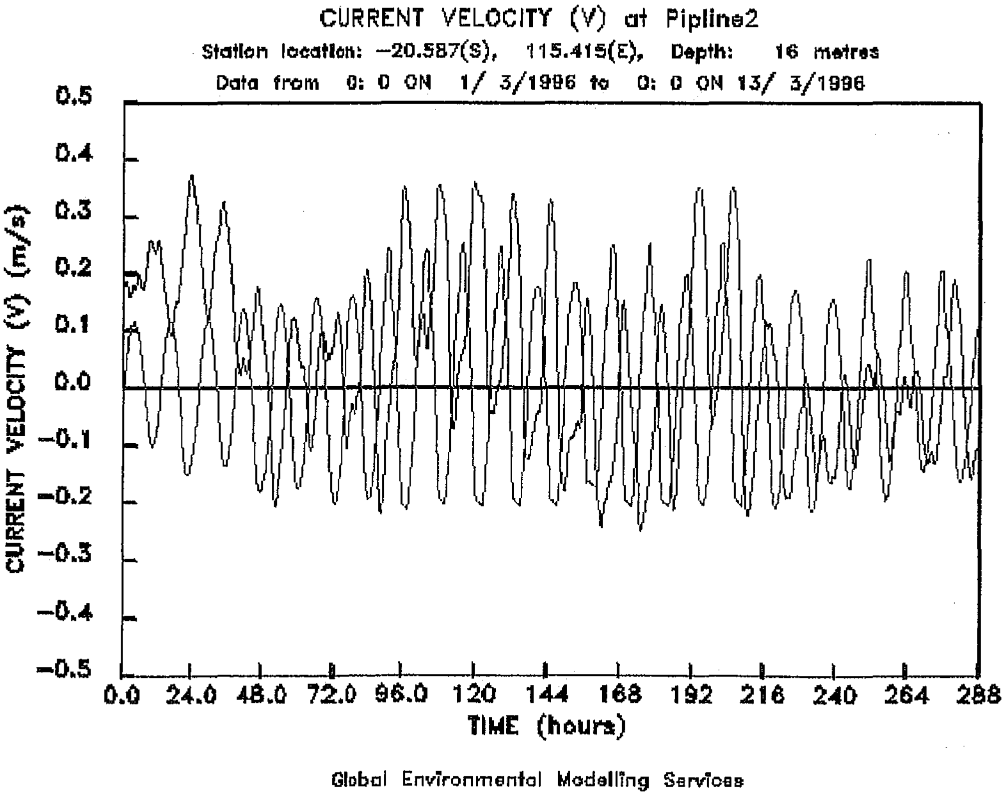

Figure 10: Comparison of the observed (blue) and predicted (red) north-south tidal current velocity at Pipeline 2.

Appendix 1: GEMS 3D Coastal Ocean Model - An Overview

The GEMS 3D Coastal Ocean Model (GCOM3D) is a three-dimensional primitive equation ocean model which has been specifically developed by Global Environmental Modelling Services (GEMS) to study and predict ocean currents on or near the continental shelf and in harbours and estuaries. GCOM3D has also been integrated into the OILMAP package to provide a comprehensive system for oil spill management. GCOM3D has been sold to a number of major companies and government agencies including Apache Energy, WAPET, BHP, AMSA, the Royal Australian Navy and the United States Navy.

Since GCOM3D is a fully three-dimensional ocean model it can also be used to predict currents and trajectories at any depth. This facility has, for example, been used to predict the fate of formation water and dredge spoil from drilling operations.

Detailed verification studies of the current predictions from GCOM3D have been carried out in Australia in locations such as Exmouth Gulf, the Onslow-Barrow Island region, Mermaid Sound, the Montebello Islands, the Gulf of Carpentaria, Bonaparte Gulf and in the waters off Sydney. These verification studies have shown that in each case the agreement between model predictions and observation has been extremely good. As a result, a high level of confidence can be attached to the ability of GCOM3D to accurately predict near-surface currents.

A.1 Description of GCOM3D

For oil spill trajectory modelling it is important to model the surface ocean current and this cannot be obtained accurately from a depth-averaged two-dimensional model. The major deficiency of two-dimensional models is that they yield no information about the vertical structure of the currents, nor can they model the thermodynamics of the ocean. Two-dimensional models include a simple parameterisation of the bottom shear stress which is assumed to be a function of the vertically averaged flow. This can lead to quite erroneous results especially in regions of large vertical variation in the ocean currents. In a two-dimensional model the depth-averaged current is constrained by the bottom friction and is always less than the surface current and usually in the wrong direction because the bottom friction will tend to direct the current along topographical gradients (particularly in shallow water). In addition the bottom stress is usually over predicted because it is calculated using the depth-averaged current and not the near-bottom current.

A further problem arises in areas of strong tidal current where the bottom current will reverse direction before the surface current at the end of the flood or ebb tides due to the action of the bottom friction producing a slower bottom current. This can introduce apparent phase errors into the prediction of the surface tidal currents by a two-dimensional model. A three-dimensional model however overcomes these problems by predicting the near-bottom current and allowing the surface current to be decoupled from the bottom friction due to the vertical layers in the model. To obtain information concerning the variation of currents in the vertical and the thermodynamic properties of the ocean a three-dimensional numerical model is therefore required.

There have been a number of significant contributions in the area of three-dimensional regional ocean models and a full review will not be attempted here. One of the first important contributions to three-dimensional regional ocean modelling came from Leendertsee (1973) who developed a "z"

coordinate model for studies in small bays and estuaries. Another important contribution came from Blumberg and Mellor (1983) who developed a three-dimensional, primitive equation, sigma coordinate model with an embedded, turbulent closure submodel. Three-dimensional ocean modelling technology has therefore been available for at least the past thirteen years and the speed of modern desktop computers has now enabled the application of three-dimensional models to a range of coastal engineering problems.

GCOM3D is a state-of-the-art three-dimensional ocean model which has been developed to study and predict ocean currents on or near continental shelves anywhere on the globe. The basic model formulation has been described previously (Hubbert, 1991) and the discussion here is limited to some of the important features for modelling near-surface currents. GCOM3D includes the non-linear advection terms and is driven by wind stress, atmospheric pressure gradients, astronomical tides, quadratic bottom friction and ocean thermal structure (if there are any temperature or salinity data). For high resolution studies the system can be nested to reduce the uncertainties associated with the specification of the boundary conditions at open boundaries. The system will run on any modern computer (e.g. DOS or UNIX machines).

To set up GCOM3D, horizontal and vertical grids must be chosen. GCOM3D simulates the vertical distribution of ocean currents by breaking the vertical water column up into a specified number of layers at a specified depth. It is also desirable to have a variable vertical grid spacing so that the resolution can be adjusted to physical requirements. Much greater resolution is generally required in the vertical dimension than in the horizontal dimension. For coastal waters GCOM3D would typically run on a horizontal grid of resolution 1 km and with up to 10 vertical levels. In complex bathymetric areas (such as the Montebello Islands) resolution of a few 100 metres is required.

GCOM3D is quite fast and efficient largely due to the numerical integration procedure which is split into three separate explicit steps. This split-explicit approach is very efficient in oceanographic models with free surfaces because of the large disparity between advective speeds and gravity wave phase speeds in deep water. The first step, which is usually referred to as the adjustment step, considers the effects of the gravity wave and Coriolis terms and solves the full continuity equation. Then follows the advective step which accounts for the remaining non-linear terms. Finally, the "physics" step accounts for the effects of surface wind stress, bottom friction stress and atmospheric pressure.

GCOM3D simulates the tidal and wind-forced flow in the region of interest, driven by any number of tidal constituents (usually at least seven - M2, S2, N2, K2, O1, K1 and P1) and forecast winds derived from a specialised offshore forecasting service. For oil spill modelling twenty-four hour forecasts of surface ocean currents and particle trajectories are produced in about 30 minutes on a Pentium PC allowing advice to be returned to operators within one hour of notification of a spill.

A.2 Meteorological Forcing

A critical component of the real-time system is the specification of the wind forecasts. The meteorological forcing can be derived from the lowest-level of a mesoscale atmospheric prediction model (Hubbert, 1991), or from observations and manual forecasts. During an oil spill or search and rescue event the forecast provided by the official forecasting service is used.

A.3 Ocean Thermodynamics

On the continental shelf the major forcing mechanisms are predominantly tidal and meteorological. In some cases however the thermodynamic structure of the ocean induces significant density currents and stratification can allow internal tides to propogate. In deeper waters, off the continental shelf, the influence of the tides diminishes and the dominant forcing is meteorological and thermodynamical.

It is therefore necessary to include thermodynamics in the modelling process in continental shelf regions affected by these processes (e.g. Leeuwin Current off West Australia and the East Australian Current). Fortunately there is a large amount of sea surface temperature (SST) data available from satellite observations. AVHRR satellite SST data is available around the Australian continental shelf at a resolution of at least 4 km. The GTS contains global SST data at a resolution of one degree. These data can be assimilated into GCOM3D to produce a good representation of the surface thermodynamic currents. This procedure has been tested with good success in studies of the East Australian Current for the Sydney Ocean Outfalls.

A.4 GCOM3D Setup

For GCOM3D to achieve operational status the following tasks must be completed:

a) Bathymetry

To set up GCOM3D a digital bathymetric data set is generated for the entire region of interest. High resolution embedded regions are achieved by manually coding depth data obtained from the Admiralty charts and incorporating any available digital sounding data obtained from industry, port authorities etc. to produce a high quality bathymetric data set with a resolution appropriate to resolve the physical oceanography of the region. This database is automatically accessed by GCOM3D once the user specifies the boundaries of the grid for current prediction.

b)Tides

To accurately model the tidal regime anywhere in the region of interest it is necessary to use at least four, and often more, tidal constituents (e.g. M2, S2, N2, K2, O1, K1, P1) to simulate the tidal flow accurately. To establish a high resolution embedded tidal constituent data set the tidal components are modelled throughout the region of interest and the variation of the amplitude and phase of each constituent established using Fourier analysis techniques.

A.5 References

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OILMAP - OILTRAK

Oil Spill Prediction and Response Management System

developed by

Applied Science Associates

Global Environmental Modelling Services

and the

Australian Institute of Marine Sciences

Appendix 2

System Description

and

Verification

May 1996

1. INTRODUCTION

OILTRAK and OILMAP are the oil spill prediction systems used by a majority of the Australian offshore oil industry. OILTRAK has been used by a large number of oil companies in Australia (e.g. Woodside, BHP, WAPET, Apache, Comalco, Command, Discovery, Hadson, Lasmo, Teikoku) for operations on the north-west shelf, Bass Strait and in the Gulf of Carpentaria. OILMAP is now considered to be the world standard oil spill management model with over one hundred users worldwide. Exxon, Chevron, Mobil and Amoco use OILMAP for their operations internationally. OILMAP includes an interactive graphical display system linked to GIS datasets which provides an important decision support system for oil spill response and contingency planning. OILMAP can be used to provide evidence of 'best practice' in the event of a spill and has been used to hindcast the Persian Gulf spill, the Exxon Valdez spill and the Braer spill. The OILTRAK and OILMAP systems are however, more complimentary in nature than competitive.

In the past, for real-time oil spill modelling, OILMAP has used predicted wind forecasts in conjunction with historic current databases. Whilst historic data on water currents may be suitable for training and contingency planning, it has no application to real time modelling. This problem arises because OILMAP does not attempt to model the ocean physics but relies on being given the surface ocean currents as input to map the path of the oil spill and incorporate weathering, chemistry and important natural resource environmental data.

OILTRAK is a fully three-dimensional ocean model with a proven capability of predicting near-surface ocean currents around the continental shelf. OILTRAK focuses on predicting the particle trajectory path produced by the surface ocean currents during an oil spill. This is precisely the input data that OILMAP requires for response predictions. OILTRAK concentrates on predicting the physical oceanography of the region driven by winds and tides and OILMAP can take this information and provide an interactive management facility to model the fate of the oil spill taking into account chemistry, weathering, oil types and up to 50 layers of GIS data locating sensitive environmental concerns and other physical resources.

About 18 months ago Graeme Hubbert (GEMS) and Brian King (AIMS) first discussed the linking of the two systems to provide a powerful tool to industry and government agencies. This linking has now been achieved. Initiated from within the OILMAP user interface (figure 1), OILTRAK now supplies fully three-dimensional ocean model predictions of near-surface currents for a specified time period. This current data is then used by OILMAP to drive the oil spill trajectory models. This combined system is now in use by WAPET and Apache Energy on the North West shelf, by BHP throughout Australia and South-east Asia and by the Australian Maritime Safety Authority (AMSA) for the National Oil Spill Response Plan and for Search and Rescue operations in the Australian region. The capabilities of this combined OILTRAK-OILMAP system are unmatched by any other oil spill prediction system.

The OILMAP-OILTRAK system is relocatable, relying only on wind forecasts, quality bathymetric data, tidal information and a detailed coastal map for the given geographic area. The system as set up for BHP, Apache and WAPET only requires the operator to input the wind forecast and specify (with the mouse) the region over which oil spill modelling will be carried out. These functions require only a few minutes of operator time. The current field is then generated automatically by running the 3D ocean model (OILTRAK) over the defined region. During the OILTRAK run, the predicted trajectory of particles are shown on the screen (the standard OILTRAK output) to give a first approximation to the fate of the oil spill. At the completion of the OILTRAK run the surface current predictions are imported to OILMAP to allow it to to predicte the path that a specific oil type would take.

The system has been designed for accurate prediction by users with little or no knowledge of hydrodynamics. Redesign of the OILMAP menu structure presents the two systems as an integrated package (see Figure 1), thus eliminating any confusion for the operators. A short training session allows the user to be confident and able to run this system in house.

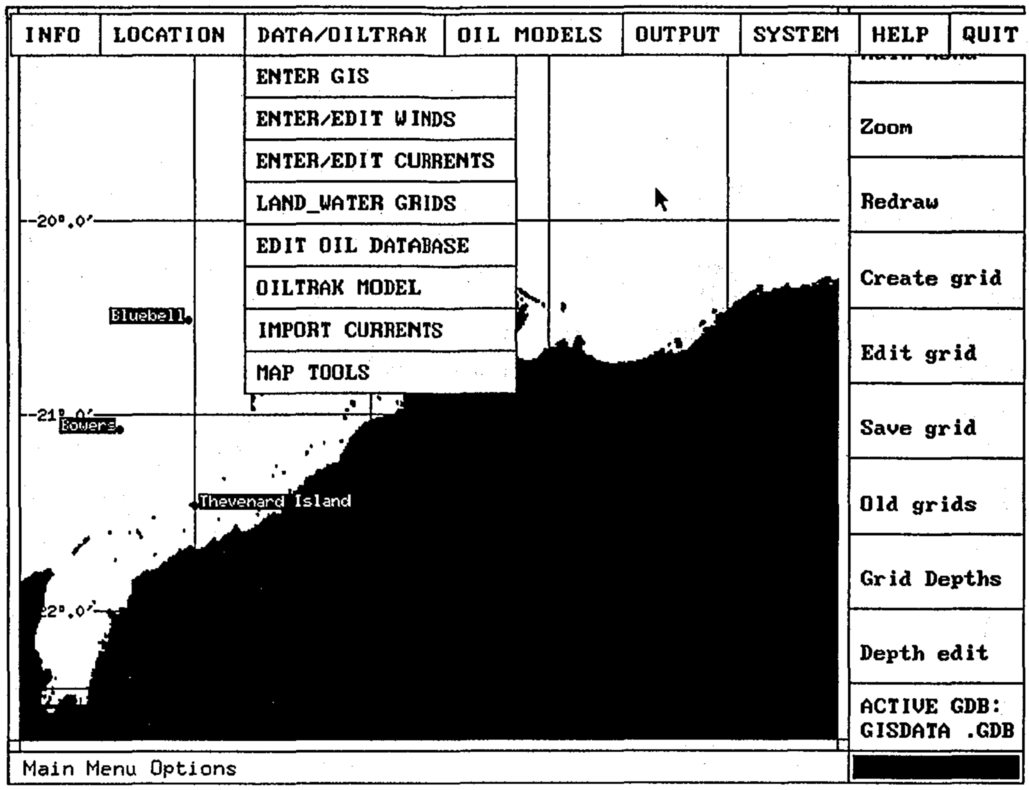


Figure 1: Redesigned OILMAP menu structure which includes OILTRAK in the DATA module

2. OILMAP - An Overview

OILMAP was developed by Applied Science Associates of Rhode Island (ASA). The Australian Institute of Marine Science (AIMS) has provided OILMAP to the Australian/Asian region since 1992. This service by AIMS is provided to industry and government agencies as an Australian owned non-profit project which aims to benefit industry and government agencies through the introduction of new and advanced marine technologies for better environmental management.

The OILMAP system is continually being developed to further meet the requirements of the people and companies using it. The system is currently available in the form of version 3.6.

2.1 OILMAP - The International Standard

OILMAP is a comprehensive Oil Spill Environmental Management System for oil spill response decision support and impact assessment, contingency planning, risk assessment and training purposes. OILMAP runs on a low-cost IBM compatible PC in the Windows or DOS environment. The OILMAP software possesses a suite of models that predict the behaviour of oil on the water surface together with a geographical information system (GIS) that can be used to assess the resources that may be at risk from the spill. These are all combined into an easy to use, menu-driven system. A powerful feature of the system is it's graphical display of the spill behaviour and GIS information.

OILMAP is designed to operate anywhere in the world and its user-friendly design is suitable for non-technical users. OILMAP can be set up to operate for any geographic area and at any scale. The system has a powerful zoom capability and finer resolution maps can be embedded as required. OILMAP is modular in design and can be set up as a stand-alone system or integrated with other ASA modelling systems (such as SARMAP) as required.

Subsequently, OILMAP has become the defacto standard software for oil spill management around the world. OILMAP currently supports companies such as Exxon, Chevron, Mobil, Amoco, ESSO Australia, BHP Petroleum, BHP Transport, US Army Corp. of Engineers, Environment Canada, The Canadian Petroleum Association, Saudi Aramco, BP, and others. OILMAP coverage exceeds 100 applications and exists in Africa, Europe and the UK, Asia, both America's. The benefits for Australia in using an internationally recognised standard system such as OILMAP are significant, and ensure long-term support for the product.

2.2 The Coastal Resource Atlas

OILMAP uses the latest information technology to store data required for oil spill response, planning, training, and crisis management. Resource information, wind data, current data, oil chemistry, over flight observations and response equipment capability and position can be imported quickly from many sources and retrieved using the OILMAP GIS and DATA menu. This information can be displayed in combination with the oil spill prediction for decision support purposes (e.g. with dispersant use maps) and impact assessment (environmental sensitivity index and cleanup response priority maps).

The data formats used by OILMAP allow data to be incorporated from many existing systems such as ARCINFO and AUTOCAD relatively simply and inexpensively. Data from other existing and new OILMAP systems set up by industry can also be transferred to any other OILMAP system immediately if required. Thus OILMAP provides the ability to have a national resource atlas in operation which makes use of other atlas developments, regardless of origin.

2.3 Oil Spill Modules

OILMAP uses a range of verified models (Spaulding *et al.*,1993; Kolluru *et al.*,1993; Spaulding *et al.*,1994) and associated tools to provide oil spill predictions for emergency response, planning situations, risk and impact assessment, training and crisis management. The models have successfully predicted the surface and sub-surface oil spill trajectories and fates of major spills worldwide. Kolluru *et al.* 1993, and Spaulding *et al.*,1994 show that OILMAP can successfully model the movement of an oil spill in 3 dimensions and predict within a few percent, the mass and chemistry of the spill as it weathers in time.

The models within OILMAP can be purchased together or individually. Each model has different functions as follows:

a) TRAJECTORY ONLY: The model predicts the oil spill trajectory and is very quick to run and set up. It is designed to provide predictions of oil spill trajectories and impacts in minutes from notification of a spill. This rapid response from OILMAP allows quick decision support for spill managers at the beginning of a response operation. This model comes within OILMAP and can be used for operational use, training of operational staff, for contingency planning and running "what-if" hypothetical scenarios of different weather and sea conditions.

b) TRAJECTORY AND FATE: The model provides a quantitative prediction of the oil spill trajectory and how it will weather with time, depending on the oil type, metocean conditions and sea state. The algorithms in the model calculate the mass of oil which will evaporate; how it will spread; if, when and how it will emulsify or mix into the water column; and how much will beach on different types of shorelines. This information is invaluable in establishing cleanup operations, for pre- and post-impact assessments, for dispersant effectiveness evaluations, etc. The model also uses observations of actual spill positions, when available, to update predictions. This feature is important to achieve the greatest accuracy of predictions during a real spill event. At the end of a spill response, this model can provide a complete report analysis, using both field observations and model best-estimate predictions, of the path, quantity and impacts of a spill for litigation purposes and public relations management. This model is a standard module of OILMAP and can be used for operational use, training of operational staff, for contingency planning and running "what-if" hypothetical scenarios of different weather and sea conditions.

c) STOCHASTIC MODEL: This model applies a Monte-Carlo simulation procedure to calculate the probability that a spill will contact particular locations on the water or shore. Using the same models as the trajectory and fates model, a large number of discrete trajectories are run from randomly selected start times within a period of interest (e.g. a season, or proposed operational period). The model then calculates the frequency with which a particular location is contacted by oil, the time-lapse before contact and the amount of oil that may arive. If the model is supplied with representative wind records for the period of interest, and sufficient trajectories are run, the results provide a statistically valid prediction of the risks for forward predictions. The stochastic model is most valuable for forward assessment of the risks associated with oil spills from particular locations, or with different seasonal weather patterns.

d) RECEPTOR MODEL: This model functions in a similar way to the Stochastic model but focusses on the destination of a spill rather than it's source. The model performs risk assessment to valuable resources by predicting whether a highly sensitive area is vulnerable to a likely spill from industry operations. Alternatively, the model can also predict likely source locations for a spill of unknown origin for litigation purposes, such as the prosecution of vessels discharging oil at sea. The model can also be used for maritime search and rescue operations for determining the origin and path of located floating debris.

e) RESPONSE MODEL: This model is similar to the Trajectory and Fates model, but also incorporates the use of response equipment into the oil spill prediction calculations. Therefore, different response strategies can be simulated in OILMAP to determine the most effective. This provides valuable decision support for the managers of an oil spill by providing justification for deploying any particular response strategy. It also ensures maximum benefit from equipment usage (particularly if stockpiles must be sourced from distant locations). This model can also be used to determine stockpile locations, based on what equipment is effective in any given region.

f) SUBSURFACE MODEL: This model provides a complete 3-dimensional capability in predicting impacts of oil spills on both the surface (birds, shorelines, mangroves) and within the water (sea-grass beds, coral reefs, fish communities). This is extremely valuable in that it is unlikely that observations of subsurface impacts will be available and post-spill monitoring programs can be designed using model predictions.

g) CHEMICAL SPILL MODEL: A chemical spill model (currently 450 different chemicals can be modelled) is also available for integration within the OILMAP system which will give the capability to obtain decision support for oil and chemical spills.

2.4 Other Benefits to the User

In addition to its database management capabilities and its range of sophisticated models, OILMAP uses animation or hard-copy printouts to show the movement of the oil spill predictions over the resource atlas. This capability assists spill managers in a number of ways, including providing:

- substantial decision support for spill managers during spill responses and in contingency planning;
- easily interpreted information that can be used by work teams responding to the spill;
- information that can be transmitted to the public or other agencies.

3. OILTRAK - An Overview

OILTRAK is a three-dimensional "primitive equation" ocean model which has been specifically developed by Global Environmental Modelling Services (GEMS) to study and predict ocean currents in order to calculate oil spill trajectories. OILTRAK has been installed in stand alone mode in the Perth and Brisbane offices of the Bureau of Meteorology Special Services Unit (SSU) to provide oil spill trajectory predictions, both for operations and planning, to a number of operators on the north-west shelf and in the Gulf of Carpentaria. The SSU also provides weather forecasts to the operators which are used to drive OILTRAK in a real-time situation. As described previously, OILTRAK has also been integrated into the OILMAP package to provide a comprehensive system for oil spill management. Current users of the combined system include Apache Energy, WAPET, BHP and the Australian Maritime Safety Authority.

Since OILTRAK is a fully three-dimensional ocean model it can also be used to predict current flows and trajectories at any depth. This facility has, for example, been used to predict the fate of formation water and dredge spoil from drilling operations.

Detailed verification studies of the current predictions from OILTRAK have been carried out in Exmouth Gulf (mat track), the Onslow-Barrow Island region (2 mat tracks), Mermaid Sound (current meter), the Montebello Islands (acoustic doppler current profilers) and off Sydney (current meters). Verification of the tidal predictions has been carried out in the Gulf of Carpentaria (Weipa tide gauge), Bonaparte Gulf (Cape Domett tide gauge) and Barrow Island (WAPET tide gauge). In each case, the agreement between model predictions and observation has been extremely good (see section 4). As a result, a high level of confidence can be attached to the ability of OILTRAK to accurately predict near-surface currents on the continental shelf anywhere around Australia.

3.1 Description of OILTRAK

For oil spill trajectory modelling it is important to model the surface ocean current. This cannot be obtained accurately from two dimensioal or depth-averaged two-dimensional models. The major deficiency of two-dimensional models is that they yield no information about the vertical structure of the currents, nor can they model the thermodynamics of the ocean. Two-dimensional models include a simple parameterisation of the bottom shear stress which is assumed to be a function of the vertically averaged flow. This can lead to quite erroneous results, especially in regions of large vertical variation in the ocean currents. In a two-dimensional model, the depth-averaged current is constrained by the bottom friction and is always less than the surface current and usually in the wrong direction because the bottom friction will tend to direct the current along topographical gradients (particularly in shallow water). In addition, the bottom stress is usually over-predicted because it is calculated using the depth-averaged current and not the near-bottom current.

A further problem arises in areas of strong tidal current where the bottom current will reverse direction before the surface current at the end of the flood or ebb tides as a result of bottom friction. A two-dimensional model can introduce apparent phase errors into the prediction of the surface tidal currents under these conditions. A three-dimensional model, however, overcomes these problems by predicting the near-bottom current and allowing the surface current to be decoupled from the bottom friction due to the vertical layers in the model. A three-dimensional numerical model is therefore required to obtain information concerning the vertical variation of currents and the thermodynamic properties of the ocean.

There have been a number of significant contributions in the area of three-dimensional regional ocean models and a full review will not be attempted here. One of the first important contributions to three-dimensional regional ocean modelling came from Leendertsee (1973) who developed a "z" coordinate model for studies in small bays and estuaries. Another important contribution came from Blumberg and Mellor (1983) who developed a three-dimensional, primitive equation, sigma coordinate model with an embedded, turbulent closure submodel. Three-dimensional ocean modelling technology has therefore been available for at least the past thirteen years and the speed of modern desktop computers has now enabled the application of three-dimensional models to a range of coastal engineering problems.

OILTRAK is a state-of-the-art three-dimensional ocean model which has been developed to study and predict ocean currents on or near continental shelves anywhere on the globe. The basic model formulation has been described previously (Hubbert, 1991) and the discussion here is limited to some of the important features for modelling near-surface currents. OILTRAK includes the non-linear advection terms and is driven by wind stress, atmospheric pressure gradients, astronomical tides, quadratic bottom friction and ocean thermal structure (if there are any temperature or salinity data). For high resolution studies the system can be nested to reduce the uncertainties associated with the specification of the boundary conditions at open boundaries. The system will run on any modern computer (e.g. DOS or UNIX machines).

To set up OILTRAK, horizontal and vertical grids must be chosen. OILTRAK simulates the vertical distribution of ocean currents by breaking the vertical water column up into a specified number of layers at specified depth levels. It is also desirable to have a variable vertical grid spacing so that the resolution can be adjusted to physical requirements. Much greater resolution is generally required in the vertical dimension than in the horizontal dimension. For coastal waters OILTRAK may typically be run on a horizontal grid of resolution 1 km and with up to 10 vertical levels. In complex bathymetric areas (such as the Montebello Islands), resolution of a few 100 metres is required.

OILTRAK is quite fast and efficient largely due to the numerical integration procedure which is split into three separate explicit steps. This split-explicit approach is very efficient in oceanographic models with free surfaces because of the large disparity between advective speeds and gravity wave phase speeds in deep water. The first step, which is usually referred to as the adjustment step, considers the effects of the gravity wave and Coriolis terms and solves the full continuity equation. Then follows the advective step which accounts for the remaining non-linear terms. Finally, the "physics" step accounts for the effects of surface wind stress, bottom friction stress and atmospheric pressure.

OILTRAK simulates the tidal and wind-forced flow in the region of interest, driven by any number of tidal constituents (usually at least seven - M2, S2, N2, K2, O1, K1 and P1) and observed or forecasted winds. Twenty-four hour forecasts of surface ocean currents and particle trajectories are produced in about 30 minutes on a Pentium PC, allowing advice to be returned to operators within one hour of notification of a spill.

3.2 Meteorological Forcing

A critical component of the real-time system is the specification of the wind forecasts. The meteorological forcing can be derived from the lowest-level of a mesoscale atmospheric prediction model (Hubbert, 1991), or from observations and manual forecasts. With the system running in the Perth and Brisbane offices of the Special Services Unit of the Bureau of Meteorology, the duty forecaster is well placed to provide this input to the model. On site operators can obtain forecasts from the SSU by phone or fax.

3.3 Ocean Thermodynamics

On the continental shelf, the major forcing mechanisms are predominantly tidal and meteorological. In some cases, however, the thermodynamic structure of the ocean induces significant density currents and stratification can allow internal tides to propogate. In deeper waters, off the continental shelf, the influence of the tides diminishes and the dominant forcing is meteorological and thermodynamical.

It is therefore necessary to include thermodynamics in the modelling process in continental shelf regions affected by currents with significant temperature differences to ambient conditions (e.g. Leeuwin Current off West Australia and the East Australian Current). Fortunately there is a large amount of sea surface temperature (SST) data available from satellite observations. AVHRR satellite SST data is available around the Australian continental shelf at a resolution of at least 4 km. Other satellites provide global SST data at a resolution of one degree. These data can be assimilated into OILTRAK to produce a good representation of the surface thermodynamic currents. This procedure has been tested with good success in studies of the East Australian Current for the Sydney Ocean Outfalls.

3.4 OILTRAK Setup

For OILTRAK to achieve operational status, the following tasks must be completed:

a) Establish a 5 minute resolution bathymetry data set to cover the entire region of interest;

b) Establish the amplitudes and phases of the major tidal component throughout the region on a 5 minute grid, and;

c) Establish high resolution bathymetric and tidal data for specified embedded regions

a) Bathymetry

To set up OILTRAK for the entire region, a 5 minute resolution digital bathymetric data set is generated. High resolution embedded regions are achieved by manually coding depth data from any available source These may include Admiralty charts, digital sounding data obtained from industry, port authorities etc. or direct measurements made for the purpose of the model. This information may be of varying quality, however, a high quality bathymetric data set will allow the model to more clearly resolve the physical oceanography of the region. This database is automatically accessed by OILMAP/OILTRAK once the user specifies the boundaries of the grid for current prediction.

b) Tides

To accurately model the tidal regime anywhere in the region of interest, it is necessary to use at least four, and often more, tidal constituents (e.g. M2, S2, N2, K2, O1, K1, P1) to simulate the tidal flow accurately. To establish a high resolution, embedded, tidal-constituent data set the tidal components are modelled throughout the region of interest and the variation of the amplitude and phase of each constituent established using Fourier analysis techniques.

4. OILTRAK VERIFICATION

Oil spill trajectories predicted by the model have been tested against several experimental data sources. These include "mat" tracks obtained by Lasmo Oil near Exmouth Gulf and by Command Petroleum near Onslow. In Mermaid Sound, Woodside Petroleum provided current meter data for verification of the model. Apache Energy undertook a high resolution verification study around the Montebello Islands using an Acoustic Doppler Current Profiler (ADCP). In all of these cases, good agreement was obtained between model predictions and observations. Most of the earlier results have been reported either in the proceedings of the 1993 Australasian Coastal Engineering Conference (Hubbert, 1993a,b) or in the 1994 APEA Journal. The more recent work carried out by Apache Energy has not yet been published and the results of this work are described in some detail.

4.1 The Montebello Islands

The Montebello Islands represents a higly-complex bathymetric region for modelling of water currents. To model this area, high quality bathymetric data were obtained from several sources. These included remote sensing surveys over the shallow areas, and extensive bathymetric and seismic surveys in the deeper waters and inter-island channels. This data provided files describing the depth at each 100 m, allowing OILTRAK to resolve underwater features that strongly affect the predicted flows.

Apache Energy has undertaken a high resolution verification study around the Montebello Islands to test the predictions of the OILTRAK model in this region. Verification was carried out using an Acoustic Doppler Current Profiler (ADCP), which measures vertical profiles of the currents. Standard acoustic current meters were also used to measure currents at specific depths. These observations were then compared with predictions made by OILTRAK driven by the tides and wind observations from Varanus Island to assess the model's accuracy in the region.

4.1.1 Field work

Ocean currents in the vicinity of the Montebello Islands were measured using a short-term instrument mooring (figure 2). The mooring consisted of an ADCP (supplied and operated by CSIRO) which was held near the water surface by a floatation package and suspended on a tight line from a heavy mooring block. The vertical pull between the floatation and mooring block was sufficient to keep the ADCP oriented toward the sea-floor under the force of the water currents experienced ($\leq$ 1 knot). The ADCP was set to record horizontal water velocities and directions at each 1 m interval from approximately 3.5 m below the water surface to approximately 3 m above the sea-floor. A conventional acoustic current meter (supplied by WNI), capable of measuring at a single depth, was suspended from a surface buoy to record velocities and directions at approximately 1.5 m below the surface. Both instruments measured each 60 seconds and recorded 5 minute averages.

The instrument mooring was deployed between 15 and 22 March 1996 for approximately 24 hour periods at four key locations around the Montebello Islands (Figure 3). This allowed the current meters to record over a number of tidal cycles at each site. The vertically-profiled data collected by the ADCP can be used to verify the predictions of the OILTRAK model at different depths. These verifications are underway. For the purposes of this comparison, measurements from the two shallowest depths (nominally 3.5 and 4.5 m depth) were averaged and compared with OILTRAK predictions at 4 m depth.

4.1.2 OILTRAK predictions and comparison to field observations

OILTRAK was used to generate predictions of the water currents at 4 m depth over a 1600 km^2 area encompassing the Montebello Islands (Figure 3). For modelling, this area was divided into 100 by 100 grid cells (10,000 total), each of which was 400 m on each side. Bathymetric data for this area was supplied at a scale of 100 m, providing up to 16 measures of depth per cell. Hourly recordings of wind speed and direction made at the Varanus Island weather station over the field sampling period (15 to 22 March 1996) provided the data for generating the wind-induced component of the water currents.

Figures 4 to 7 show the wind and tidal driven currents that were predicted by OILTRAK at 4 m depth during one full tidal-cycle (flood, slack, ebb, slack) in the experimental period. These currents account for both tide and wind forces at this time. These plots illustrate the complexity of the flow around the Island chain and, in particular, the large predicted variation in current velocity and direction associated with inter-island channels and with sharp changes in bathymetry (e.g. moving from deep water over the shallow area south of Hermite Island). This highlights the importance of modelling in this area at fine spatial scales, and with accurate bathymetric data.

Figure 8 compares the observed tidal heights with those predicted by OILTRAK for WAPET tanker mooring. The good agreement in both phase and magnitude between predicted and observed values indicates that the tidally-forced component of the water currents was being modelled with good accuracy.

Figures 9 to 12 compare the east-west and north-south components of the water currents measured by ADCP and predicted by OILTRAK at the two sites adjacent to the proposed Wonnich well (ADCP1 and ADCP2). These comparisons show that the model is simulating the north-south and east-west structure of the current flow with good (but not perfect) accuracy. The complexity of the current flow near ADCP1, for example, where the currents reach speeds of 2 knots whilst crossing the shallow reef areas south of Hermite Island makes the prediction at ADCP1 a good result. In general, the ebb currents flow south-west through the this site while the flood currents flows east-north-east. The flow is reasonably complex, however, due to eddies shed near the coral reefs close to this site.

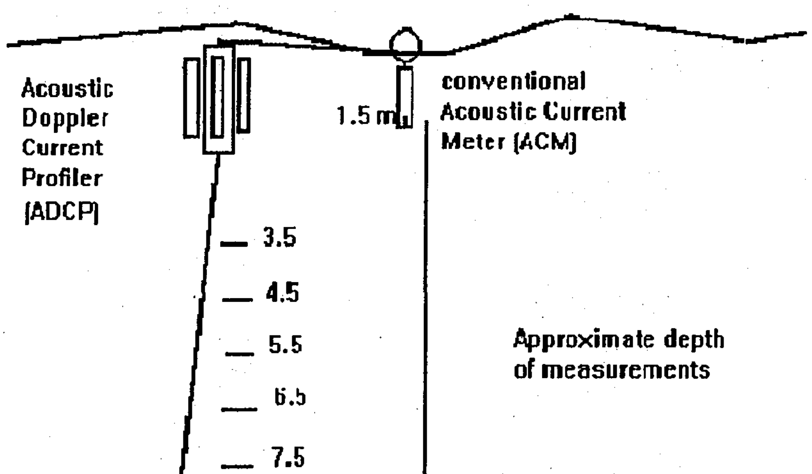
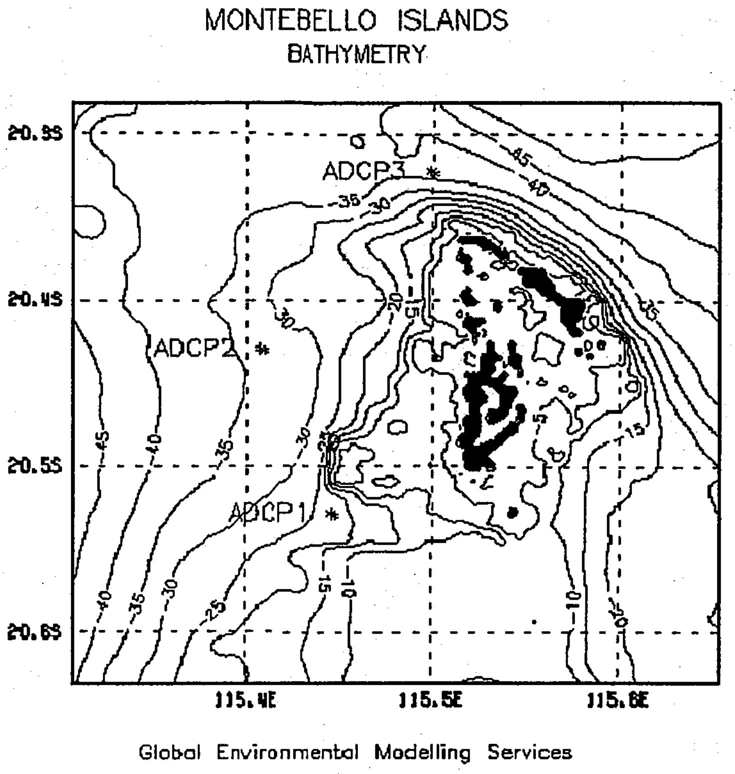


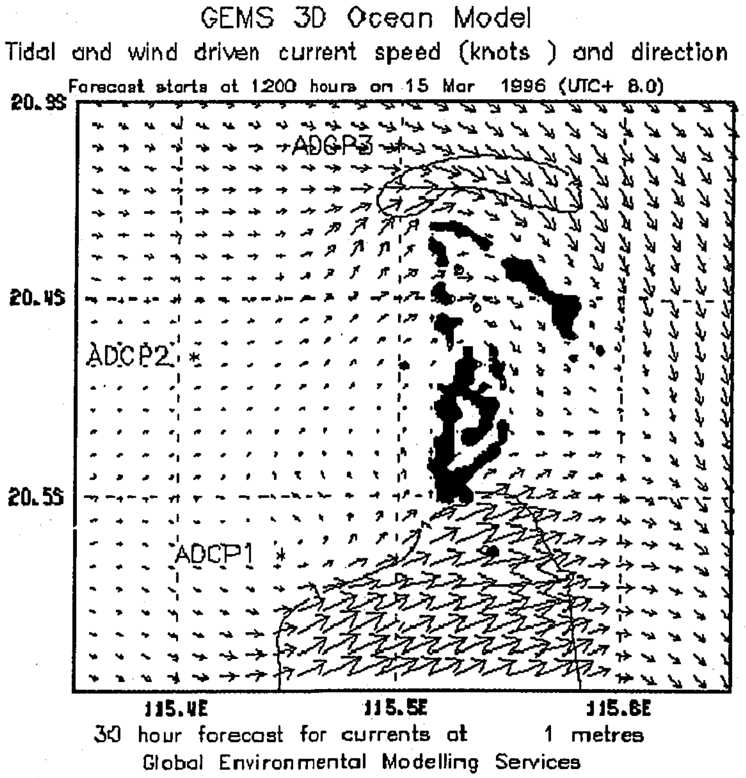
Figure 2: Arrangement of instruments used to profile ocean currents at the deep sites



MONTEBELLO ISLANDS
BATHYMETRY

Global Environmental Modelling Services

Figure 3: Bathymetry used by OILTRAK in the Montebello Island region. Note that the position of ADCP4 is outside the area of this model.



GEMS 3D Ocean Model
Tidal and wind driven current speed (knots) and direction
Forecast starts at 1200 hours on 15 Mar 1996 (UTC+ 8.0)

30 hour forecast for currents at 1 metres
Global Environmental Modelling Services

Figure 4: OILTRAK forecasts for wind and tidal driven near-surface currents during a flood tide 30 hours into the ADCP experimental period

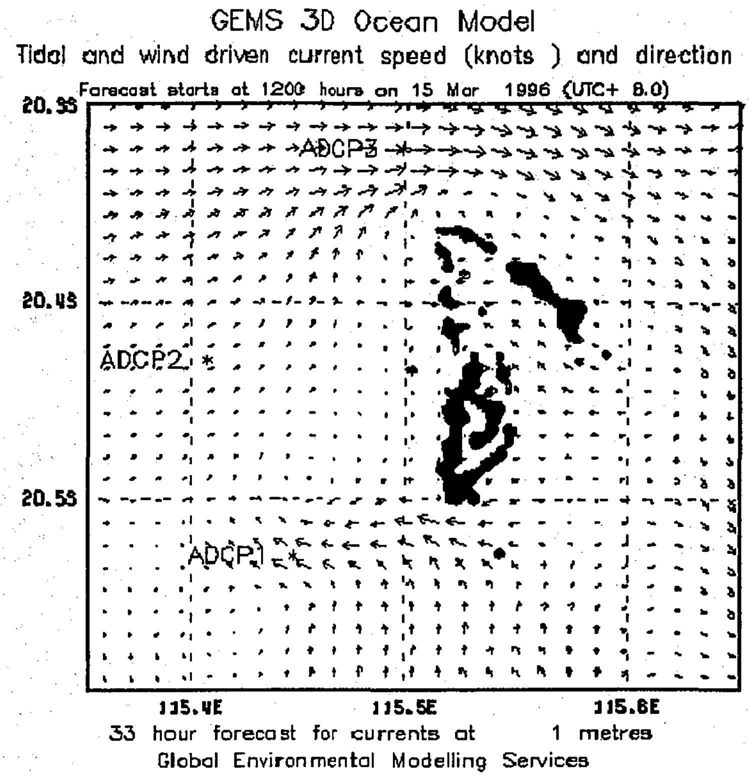


Figure 5: OILTRAK forecasts for wind and tidal driven near-surface currents at the turn of a flood tide 33 hours into the ADCP experimental period

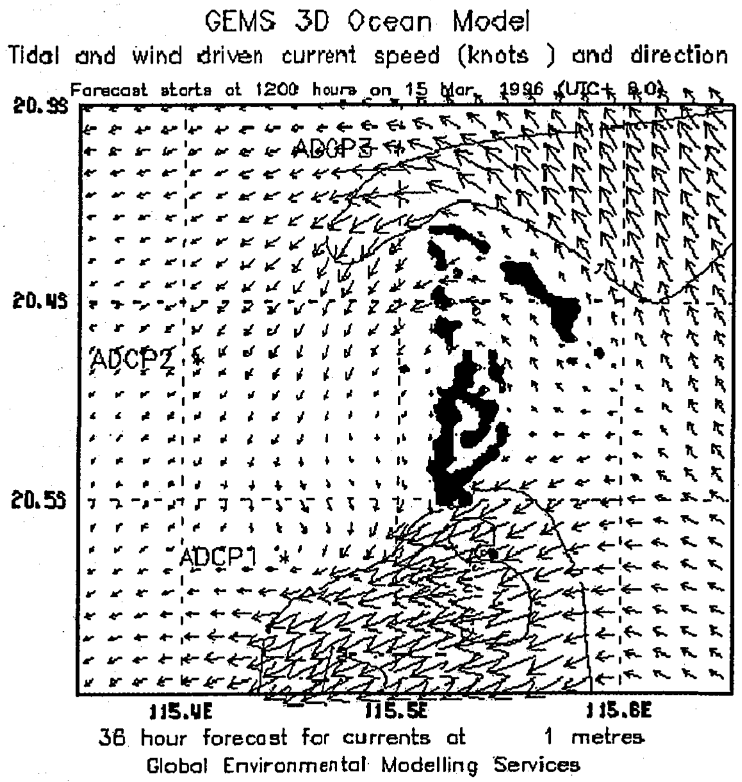


Figure 6: OILTRAK forecasts for wind and tidal driven near-surface currents during an ebb tide 36 hours into the ADCP experimental period

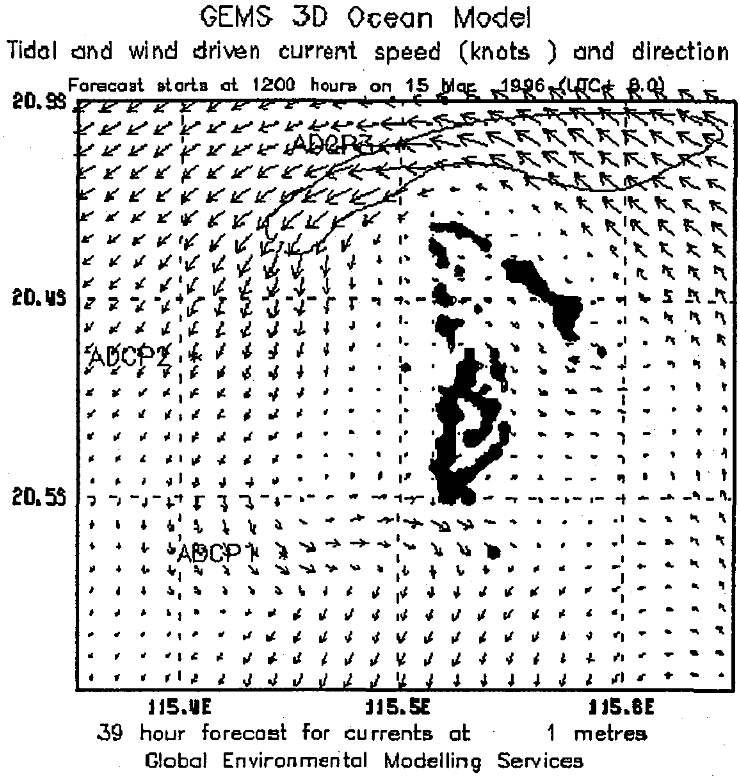


Figure 7: OILTRAK forecasts for wind and tidal driven near-surface currents at the turn of an ebb tide 39 hours into the ADCP experimental period

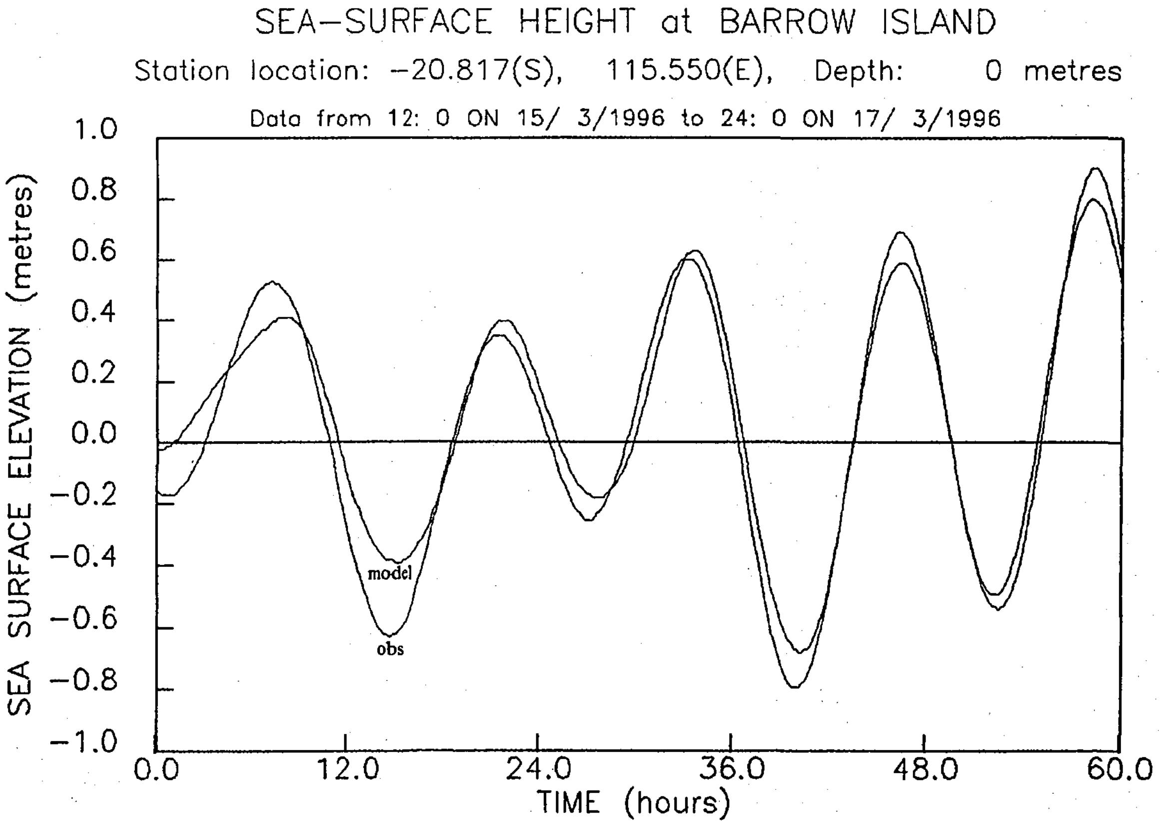


Figure 8: Model predictions of tidal heights compared with observations on April 16 and 17, 1996 at WAPET tanker mooring on Barrow Island

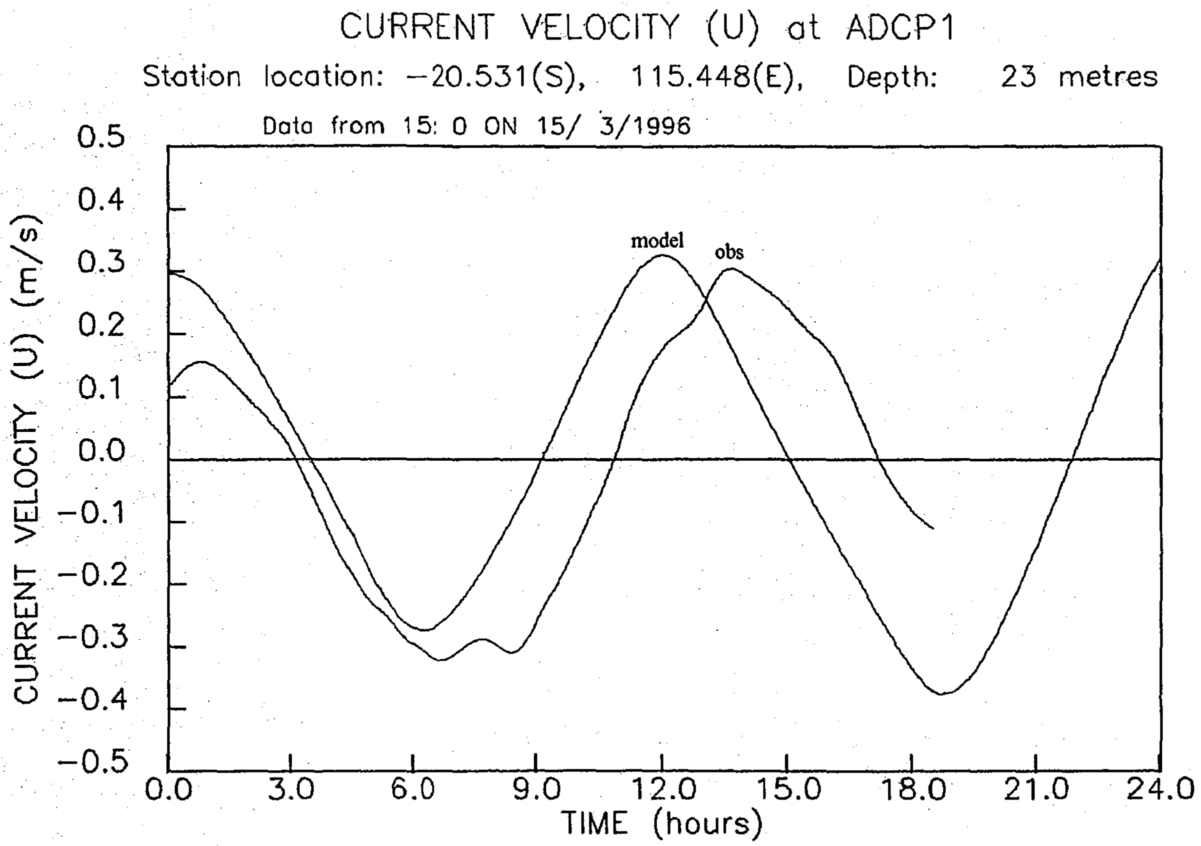


Figure 9: Model predictions of the west-east current component compared with observations on April 16 1996 at site ADCP1 near the Montebello Islands

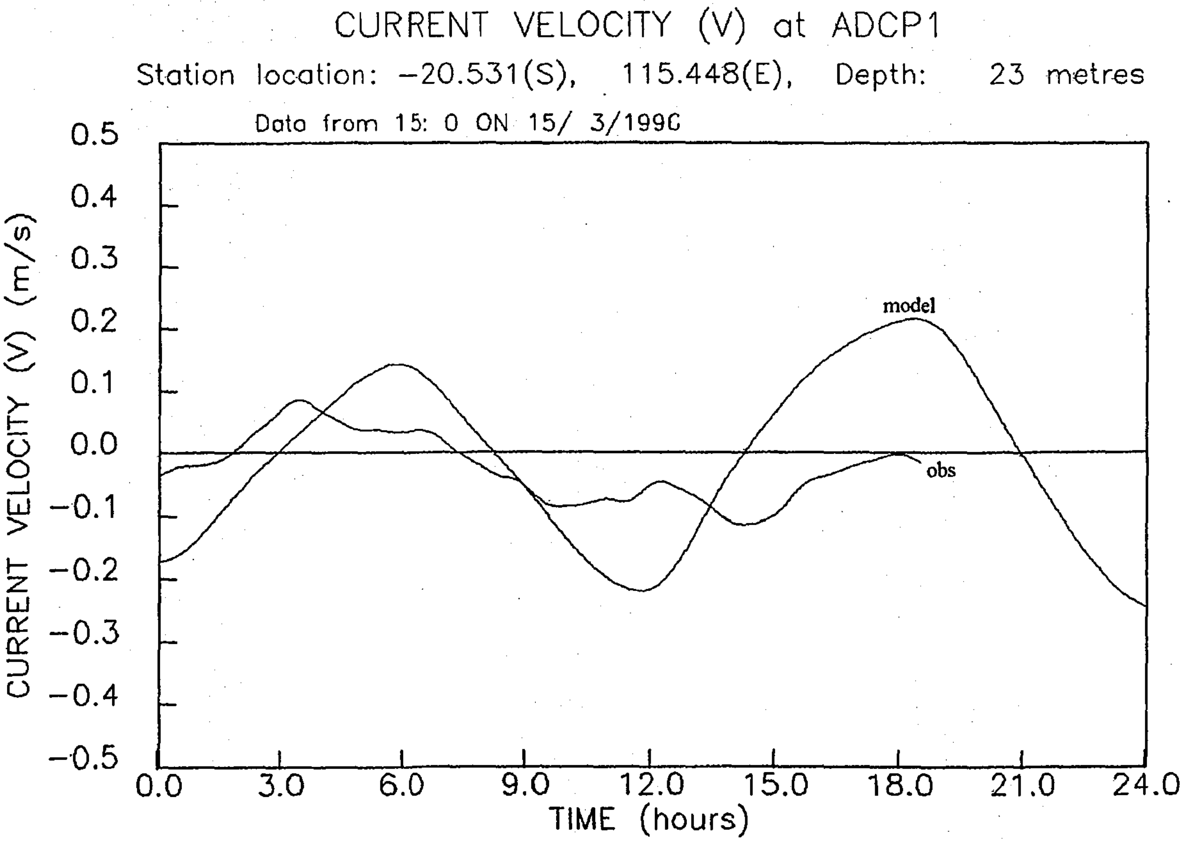


Figure 10: Model predictions of the south-north current component compared with observations on April 16 1996 at site ADCP1 near the Montebello Islands

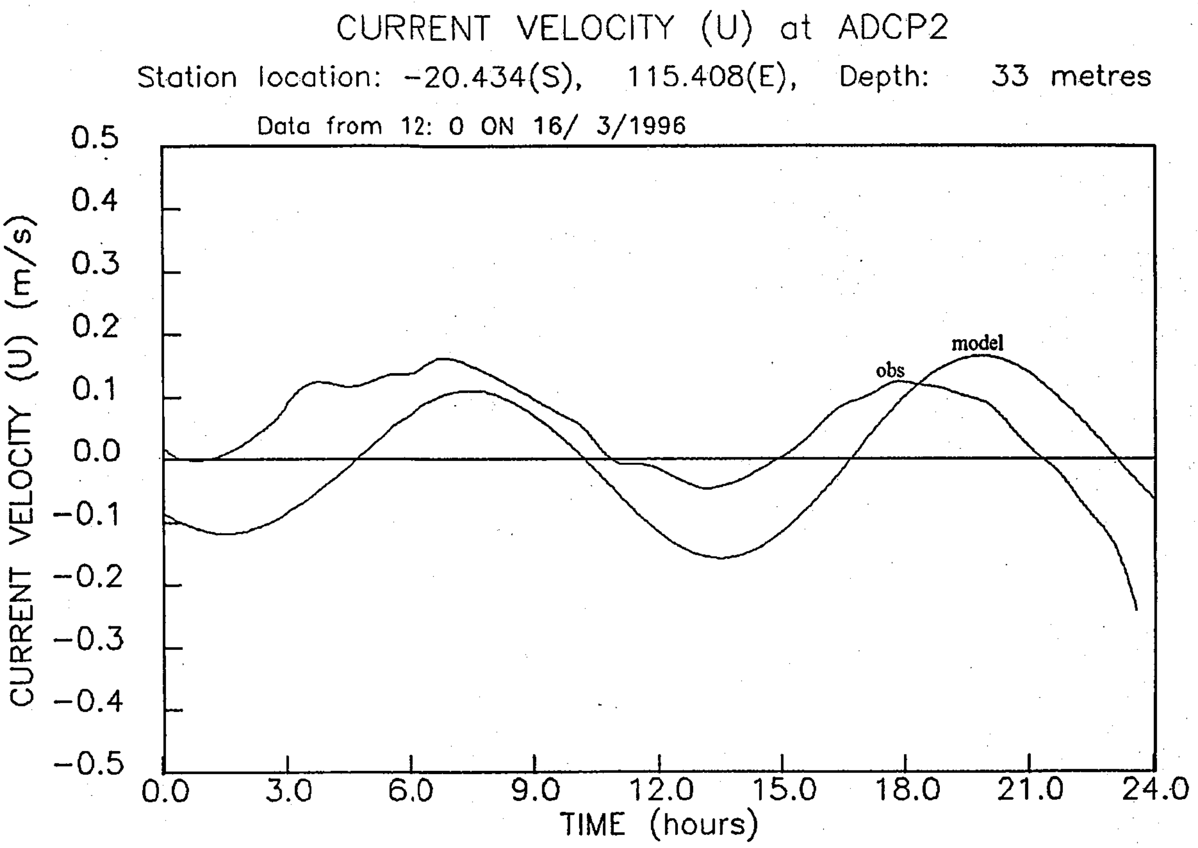


Figure 11: Model predictions of the west-east current component compared with observations on April 17 1996 at site ADCP2 near the Montebello Islands

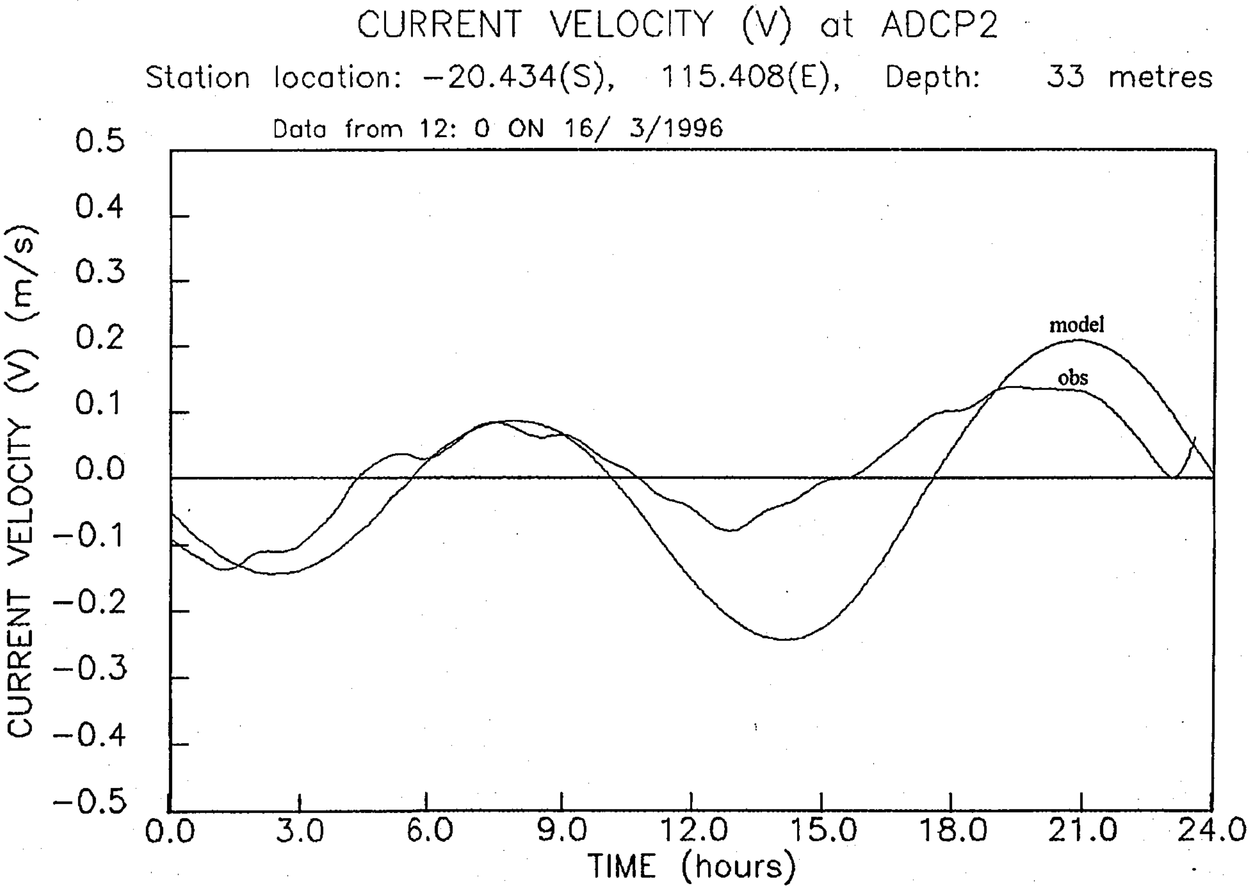


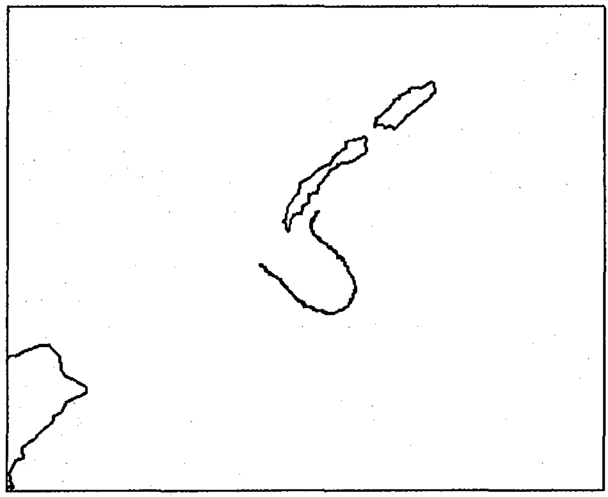
Figure 12: Model predictions of the south-north current component compared with observations on April 17 1996 at site ADCP2 near the Montebello Islands.

4.2 Exmouth Gulf Verification

Lasmo Oil requested the simulation of a "mat" track near the Muiron Islands in the mouth of Exmouth Gulf as a test of the model's ability to simulate surface ocean currents and particle trajectories, within acceptable errors. A "mat" was dropped at 7:45 a.m., September 28, 1992 local time and tracked using a ship's Global Positioning System (GPS) until 6:00 p.m. the same day. The winds observed on the ship were approximately 15 knots from the south-south-west in the morning dropping to 8 knots from the south-west in the afternoon .These winds together, with seven tidal constituents (M2, S2, N2, K2, O1, K1 and P1), were used to drive the oil spill trajectory model on a grid of resolution 700 metres and with 8 vertical levels (the surface layer was four metres thick). The 700 metre horizontal resolution was chosen so as to resolve the gap between North and South Muiron Islands. The observed and predicted tracks are shown in figures 13 and 14.

Buoy Drift Track

Buoy released at 23:40 on 27 Sept 1992 (UTC)

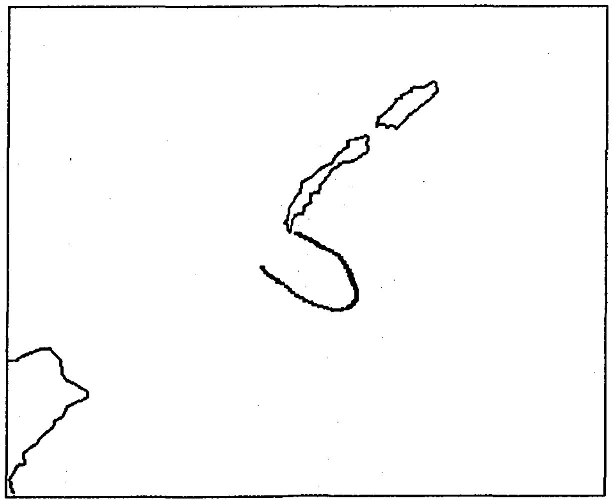


Global Environmental Modelling Services

Figure 13: Observed track of spill mat near Muiron Islands

OILTRAK - 3D Regional Ocean Model

Particle Released at 23:40 on 27 Sept 1992 (UTC)



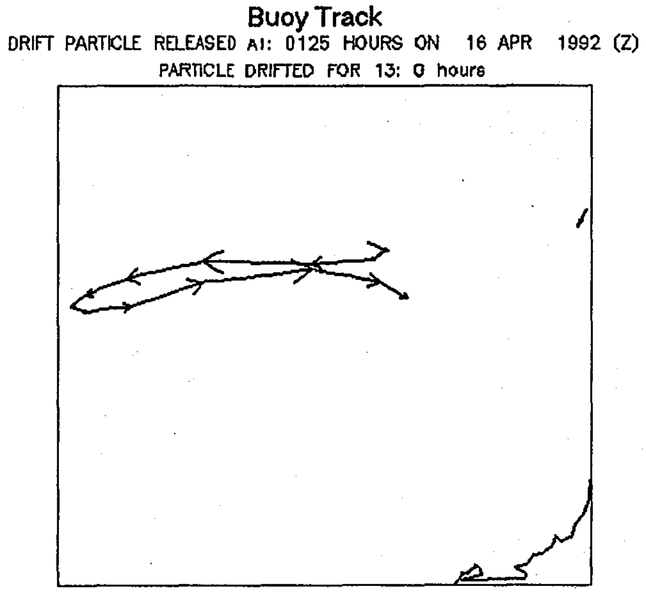
Particle drifted for 11:30 hours

Global Environmental Modelling Services

Figure 14: Predicted path of spill mat near Muiron Islands using OILTRAK

4.3 Onslow Region Verification

Command Petroleum requested the simulation of two mat tracks in the Onslow Barrow Island region to test the model's ability to predict surface ocean currents and particle trajectories. Two mat tracks and wind speed and direction data were provided for successive days (16th and 17th) in April, 1992. The oil spill model was set up on a grid with 2km resolution and 8 vertical levels (with a surface layer 4m thick). OILTRAK was driven by observed winds and by seven tidal constituents to simulate the trajectories of the two mats. The observed and predicted tracks for each of the two days are shown in figures 15 to 18.

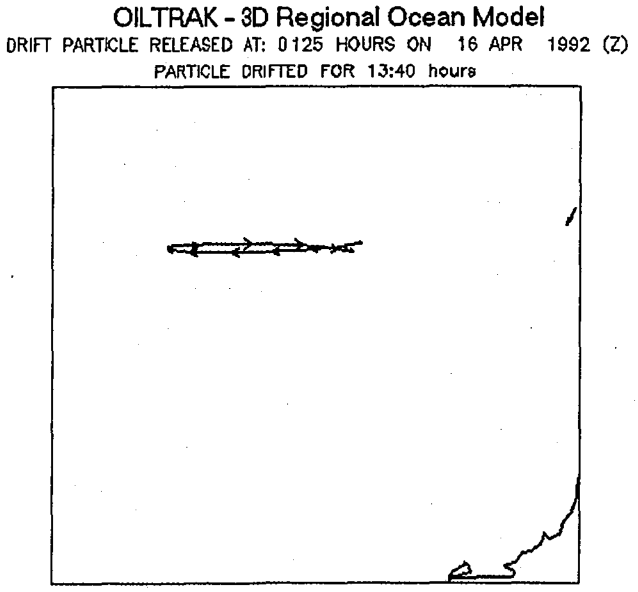


Buoy Track

DRIFT PARTICLE RELEASED AT: 0125 HOURS ON 16 APR 1992 (Z)

PARTICLE DRIFTED FOR 13: 0 hours

Figure 15: Track of spill mat observed by Command Petroleum on 16th April 1992 between Onslow and Barrow Island

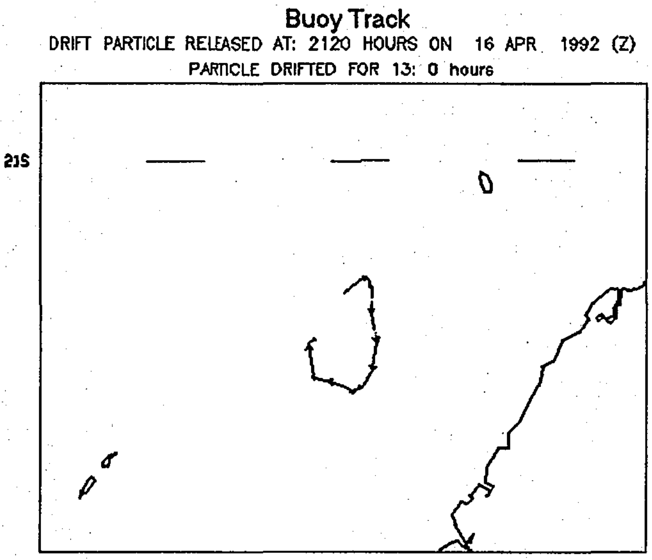


OILTRAK - 3D Regional Ocean Model

DRIFT PARTICLE RELEASED AT: 0125 HOURS ON 16 APR 1992 (Z)

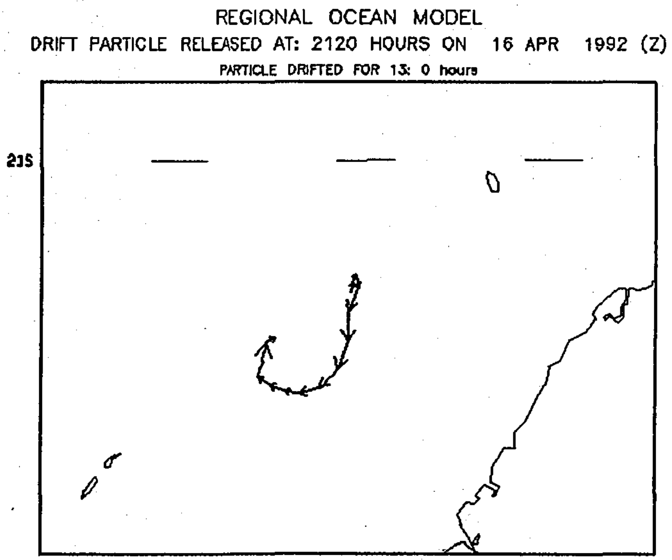
PARTICLE DRIFTED FOR 13:40 hours

Figure 16: Track of spill mat predicted by OILTRAK on 16th April 1992 between Onslow and Barrow Island



Buoy Track
DRIFT PARTICLE RELEASED AT: 2120 HOURS ON 16 APR 1992 (Z)
PARTICLE DRIFTED FOR 13: 0 hours

Figure 17: Track of spill mat observed by Command Petroleum on 17th April 1992 between Onslow and Barrow Island



REGIONAL OCEAN MODEL
DRIFT PARTICLE RELEASED AT: 2120 HOURS ON 16 APR 1992 (Z)
PARTICLE DRIFTED FOR 13: 0 hours

Figure 18: Track of spill mat predicted by OILTRAK on 17th April 1992 between Onslow and Barrow Island

4.4 Mermaid Sound Verification

The Oil spill trajectory model predictions in Mermaid Sound were verified against existing current meter data provided by Woodside Petroleum. At the site chosen for the verification (latitude 20 deg 31.4 mins, longitude 116 deg 43.7 mins, depth 14 m) the current meter was at a depth of 6 m. The Perth office of the SSU provided historical hourly wind data for a three day period (April 27 - 29, 1986) during the current meter observations. OILTRAK was run for this 72 hour period driven by winds and by five tidal constituents (M2, S2, K2, K1, O1) with vertical levels set at 2, 6, 10, 14, 18, 25 and 40 metres. The second level coincided with the depth of the current meter observations. A comparison of the observed current speed time series with the model predictions is shown in figure 19.

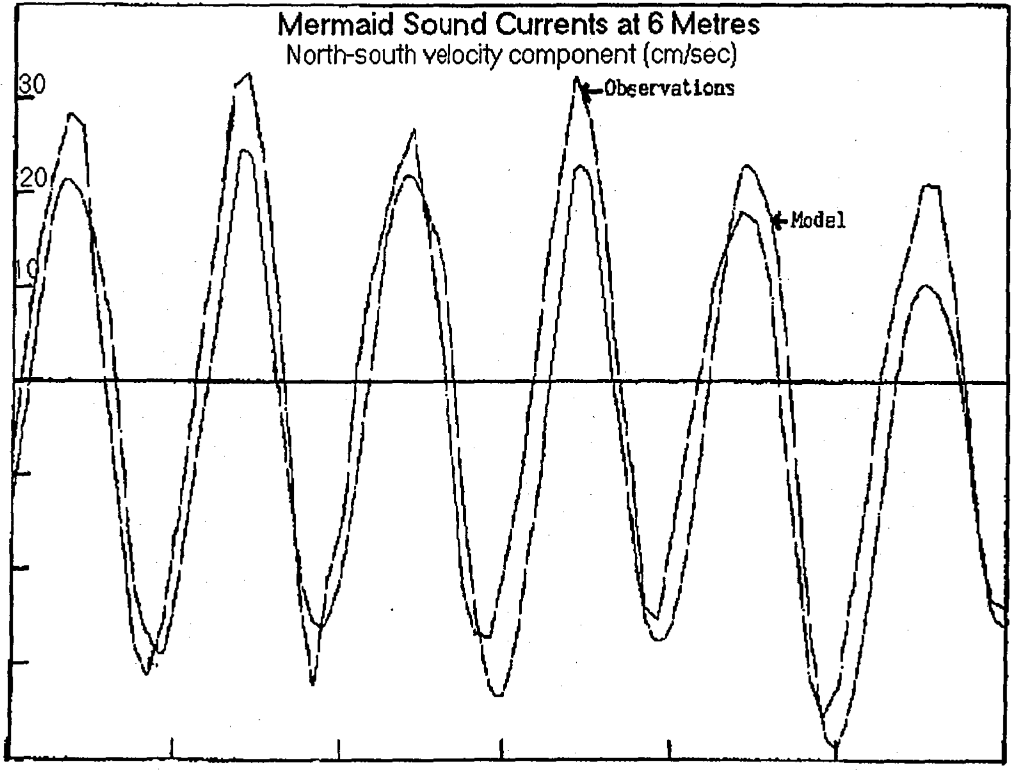


Figure 19: Comparison of observed currents and predictions from OILTRAK at a depth of 6 metres in Mermaid Sound for the period April 27 to 29, 1986.

4.5 Sydney

The three-dimensional ocean model has also been used for other applications such as predicting the currents near the Sydney ocean outfalls for the New South Wales EPA via a contract with Australian Water and Coastal Studies Ltd (AWACS). Comparison has been made between model predictions of currents off Sydney with measurements at the Ocean Reference Station (ORS) installed by the Sydney Water Board as part of the ocean outfall monitoring program. Comparison of model trajectory predictions were also made with the track of a drifting buoy released by the Australian Navy. Good agreement was obtained in both cases (Figures 20 to 23).

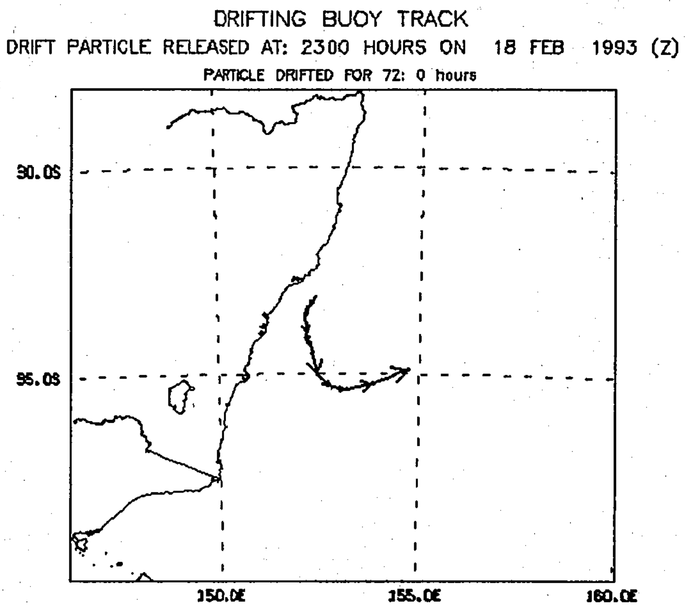


Figure 20: Satellite track of drift buoy observed for three days after release by the Australian Navy on February 19, 1993.

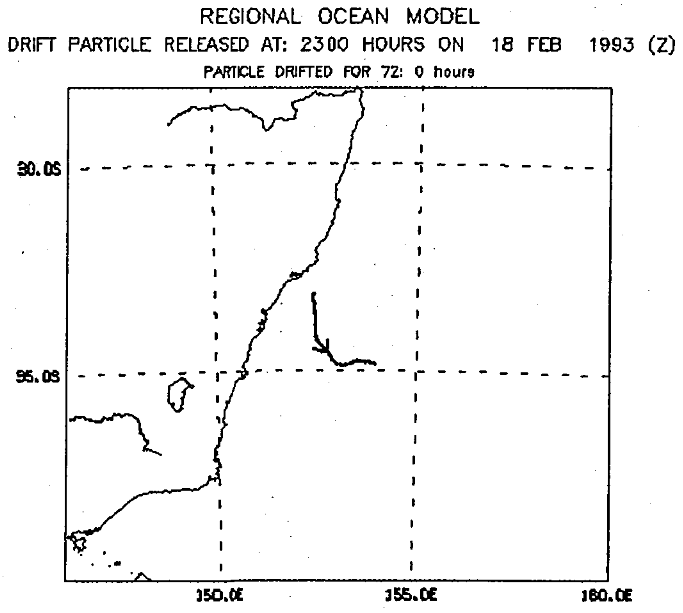


Figure 21: Track predicted by OILTRAK for the three days after release on February 19, 1993.

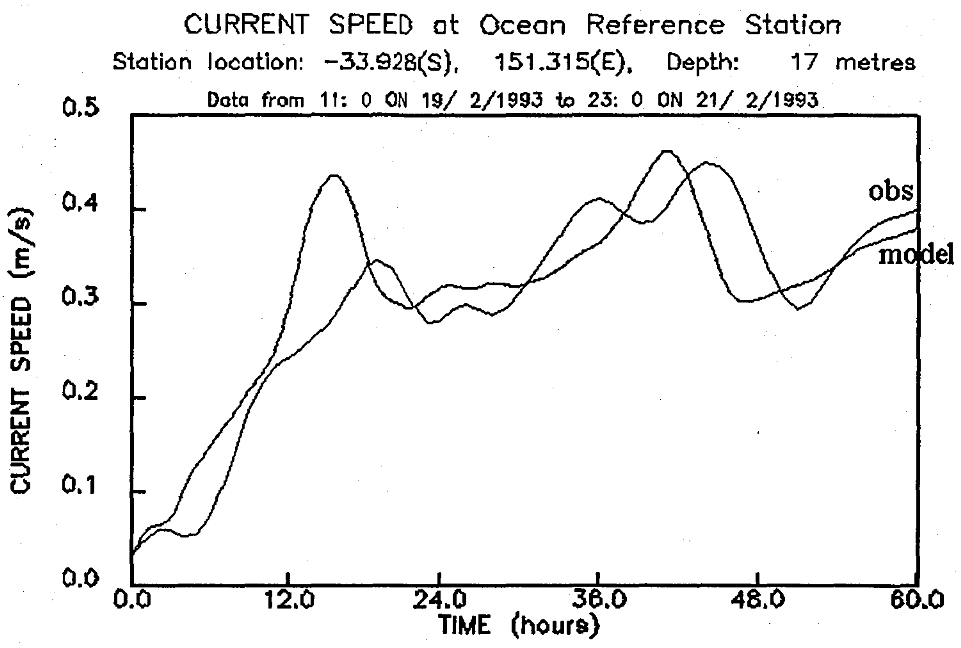


Figure 22: Comparison of observed current speeds with predictions from OILTRAK at a depth of 17 metres at the Sydney Water Board Ocean Reference Station (near Sydney) for February 19 to 21, 1993.

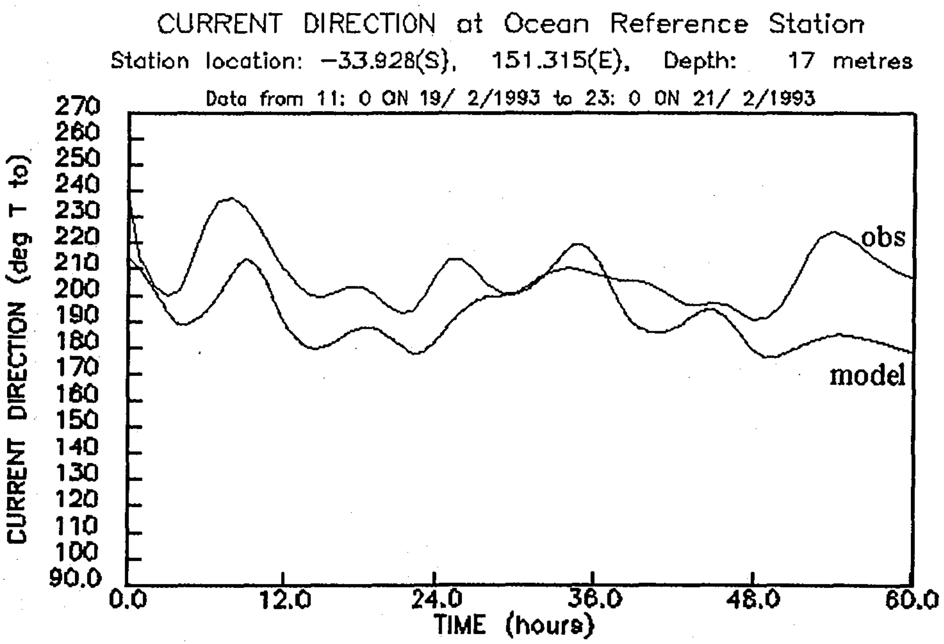


Figure 23: Comparison of observed current directions with predictions from OILTRAK at a depth of 17 metres at the Sydney Water Board Ocean Reference Station (near Sydney) for February 19 to 21, 1993.

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