Stage 2 Research Program 2003 - 2005


In-situ field measurements for Adelaide Coastal Waters Study

Final Technical Report
Acknowledgement

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Abstract

Extensive hydrographic field surveys have been carried out in Adelaide Metropolitan waters during the period September 2003-November 2004. To this end, we have measured vertical profiles of hydrographic parameters (temperature and salinity) and turbidity on a station grid within 10 km distance from the shore and along the coast from Port Gawler to Sellicks Beach. In addition to this, several bottom moorings have been deployed over periods of 3-5 weeks at different times and locations. This report gives the details of the surveys undertaken and summarises the key findings of our observations.
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1. Background

1.1. Introduction

The Adelaide Coastal Waters Study (ACWS) is a multi-disciplinary project that aims at understanding factors that contribute to seagrass loss, coastal erosion, and water quality degradation, which have been of public concern in South Australia over the last decades. As part of this project, extensive field surveys have been carried out along Adelaide's metropolitan coast using R/L Hero (Figure 1.1), which is a research facility of Flinders University.

![Research Launch (R/L) Hero at the boat ramp of North Haven.](image)

**Figure 1.1.** Research Launch (R/L) Hero at the boat ramp of North Haven.

The objectives of these surveys were to understand seasonal and spatial variations of water mass properties (temperature, salinity and density) including vertical stratification, and to quantify water movement patterns in conjunction with turbidity events. This comprehensive and unique suite of data has been acquired for initialisation and verification of numerical modelling studies undertaken in Sub-Task 2 of PPM 2 and will form the first basis of future studies undertaken in Adelaide metropolitan waters. This report presents the findings of our field observations that comprise a total of 270 field stations and a dozen moorings.
1.2. Physical Oceanography of Gulf St. Vincent

1.2.1 Bathymetry

Gulf St. Vincent is an inverse estuary where evaporation exceeds precipitation by far with only limited exchange with the open ocean via Investigator Strait to the west and Backstairs Passage to the south-east (Lewis, 1982). Adelaide, the capital city of South Australia, lies on the eastern side of Gulf St. Vincent. The gulf extends ~170 km from Port Wakefield at the head to Cape Jervis in the south. The typical width in the south is 50-60 km, giving the gulf a surface area of about $7.3 \times 10^3$ km$^2$. The typical water depth of Gulf St. Vincent is 35 m with regions shallower than 15 m located in the northernmost third of the Gulf (Figure 1.2). The volume of the Gulf can thus be estimated at approximately 175 km$^3$. Notice the pronounced seabed depression of a depth variation of ~10 m that connects the northern shallows with the southern deeper portions of the Gulf.

![Figure 1.2: Topography of Gulf St. Vincent. Contours are marked in metres. Sourced from Bowers and Lennon (1990). The dashed rectangle indicates the study region of the Adelaide Coastal Waters Study.](image-url)
1.2.2 Tides in Gulf St. Vincent

The main tidal features are the rapid progression of the tides through the Gulf, taking <30 minutes to travel from west to east (Easton, 1970; Bye, 1976; Bowers and Lennon, 1989; Noye and Grzechnik, 1995). There is also an increase in amplitude of the tides from the mouth to the head of the Gulf with the maximum tidal range of ~180 cm occurring at the head. Because the major solar tide ($S_2$) has virtually the same amplitude throughout the gulf as the major lunar tide ($M_2$), then every 14.77 days the two tides are in opposition and form the neap tides, when the semi-diurnal component of the tide is virtually absent (Noye and Grzechnik, 1995). At equinoxes, the diurnal tide vanishes also, causing the water level to become uniform for a whole day, a feature, named by Matthew Flinders as a “dodge tide”. For the Adelaide metropolitan area, the tidal elevation amplitudes vary between 38-50 cm for the $M_2$ tide, 39-49 cm for the $S_2$ tide, 14-16 cm for the $O_1$ tide, and 24-25 cm for the $K_1$ tide (Noye and Grzechnik, 1995). Thus, the max tidal range along the Adelaide metropolitan coast is ~140 cm.

Tidal current movement is mainly linear close to the eastern side of Gulf St. Vincent, with little lateral motion, for both the diurnal and semi-diurnal constituents (Noye and Grzechnik, 1995). Tidal flow speeds along the Adelaide metropolitan coast are predicted to be of the order of 30 cm/s (Noye and Grzechnik, 1995). Tidal flows in Backstairs Passage are swift with speeds of up to 1 m/s.

1.2.3 Salinity Balances in Inverse Estuaries with Application to Gulf St. Vincent

Both South Australian Gulfs; that is, Spencer Gulf and Gulf St. Vincent are subject to excessive evaporation of ~1.25 m/year. The highest evaporation rates occur in summer and at that time the loss rate is 0.25 m/month (Bowers, 1990). Precipitation is comparatively negligible. Consequently, Gulf waters become hypersaline, and a salinity gradient is created, ranging from oceanic salinities at the mouth to maximum salinities at the heat of the Gulfs. These water bodies are called inverse estuaries. In an inverse estuary, the freshwater loss by evaporation is replaced by an inflow of water from the adjacent ocean proper. If there is to be no long-term accumulation of salt in the estuary, there must be mechanisms for balancing the salinity increase from evaporation with the inflow of water of relatively lower salinity.

In the following we explore different mechanisms that can balance the evaporative salt increase and volume decrease in an inverse estuary. Any of these mechanisms must conserve volume. In other words, the evaporative volume loss $EA$, where $E$ is evaporation rate and $A$ is the surface area of the Gulf, must be balanced by a net volume transport into the Gulf $Q = vHW$, where $v$ is the flow speed, $H$ is the mean water depth, and $W$ is the average width of the Gulf. From this, we find a net current of speed of $v \approx 5$ km/year $\approx 0.15$ mm/s sufficient to conserve the water volume of Gulf St. Vincent.
A first model (Figure 1.3) could be an advective compensation of evaporative salinity increases by means of a uniform inflow. This scenario is described by the steady-state equation:

\[ \frac{\partial S}{\partial y} = \frac{E}{H} S, \]  

where the coordinate \( y \) runs along the estuary axis with \( y = 0 \) placed at the mouth of the estuary. The solution of this equation is an exponential increase in salinity up the Gulf; that is,

\[ S(y) = S_o \exp \left( \frac{E}{Hv} y \right), \]  

where \( S_o \approx 35 \text{ psu} \) is the oceanic salinity near the mouth of the estuary. With \( v = 5 \text{ km/year} \) (required to balance the evaporative volume loss), \( E = 1.25 \text{ m/year} \), \( H = 35 \text{ m} \), and a length of \( L = 170 \text{ km} \), according to the above model, salinity would increase to unrealistically high values of threefold the ocean salinity at the head of the Gulf. Consequently, the above model is unrealistic and can be withdrawn from further consideration.

Another model would be a density-driven lateral exchange circulation influenced by the Coriolis force, such that there is inflow of lower salinity water along the left margin of the Gulf, associated with a volume transport \( Q_{in} \), and an outflow of higher salinity water at the opposite side of a volume transport \( Q_{out} \) (Refer Figure 1.4).

Note that vertical stratification is absent in this model.
\[ W = 50 \text{ km} \]

\[ L = 170 \text{ km} \]

**Figure 1.4:** A more realistic model of the salt balance in Gulf St. Vincent. In this model, there is a volume inflow of lower salinity water along the left coast of the estuary and higher salinity water escapes the Gulf along the opposite side. Flow rates can be estimated from conservation principles of salt and volume. Lateral mixing between inflow and outflow provides the means for a steady-state salinity distribution.

From conservation principles of salt mass and volume, the volume transports into and out of the estuary can be determined as:

\[ Q_{\text{in}} = \frac{S_{\text{out}}}{(S_{\text{out}} - S_{\text{in}})} EA \]  \hspace{1cm} (3)

\[ Q_{\text{out}} = -\frac{S_{\text{in}}}{(S_{\text{out}} - S_{\text{in}})} EA \]  \hspace{1cm} (4)

With a typical salinity of 37 psu for Gulf St. Vincent and a typical salinity difference of 0.5 psu across the width the Gulf, the associated flow speeds can be estimated at \( \sim 771 \text{ km/year} = 2.5 \text{ cm/s} \), with a slight imbalance between inflow and outflow balancing the evaporative volume loss in the estuary. Note that this model, which is supported by the lateral salinity distribution observed in Gulf St. Vincent (see Figures 1.6-1.8), takes into account lateral mixing between inflow and outflow.

The flushing time of an estuary is defined as the time it takes to replace the entire water volume of the estuary by means of ambient ocean water. Accordingly, the flushing time for the above scenario would be \( V/Q_{\text{in}} \) with \( V \) being the volume of the estuary. This gives a flushing time of Gulf St. Vincent of approximately 3 months.

In the density-driven circulation, the inflow into the estuary travels toward the head of the estuary, where it becomes sufficiently dense (owing to its high salinity) that it leaves the estuary via a dense bottom outflow. In Gulf St. Vincent, this density-driven circulation seems to be largely horizontal void of vertical stratification. In contrast to this, the exchange circulation in Spencer Gulf is stratified with an inflowing surface current overlying a deep, saline outflow (Figure 1.5). Since a density-driven circulation brings water of lower salinity into the Gulf and the outflow is exporting hypersaline water into the adjacent ocean, this mechanism produces a net removal of salt from the inverse estuary, which can balance its evaporative salinity increase.
Figure 1.5: Maximum observed near-bottom salinity during a survey of the Spencer Gulf region, 16-23 June 1986. The contour interval is 0.2 psu. Sourced from Lennon et al. (1987). Note that this survey includes measurements in Investigator Strait, Backstairs Passage and lower Gulf St. Vincent.

Many studies of similar inverse estuarine circulation systems, such as in the Persian Gulf (e.g. Sadrinasab and Kämpf, 2004), have found that the density-driven circulation underwent a distinct seasonal cycle, being strongest when the density difference between the estuary water and water outside the mouth is greatest. This can be expected to occur during winter months when the hypersaline water column approaches minimum temperatures. In the case of Spencer Gulf, the density-driven exchange circulation occurs in winter only, so that most of the salt that accumulates in the Gulf during summer evaporation is removed by the density-driven flow over a few winter months. Accordingly, the flushing time of lower Spencer Gulf is only a few months (Bowers, 1990), but flushing is confined to winter months. The reason of this rapid flushing is that lateral flow speeds inherent with the density-driven circulation in Spencer Gulf are fairly swift (~10 cm/s) (Lennon et al., 1987).

In contrast to Spencer Gulf, only a few direct field observations have been conducted in Gulf St. Vincent. The little observational evidence available suggests that stratification rarely exist in Gulf St. Vincent (Bye, 1976; de Silva Samarasinghe and Lennon, 1987). Although gravity currents are observed in Gulf St. Vincent, they are of a transient nature (de Silva
Samarasinghe and Lennon, 1987) and there is no sustained winter outflow. Reasons thereof might be swift tidal flows of up to 1 m/s in Backstairs Passage (Noye and Grzechnik, 1995) that operate to destroy any vertical density stratification. As a result of this, there are persistent strong lateral salinity gradients across Backstairs Passage, as seen in Figure 1.5, and a vertically stratified density-driven outflow can only develop transiently during times of weak tidal flow; that is, during the dodge tide. Bye (1976) and de Silva Samarasinghe and Lennon (1987) speculated that the wind-driven circulation was the principal means of flushing of salt out of Gulf St. Vincent, but this has never been verified. It appears that a density-driven exchange circulation is common to both South Australian Gulfs, with the difference that in Spencer Gulf this circulation exhibits vertical stratification, whereas it is more horizontal in Gulf St. Vincent. Nevertheless, flushing of both Gulfs is likely to attain a distinct seasonal signature occurring during winter cooling.

1.2.4 Historical Hydrographic Observations in Gulf St. Vincent

In 1975, two larger-scale hydrographic surveys have been undertaken in the northern half of Gulf St. Vincent. Findings are reported in King (unpublished cruise report, 1976). The first survey took place in early March 1975 consisting of 31 field stations. The second survey of 46 field stations was conducted in June/July 1975. The aim of these surveys was to measure the Gulf-wide temperature-salinity structure at the end of summer and in mid-winter. Measurements were taken at the surface, at depths of 1 m, 2 m, 5 m, 10 m, 15 m, etc. and at the bottom. King (1976) mentions earlier measurements in 1973 and 1974 described by D. A. Bullock and N. R. Walter. These cruise reports were not available to the author. Note that only a few stations of these surveys were undertaken in Adelaide coastal waters.

The observed surface-to-bottom differences in temperature and salinity were fairly small, so that it is sufficient to show the horizontal distributions of depth-averaged properties. In early March 1975, the temperature varied spatially from 20.8°C and 22.4°C. Figure 1.6 shows the horizontal structure of water temperature. Interestingly, the warmest water >22°C was observed centred over the seabed depression (see Figure 1.2).
Figure 1.6: Horizontal surface temperature and salinity distributions for early March 1975. Station positions are shown as dots. Taken from King (unpublished cruise report, 1976). The author added arrows to indicate the flow pattern.

The salinity distribution shows a sharp salinity front across with salinity varies spatially by 1 psu. A hypersaline plume is seen to extend southward, and salinities are generally lower along the western side of the Gulf than along its eastern side. This is an indication of a clockwise circulation pattern, as indicated by the arrows in Figure 1.6. Owing to relatively small temperature gradients, the density distribution (not shown) resembles the salinity pattern.

In winter 1975, the temperature distribution was largely correlated with topographic contours, with shallow water being colder by 1-2°C than the deeper water (Figure 1.7). For water depths of ~35 m, the water column had a temperature of >14.5°C, whereas colder water of temperatures between 11 and 13°C was observed in shallower regions (water depth to 15 m). Again, a tongue of relatively warm (~14°C) water was observed centred over the seabed depression, similar to the temperature distribution in summer 1975.

The winter salinity distribution resembled that observed earlier in summer and indicates northward flow of slightly fresher water along the western side of Gulf St. Vincent and somewhat irregular southward flow along the eastern side. Interestingly, there seems to be spatial oscillations off the Adelaide metropolitan coast. This is an indication of the presence of dynamic instabilities (eddies), which are common features at density fronts. Also, salinities near the head of the Gulf were markedly reduced compared to the summer observations, suggesting intensified exchange with lower-salinity water from the south in winter. Nevertheless, there were no significant seasonal variations in salinity near the Adelaide
metropolitan coast, where both surveys observed a salinity range of 37.2-37.6 psu, with the highest values observed in the north.

The larger-scale density distribution in winter (not shown) largely resembled the salinity distribution, but densities were systematically greater in winter compared with summer owing to temperature effects. Thus, the salinity distribution seems to control the local dynamics in the Gulf, whereas temperature seems to control the overall density of Gulf water.

**Figure 1.7**: Horizontal surface temperature and salinity distributions for June/July 1975. Station positions are shown as dots. Taken from King (unpublished cruise report, 1976). The author added arrows to indicate the flow pattern.

In March 1976, hydrographic observations have been conducted in northern Gulf St. Vincent (Symonds, 1977). In addition to this, a higher-resolution field survey has been undertaken in northern parts of Adelaide metropolitan waters in September 1976 (Symonds, 1977). Figure 1.8 shows the salinity distribution for the larger-scale survey in March 1976.
The salinity distribution observed in March 1976 is similar to that found in March 1975. Along the western margin of the Gulf, there was a northward flow of slightly reduced salinities of 36.3 psu. Salinity sharply increased toward the head of the Gulf and there was an indication of southward flow of higher salinity water along the eastern margin of the Gulf. Interestingly, salinities along the Adelaide metropolitan coast of 36.7-37.1 psu were smaller by 0.5 psu as compared with the measurements from March 1975. Reasons of this significant year-to-year variation might be a variation of the strength of the southward flow of hypersaline water from the north, which might have been stronger in summer 1975 than a year later. This suggests that the Gulf-wide circulation and its seasonal and interannual variation be a major control of the temperature and salinity structure along the Adelaide metropolitan coast.

Figure 1.8: Horizontal surface salinity distribution for March 1976. Station positions are shown as dots. Taken from Symonds (1977). The author added arrows to indicate the flow pattern.
Figure 1.9: Horizontal surface salinity distribution for September 1976 in northern parts of Adelaide metropolitan waters. Station positions are shown as dots. Taken from Symonds (1977). The author added arrows to indicate the flow pattern.

Figure 1.9 shows the salinity distribution for the fine-scale survey undertaken in September 1976 in northern parts of Adelaide metropolitan waters. Here, a plume of elevated salinities is seen to spread southward along the metropolitan coast. The temperature of this plume was between 12 and 13°C and it appeared to detach from the coast near Outer Harbour. This feature of a saline plume suggests that the shallow water <10 m along the eastern margin of Gulf St. Vincent can operate as a conductor of dense saline flow influencing the Adelaide metropolitan waters in winter. Seasonal and interannual variations of such salinity incursions are not known.
1.2.6 Bathymetric Features of the Study Region

The extent of the study region and its bathymetric features is shown in Figure 1.10. The study region exhibits significant spatial variations in water depth. The zone of water depths to 10 m is significantly wider (~10 km) in the northern part compared to the south, where it has a width of ~1 km. Shallow water depth intensifies the temporal response of the water column to air-sea fluxes owing to a limited volume. Accordingly, greater seasonal variations of temperature and salinity can be expected to occur in the northern shallow zones compared with the southern deeper regions. The largest inlet in the study region is the Barker Inlet/Port River system, which exchanges its water proper with the adjacent shallow water regions. Noticeable is the shipping channel of a depth of 10 m near Outer Harbour and the existence of some pronounced bathymetric undulations in the depth range of 20-25 m.

Figure 1.10. Bathymetry (m) of the study region. Eastings and northings (km) are used as a local coordinate system with the point of origin being located at 243095.84 Easting and 6076441.29 Northing using the projection UTM Zone 54 and datum GDA94.
1.3. Methodology

1.3.1. Design of Field Program

The study region extends ~10 km offshore and ~80 km longshore from Port Gawler in the north to Sellicks Beach in the south (Figure 1.11). We have surveyed this region in different seasons of the year during the period September 2003-November 2004. Each of the surveys was undertaken on a fine spatial station grid on the basis of offshore transects with a station spacing of 0.5-1 nautical miles and a distance of 3 nautical miles between transects.

Figure 1.11. Study region of the Adelaide Coastal Waters Study. Copyright 2003 Fullers Maps and Carto Tech Services.

At each station, a profiling AANDERAA RCM 9 current meter has been lowered in the water column to measure temperature, electrical conductivity, horizontal flow (speed and direction), turbidity, and pressure in depth increments of 1-2 metres. This instrument was used in a direct-reading mode. A cable connected the instrument with a deck display unit from which values were recorded manually.

Salinity is the amount of salt in grams dissolved in a kilogram of water. From the measured electrical conductivity and temperature data, salinity was calculated from the Practical Salinity Scale 1978 (Unesco, 1981). Salinity carries units of psu (practical salinity units), which is equivalent to a mass concentration g/kg or ppt (parts per thousand). Pressure effects on conductivity can be ignored in shallow water <50 m.

Density of seawater is the ratio between mass and volume of a seawater sample. For convenience, most physical oceanographers use a quantity called “sigma-t”, which is true density minus 1000 kg/m$^3$. This unit is used throughout this report. Density of seawater was calculated from the International Equation of State 1980 (Unesco, 1981) as a function of
temperature and salinity. Pressure effects on density can be ignored in shallow waters of <50 m in water depth.

1.3.2 Accuracy of Readings

The accuracy of readings was ±0.05°C for temperature, ±0.05 psu for salinity, and ±0.05 kg m⁻³ for the density anomaly sigma-t. The accuracy of moored RCM-9 current measurements was ±0.15 cm/s for lateral velocity and ±5° for lateral flow direction. Hydrographic data was not corrected for cases of marginally unstable density stratification arising from data inaccuracies.

1.3.3 Boat-Recorded Flow Velocities

Boat-recorded current speeds were in a range 2-40 cm/s. Unfortunately, current speeds (and directions) measured by the RCM 9 instrument aboard R/L Hero were strongly biased by boat drift and tidal variations and are therefore not used in this report.

1.3.4 Turbidity Readings

Turbidity is a measure of the backscatter of infrared light in the water column, expressed in units of NTU (Nephelometric Turbidity Unit). There are two principal sources of turbidity in the water column. One source is the input of fine particular matter (silts and clays) by rivers or stormwater drains. The other source is local resuspension of bed sediment, which may contain sand fractions. Owing to a greater settling speed, resuspended medium-sized sand quickly settles down on the seabed within minutes in the absence of ambient turbulence and active resuspension events are characterised by a markedly increased turbidity adjacent to the seafloor within a distance of a metre. Finer sediment, such as silts, has a much smaller settling speed and can stay suspended in the water column for many hours to up to days. Owing to small settling speeds, finer sediment is typically well stirred over the water column resulting in a depth-uniform turbidity. Owing to budget constrains, turbidity data presented in this report could not be calibrated against sediment samples. The range and resolution of the turbidity sensor used are 100 NTU and 0.1 NTU, respectively. Note that only a few events of elevated turbidity levels >2 NTU were recorded in our field surveys. Owing to a strong temporal bias, lateral distribution maps of turbidity are not shown in this report. Instead of this, selected off-shore transects of turbidity and graphs of depth-averaged turbidity versus total water depth including all turbidity data of a survey are presented.

1.3.5 Summary of Cruises

During the period September 2003 and August 2004, 23 cruises have been conducted aboard R/L Hero with a total of 270 field stations (Table 1). The conduction of surveys was dependent on weather conditions and availability of boat personnel. To this end, there has been some temporal delay in some of the field campaigns leading to unavoidable sampling errors. The field surveys in February and August 2004 had the least temporal delay and the entire study region could be surveyed within 4-6 field trip days. In addition to spatial surveys we have conducted a fine-scale study in vicinity of the Torrens River outlet in May and June 2004 to explore the temperature, salinity and turbidity structure in the near-shore after events of significant precipitation.
Table 1: Number of cruises and stations for different months.

<table>
<thead>
<tr>
<th>Month</th>
<th>No. of Cruises</th>
<th>No. of Stations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sept 03</td>
<td>1</td>
<td>8</td>
</tr>
<tr>
<td>Oct 03</td>
<td>3</td>
<td>33</td>
</tr>
<tr>
<td>Nov 03</td>
<td>5</td>
<td>51</td>
</tr>
<tr>
<td>Dec 03</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>Feb 04</td>
<td>6</td>
<td>71</td>
</tr>
<tr>
<td>May 04</td>
<td>2</td>
<td>27</td>
</tr>
<tr>
<td>June 04</td>
<td>1</td>
<td>8</td>
</tr>
<tr>
<td>Aug 04</td>
<td>4</td>
<td>67</td>
</tr>
<tr>
<td>Total</td>
<td>23</td>
<td>270</td>
</tr>
</tbody>
</table>

1.3.6 Summary of Mooring Deployments

A number of bottom moorings have been laid out as part of the Adelaide Coastal Waters Study to explore local temporal variations of water mass properties, flows and turbidity over deployment periods of 20-50 days. Table 2 summarises these deployments. This included deployments of RCM 9 current meters, S4 current meters, and tide gauges.

Table 2: Summary of mooring deployments undertaken as part of the ACWS.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Mooring period</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tide gauge</td>
<td>13/10/03-3/12/03</td>
<td>Sellicks Beach</td>
</tr>
<tr>
<td>RCM 9</td>
<td>30/1/04 - 5/3/04</td>
<td>off Semaphore</td>
</tr>
<tr>
<td>Tide gauge</td>
<td>30/1/04 - 5/3/04</td>
<td>off Semaphore</td>
</tr>
<tr>
<td>RCM 9</td>
<td>5/2/04 - 5/3/04</td>
<td>near Hallett Cove Beach</td>
</tr>
<tr>
<td>Tide gauge</td>
<td>5/2/04 - 5/3/04</td>
<td>near Hallett Cove Beach</td>
</tr>
<tr>
<td>S4</td>
<td>5/2/04 - 5/3/04</td>
<td>off Brighton</td>
</tr>
<tr>
<td>RCM 9</td>
<td>7/5/04 - 13/7/04</td>
<td>off Torrens River outlet</td>
</tr>
<tr>
<td>RCM 9</td>
<td>7/5/04 - 13/7/04</td>
<td>off O'Sullivan's Beach</td>
</tr>
<tr>
<td>S4</td>
<td>10/5/04 - 13/7/04</td>
<td>off Port River entrance</td>
</tr>
<tr>
<td>RCM 9</td>
<td>19/10/04 – 16/11/04</td>
<td>off Barker Inlet</td>
</tr>
<tr>
<td>RCM 9</td>
<td>19/10/04 – 16/11/04</td>
<td>in main shipping channel</td>
</tr>
</tbody>
</table>

1 Tide gauges measure sea level elevations.
2 S4 current meters measure flow speed and direction only.

1.3.7 Sampling Errors and Instrument Fouling

Our field surveys included unavoidable temporal sampling errors. For example, a residual air-sea heat flux of ~200 W/m² can heat up a 10 m thick water column by 0.5°C per day. Thus, field stations taken over a time span of a few weeks may include a significant temporal bias in the temperature readings when plotted in a single contour map.
Figure 1.12. The state of an RCM 9 current meter after 6 weeks of deployment in Adelaide Metropolitan waters off Semaphore.

Some of our moorings, in particular those laid out near the entrance of Port River/Barker Inlet, have experienced significant algae growth, a feature called "instrument fouling". Figure 1.12 shows an example of this. This fouling has led to a significant bias of electrical conductivity readings resulting in erroneous salinity and, consequently, density values. Significant fouling occurred within 2 weeks of our last deployments near the entrance of Port River/Barker Inlet.

1.3.8 Data Interpolation and Visualisation

Eastings and northings (km) are used as a local coordinate system with the point of origin being located at 243095.84 Easting and 6076441.29 Northing using the projection UTM Zone 54 and datum GDA94. The distance (km) used in graphs refer to this point of origin. Cross-shore transects presented in this report run from west to each, whereas longshore transects run from south to north.

For interpolation of data between field stations, we have used a simple iteration method based on the two-dimensional diffusion equation. This method was employed either in the horizontal plane for lateral distributions or in the vertical plane for vertical transects. In this method, the field observations are treated as local, fixed sources and values between stations are derived from the steady state distribution of the diffusion equation, calculated by a simple iteration scheme.

Lateral and/or vertical diffusion coefficients need to be prescribed in this method. For interpolation along vertical transects, lateral diffusion coefficients were taken one order of magnitude greater than vertical diffusion coefficients, which accounts for the anisotropy between horizontal and vertical spacings inherent with the measurements. At vertical and lateral boundaries, this method assumes vanishing spatial gradients, representing zero-flux conditions. This method, using Fortran and Matlab software, turned out to be fairly robust, in particular for irregular bathymetry and coastline.

Most graphs were produced with Matlab software (The MathWorks). Some graphs were produced with Excel Spreadsheet software.
2. Observational Findings

2.1. September 2003 Transect

2.1.1 Overview

On 10th September 2003, one field survey has been conducted comprising 6 stations located in the northern half of the study region. The station spacing was 3 nautical miles and readings were taken at vertical increments of 1-2 m. Figure 2.1 shows the station locations. Owing to bad weather conditions (swell >1m), we could not undertake a second cruise in September to acquire data from farther in the south.

The aim of this first cruise was to derive a north-south distribution of water mass properties (temperature and salinity) to initialise the numerical model employed in Sub-Task 2 of PPM 2.

Figure 2.1: Station locations of the September 2003 cruise together with bathymetry (m).
2.1.2 Findings

In September 2003, the temperature of Gulf water was of a range of 13-14.5°C (Figure 2.2). Some thermal stratification occurred in the northern, shallower parts of the study region with vertical temperature gradients of <1°C. Except for the shallower regions (depth <5-10 m) in the north, the water column appeared to be well mixed in the vertical.

The observed salinities occupied a range of 36.9-37.2 psu. The salinity distribution reveals the interesting feature of a region of elevated salinities of 37.15 psu over a distance of 10 km in total water depths of ~10 m. In comparison to this, salinities are lower than 37 psu both in the south and in the north, the latter presumably owing to exchange with riverine input from the Port River/Barker Inlet system. This structure resembles that of a so-called “salt plug” (Wolanski, 1986).

Observed densities (sigma-t) were in a range of 27.6-28.0 kg m\(^{-3}\). The density distribution, comprising both thermal and saline effects, revealed this “salt plug”. Density within this region was ~0.4 kg m\(^{-3}\) greater compared with that of relatively warm inshore water in the north, where both lower levels in salinity and higher temperatures produce a thin buoyant surface layer within a distance of 5 km from the coast and limited to a water depth of 5 m.

Turbidity levels in the northern, shallow part were only marginally elevated (~0.5 NTU).

![Figure 2.2: Longshore vertical transects of temperature (°C), salinity (psu), and density (sigma-t; kg m\(^{-3}\)) for the cruise on 10th September 2003. Note a localised error in surface salinity data at distance 76 km, leading to unstable density stratification.](image-url)
2.2. October 2003 Transect

2.2.1 Overview

On 13th/14th October 2003, a north-south transect comprising 12 stations has been completed aboard R/L Hero, again using the RCM 9 current meter. The station spacing was 3 nautical miles except for a gap in the middle of this transect (Figure 2.3). Again, temperature, salinity and density profiles were taken in depth increments of 2 m. In contrast to the September 2003 transect, the October data included measurements from the southern regions.

Figure 2.3: Station locations of October 2003 cruises together with bathymetry (m).
2.2.2 Findings

Atmospheric warming of surface water has led to establishment of weak vertical thermal stratification being most pronounced in shallow waters in the north where the vertical temperature gradient exceeded 1°C (Figure 2.4). There was a general northward temperature increase by 1.5°C over a long-shore distance of 70 km. Southern water was relatively cold (<14°C) and less stratified compared with shallow water in the north. The steep change in water depth from 10 m to 20 m over a distance of <10 km appeared to separate warmer near-shore water from colder water in the south, as also seen in our September measurements. In this zone, temperature varied laterally by >1°C over a distance of 5 km.

\[\text{Figure 2.4: Longshore vertical transects of temperature (°C), salinity (psu), and density (\(\sigma-t\), kg m}^{-3}\text{) for the cruises on 13}^{\text{th}}\text{ and 14}^{\text{th}}\text{ October 2003.}\]

Elevated salinities of >37.1 psu were found in the northern, shallow regions. A “tongue” of moderately saline water of a salinity of ~37.0 psu extended from the shore over a distance of 50 km to a water depth of 20 m. This tongue of saline water is presumably the trace of a density-driven gravity current that occurred when the shallow waters were cooler and thus denser than offshore water, as being observed in September (see Figure 2.2). Moreover, there existed a surface layer, ~5 m thick and of a relatively low salinity of <36.8 psu, that extended northward over a distance of ~20 km. This feature, associated with surface-to-bottom salinity differences of ~0.2 psu, could be the remnant signature of a northward flow, compensating for the southward flow of dense bottom water inherent with a gravity current.
During the period September-October 2004, atmospheric warming reduced the density of the shallow water such that the density excess in the shallowest water as observed in September has disappeared. This warming has presumably stopped the gravitational exchange circulation between shallow and deeper water. Interestingly, owing to this thermal effect on density, shallow water could remain more saline compared with deeper water in the south.

The density distribution also shows remnants of the gravity current in terms of elevated near-bottom densities of >27.65 kg/m$^3$ (sigma-t units) adjacent to the shallow northern regions. This implies that the associated gravity current either stagnated in this region or that it crossed this transect to flow downward on the slope toward greater water depth. Both thermal and haline stratification led to a vertical density stratification of surface-to-bottom differences of ~0.4 kg m$^{-3}$. The exception were well-mixed near-shore water (water depth < 5 m), becoming regularly exposed to vigorous vertical mixing owing to wave breaking. Notice that one station showed elevated salinities near the surface, but this might have been a reading error. Note that in contrast to our September measurements, there was no indication of riverine discharge from Port River/Barker Inlet.

In summary, temperature, salinity and density patterns observed in October 2003 point to the existence of a density-driven overturning circulation, occurring in earlier months (July-September), that presumably operated as a (partial) flushing mechanism of the northern shallow water regions (<10 m).

Turbidity was absent in this longshore transect, that, however, only included a few shallow stations.
2.3. Mid-October/Early November 2003 Survey

2.3.1 Overview

Northern parts of the study region were surveyed during the period from 16th October to 6th November 2003, comprising three field-trip days with a total of ~40 stations. Figure 2.5 indicates the station locations together with the deployment locations of two tide gauges that measured sea level variations over a period >30 days, used for tidal analysis to produce tidal boundary conditions for the numerical model employed in Sub-Task 2 of PPM2.

![Figure 2.5: Left panel: Station locations of October/November 2003 cruises together with bathymetry (m). TG1a and TG2a indicate the locations of tide gauge deployments. T1a-T4a are selected transects referred to in the text. Right panel: Interpolated horizontal distribution of sea surface temperatures (°C).](image-url)
2.3.2 Findings

The distribution of sea surface temperatures (Figure 2.5) shows a zone of warmer (~17°C) water off Outer Harbour. Transects farther to both the north and the south had smaller temperatures of ~15.8°C. The warm zone extended over a long-shore distance of ~10 km. It is likely that this pronounced localised temperature anomaly was caused by a transient atmospheric warming event that occurred in the week before the survey.

![Figure 2.5: Bathymetry and Sea Surface Temperature](image)

**Figure 2.5:** Bathymetry and Sea Surface Temperature

The surface distribution of salinity, on the other hand, resembled that captured by the September/October long-shore transects. Thus, the salinity distribution was presumably much less temporally biased than the temperature distribution. Surface salinity was greatest in the northern, shallow regions around the Barker Inlet with values of 37.3 psu (Figure 2.6). In contrast to this, salinities in the southern region were relatively low (~36.9 psu), leading to a northward salinity increase of 0.4 psu over a longshore distance of 30 km. Notice that the salinity structure and the salinity range are similar to those observed in September 1976 (see Figure 1.7).

![Figure 2.6: Bathymetry and Sea Surface Salinity](image)

**Figure 2.6:** Left panel: Station locations of October/November 2003 cruises together with bathymetry (m). Right panel: Interpolated horizontal distribution of sea surface salinities (psu).

The surface distribution of density (Figure 2.7) is strongly biased by the temperature distribution, showing spatial variations of 0.5 kg/m³ with the zone of lowest densities coinciding with the zone of highest temperatures. Nevertheless, the northern, shallow regions
still appear to hold the densest water mass (sigma-t >27.6 kg/m$^3$) owing to elevated salinities and low temperatures at the time of the measurements.

**Figure 2.7:** Left panel: Station locations of October/November 2003 cruises together with bathymetry (m). Right panel: Interpolated horizontal distribution of sea surface densities (sigma-t, kg/m$^3$).

In the following, the focus is placed into vertical offshore transects of temperature, salinity, and density, each taken on a certain day. In addition to this, transects of elevated turbidity are shown.

Transect T1a (see Figure 2.5), taken on 3rd November, shows high salinities of >37.4 psu in the northern region confined to shallow water depths <5m (Figure 2.8). The water column was fairly well mixed in the vertical to a water depth of 5-7 m. Near-shore water was relatively cold (~15.5°C) at the time of the measurements, leading to elevated densities of >27.7 kg/m$^3$. Notice that this density corresponds to the density of deeper bottom water found farther in the south (see Figure 2.4). At a distance of ~6 km from the shore, there were slight thermal and haline stratifications, resulting in a density stratification of surface-to-bottom differences of ~0.2 kg/m$^3$. The density distribution indicates the existence of offshore bottom flow, driven by the density excess of near-shore water. Near-shore water attained elevated turbidity values of >2 NTU (Figure 2.9). Interestingly, the observed turbidity distribution resembles the density distribution, which might be just due to the circumstance that both elevated densities and elevated turbidity are confined to the near-shore zone, where wave breaking provides the means of vertical stirring.
Note that a total of ~30 mm of rain (Source: Bureau of Meteorology) fell in the week prior to our measurement, indicating that there has been substantial inflow of stormwater enriched with fine sediment into the coastal zone. Nevertheless, the lateral salinity distribution (see Figure 2.6) indicates inflow of high-salinity water from the north, void of substantial river input, so that the elevated turbidity levels observed were presumably caused by wave-induced re-suspension of fine sediment in shallow northern parts of the study region.

**Figure 2.8:** Cross-shore transect T1a (for location, see Figure 2.5) showing vertical sections of temperature, salinity and density (sigma-t). Stars indicate the station locations. Note localised errors in salinity data in the 3 stations near the coast, leading to marginally unstable density stratification.

**Figure 2.9:** Cross-shore transect T1a (for location, see Figure 2.5) showing a vertical section of turbidity. Stars indicate the station locations.
Figure 2.10. Cross-shore transect T2a (for location, see Figure 2.5) showing vertical sections of temperature, salinity and density (sigma-t). Stars indicate the station locations.

Figure 2.11. Cross-shore transect T3a (for location, see Figure 2.5) showing vertical sections of temperature, salinity and density (sigma-t). Stars indicate the station locations.
Transect T2a, also taken on 3rd November off Outer Harbour, showed a slight vertical temperature stratification of anomalies ~0.5°C (Figure 2.10). The salinity pattern indicates some entrainment of lower-salinity water stemming from the Port River. Surface temperatures were 1°C higher compared with transect T1a, measured on the same day, whereas the zone of elevated salinities in the near-shore zone was absent. Here, surface warming has led to a slight vertical density stratification of top-to-bottom differences of 0.3 kg/m³. Similar to transect T1a, turbidity levels were elevated in a range of 1.2-1.6 NTU (not shown).

Transect T3a was taken on 16th October; that is, 2 weeks before transects T1a and T2a. In comparison, this transect showed much higher temperatures in near-shore water of >17°C (Figure 2.11). Temperature varied laterally by 2.5°C over a distance of 7 km. The salinity distribution showed a tongue of higher salinity water (>37.1 psu) extending offshore over a distance of 8 km. Except in the well-mixed near-shore zone, there appeared a distinct saline stratification in the upper 5 m of the water column with vertical salinity anomalies of >0.3 psu. Vertical density stratification, associated with density anomalies of ~0.5 kg/m³, was the combined effect of thermal and saline stratification. Owing to the dominance of thermal effects on density, less dense water was found in the near-shore zone. The salinity tongue can be interpreted as the trace of a gravity current that was active when the near-shore zone was cooler and thus denser. In the near-shore zone, turbidity attained elevated levels of up to 2 NTU (not shown).

Figure 2.12: Cross-shore transect T4a (for location, see Figure 2.5) showing vertical sections of temperature, salinity and density (sigma-t). Stars indicate station locations.
Transect T4a, also taken on 16th October as transect T3a, showed a relatively warm near-shore zone with temperatures of ~16°C. A zone of elevated salinities >37.0 psu extended offshore to a total depth of 20 m (Figure 2.12). The entire region appeared to be fairly well mixed in the vertical, and temperature effects led to establishment of a less dense water body in the near-shore zone. Turbidity was slightly elevated in the near-shore zone to a water depth of ~5 m (Figure 2.13). Note that there has been only little rainfall (~2.5 mm) in the week prior to this measurement (but 30 mm of rain fell in the first week of October 2003). This indicates that the elevated turbidity levels were caused by wave-induced re-suspension.

Figure 2.14: Temperature-salinity diagram of all hydrographic measurements taken during the period September-early November 2003. The solid lines are density contours with a contour interval of 0.5 kg/m³ (in sigma-t units). The ellipses indicate occasions of maximum densities >27.5 kg/m³.
Figure 2.14 shows a temperature-salinity diagram of all measurements taken during the period September to early November 2003. This includes spatial (lateral and vertical) and temporal variations. Shown are also contours of density (sigma-t, kg/m$^3$) from which the density of individual water samples can be estimated.

During this period, water temperatures were in a range of 13-17$^\circ$C, salinities ranged between 36.5 and 37.5 psu, and the density range was 27.0-28.0 kg/m$^3$ (sigma-t units), centred near 27.5 kg/m$^3$. There were two occasions that resulted in relatively high densities of >27.6 kg/m$^3$. One had a moderate salinity of 37.0 psu but was coolest at ~13$^\circ$C. This water body was observed on 10th September 2003 in the shallow, northern regions of the study region. The other density maximum was associated with high salinities of up to 37.5 psu at temperatures of 15$^\circ$C. This event occurred on 3rd November 2003 in the northern, shallow regions of the study region. Presumably, lateral incursion of higher salinity water from the north caused this.

As seen above, total water depth has a pronounced effect on temperature, salinity and density of the water column. This effect, called shallow-water effect, is associated with a reduced volume of water interacting with the atmosphere via air-sea heat and freshwater fluxes. The following figures reveal effects of total water depth on temperature, salinity, density and turbidity observed in the study region during the period September-early November 2003.

![Figure 2.15: Depth-averaged temperature versus total water depth for all stations completed during the period September-early November 2003.](image-url)
Figure 2.16: Depth-averaged salinity versus total water depth for all stations completed during the period September-early November 2003.

Temperature in shallow water <10 m experienced the greatest temporal variations (Figure 2.15) in response to a general atmospheric warming over this 2.5-month period. In September, shallow water body was relatively cold at temperatures of 14°C. In mid-October, shallow water of depths <10 m had the highest temperatures in a range of 16-17°C. Deeper water (depth > 15 m) attained temperatures of 14-15°C.

Salinities attained the largest values >37.3 psu in the depth range of 5-10 m (Figure 2.16), whereas deeper water had lower salinities of ~36.9 psu. Generally, shallower water was more saline than deeper water with a salinity contrast between both of 0.2-0.6 psu. Influx of low salinity water from coastal sources was insignificant, so that salinity in shallow water generally exceeded offshore values, except for a few shallow stations that showed slightly lowered salinities of 36.7-36.9 psu.

Figure 2.17: Depth-averaged density (sigma-t) versus total water depth for all stations completed during the period September-early November 2003.
In response to temperature changes, density experienced the strongest temporal variations in shallow waters (Figure 2.17). During September, cold temperatures produced a density excess in shallow water, being the source of driving a gravitational exchange circulation between shallow and deeper water. In October, atmospheric warming led to a density deficit in shallow water, presumably stopping the gravity current. In early November, on the other hand, salinities in the northern shallow regions increased. Despite higher temperatures, this resulted in a situation where the shallow water attained relatively high densities >27.6 kg/m³ similar to the highest densities observed in September. This may have caused a transient gravity current.

![Figure 2.18](image)

**Figure 2.18:** Depth-averaged turbidity versus total water depth for all stations completed during the period September-early November 2003.

Occasionally, turbidity attained elevated levels of 1-2 NTU in shallow water (Figure 2.18). Only two stations had a turbidity >2 NTU. Deeper water >10 m did not show any signs of sediment suspension. Note that ~65 mm of rain fell on 11 days in October 2003 (Source: Bureau of Meteorology). Thus, the generally elevated turbidity levels observed in the near-shore zone might be the remnant signature of riverine injection of fine sediment into the near-shore zone kept in suspension by wave action.

### 2.4. Late November 2003 Survey

#### 2.4.1 Overview

Central and southern parts of the study region were surveyed during the period from 20\(^{th}\) November to 3\(^{rd}\) December 2003, comprising four field-trip days with a total of ~35 stations. The station locations are shown in Figure 2.19. Notice a station gap in the southern portion of this survey.
Figure 2.19: Left panel: Station locations of late November 2003 cruises together with bathymetry (m). TG1a and TG2a indicate the locations of tide gauge deployments. T1b - T6b are transects referred to in the text. Right panel: Interpolated horizontal distribution of sea surface temperatures (°C).

2.4.2 Findings

The distribution of sea surface temperatures (Figure 2.19) shows that shallow waters in central regions of the study region had warmed up to approach temperatures >20°C, which is 3-4°C warmer than observed 2-4 weeks before. Waters in the south attained temperatures of 17-18°C, so that there existed a north-south temperature gradient of ~3 °C over a distance of 30 km. Shallow-water effects are apparent with the 19°C-temperature contour roughly being aligned with the 15-m depth contour.
Salinities were generally greater in the central, shallower regions with values of 36.7-36.8 psu (Figure 2.20). In contrast to this, deeper water in the south attained salinities of ~36.6 psu. One station on transect T6b showed anomalously high salinities >37 psu, most likely due to a reading error. North-south gradients in salinity were relatively small; that is, less than 0.2 psu over 30 km.

The individual contributions of temperature and salinity to density lead to a density distribution (Figure 2.21) with minimum densities of 26.0 kg/m$^3$ (sigma-t units) in shallow, central parts and maximum values around 26.6 kg/ m$^3$ in the south. The steep transition zone of water depths from 10 m to 20 m marked a density front, separating shallow, warmer water from a deeper, colder water body. The density difference across this front was >0.5 kg/m$^3$ over a distance of 5 km. Temperature effects had a greater contribution to density than salinity had. Therefore, the density front observed can be referred to as a temperature front.

Note that turbidity levels were negligibly low <1 NTU for all stations conducted in late November 2003. This might be related to the lack of rainfall during this month which was only a total of 6 mm (Source: Bureau of Meteorology) and is also indicative of low swell energy propagating into the Gulf.
Transect T1b, taken on 20\textsuperscript{th} November, showed elevated water temperatures $>20^\circ\text{C}$ and elevated salinities $>36.9$ psu in shallow ($<10$ m) water (Figure 2.22). Offshore water attained temperatures of 18-18.5$^\circ\text{C}$ and salinities of 36.75 psu. Vertical temperature anomalies were less than 1$^\circ\text{C}$. Temperature dominated over salinity in the density distribution, so that a "wedge" of lesser dense water occupied the near-shore zone over a distance of $\sim$2 km and to a water depth of 10 m. This thermal dominance in the density distribution operated to retain relatively saltier water in the near-shore zone. Vertical density differences of $\sim$0.25 kg/m$^3$ were mainly associated with thermal stratification. Lateral density gradients were fairly large at $\sim$0.5 kg/m$^3$ over a distance of 4 km.
Transect T2b was taken on 20th November 2003; just three nautical miles south of transect T1b. Again, warming of near-shore water has led to formation of a relatively warm (>20°C)
water column in the near-shore zone (Figure 2.23). This region had a salinity of >36.9 psu and was \(-0.5\) kg/m\(^3\) less dense compared with offshore water. The width of this warm near-shore zone was about 3 km. It can also be seen that solar radiation created a shallow “thermocline” occupying the uppermost 5 m of the water column. Vertical temperature differences across this “thermocline” are up to 1\(^\circ\)C.

Transect T3b was taken on 27\(^{th}\) November 2003, a week later than transects T1b and T2b and located farther to the south. In contrast to former transects, transect T3b showed saline stratification in both near-shore and offshore water with a thin lower salinity surface layer, ~2-3 m in thickness, being situated over a saltier water body (Figure 2.24). Vertical salinity differences in this region were >0.2 psu. Here, both temperature and salinity effects supported a vertical density stratification in the near-shore zone with a surface-to-bottom difference of ~0.2 kg/m\(^3\).

![Image of temperature, salinity, and density profiles](image)

**Figure 2.24:** Cross-shore transect T3b (for location, see Figure 2.19) showing vertical sections of temperature, salinity and density (sigma-t). Stars indicate the station locations. Note localised errors in salinity data, leading to marginally unstable density stratification.

Transect T4b, taken on 27\(^{th}\) November 2003, showed the effect of solar warming of the upper 2-5 m of the water column and the existence of relatively saline (>36.9 psu) bottom water at a distance of 2 km from the shore (Figure 2.25). Unfortunately, this transect did not cover the near-shore region, but presumably the saline bottom layer extended toward the shore.
Transects T5b and T6b were taken on 26th November and 3rd December 2003, respectively at the southern end of the study region.

Transect T5b, taken on 26th November 2003, had 11 stations over an offshore distance of 8 km. Again, the warmest water of temperatures of >18°C was found near the shore and water temperature sharply decreased to <17°C over a distance of ~2 km from the shore (Figure 2.26). Surface-to-bottom temperature differences were generally less than 0.2°C, so that and vertical temperature stratification was almost absent. The salinity distribution, on the other hand, showed the interesting feature of a “tongue” of elevated salinities >36.8 psu that surfaced in the near-shore zone and extended offshore to a water depth of ~25-30 m. This feature was also seen in transect T4b. The salinity in this tongue was ~0.3 psu greater compared with that of surface water. This created a tongue of marginally elevated densities (density excess ~0.1 kg/m³), indicating an offshore density-driven bottom flow, being initiated during a transient event of atmospheric cooling.

Transect T6b, taken on 3rd December, showed a slight thermal stratification of vertical temperature anomalies of ~1°C, which dominated the density stratification over salinity effects (Figure 2.27). Near the shore our readings indicate an anomalously high near-surface salinity ~37 psu in conjunction with a low water temperature of 16.5°C, implying an instable density stratification. This feature is most likely due to a reading error. Nevertheless, also this transect suggests the existence of a density-driven offshore flow.
Figure 2.26. Cross-shore transect T5b (for location, see Figure 2.19) showing vertical sections of temperature, salinity and density (sigma-t). Stars indicate the station locations.

Figure 2.27 Cross-shore transect T6b (for location, see Figure 2.19) showing vertical sections of temperature, salinity and density (sigma-t). Stars indicate the station locations.
The temperature-salinity diagram of the late-November measurements (Figure 2.28) shows that water temperatures were in a range 16.5-21.5°C, salinities varied between 36.5 psu and 37.0 psu, and densities occupied a range of 25.7-26.9 kg/m³. The main difference to the September-October findings is that the water column became warmer owing to a positive heat flux into the water column, resulting in densities being less than observed in September and October. Salinities of deeper water in southern parts of the study region were in a range similar to that observed during October.

**Figure 2.28.** Temperature-salinity diagram of all hydrographic measurements taken in late November 2003. The solid lines are density contours with a contour interval of 0.5 kg/m³ (in sigma-t units).

**Figure 2.29.** Depth-averaged temperature versus total water depth for all stations completed during late November 2003.
In late November 2003, shallow water was generally warmer compared with deeper water (Figure 2.29), attaining temperatures in excess of 21°C. In contrast to this, the southern, deeper portions of the study region showed temperatures of slightly below 18°C. Salinity attained slightly elevated values of >36.9 psu in shallow water (Figure 2.30), whereas deeper water >15 m had salinities of 36.6-36.8 psu. Apart from a few shallow stations in the very south of the study region, shallow water was generally less dense compared with deeper, offshore water (Figure 2.31) with a density deficit of >0.5 kg/m³. Except for a single occasion showing a turbidity of ~0.8 NTU, evidence of any sediment suspension in the southern portion of the study region was lacking (Figure 2.32).
Figure 2.32: Depth-averaged turbidity (NTU) versus total water depth for all stations completed during late November 2003.

Figure 2.33: Sea-level variations recorded with a tide gauge at location TG1a (Easting: 260230.931; Northing: 6160805.813). The top panel shows variations in sea level, starting from 14/10/03 at 10:30am local time with a sampling period of 10 minutes. The bottom panel shows a low-pass filtered time series of sea level variations using a running-mean window average over 48 hours.

The tide gauge recording at the northern end of the study region revealed tidal sea level variations of a range of ~2 m (Figure 2.33), being maximum during spring tides and almost vanishing during the neap tides (dodge tides). Wind-induced sea level variations (local or remote) were ±0.3 m on synoptic time scales (3-10 days), being 30% of the amplitude of tidal sea level variations.

Sea level recordings at the southern end of the study region (Figure 2.34) were fairly similar to those at the northern end, and showed a similar response to remote atmospheric forcing.
Figure 2.34: Sea level variations recorded with a tide gauge at location TG2a (Easting: 267424.9601; Northing: 6088836.016). The top panel shows the variations in sea level starting from 13/10/03 at 10:20am local time with a sampling period of 10 minutes. The bottom panel shows a low-pass filtered time series of sea level variations using a running-mean window average over 48 hours.
2.5. February 2004 Survey

2.5.1 Overview

The entire study region could be covered by field stations during the period 12-26 February 2004. To this end, ~70 stations were sampled. Figure 2.35 shows the station locations. In addition to this, we deployed two RCM current meters equipped with temperature, conductivity and turbidity sensors in northern and southern parts of the study region in conjunction with an S4 current meter (measurements of current speed and direction only) deployed in central parts of the study region. Note that no rainfall was recorded for the entire month (Source: Bureau of Meteorology). Consequently, turbidity events that occurred in February were related to wave re-suspension.

2.5.2 Findings

![Figure 2.35.](image)

**Figure 2.35.** Left panel: Station locations of February 2004 cruises together with bathymetry (m). M1c and M3c indicate the locations of RCM-9 deployments. M2c indicates the location of the S4 deployment. T1c-T13c are transects referred to in the text. Right panel: Interpolated horizontal distribution of sea surface temperatures.
During February 2004, shallow water in northern parts of the study region attained temperatures of $>24.5^\circ$C, whereas the deeper regions in the south had temperatures of $\sim22^\circ$C (Figure 2.35). The sharp temperature change of $2.5^\circ$C occurred over a distance of 10 km near Holdfast Bay, which marks the transition between the deep southern parts of the study region and extended shallow regions in the north. Note that there was a time gap of 6 days from 19th-25th February between transects T6c and T7c. Within this period, a synoptic weather system brought cold air temperatures ($\sim20$-$25^\circ$C) to this region (Source: Bureau of Meteorology), which might have caused transient cooling of the water column. Nevertheless, estimates suggest that such a cooling event cannot account for the observed temperature contrast of $\sim2^\circ$C between the northern and southern part of the study region which is more likely caused by a transition between a shallow to a deeper water column.

Surface salinity showed an alternating pattern of high ($>37.3$ psu) and low ($<37.1$ psu) salinities along the coast on length scales of 20 km (Figure 2.36). Note that, similar to the situation in November 2003, there appeared to be a lateral inflow of higher-salinity water of a salinity of 37.4 psu from the north along the coast off Port Gawler.
Temperature effects were the major control of the lateral density distribution, leading to a marked density front in the centre of the study region. Density variations across this front were 0.5 kg/m$^3$ over a distance of 5-10 km (Figure 2.37). Owing to temperature effects, the summer water densities were much smaller (25-26 kg/m$^3$) compared with autumn months, when we observed values of 27-28 kg/m$^3$.

A longshore transect of hydrographic properties reveals the structure of the density front, observed in February 2004, in more detail. Figure 2.38 shows field station used for this longshore transect. These field stations were conducted over a period of 14 days. Stations in the north were taken first. Note that this transect includes shallow water (<10 m) in the north, deeper water (>20 m) in central parts, and then again shallow water in the south.
Figure 2.38: Bathymetry (m) and selected station locations of February 2004 cruises used to produce longshore vertical transects of hydrographic properties.

Figure 2.39. Longshore vertical transects of (top) temperature, (middle) salinity and (bottom) density (sigma-t) in February 2004. Stars indicate the station locations. Note errors in salinity data, leading to marginally unstable density stratification.
Shallow water in northern parts of the study regions was relatively warm (>23.5°C) but, except for the near-shore zone, less salty (salinity <37.0 psu) compared with deeper water in the south that attained temperatures of 21.5-22.5°C and salinities of 37.4 psu (Figure 2.39). The zone of steep depth changes from 10 m to 20 m is seen to separate warmer inshore water from colder offshore water.

Salinity generally decreased northward along this transect. The alternating surface signature of salinity (see Figure 2.37) shows up in this transect as a surface “lens” of relatively fresher water in southern parts of the study region. This lens had a length scale of 10 km and was confined to the upper 5 m of the water column. It was less saline by 0.5 psu, colder by 0.5°C, and less dense by <0.2 kg/m³ compared with ambient water.

Owing to warmer temperature, the northern, shallow water was less dense at a density of ~25 kg/m³ (sigma-t) than deeper water in the south, which had a density of ~26 kg/m³. Vertical density stratification was fairly weak and a sharp lateral density contrast of ~1 kg/m³ existed in the zone of steep changes in water depths from 10 to 20 m. This density front is a signature of limited exchange between shallow and deep water.

Figure 2.40: Cross-shore transect T1c (for location, see Figure 2.35) showing vertical sections of temperature, salinity and density (sigma-t). Stars indicate the station locations.

Transect T1c, taken on 12 February 2004, showed that the warmest (~23.7°C) and most saline water (>37.4 psu) was confined to the near-shore zone (Figure 2.40). Presumably, this water mass moved in the study region from shallow water farther up the Gulf. Lateral density gradients were fairly small (<0.1 kg/m³) owing to a compensating effect of temperature and salinity effects. Vertical density stratification was largely absent. Turbidity was only marginally elevated (~0.5 NTU) at the station closest to the shore. Unfortunately, owing to time constraints, we could not take another measurement in shallower water.
In contrast to this, Transect T2c, taken on 16 February 2004, showed reduced salinities of 37.1 psu in the warm near-shore zone, leading to markedly reduced densities of ~24.9 kg/m$^3$ (sigma-t unit) near the coast (Figure 2.41) with lateral differences of ~0.5 kg/m$^3$ over a distance of ~2 km.

The water column in the near-shore zone was well mixed in the vertical. Offshore water (water depth >10m) was slightly vertically stratified both in temperature and salinity, yielding a vertical density stratification of surface-to-bottom differences of ~0.4 kg/m$^3$. Interestingly, there existed a tongue of elevated near-bottom salinities >37.3 psu "entering" the deeper portions of this transect. This feature could be the result of gravitational adjustment of the density front. Note that such an adjustment is associated with offshore flow of surface water and onshore flow of bottom water leading to the formation of a so-called retrograde density front.

Similar to transect T1c, this transect showed slightly elevated turbidities of ~0.5 NTU in the near-shore zone.

**Figure 2.41:** Cross-shore transect T2c (for location, see Figure 2.35) showing vertical sections of temperature, salinity and density (sigma-t). Stars indicate the station locations.
Figure 2.42: Cross-shore transect T3c (for location, see Figure 2.35) showing vertical sections of temperature, salinity and density (sigma-t). Stars indicate the station locations.

Figure 2.43: Cross-shore transect T4c (for location, see Figure 2.35) showing vertical sections of temperature, salinity and density (sigma-t). Stars indicate the station locations.
Figure 2.44: Cross-shore transect T5c (for location, see Figure 2.35) showing vertical sections of temperature, salinity and density (sigma-t). Stars indicate the station locations.

Figure 2.45: Cross-shore transect T6c (for location, see Figure 2.35) showing vertical sections of temperature, salinity and density (sigma-t). Stars indicate the station locations. Note an error in surface salinity data at distance 24.5 km.
The feature of a surface wedge of low density was common to all cross-shore transects measured in the northern half of the study region, including transects T3c-T6c, taken between 17th and 19th February 2004 (Figures 2.42 to 2.45). Transect T3c was slightly different from the other transects, in that the near-shore zone was vertically stratified with top-to-bottom differences in temperature of 1°C and in density of 0.2 kg/m³ (Figure 2.42). Transect T6c included a single station where the surface salinity was markedly reduced (Figure 2.45), presumably due to a reading error. Note that transects T3c -T6c were void of elevated turbidity levels.

Cross-shore transects in the southern half of the study region were significantly different from those taken in the northern half of the study region. The density front marks the transition between these regimes. For instance, Transect T7c, taken on 25 February 2004, revealed a near-shore zone being ~1°C cooler than offshore water (Figure 2.46), whereas there was no evidence of salinity stratification. As a result of this, inshore water was denser by 0.3 kg/m³ than offshore water. Turbidity levels were virtually zero in this transect.

![Figure 2.46: Cross-shore transect T7c (for location, see Figure 2.35) showing vertical sections of temperature, salinity and density (sigma-t). Stars indicate the station locations.](image)

Transects T8c-T10c, all taken on 25 February 2004, showed slight thermal stratification in the upper 2 m of the water column and a near-coastal source of slightly colder bottom water (Figures 2.47 to 2.49) of a density excess of ~0.1 kg/m³ relative to ambient water. This density excess was smaller than those observed in transect T7c. Elevated turbidity levels in near-shore water were not recorded.
Figure 2.47. Cross-shore transect T8c (for location, see Figure 2.35) showing vertical sections of temperature, salinity and density (sigma-t). Stars indicate the station locations. The high bottom salinity reading is presumably a reading error.

Figure 2.48. Cross-shore transect T9c (for location, see Figure 2.35) showing vertical sections of temperature, salinity and density (sigma-t). Stars indicate the station locations.
Transects T11c and T12c, taken on 26th February, just a day after transects T8c-T10c, showed significantly different distributions of water mass properties (Figures 2.50 and 2.51). Here, a relatively cold water mass of temperatures <21.5°C and "low" salinities of 37.1 psu is seen to progress toward the shore and a tongue of warmer and more saline bottom water extends from the near-shore zone over a distance of 5 km offshore. As the density of this tongue is greater by 0.1-0.2 kg/m$^3$ compared with ambient water this feature suggests evidence of a local gravity current occurring in mid-summer. Note that the onshore extension of lower-salinity water is also seen both in the longshore transect (Figure 2.39) cutting through its "nose" and in the surface salinity distribution (Figure 2.36). This onshore incursion of lower-salinity water may be the signature of a dynamic instability of the larger-scale circulation in the Gulf.

In contrast to the former transects, transect T13c, also taken on 26 February 2004, showed very weak vertical stratification with surface-to-bottom differences of <0.4°C in temperature, <0.1 psu in salinity, and <0.05 kg/m$^3$ in density (Figure 2.52).

Transects T11c-T13c were void of elevated turbidity levels.
Figure 2.50: Cross-shore transect T11c (for location, see Figure 2.35) showing vertical sections of temperature, salinity and density (sigma-t). Stars indicate the station locations.

Figure 2.51: Cross-shore transect T12c (for location, see Figure 2.35) showing vertical sections of temperature, salinity and density (sigma-t). Stars indicate the station locations.
Figure 2.52: Cross-shore transect T13c (for location, see Figure 2.35) showing vertical sections of temperature, salinity and density (sigma-t). Stars indicate the station locations. Marginally greater surface salinities are not necessarily due to erroneous data, since some degree of unstable density stratification can be maintained before thermohaline convection mixes the water column.

Figure 2.53: Temperature, salinity, and density (sigma-t) recorded by a moored RCM-9 instrument at location M1c (off Semaphore) starting from 30/1/04 at 11:30am local time. The instrument was deployed 5 m above the seafloor at a total water depth of 10 m. The deployment location is Easting: 269540.4698 and Northing: 6124967.867. Crosses indicate values of boat-based measurements at the location of the mooring.
Over a total period of 35 days, the RCM-9 instrument recorded temperature variations in northern parts of the study region of ~2°C (Figure 2.53) between 3\textsuperscript{rd} and 16\textsuperscript{th} February 2004. Concurrent with the warming period, density decreased by 0.8 kg/m\textsuperscript{3} over a period of two weeks. Salinity experienced an increase by 0.3 psu occurring on 16\textsuperscript{th} February 2004. For unknown reasons, there were short-lived sharp variations (jumps) in the salinity recordings. The fouling problem was apparent after 30 days of mooring deployment.

![Figure 2.54](image)

**Figure 2.54:** Current speed and turbidity recorded by a moored RCM-9 instrument at location M1c starting from 30/1/04 at 11:30am local time.

![Figure 2.55](image)

**Figure 2.55:** Progressive vector diagram and hodograph for the horizontal velocities recorded by a moored RCM-9 instrument at location M1c starting from 30/1/04 at 11:30am local time.
Currents were strongest at ~35 cm/s during spring tides and almost absent during dodge tides (Figure 2.54). It should be mentioned that the recording interval chosen (10 minutes) could not resolve swell-induced flow variations. Turbidity was slightly elevated during the period 24th February - 5th March 2005 attaining values of ~1.5 NTU during the second hide tide phase of the deployment period, whereas turbidity remained low during the first high tide. The turbidity event during the second high tide could have been caused by incident swell superimposed on already elevated current speeds of the spring tide. This remains to be verified by the wave model applied in sub-task 2 of this study.

Tidal flow varied linearly along the shore; that is, in a north-south direction (Figure 2.55) with only little variations normal to the coast. The progressive vector diagram (see Figure 2.55) indicates a residual drift at a rate of 1.7 km per day, in a mainly northward direction of a slightly westward tendency. The tidal long-shore displacement distance of a water parcel over a tidal cycle is ~2 km. Note a short-term reversal of the drift direction being absent at mooring locations M2c and M3c (see below), which excludes atmospheric variations as a forcing mechanism of this. This drift reversal occurred during 16th-20th February; that is, during the dodge tide, presumably owing to the local influence of a meso-scale eddy. Note that this drift reversal was not correlated with the occurrence of elevated turbidities.

The moored S4 instrument at location M2c; that is, off Brighton in central parts of the study region, showed tidal currents of variations and strength similar to those observed at location M1c (Figure 2.56). At this location, the progressive vector diagram indicates a residual northward to north-eastward drift of ~3.5 km per day roughly aligned with the shore. Reasons for the observed variations of the drift direction remain to be explored by means of hydrodynamic modelling.

![Progressive Vector Diagram](image)

**Figure 2.56:** Progressive vector diagram and hodograph based on lateral velocities measured by a moored S4 instrument at location M2c (off Brighton) starting from 30/1/04 at 9:30am local time and recording until 26/2/04. The instrument was deployed 5 m above the seafloor at a total water depth of 10 m. The deployment location is Easting: 265078.665 and Northing: 6141597.47.

At mooring location M3c, in southern parts of the study region, we observed a warming of the water column by 3°C over 12 days, from 5th - 17th February 2004 (Figure 2.57). This warming took place in concert with that observed at mooring M1c in the northern part of the study region. Afterward, the water column remained at a largely constant temperature of ~21.8°C over 10 days and then cooled down by 1°C in the last week of the recording. Salinity showed a sharp transient change by ~0.4 psu during the period 17th February - 12th March 2004 inherent with the appearance of relatively high salinities of 37.4 psu. This sharp variation of salinity was presumably caused by the passage of a salinity front through this region (see Figure 2.36).
Figure 2.57: Temperature, salinity, and density (sigma-t) recorded by a moored RCM-9 instrument at location M3c (off Hallett Cove Beach) starting from 5/2/04 at 9:30am local time. The instrument was deployed 2 m above the seafloor at a total water depth of 5 m. The deployment location is Easting: 268596.869 and Northing: 6110013.59. Crosses indicate values of boat-based measurements at the location of the mooring.

Figure 2.58: Current speed and turbidity recorded by a moored RCM-9 instrument at location M3c starting from 5/2/04 at 9:30am local time. The red circle indicates the reported time of sewage release from Christies Beach Wastewater Treatment Plant.
Figure 2.58 shows current and turbidity data of a mooring deployed 2 m above the seafloor in a total water depth of 5 m during the period 5 February - 12 March 2004 near Hallett Cove Beach. Maximum tidal current speeds were 40 cm/s, being slightly stronger compared with the other moored measurements.

Commencing on 20 February 2004 and lasting for ~10 days, we observed a major turbidity event peaking at 100 NTU. This event, most likely being caused by release of raw sewage from the Christies Beach Wastewater Treatment Plant, peaked during the dodge tide; that is, in the absence of tidal flushing.

According to (unofficial) information from the Marion Council, sewage was released on 14th - 15th February 2004 owing to a power blackout in the absence of backup generator. According to this information, which could not be verified as part of this study, a total of 700-800 thousand litres of raw sewage was released into the near-shore zone. In the absence of other plausible physical generation mechanisms, the author believes this to be the source of turbidity seen in Figure 2.58.

With the subsequent spring tide and its stronger currents, turbidity remained at a fairly high level of 20 NTU for an uncertain time. Since turbidity did not significantly change during this event within a tidal period, the lateral extent of this turbidity "plume" exceeded the lateral tidal displacement distance, which in this region is about 4 km. Note that our boat-based survey did not reach into the near-shore zone of the mooring deployment and we did not measure any elevated turbidity values farther offshore. Therefore, it can be concluded that the observed turbidity plume was trapped in the near-shore zone.

![Progressive Vector Diagram and Hodograph](image)

**Figure 2.59**: Progressive vector diagram and hodograph for the horizontal velocities recorded by a moored RCM-9 instrument at location M3c starting from 5/1/04 at 9:30am local time.

The hodograph (Figure 2.59) shows that tidal current ran predominantly in a north-south direction parallel to the shore. Interestingly, the progressive vector diagram (see Figure 2.59) indicates a residual drift of 2.7 km/day toward the south to south-east, being opposed to the residual flows observed in northern parts of the study region. A residual onshore flow occurred during the last 10-15 days of the deployment, which indicates the absence of long-shore drift of the turbidity plume. Tidal displacement distances during spring tides are ~4 km.

During February 2004, temperatures in the study region were in a range of 21-25°C, salinities varied from 36.8-37.5 psu (with a few data points outside of this regime), and density was in
a range of 24.7-26.2 kg/m$^3$ (sigma-t units) (Figure 2.60). The northern shallow regions were clearly dynamically isolated from the deeper southern regions with a density deficit of 0.5 kg/m$^3$.

**Figure 2.60:** Temperature-salinity diagram of all measurements taken in February 2004.

**Figure 2.61:** Depth-averaged temperature versus total water depth for all stations surveyed in February 2004.
Shallow water in the north of the study region was 3°C warmer compared with the deeper regions in the south (Figure 2.61). Surprisingly, except for a few near-shore stations, the northern shallow regions showed many stations of a salinity less by 0.2-0.4 psu compared with deeper water to the south (Figure 2.62) despite maximum summer evaporation and the absence of significant riverine discharge. According to both warm temperatures and relatively low salinities, the water body in the northern shallow regions had a markedly reduced density compared with the southern regions (Figure 2.63).

**Figure 2.62:** Depth-averaged salinity versus total water depth for all stations surveyed in February 2004.

**Figure 2.63:** Depth-averaged density (sigma-t) versus total water depth for all stations surveyed in February 2004.
Turbidity (NTU)

0.6
0.4
0.2
0
0 5 10 15 20 25 30
Total Water Depth (m)

Figure 2.64: Depth-averaged turbidity versus total water depth for all stations surveyed in February 2004.

Only a few near-shore stations showed marginally elevated turbidity levels of ~0.5 NTU (Figure 2.64). Interestingly, three deep stations indicated marginally elevated turbidity levels, but this might have been caused by inference of the instrument with the seabed, stirring up bed sediment. Figure 2.65 shows a cross-shore transect of an event of elevated turbidity levels in the near-shore zone.

Figure 2.65: Turbidity along vertical transect T2c (for location, see Figure 2.35), taken on 16th February 2004.
2.6. May-June 2004 Surveys

2.6.1 Overview

During 19th - 21st May 2004, about 30 field stations have been conducted in the shallow northern part of the study region (Figure 2.66). Due to a sparse station grid, cross-shore transects are not discussed in this chapter. The field campaign included 8 stations taken in the vicinity of the Torrens River outlet, aiming at measuring water mass properties after periods of substantial precipitation. This was accompanied by a deployment of an RCM-9 current meter just off the Torrens River outlet. Note that 8 mm of rain fell during 1st-15th May with heavy rainfall of 23 mm occurred over 3 days (16th-18th May) prior to our field campaign (Source: Bureau of Meteorology). As a result of this, freshwater discharge through Torrens River increased to ~35 ML/d (Jeremy Wilkinson, personal communication).

The fine-scale survey around the Torrens River outlet was repeated on 16th June 2003. In addition to this, we have deployed a current meter off Hallett Cove Beach, at approximately the same location as in our February 2004 survey. Note that ~ 35 mm of rain fell in the week prior to this survey leading to enhanced run-off from the Torrens River to >50 ML/day (Jeremy Wilkinson, personal communication).

Figure 2.66: Left panel: Station locations of May 2004 cruises together with bathymetry (m). M1d and M2d indicate the locations of RCM-9 deployments. A fine-scale hydrographic survey has been conducted around mooring location M1d, which was placed near the Torrens River outlet. Right panel: Interpolated horizontal distribution of sea surface temperatures (°C).
2.6.2 Findings

In May 2004, shallow, near-shore water was generally slightly colder (15.2-15.3°C) compared with offshore water that attained temperatures of 15.4-15.8°C (Figure 2.66). The highest salinity of ~38.2 psu was again observed in the near-shore zone off Port Gawler in a plume that appeared to migrate southward along the coast (Figure 2.67). This instance was the highest salinity recorded during the entire field program. Again, we have found evidence of lateral incursion of extremely saline water into Adelaide coastal waters stemming from farther up the Gulf.

Figure 2.67: Left panel: Station locations of May 2004 cruises together with bathymetry (m). Right panel: Interpolated horizontal distribution of sea surface salinity (psu).
The density distribution (Figure 2.68) clearly shows this near-shore zone of elevated salinities attaining extremely high densities of >28.4 kg/m$^3$ (sigma-t units). Near the Torrens River outlet, density is relatively low at 27.7 kg/m$^3$ in sigma-t units.

In our fine-scale study, vertical temperature profiles taken in the vicinity of the Torrens River outlet on 19th May 2004 revealed that the water column was coldest (<15°C) close to the outlet with increasing temperatures of 15.5°C further offshore (Figure 2.69). There was no indication of significant vertical stratification in temperature. Salinities around the Torrens River outlet on 19th May were in a range of 37.1-37.25 psu (Figure 2.70). There was no vertical salinity stratification except for two stations showing slightly decreased surface salinities. Overall, inshore salinities were ~0.2 psu lower compared with offshore measurements (see Figure 2.67), suggesting that riverine discharge become uniformly mixed over the near-shore zone. Note that strong precipitation (~20 mm) occurred on 18th May (Source: Bureau of Meteorology; that is, one day before our measurements, leading to enhanced freshwater discharge through Torrens River of ~35 ML/d (Jeremy Wilkinson, personal communication).
Figure 2.69: Vertical temperature profiles for stations conducted in close vicinity of the Torrens River outlet on 19th May 2004. Total water depth is an indicator of distance from river mouth.

Figure 2.70: Vertical salinity profiles for stations conducted in close vicinity of the Torrens River outlet on 19th May 2004. Total water depth is an indicator of distance from river mouth.

Figure 2.71: Vertical density (sigma-t) profiles for stations conducted in close vicinity of the Torrens River outlet on 19th May 2004. Total water depth is an indicator of distance from river mouth.

Vertical density profiles in proximity of the Torrens River outlet on 19th May (Figure 2.71) largely reflected the salinity distribution. Most stations had a density around 27.6 kg/m$^3$ (sigma-t) and only two stations showed reduced densities near the surface. Nevertheless, near-shore water appeared to be less dense by 0.1 kg/m$^3$ as compared with offshore water.
Figure 2.72: Vertical turbidity profiles for stations conducted in close vicinity of the Torrens River outlet on 19th May 2004. Total water depth is an indicator of distance from river mouth.

Vertical profiles of turbidity adjacent to the Torrens River outlet on 19th May showed an interesting structure (Figure 2.72). Maximum turbidity values of >12 NTU was observed just off the outlet where there was also a markedly vertical stratification in turbidity. Turbidity (and its vertical variations) decreased substantially with increasing distance from the outlet to a vertically uniform value of ~1.5 NTU. Since heavy rainfall occurred the day prior to the measurements, this turbidity signature was caused by enhanced discharge from the Torrens River.

Figure 2.73: Vertical temperature profiles for stations conducted in close vicinity of the Torrens River outlet on 16th June 2004. Total water depth is an indicator of distance from river mouth.

Figure 2.74: Vertical salinity profiles for stations conducted in close vicinity of the Torrens River outlet on 16th June 2004. Total water depth is an indicator of distance from river mouth.
Figure 2.75: Vertical density (sigma-t) profiles for stations conducted in close vicinity of the Torrens River outlet on 16\textsuperscript{th} June 2004. Total water depth is an indicator of distance from river mouth.

The fine-scale survey in proximity of the Torrens River outlet was repeated on 16\textsuperscript{th} June 2004. Note that ~35 mm of precipitation occurred over 1 week prior to this survey (Source: Bureau of Meteorology).

At this time, the temperature of the water column was much cooler at ~13.7\textdegree{}C (Figure 2.73) and its salinity was markedly increased to values of 37.6 psu (Figure 2.74), which is 0.4 psu more saline than observed in May. Again, the water column was fairly well mixed in the vertical. Owing to low temperatures, density of the water column was increased to >28.2 kg/m\textsuperscript{3} (Figure 2.75), being by 0.6 kg/m\textsuperscript{3} denser in comparison to the May survey.

Figure 2.76: Vertical turbidity profiles for stations conducted in close vicinity of the Torrens River outlet on 16\textsuperscript{th} June 2004. Total water depth is an indicator of distance from river mouth.
Turbidity attained maximum levels >3 NTU on 16th June with the largest values of >9 NTU close to the Torrens River outlet (Figure 2.76). The turbidity pattern is similar to that observed on 19th May 2004 and, again, can be clearly related to enhanced riverine discharge after heavy rainfall, increasing the flow rate of the Torrens River to >50 ML/day (Jeremy Wilkinson, personal communication).

**Figure 2.77:** Depth-averaged temperature versus total water depth for all stations conducted during May-June 2004. Pink squares and green triangles indicate stations near the Torrens River Outlet taken on 19th May and 16th June 2004, respectively.

Figure 2.77 shows that in May 2004 water temperatures slightly increased with increasing total water depth. At this time, the water column near the Torrens River outlet had temperatures similar to those found in the northern shallow regions. In June 2004, water off the Torrens River outlet was significantly colder at temperatures around 14°C.

**Figure 2.78:** Depth-averaged salinity versus total water depth for all stations conducted during May-June 2004. Pink squares and green triangles indicate stations near the Torrens River Outlet taken on 19th May and 16th June 2004, respectively.
On the other hand, salinities were lowest at <37.2 psu in shallow water off the Torrens River outlet in May 2004, which contrasted the high salinities >38.0 psu found in shallow regions off Port Gawler (Figure 2.78). In June 2004, salinity of shallow water off the outlet of the Torrens River increased to values around 37.5 psu, despite the inflow of river-derived freshwater.

**Figure 2.79:** Depth-averaged density (sigma-t) versus total water depth for all stations conducted during May-June 2004. Pink squares and green triangles indicate stations near the Torrens River Outlet taken on 19th May and 16th June 2004, respectively.

**Figure 2.80:** Depth-averaged turbidity versus total water depth for all stations conducted during May-June 2004. Pink squares and green triangles indicate stations near the Torrens River Outlet taken on 19th May and 16th June 2004, respectively.
Density in shallow water of the northern region generally decreased with increasing total water depth (Figure 2.79) and fairly dense water of a density $>28.0 \text{ kg/m}^3$ (sigma-t) was observed in this region. In contrast to this, shallow water off the Torrens River outlet had lower densities of 27.6 kg/m$^3$ in May 2004, but these markedly increased to $>28 \text{ kg/m}^3$ in June 2004 associated with fairly low sea temperatures $<14^\circ\text{C}$.

Compared with the northern shallow regions, turbidity off the Torrens River outlet was elevated for both of our fine-scale surveys with values ranging between 2 and 10 NTU (Figure 2.80).

During the period May-June 2004, temperature varied in a range of 13.8-16$^\circ\text{C}$, salinity occupied a range of 37-38.2 psu, and densities were commonly fairly large in a range of 27.5-28.0 kg/m$^3$ in sigma-t units. The temperature-salinity diagram (Figure 2.81) summarises the ranges in hydrographic properties observed.

![Temperature-Salinity Diagram](image)

**Figure 2.81:** Temperature-salinity diagram of all hydrographic measurements taken in the period May-June 2004. The solid lines are density contours with a contour interval of 0.5 kg/m$^3$ (in sigma-t units).

At the mooring location M1d off the Torrens River outlet, we observed a gradual cooling of the water column from 16.5 to 15.3$^\circ\text{C}$ over a period of 12 days, then remaining largely constant afterward (Figure 2.82). Salinity increased from 37.0 to 37.4 psu over the first 10 days of the deployment, and then decreased by 0.3 psu over the next 4 days. Strong salinity variations of $>0.4 \text{ psu}$ were observed between days 16-19 of the deployment. The first marked salinity decrease can be related to the rainfall event on 18th May, whereas there is no obvious correlation with rainfall variability for the second sharp salinity variation during the period 23rd-26th May. The latter is presumably caused by transient passage of a water mass of greater salinities from the north (see Figure 2.67), which remains to be verified by means of hydrodynamic modelling.
Density increased over the first 12 days of the deployment period in conjunction with the salinity increase and temperature decrease observed. The salinity drop, observed around day 12 of the deployment, led to a slight density decrease, whereas advection of saline water into the near-shore zone from day 16 to day 19 transiently triggered the occurrence of maximum densities of ~28.0 kg/m$^3$ (sigma-t units).

Figure 2.82: Temperature, salinity, and density (sigma-t) recorded by a moored RCM-9 instrument at location M1d (off Torrens River outlet) starting from 7/5/04 at 2:22pm local time. The instrument was deployed 2 m above the seafloor at a total water depth of 5 m. The deployment location is Easting: 270815.62 and Northing: 6131179.16. Crosses indicate values of boat-based measurements at the location of the mooring.

Tidal currents attained maximum speeds of ~30-35 cm/s (Figure 2.83), showing some short-lived (<1 day) events of non-tidal flows of a similar magnitude. It seems that some of these short-lived enhancements of the flow resulted in peaks in turbidity, attaining local maximum values of >7 NTU. Turbidity levels were locally elevated (>2 NTU) over periods of 2-5 days. A series of discrete turbidity events can be identified. The events on day 6 (13th May), day 8 (15th May), and day 17 (23rd May) occurred in the absence of peak rainfall and indicate swell-induced re-suspension. On the other hand, the event on day 11 (18th May), lasting for ~4 days, can be clearly related to enhanced riverine inflow associated with the peak rainfall event on 18th May. After day 15, from 23rd May onward, rainfall was more or less persistent, which explains why turbidity levels remain elevated (values >1 NTU) throughout this period.

The progressive vector diagram indicates irregular residual flow of varying strength and direction (Figure 2.84). Dynamical reasons of these variations remain to be explored by means of hydrodynamic modelling. The hodograph indicates tidally varying flow being largely oriented parallel to the coastline.
Figure 2.83: Current speed and turbidity recorded by a moored RCM-9 instrument at location M1d (off Torrens River outlet) starting from 7/5/04 at 2:22pm local time. The cross indicates the value of boat-based measurements at the location of the mooring.

Figure 2.84: Progressive vector diagram and hodograph based on lateral velocities recorded by a moored RCM-9 instrument at location M1d (off Torrens River outlet) starting from 7/5/04 at 2:22pm local time over a period of 23 days.
Mooring M2d, located off Hallett Cove Beach, showed a gradual cooling by 3.5°C over the deployment period of 40 days (Figure 2.85) displaying trends in temperature similar to those observed off the Torrens River outlet. Salinity displayed a total variation of 0.4 psu over this period. For unknown reasons there were occasions during which salinity changed sharply by ~0.25 psu. Density gradually increased from 27.2 to 28.1 kg/m$^3$ over the measurement period of 40 days.

Mooring M2d measured peak tidal currents of 25 cm/s in strength (Figure 2.86), being superimposed by non-tidal events during which the current speed increased to values of >30 cm/s. Turbidity was only marginally elevated showing a few short-lived spikes during which turbidity values increased to ~10 NTU. Interestingly, some peak turbidity events occurred in concert with those observed at mooring location M1d, such as on 15th, 18th and 24th May, indicating swell-induced re-suspension of bed sediment.
The progressive vector diagram at mooring location M2d indicates a residual drift at a rate of 2.45 km/day in a mainly southward direction (Figure 2.87). Interestingly, this drift is of strength and direction similar to those observed at this location in February 2004 (see Figure 2.59). The tidal flow runs largely parallel to the coast with slightly stronger southward speeds.

In comparison, water temperatures were systematically greater by 1°C for the mooring near Hallett Cove Beach compared with that off the Torrens River outlet (Figure 2.88). Salinities were typically greater by 0.5 psu for the northern mooring except for two events during which the salinities at both moorings approached similar values. The general salinity increase toward the north is in consistency with previous observational evidence (e.g. Symonds, 1977). However, it should be noted that the salinity data acquired has not been calibrated.
against laboratory samples, so that some uncertainty remains. Owing to differences in both
temperature and salinity, the density differences between the moorings alternated between
±0.2 kg/m³ on time scales of 2-7 days.

![Figure 2.88](image)

**Figure 2.88:** Temperature, salinity, and density (sigma-t) recorded by moored RCM-9
instruments at locations M1d (blue lines; off Torrens River outlet) and M2d (red lines, off
Hallett Cove Beach).
2.7. August-September 2004 Survey

2.7.1 Overview

During the period 17th August - 2nd September 2004, we have completed 66 stations covering the entire study region. Figure 2.89 shows the station locations, which are similar to those completed in February 2004. In addition to this, we have deployed two RCM-9 current meters on 19 October 2004 near the entrance to the Barker Inlet/Port River. Mooring data are discussed in the following section. Note that 50 mm of rain fell in the first week of August (Source: Bureau of Meteorology), whereas rainfall for the rest of the month was more sporadic with 5 mm and 5.6 mm occurring on 14th and 29th August, respectively.

Figure 2.89: Left panel: Station locations of August-September 2004 cruises together with bathymetry (m). M1e and M2e indicate the locations of RCM-9 deployments. T1e - T13e indicate individual cross-shore transects that are discussed in the text. Right panel: Interpolated horizontal distribution of sea surface temperatures (°C).
2.7.2 Findings

During August/September 2004, the shallow water in the northern part of the study region attained temperatures of 12.4-13°C, whereas deeper water in the south was relatively warmer with temperatures of up to 14°C (Figure 2.89).

Salinities in the northern region were generally higher (~37.0-37.1 psu) compared with the southern regions (Figure 2.90), where salinities were 36.8 psu. An exemption to this was a narrow near-shore zone near Port Gawler that showed markedly decreased salinities of ~36.0 psu, an indication of riverine discharge from the Port River/Barker Inlet incurred by heavy rainfall in the first week of August and subsequently moved north-westward along the shore. The width of this "plume" was about 5 km. Salinities are at maximum off Outer Harbour, which is an indication of the existence of a localised "salt plug".

![Figure 2.90](image)

**Figure 2.90**: Left panel: Station locations of August-September 2004 cruises together with bathymetry (m). Right panel: Interpolated horizontal distribution of sea surface salinity (psu).

Density generally increased toward the north of the study region (Figure 2.91) as a result of both decreasing temperature and increasing salinity. The zone of maximum salinities off Outer Harbour attained the greatest density of >28.0 kg/m³. The low-salinity tongue along the northern coast was associated with low densities of 27.0-27.4 kg/m³ (sigma-t units). Note that only two field stations contribute to this low-salinity tongue. Nevertheless, the author believes that this feature is real as it is seen closest to the shore in two subsequent transects.
Figure 2.91: Left panel: Station locations of August-September 2004 cruises together with bathymetry (m). Right panel: Interpolated horizontal distribution of sea surface density (sigma-t, kg/m$^3$).

Transects T1e-T8e were taken during the period 17th – 23rd August 2004. These transects show near-shore zones of reduced salinity. Lateral salinity differences across the near-shore zone were most pronounced in the two northernmost transects (T1e and T2e) where differences of >2 psu occurred over a distance of 1 km (Figures 2.92-2.93). This salinity contrast created a relatively low density in the near-shore zone of 26.5 kg/m$^3$, being by 1.5 kg/m$^3$ less dense compared with ambient water. This low-salinity plume, observed in the near-shore zone off Port Gawler, was the most pronounced low-salinity feature of the entire field program. In contrast to this, transects T3e-T8e indicated much smaller lateral salinity anomalies of only 0.1-0.3 psu with the density in the near-shore zone being only marginally smaller compared with offshore water (Figures 2.94-2.99). Some entrainment of land-derived freshwater is apparent in these transects, but its effect is seen to be negligibly small in terms of salinity variations of the near-shore zone. Note that all transects T1e-T8e showed elevated turbidity levels of up to 1 NTU is the near-shore zone (water depth <5 m) and ~0.5 NTU for deeper stations.

Transects T9e-T13e, taken in the deeper, southern parts of the study region on 25th August and 2nd September 2004, were largely void of coastal low-salinity intrusions and salinity anomalies were generally fairly small (~0.2 psu) (Figures 2.100-2.104). On 25th August, a thin surface layer (a few metres thick) existed being marginally warmer (~0.7°C) compared with water underneath. In these southern regions, the water column below 15 m depth was filled by a distinct, cold (~13.0-13.2°C) and saline (36.7-36.8 psu) water mass, presumably stemming from the northern, shallow regions of the Gulf and being moved toward the south.
in form of a bottom-attached, density-driven gravity current. Note that except for transect T9e that showed turbidity levels of ~3 NTU in the near-shore zone, stations in this part of the study region were void of elevated turbidity.

Figure 2.92: Cross-shore transect T1e (for location see Figure 2.89), taken on 17th August 2004, showing vertical sections of temperature, salinity and density (sigma-t). Stars indicate the station locations.

Figure 2.93: Cross-shore transect T2e (for location see Figure 2.89), taken on 17th August 2004, showing vertical sections of temperature, salinity and density (sigma-t). Stars indicate the station locations.
Figure 2.94: Cross-shore transect T3e (for location see Figure 2.89), taken on 17th August 2004, showing vertical sections of temperature, salinity and density (sigma-t). Stars indicate the station locations.

Figure 2.95: Cross-shore transect T4e (for location see Figure 2.89), taken on 17th August 2004, showing vertical sections of temperature, salinity and density (sigma-t). Stars indicate the station locations.
Figure 2.96: Cross-shore transect T5e (for location see Figure 2.89), taken on 23rd August 2004, showing vertical sections of temperature, salinity and density (sigma-t). Stars indicate the station locations.

Figure 2.97: Cross-shore transect T6e (for location see Figure 2.89), taken on 23rd August 2004, showing vertical sections of temperature, salinity and density (sigma-t). Stars indicate the station locations.
Figure 2.98: Cross-shore transect T7e (for location see Figure 2.89), taken on 23\textsuperscript{rd} August 2004, showing vertical sections of temperature, salinity and density (sigma-t). Stars indicate the station locations.

Figure 2.99: Cross-shore transect T8e (for location see Figure 2.89), taken on 23\textsuperscript{rd} August 2004, showing vertical sections of temperature, salinity and density (sigma-t). Stars indicate the station locations.
Figure 2.100: Cross-shore transect T9e (for location see Figure 2.89), taken on 25th August 2004, showing vertical sections of temperature, salinity and density (sigma-t). Stars indicate the station locations. Note local errors in salinity data.

Figure 2.101: Cross-shore transect T10e (for location see Figure 2.89), taken on 25th August 2004, showing vertical sections of temperature, salinity and density (sigma-t). Stars indicate the station locations.
Figure 2.102: Cross-shore transect T11e (for location see Figure 2.89), taken on 2nd September 2004, showing vertical sections of temperature, salinity and density (sigma-t). Stars indicate the station locations. Note local errors in salinity data.

Figure 2.103: Cross-shore transect T12e (for location see Figure 2.89), taken on 2nd September 2004, showing vertical sections of temperature, salinity and density (sigma-t). Stars indicate the station locations.
To examine potential exchange of the northern, shallow regions with the southern deeper water during the period August-September 2004, we have produced longshore vertical transects of temperature, salinity, and density. Figure 2.105 shows the stations contributing to this transect.

**Figure 2.105**: Station locations (crosses) of the long-shore transects. Stations were taken during the period 17th August to 2nd September 2004 from north to south.
Shallow water in the north attained cold temperatures of 12.0-12.5°C, being ~1°C colder compared with deeper water in the south (Figure 2.106). Also its salinity of >37.2 psu was greater by 0.5 psu than observed in the south. This resulted in a density excess 0.4 kg/m³ in the shallow water, driving a gravity current of ~37 psu in salinity and 12.8°C from the shallow regions toward deeper regions over a long-shore distance of 30 km. Apparently, this plume, ~10 m in thickness, experienced entrainment of ambient water, thereby losing its initial source water characteristics during the descent. This descent is (virtually) compensated by a northward flow in the uppermost 10 m of the water column, bringing warm (~13.5°C) and relatively fresh (~36.7 psu) water toward the north. Notice the near-shore zone of river-derived low salinity water in the very north of the study region.

**Figure 2.106:** Longshore vertical transects of temperature (°C), salinity (psu), and density (sigma-t, kg m⁻³) for the long-shore transect shown in Figure 2.105. The two southernmost stations are not included.

The temperature-salinity diagram for all hydrographic measurements taken during the period August-September 2004 shows that water temperatures were in a range of 12-14°C, salinity occupied a range of 36.5-37.4 psu, and density varied from 27.4-28.4 kg/m³ in sigma-t units (Figure 2.107). Notice that this water mass was substantially fresher by ~1 psu than observed in May-June 2004. Thus, during the May-September there has been a substantial addition of low-salinity water to the entire study region, most likely due to influences by the Gulf-wide circulation, which has not been the focus of this study.

The gravitational exchange circulation, which is of a structure similar to that observed in October 2003, leads to an export of shallow water including its biochemical signature toward
deeper regions in the south. Thus, some portion of the shallow northern regions, being influenced by effluent discharge from the Barker Inlet/Port River system, becomes presumably partially flushed during the period May-October. The effectiveness of this flushing and its impacts on deeper marine habitat in a depth regime of 10-20 m need to be addressed in future research.

The flow speed and width of an oceanic density front can be estimated using simple geostrophic adjustment theory for two-layer problems (e.g. Gill, 1982). The frontal flow speed scales as

\[ v = \frac{\Delta \rho}{\rho_o} g h, \]  

where \( \Delta \rho \) is density contrast across the front, \( \rho_o = 1027.8 \text{ kg m}^{-3} \) is reference density, \( g = 9.81 \text{ m s}^{-2} \) is acceleration due to gravity, and \( h \) is thickness of the relatively denser water layer. With \( \Delta \rho \sim 0.4 \text{ kg m}^{-3} \) and \( h \sim 10 \text{ m} \) (see Figure 2.106), the resultant frontal flow would attain a speed of \( \sim 20 \text{ cm s}^{-1} \), which is of a magnitude similar to that of tidal currents observed by our mooring deployments. Thus, this density-driven flow should be detectable by means of current meter deployments. The width of such a geostrophic front, given by the internal deformation radius, would be \( \sim 2.4 \text{ km} \), which roughly corresponds to the width of the zone of rapid density changes seen in Figure 2.106.

![Temperature-salinity diagram](image)

**Figure 2.107:** Temperature-salinity diagram of all hydrographic measurements taken in the period August-September 2004. The solid lines are density contours with a contour interval of 0.5 kg/m$^3$ (in sigma-t units).
**Figure 2.108**: Depth-averaged temperature versus total water depth for all stations conducted during August-September 2004.

**Figure 2.109**: Depth-averaged salinity versus total water depth for all stations conducted during August-September 2004.
The depth-distributions of depth-averaged water mass properties show that the shallow, northern region of the study domain held cooler (Figure 2.108), more saline (Figure 2.109), and thus denser water (Figure 2.110) compared with the deeper southern regions. An exception to this is the near-shore zone off Port Gawler that during the time of the measurements experienced a long-shore flow of river-derived low-salinity water.

Turbidity was elevated to levels of 0.5-1 NTU to a total water depth of ~14 m (Figure 2.111) in the northern part of the study region, where measurements were taken during the period 17th –23rd August. These elevated turbidity levels are likely the remnant trace of heavy rainfall and coastal run-off that has occurred in the first week of August.
2.8. October-November 2004 Moorings

2.8.1 Overview

In addition to the spatial field surveys, we have deployed two RCM 9 moorings on 19th October 2004 in the vicinity of the entrance to Barker Inlet/Port River. The mooring locations are shown in Figure 2.89. The distance between the moorings was only 3-4 km. Mooring M1e was located slightly farther north, 2 m above the seabed in a total water depth of 5 m. Mooring M2e was located at the margin of the main shipping channel, 5 m above the seabed in a total water depth of 10 m. Both moorings experienced significant fouling on time scales of 2-3 weeks, seen in a rapid decrease of salinity. This can be taken as an indicator of substantial biomass growth in this region.

2.8.2 Findings

At mooring site M1e, temperature varied by ~1-2°C daily, reflecting the diurnal cycle of heat-flux variations (Figure 2.112). Overall, temperature was in a range between 17 and 19.5°C, with a drop by 0.5°C occurring around 4th December and diurnal variations of up to 1.5°C. Salinity, on the other hand, varied in a range of 36.6 - 37.2 psu. The gradual decrease in salinity after day 15 (from 4th December 2004 onward) was most probably the effect of fouling. Density varied between 26 and 27.4 kg/m³ in sigma-t units.

Figure 2.112: Temperature, salinity, and density (sigma-t) recorded by a moored RCM-9 instrument at location M1e starting from 19/10/04 at 11:45am local time. The instrument was deployed 2 m above the seafloor at a total water depth of 5 m. The deployment location was Easting: 267875.71 and Northing: 6151812.436.
Figure 2.113: Current speed and turbidity recorded by a moored RCM-9 instrument at location M1e starting from 19/10/04 at 11:45am local time. The instrument was deployed 2 m above the seafloor at a total water depth of 5 m.

Figure 2.114: Progressive vector diagram and hodograph based on lateral velocity recorded by a moored RCM-9 instrument at location M1e starting from 19/10/04 at 11:45am local time. The instrument was deployed 2 m above the seafloor at a total water depth of 5 m.
Interestingly, the observed lateral flow was generally weak with speeds <20 cm/s (Figure 2.113), except for an event around 4th December 2004, lasting 3-4 days, during which the current speed increased to ~30 cm/s in two subsequent pulses. During this event, turbidity increased to values of ~8 NTU. This indicates re-suspension of bed sediment by incident swell, which remains to be verified by means of hydrodynamic modelling.

The progressive vector diagram indicates a residual flow of 3.3 km/day along the shore in a north-westward direction (Figure 2.114). The hodograph shows that the tidal flow in this region is fairly weak (~15 cm/s) and that it does not have a preferred direction.

At the margin of the shipping channel (mooring site M2e), temperature varied between 17 and 20° with rapid drops by 1°C occurring on 4th and 22nd December (Figure 2.115). The first general drop in temperature occurred in parallel to that observed at mooring site M1. Salinity readings of 36.9 psu are similar to those of the other mooring. The rapid decrease in salinity commencing on day 15 (4th December), however, was caused by fouling. Accordingly, density varied between 26.4 and 26.7 kg/m³ during the first 14 days of this mooring. Density readings afterward were strongly biased by fouling.

![Image](image_url)

**Figure 2.115:** Temperature, salinity, and density (sigma-t) recorded by a moored RCM-9 instrument at location M2e starting from 19/10/04 at 1:09pm local time. The instrument was deployed 5 m above the seafloor at a total water depth of 10 m. The deployment location was Easting: 269031.49 and Northing 6147991.1.
Despite the short distance of a few kilometres from mooring site M1e, the tidal flows at site M2e were substantially stronger with peak values of 60-80 cm/s (Figure 2.116), the strongest currents observed in the entire field program. After day 35 (26th December), we observed turbidity values increasing to peak values of 100 NTU and showing strong short-lived fluctuations. In the view of erroneous temperature and salinity readings from day 15 onwards, instrument fouling was likely the cause of this.

Figure 2.117: Progressive vector diagram and hodograph based on lateral velocity recorded by a moored RCM-9 instrument at location M2e starting from 19/10/04 at 1:09pm local time. The instrument was deployed 5 m above the seafloor in a total water depth of 10 m.
The progressive vector diagram indicates a residual flow at a rate of 2.2 km/day toward the west to southwest (Figure 2.117). The hodograph reveals the interesting feature that the tidal flow at mooring site M2e is aligned with the axis of the shipping channel, suggesting that the shipping channel operate as a local amplifier of tidal flows.
3. Interpretation of Observational Findings

3.1. Influences of the Gulf-Wide Circulation

This report presents findings of the most comprehensive field surveys ever conducted in Adelaide Metropolitan waters. Gulf St. Vincent is an inverse estuary of a salinity that exceeds the salinity of the adjacent sea. The circulation in this Gulf is only poorly understood, but there appears to be a general clockwise circulation in the northern parts of the Gulf, so that Adelaide Metropolitan waters becomes exposed to water flow of saline water stemming from the head of the Gulf (see Figure 1.9). Consequently, a long-term accumulation of salt in this region can only by compensated by lateral entrainment of lower salinity water from western portions of the Gulf. Consideration of these larger-scale influences is important to understand salinity variations observed in Adelaide Metropolitan waters.

![Temperature–Salinity Diagram](image)

**Figure 3.1:** Temperature-salinity diagram of all hydrographic measurements undertaken as part of the Adelaide Coastal Waters Study during the period September 2003 – August 2004. The solid lines are density contours with a contour interval of 0.5 kg/m$^3$ (in sigma-t units). Ellipses indicate temperature-salinity ranges observed in the northern shallow parts of the study region.
3.2. Seasonal Cycle of Temperature, Salinity and Density

The seasonal cycle of the temperature-salinity structure is best described by means of a temperature-salinity-time diagram with measurements taken over the period of a year (Figure 3.1). Over a year, one would expect the temperature of Gulf water to exhibit a distinct seasonal cycle with the highest temperatures occurring by the end of summer and the lowest ones during end of winter. This takes place in the study region with late summer temperatures of >25°C and late winter temperatures of ~12°C. Thus, temperatures vary by ~13°C over a year. This temperature variation appears to control the overall density of Gulf water with low values of 25 kg/m$^3$ in sigma-t observed in late summer and high values of >28 kg/m$^3$ in winter. Accordingly, maximum density-driven exchange of Gulf water with water of the adjacent ocean can be expected to occur during wintertime.

Figure 3.2: Temperature-salinity diagram of all hydrographic measurements undertaken as part of the Adelaide Coastal Waters Study during the period September 2003 – August 2004. The solid lines are density contours with a contour interval of 0.5 kg/m$^3$ (in sigma-t units). Ellipses indicate temperature-salinity ranges observed in the southern deeper parts of the study region.
Seasonal variations in salinity, on the other hand, reveal information on the larger-scale influences, given that local riverine discharge is insignificant in terms of salinity changes. In the absence of mixing and advection, salinity of a 10-m thick water column would increase at a rate of about 0.75 psu per month during summer evaporation of ~20 cm/month. In wintertime, the same water column would experience a somewhat smaller salinity increase of, say, 0.25 psu per month. In a steady state, salinity would remain constant with time. Finally, salinity would decrease with time, if the entrainment of low salinity water overrode the effect of evaporation. Salinity in Adelaide Metropolitan waters varies by 1.5 psu over a year. There are three distinct phases of salinity changes. During August – February, salinity remains fairly constant at ~37 psu. This indicates a balance between evaporative salinity increases and entrainment of lower salinity water. During February – May, salinity markedly increases by 1 psu. This increase is the combined effect of evaporation and incursion of high salinity water from the head of the Gulf. During May – August, the study region experiences a significant decrease in salinity by 1 psu, which completes the cycle. During this period, the combined effect of temperature and salinity remains the water density at a fairly high level >28 kg/m$^3$ ($\sigma_t$) over a period of 3-4 months. The salinity decrease is associated with lateral entrainment of lower salinity water dominating over evaporative salinity increases.

Figure 3.3 is a summary of the seasonal cycle of temperatures and salinities for Adelaide Metropolitan waters, indicating approximate values for each month of the year. Year-to-year variations of hydrographic parameters are not well understood.

### 3.3. Exchange between Shallow and Deeper Water

The deeper regions in southern parts of the study region display seasonal variations in temperature and salinity similar to those observed in the shallower northern regions (Figure 3.2). This is evidence that the Gulf-wide circulation controls the water mass properties in Adelaide Metropolitan waters. Owing to shallow water effects, however, seasonal temperature variations in the northern shallow regions are more pronounced compared with those observed in the southern deeper regions (compare Figures 3.1-3.2). To this end, northern regions are ~3°C warmer in late summer and ~1°C colder in late winter than water in the south. Also, there are salinity contrasts between these regions. During May – October, the northern regions show higher salinities than found in the south, whereas in summer they were surprisingly less saline than southern water.

In summer, a relative density deficit characterises the northern shallow regions. This leads to the formation of a density front roughly aligned with the 15-m topographic contour, indicating a limited exchange between the northern and southern regions of the study region. In winter, on the other hand, shallow water in the north is denser compared with deeper water in the south. This density contrast triggers a density-driven overturning circulation between these regions being superimposed on the Gulf-wide circulation. While the northern regions around the Barker Inlet/Port River system appear to be isolated from the Gulf-wide circulation in summer, this density-driven circulation operates as a local flushing mechanism of the northern shallow regions. Inherent with this circulation are surface-to-bottom differences in salinity of 0.2 psu and in density of 0.2 kg/m$^3$, which are fairly small. Nevertheless, as seen in the measurements, this density contrast is sufficient to export shallow water into greater depths of the Gulf of >20 m over a horizontal distance of 30 km.
Figure 3.3: Temperature-salinity diagram of all hydrographic measurements undertaken as part of the Adelaide Coastal Waters Study during the period September 2003 – August 2004. The solid lines are density contours with a contour interval of 0.5 kg/m³ (in sigma-t units).

3.4. Turbidity and Other Features of the Near-Shore Zone

Overall, our field measurements indicate that the near-shore zone is typically well mixed in the vertical. Consequently any input of riverine and wastewater discharge becomes uniformly mixed over and trapped within the near-shore zone, which extends to a water depth of 5-10 m within a distance of a few kilometres from the shore. Owing to relatively small volume inputs from land-derived discharge, mixing within the near-shore zone operates to significantly dilute potentially harmful substances with the ambient water body.

In summer shallow water in northern parts of the study region become dynamically isolated from the southern deeper parts. In this period, inflow from the Barker Inlet/Port River system can become trapped in this region with the potential risk of the development of local harmful algae blooms or the introduction of other diseases. An exchange between the shallow near-shore zone and deeper water takes place during winter in form of a local gravitational overturning circulation. During this period, land-derived water can potentially pollute deeper portions of the Gulf. For instance, during this period, a noxious weed currently overtaking the Port River, known as – caulerpa taxifolia – could be introduced to large parts of Gulf St. Vincent where it could severely affect the state’s wild seafood industry.
Our measurements showed that elevated turbidity levels were confined to the near-shore zone. Turbidity levels observed varied substantially in time (both on synoptic and seasonal time scales) and space in response to seasonal variations of coastal run-off of turbid water and swell-induced local re-suspension of bed sediment. Generally, turbidity levels were higher (1-2 NTU) after peak rainfall events such as in October 2003 compared with “dry” months such as February 2004. In vicinity of the Torrens River outlet, turbidity levels increased to high values >10 NTU after substantial rainfall events in May and June 2004. During these times, our mooring data suggest that incident swell operates to keep finer sediment previously introduced by riverine discharge in suspension. Further evidence of this is the frequent observation of highly murky water and deposition of fine sediment along the beach after storm events in winter. Our data suggest that the combined effect of local discharge of fine sediment and wave-induced resuspension can sustain elevated turbidity levels in the near-shore zone over several weeks. In contrast to this, months of low precipitation such as February 2005 were largely void of elevated sediment levels, which can be related to absence of coastal run-off. An exemption to this was our observation of a major turbidity event in the near-shore zone off Hallett Cove Beach that was presumably associated with the release of sewage into this zone. During this event, turbidity increased to significant values of ~100 NTU over a period of ~10 days. The impact of such events on the health of seagrass and other marine habitat is unknown.

Findings of our field surveys are biased both temporally and spatially. Moreover, our moored measurements were not designed to capture the energy of incident swell. Therefore, on the basis of our field data alone, it is often difficult to tell whether observed turbidity events be the effect of local or remote riverine sediment supply into the coastal zone, swell-induced re-suspension or a combination thereof. We therefore hope that the mechanisms inherent with the observed turbidity events and the fate of turbid plumes will be revealed in the hydrodynamic modelling sub-task 2 of this study, which predicts the dispersion of coastal river-derived sources including effects of local swell-related bed shear stresses. Modelling will also help to understand the net drift observed at our mooring locations in response to atmospheric forcing.

3.5. Recommendations for Future Research

Clearly, understanding of the flushing of Adelaide Metropolitan waters requires the knowledge of the Gulf-wide circulation including seasonal and year-to-year variations, not available so far. Therefore, further hydrographic field observations are required on a Gulf-wide scale that, in conjunction with hydrodynamic modelling, can provide a complete picture of the circulation in Gulf St. Vincent and how this modifies the water mass characteristics along the Adelaide Metropolitan coast. Furthermore, our field surveys in Adelaide coastal water had some temporal gaps in March-April and June-July, which were unavoidable owing to budget constraints. These are the times when a significant increase and decrease in salinities of ~1 psu occurs. Future hydrographic field surveys are required to fill in these temporal gaps.

In terms of potentially disastrous effects on water quality in Adelaide coastal waters, such as importation of the toxic weed caulerpa taxifolia, future research clearly needs to focus more on the exchange between Port River and Barker Inlet with the adjacent Gulf. This also requires a careful monitoring of water quality in this region both during summer and winter. Reduced light levels associated with turbidity events occurring in the near-shore zone might have detrimental effects on the water quality and the health of seagrass. We observed a transient turbidity event with peak levels of 100 NTU over a period of ~10 days. Further (ecologic) research is required to understand effects of such transiently significantly reduced light levels on seagrass health.
References


