Chapter 9

Conclusions

In this thesis two programs for the computation of tides have been modified to include storm surges. Additionally, a program has been developed to simulate the movement of various particles in the ocean (particularly prawn larvae and organic sediments), the advection of which is dictated by the current predictions, and diffusion by a random walk method. All three have been applied to various scenarios in Southern Australian coastal seas.

The first of these programs is known as **ted**. This is intended for latitudinally small regions, where the curvature of the Earth is not significant, and involves the prediction of elevation and current values on a Cartesian co-ordinate grid. Coastal boundaries are simulated by a zig-zagged arrangement, where boundary points intersect perpendicular velocity gridpoints in order to prevent flow. Wetting and drying interactions of tidal flats may be simulated in this case.

When the extent of the region of interest is large enough for the Earth's curvature to be deemed important, the **tsoc** program for use on a spherical co-ordinate grid is appropriate. This uses a piecewise linear coastal boundary to improve coastal interactions, which is described by Matthews (1995). Tidal flat wetting and drying is not incorporated when this coastal boundary type is defined.

A program has been produced to describe the Lagrangian–Stochastic tracking of particles in ocean domains. Initially applied to oil spill trajectory prediction by Lewis et al. (1996b), the program has been redeveloped to simulate characteristics specific to the movement of suspended sediment and pelagic larvae. Particle advection relies upon the currents at various depth levels calculated by the **ted** model, while diffusion is dictated by random walk methods. Various boundary conditions for particle behaviour near the extremities of the model have been defined. Additionally, particle behaviour specific to prawn larvae and organic sediment dispersal has been incorporated.

In Chapter 2 the mathematical equations and numerical approximations of the **ted** and **tsoc** models have been summarised. A transformation of the depth co-ordinate ($z \rightarrow \eta$) is used to map the sea surface and bed onto flat planes. Initial and boundary conditions are described, with a particular interest given to the discussion of open boundary conditions for storm surge modelling. It was concluded that the major error in storm surge modelling was due to the approximation of meteorological effects, and that the Orlanski–Sommerfeld radiation condition could be used more effectively if an estimate of sea level at the boundary could be made. A description of the wetting and drying of tidal flats for Cartesian co-ordinate models is given, as is a consideration of tidal model calibration and tidal analysis.

In Chapter 3 a three-dimensional Cartesian co-ordinate tidal model of Gulf St. Vincent, South Australia, is presented. The region is divided into gridpoints of size $1500\,\mathrm{m} \times 1500\,\mathrm{m}$, with a time step of $45\,\mathrm{s}$. There is a specification of 10 depth intervals, with a κ value of 5 applied to determine vertical gridspacing. Winds are set at zero, and atmospheric pressure at one atmosphere ($101325\,\mathrm{Pa}$). There are 125 rows and 104 columns, of which 5255 are active computational elements and 38 are open boundary elements. This model includes two open boundaries; Investigator Strait (to the south-west) and Backstairs Passage (to the south). The four major tidal constituents (O_1, K_1, M_2, S_2) were obtained from tidal stations on either side of each boundary. These were interpolated linearly and reconstituted to estimate tide heights on the open boundaries. Adjustments were made using a depth-averaged model of the Gulf in order to correctly model the interactions between M_2 and S_2 in the region. The optimal values for the eddy viscosity parameters were found to be $0.0000014\,\mathrm{m^2\,s^{-1}}$ (α) and 0.0065 (β). The overall complex error over 15 stations was found to be $\epsilon = 0.01897\,\mathrm{m}$, with the behaviour of the semi-diurnal constituents accurately produced.

The production of tide height amplitude and phase diagrams, as well as tidal ellipses throughout the Gulf was conducted. K_1 was found to be stronger than O_1 throughout the model in both elevation and velocity, but M_2 and S_2 dominate. Current ellipses are generally linear, oriented east-west in Investigator Strait and north-south in the upper Gulf. There is some elliptical motion near the separation point of Investigator Strait and Backstairs Passage. Calculations of monthly mean residual elevation and currents show that the major non-linear interactions occur in the tidal flat region known as Troubridge Shoals, which is expected due to the clipping of the signal in this region. Further interactions are seen near the Backstairs Passage open boundary.

The Gulf St. Vincent model is applied to storm surge hindcasting in Chapter 4. Observed sea levels were considered for a storm event during the first half of June 1999. Meteorological effects were determined from interpolation and extrapolation of wind and atmospheric pressure records at Adelaide Airport, Cape Willoughby and Neptune Island. This method was found to give accurate predictions of wind and pressure at Troubridge Shoals.

Initially, the model was run with tidal forcing on the open boundaries and meteorological effects at the surface. It was found that the influence of pressure upon sea level prediction is virtually nil, and that of wind is small, except in the case when winds are strong and from the south-west (the direction of longest fetch). The combination of wind and pressure effects was not enough to accurately simulate surges in the Gulf, so it was decided to introduce external surges at the open boundaries. These move from west to east around the Great Australian Bight. It was decided that the sea level record at Outer Harbor could be used, and a test pulse was introduced to the model to determine the time it takes for a wave to travel from each boundary to Outer Harbor. It was determined that the Outer Harbor record could be used at each open boundary, with the Investigator Strait boundary leading by 2.75 hours, and the Backstairs Passage boundary leading by 1.75 hours. An amplitude correction factor of 0.95 was also applied, to take into account amplification of waves as depth decreases. The non-tidal sea levels (residuals) at Outer Harbor, Port Stanvac and Giles Point were extremely well predicted by this modelling technique.

Testing of the open boundary condition was considered with the introduction of a sub-model of the Gulf St. Vincent (GSV) model, known as the Northern Gulf St. Vincent (N-GSV) model. This sub-model is identical to the GSV model but with the open boundary moved northward, to now be located 3 km to the north of Giles Point and oriented east-west. A test pulse was found to take 0.25 hours to reach Outer Harbor from this boundary. A comparison of predictions of elevation and velocity from each of the models was undertaken, with error measures determined in relation to distance from the N-GSV open boundary. It was concluded that the prediction of storm surge sea level is not reasonable if only tides and meteorological effects are included, even though this is adequate for the prediction of currents. As well as this, it was found that the predictions were sufficiently similar to show that the Orlanski–Sommerfeld radiation boundary condition combined with an estimate of the storm induced sea level on the open boundary is a valid method of simulating storm surges. Errors close to the boundary were found to reduce to constant levels throughout the model within three elements of the open boundary.

The currents predicted by the Gulf St. Vincent storm surge model have been investigated. Time series of currents at particular points and snapshots of the entire domain show that external surges have a lesser influence upon overall currents than tides and meteorological effects. This is attributed to the slower rising of the sea level due to external surges compared with the tide. Tidal flows are dominant in calm conditions, with near surface velocities stronger than those at the bottom, and directions of the two identical at each depth level. When meteorological effects are present, currents near the surface in shallow water are generally directed the way of the wind. Additionally, wind induced currents are the most significant when the fetch is long, that is when the winds are from the south or south-west. Bottom currents are significantly less than those at the surface, and can sometimes be in the opposite direction, particularly near the coast when tidal flows oppose wind direction. Currents at the bottom are less affected by the meteorological effects than those at the surface.

In Chapter 5 a spherical polar co-ordinate model of the Great Australian Bight (GAB) is introduced. The model is a modification of that produced by Matthews (1995), with an 'L' shaped open boundary running from Esperance to the tip of the Eyre Peninsula. The computational grid has elements of dimension $5' \times 5'$, and consists of 47 rows and 181 columns. There are 11 depth levels (10 depth intervals), with a κ value of 5. A time step of 20 s was used. Estimation of the five major tidal constituents in the region, namely O_1, K_1, M_2, S_2 and M_3, was determined on the open boundary. The model was originally calibrated for tides, and it was found that the optimal values for the vertical eddy viscosity parameters were $0.0000014\,\mathrm{m}^2\,\mathrm{s}^{-1}$ (α) and 0.025 (β). The overall complex difference was found to be $\epsilon = 0.0178\,\mathrm{m}$. Co-amplitude and phase diagrams and tidal ellipses were calculated for each constituent, showing an amplification of elevations and currents along the edge of the continental shelf. Calculation of tidal residual circulation shows a number of weak eddys, particularly at the surface near the open boundary south of Thevenard. These circulations are significantly weaker near the sea floor. Tidal currents show stronger flows at the surface than near the sea floor.

The simulation of the effects of a low pressure system (the remnants of Tropical Cyclone OLIVIA, April 1996) on sea level and currents in the Great Australian Bight has been considered. This caused significant surges at Esperance, Thevenard and Port Lincoln, indicating its west-east movement. Simulation of the atmospheric pressure field was conducted via a least-squares error bi-cubic spline fitting procedure, and the geostrophic wind was calculated from the pressure gradient. The strongest winds were found to occur near Thevenard in the eastern part of the Bight. This corresponds to the large negative surge recorded there during the storm.

The open boundary of the Great Australian Bight model was split into three sections to allow specification of sea level. The central section, in deep water to the south-west, had the inverse barometric pressure effect applied. The eastern section was then determined via linear interpolation between the (smoothed) observations at Esperance and the central section. Similarly, the (smoothed) observations at Port Lincoln (with a 3 hr time difference) were applied to the east-most point of the boundary, and all points remaining were determined by linear interpolation in space. Simulations using combinations of surge, pressure and wind effects found that the wind was the dominant factor influencing sea levels at Thevenard during this storm. Surface currents were found to be significantly different to those of the tide. It was found that when surge currents are directed parallel to the coastline, currents at all levels are generally in the same direction, but when currents are perpendicular to the coast, surface and bottom currents oppose.

The development of a Lagrangian–Stochastic particle tracking routine for use in coastal seas is described in Chapter 6. This routine is adaptable, and can represent a number of buoyant particles, including oil slicks, sediment and larvae. Advection is formulated using velocity values which have been obtained from a previous application of the **ted** model. The velocity at the particle position is determined from the surrounding gridpoints using a bilinear interpolation scheme. Additionally, for increased accuracy, a temporal linear interpolation is carried out within the model so that velocity data need not be available at every time step.

Two grid types are considered; the Arakawa A and C grids. Advection was tested using a time and space varying field using both models, with the error measure of the Arakawa C grid away from boundaries performing slightly better than the Arakawa A grid, albeit by less than 0.5%. Various formulations of the closed boundary condition which depend upon the type of particle and coastline being considered have been formulated and tested. Additionally, tidal flat wetting and drying has been incorporated into the particle tracking routine. Particles that cross the open boundary have been allowed to return to the model if their time outside of the model is not considered to be excessive, but only if currents near the open boundary dictate this. The Arakawa A grid type was chosen over the Arakawa C grid for use in applications due to the minimal difference between the results obtained using the two grids and the relative ease of use of the former with output from the standard **ted** model. A number of methods of diffusion were considered, each based upon the random walk method. Tests were conducted on this aspect, with each method performing well.

In Chapter 7 the dispersal of western king prawn (*Penaeus latisulcatus*) larvae in Gulf St. Vincent is simulated. A minor consideration of the life cycle and biology of the prawn species is given, with the emphasis on the vertical migration of larvae. Two methods in particular have been investigated. The first of these is the *single* life stage behaviour model, as used by Nixon (1996), where prawns are always considered to be in the larval stage, and thus migrate from the surface (5% of total depth from surface) during the night to the bottom (5% of total depth from sea floor) during the day. Times of sunrise and sunset are calculated from observations. The second method considered is the incorporation of *dual* life stage behaviour, as used by Rothlisberg et al. (1996). Here the prawns are initially in the larval state, but after 20 days revert to postlarval behaviour, where they are considered to be near the surface for the first three hours of the flood tide if the depth of the water is less than 15 m, and stationary at the bottom at all other times.

Spawning and settlement data has been obtained from Kangas (1997) for two scenarios, in 1990 and 1991. The spawning data has been converted into a distribution of particles throughout the Gulf, which was used as an initial condition. Settlement data was made available at four stations in the northern part of the Gulf, namely Port Arthur, Port Wakefield, Port Clinton and Ardrossan. This was converted to a percentage of the total settlement for each time considered. It was thought to be unreasonable to expect that the rate of mortality is identical in different spawning seasons, and sampling methods meant that there was not enough information about mortality to accurately incorporate it into the model. Instead, it was assumed that the mortality rate is relatively constant throughout the Gulf at a given time, so the proportions of particles that are modelled to settle for a particular spawn may be compared to the proportions of settling prawns.

Various factors relevant to the simulation of prawns have been described. These include the addition of a pre-settlement duration time (6 weeks) and the incorporation of single and dual life stage behavioural characteristics. Additionally, larvae are allowed to move parallel to the coastal boundary until the pre-settlement duration time is passed, or until they are deemed (through a random variable) to have been near the boundary for sufficient time to settle. Particles that leave the model via the open boundary are allowed to return if velocities dictate. The wetting and drying of tidal flats has been incorporated in the modelling. Diffusion parameters were set to $10\,\mathrm{m^2\,s^{-1}}$ in both axis directions.

Wind and pressure records were available at Adelaide, Cape Borda and Cape Willoughby. These were used to determine the meteorological data fields during the 8 weeks from 15 January 1990 (Run 1) and 27 November 1990 (Run 2). These were applied with the external surge in the same method as described for Chapter 4, and excellent simulation of the observed residual elevation at Outer Harbor was obtained. The simulation of prawn larvae dispersal using the particle tracking technique for both time periods with both single and dual life stage behaviour has been considered. Dispersal induced by tidal and meteorological currents has been compared to that for the full storm surge. Outputs are in the form of time series of particle densities at each of the four settlement stations and two-weekly snapshots of particle distribution. Additionally, the distribution of particles around the northern coast was considered. It was found that the use of dual life stage behaviour increases the settling numbers dramatically compared to the single life stage. The inclusion of the external surge in computation slightly improved the dispersal of larvae when compared to observations. This was mainly attributed to improved sea level prediction and the subsequent tidal flat interactions. Overall, however, it was determined that the proportion of larvae that were predicted to settle in nursery areas in which settlement numbers were recorded agrees well with observations if dual life stage behaviour is applied regardless of whether external surges are included in the modelling of currents.

Chapter 8 discusses the development of a fine grid (500 m, 20 s time step) Cartesian co-ordinate storm surge model and subsequent particle dispersion in Boston Bay, South Australia. This is based upon the abnormal deaths of large amounts of southern bluefin tuna (*Thunnas maccoyii*) in tuna farms in the region during the April 1996 storm previously described. The three-dimensional model was calibrated for tide heights, with parameters of the vertical eddy viscosity, α and β, set to $0.0000014\,\mathrm{m^2\,s^{-1}}$ and 0.015 respectively. The amplitudes and phases for O_1, K_1, M_2 and S_2 from Port Lincoln were modified according to modelled errors to determine the open boundary forcing data. The effects of eddy viscosity changes upon currents within the region were investigated, with predictions compared to historical observations. It was found that variation of β gave the most significant difference in the prediction of current, with lower values (such as $\beta = 0.004$) predicting magnitude well, but direction less accurately than higher values ($\beta = 0.015$). Because the overall differences in predictions were small, it was decided that the latter value simulated the currents adequately.

The "disaster" of April 1996, where an estimated 1700 tonnes of farmed tuna died during the passing of the remnants of tropical cyclone OLIVIA, was simulated. Biological investigation determined that strong winds that persisted from the north-west (a fetch of approximately 350 km) were responsible for the stirring of fine almost neutrally buoyant organic sediment from the sea floor of Boston Bay. This coated the gills of the tuna and choked them. The daily and cumulative mortalities from a number of tuna farms have been investigated, with farm losses ranging from 20–99% of stock.

Fifteen minute sea level data available from Port Lincoln jetty during the time of the storm were smoothed and transferred to the open boundary of the model. Winds were also applied, observed from Port Lincoln Airport, and were found to have negligible effect upon sea level prediction. The resultant modelled sea level at Port Lincoln has a mean error of 0.0106 m in a range of approximately 1.5 m. Investigation of currents revealed that the tides during this neap cycle were extremely small. It was found that external surges had a significant effect upon currents, particularly to the north and south of Boston Island. Upon the introduction of wind, there was a significant increase in current velocities, with surface and bottom current directions often opposing.

Initial tracking of particles considered the advection of individual particles from each of five initial positions, determined from information provided by divers. A comparison of tracks for depths near the surface (20% of total depth below surface) and near the sea floor (30% of total depth above the sea floor) was conducted. It was found that particles from the same site often moved in opposite directions at the sea bed and surface, with those released from some points found to move to opposite ends of the Bay after five days.

To investigate particle dispersal during the time of unusual mortalities, 288 particles were gradually released from each of the five release points over a 12 hour period from 18:00 hr 11/4/1996 (CST). Advection was simulated using the currents at 30% of the total depth above the sea floor. Diffusion was simulated using the parameters $D_x = D_y = 10\,\mathrm{m^2\,s^{-1}}$. Particles were allowed to settle out of suspension 24 hours after the release of the final particle at a random rate such that half of the particles would settle within each subsequent 24 hour period. Particle dispersal and the simulated and cumulative numbers of particles at each tuna farm has been shown. The overall cumulative tuna losses were found to match well with the concentrations of particles simulated for farms that were not removed from the Bay after the storm.

More accurate simulation of tides using the models considered in this thesis could be obtained if more constituent frequencies were input at the relevant open boundaries. These could include related constituents, and the modelling of their behaviour (in the Great Australian Bight and Gulf St. Vincent in particular) could be investigated. Additionally, throughout this thesis the hindcasting of storm surges has been conducted. It is desirable to incorporate these methods into the forecasting of surges. This may be achieved through the statistical analysis of historical sea level and meteorological (wind and pressure) time series. Forecasts of these time series could then be incorporated into the tidal and storm surge model, thereby enabling the future prediction of surges and particle dispersal.