Final Report: A0074 - Monitoring and Assessing Salinity and Temperature Variations in Hervey Bay

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Executive Summary

This report documents five hydrographic surveys that were conducted in Hervey Bay during September 2004, August 2007, December 2007, May 2008 and June 2008. Four of those were funded by the BMRG activity A0074 - *Monitoring and Assessing Salinity and Temperature Variations in Hervey Bay*. Each survey covered an area of about 4000 km^2. A total of 269 vertical temperature, conductivity and depth (CTD) profiles were collected on a sampling grid of approximately five nautical miles in both longitudinal and latitudinal direction.

The hydrographic situations observed document the existence of a hypersalinity or maximum salinity zone along the western region of Hervey Bay in four out of five surveys. The surveys were conducted during a period of variable freshwater supply from precipitation and river discharge which together with evaporation influence salinity within Hervey Bay. The Mary River is the main tributary in the region supplying most of the total river discharge to Hervey Bay.

Two particular notable rainfall events took place during August 2007 and May/June 2008, and this report documents the response of Hervey to those events. The August 2007 hydrographic survey followed a rainfall event which had no significant basin-wide impact upon the hypersalinity zone. In contrast, the May/June 2008 rainfall event resulted in the erosion of the hypersalinity zone. In both cases, the Mary River discharge was about the same. The difference in the basin-wide response is most likely due to the more wide-spread rainfall in May/June 2008 which pre-conditioned the Bay and lowered salinity throughout. Mary River discharge subsequently resulted in a complete erosion of the salinity maximum zone.

The data reported in this document link river catchments and processes to a coastal system. Changes in river discharges are impacting directly upon the hydrographic structure of Hervey Bay.

Acknowledgement

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1. Introduction

This report presents an assessment of the hydrographic conditions of Hervey Bay, Queensland and documents data that were obtained during four hydrographic surveys into the bay. The surveys were conducted during August 28-30 and December 4-7, 2007 as well as May 26-27 and June 16-18, 2008.

A total of 269 conductivity, temperature and depth (CTD) profiles are reported which were recorded with a Sea-Bird Electronics SBE 19plus SEACAT Profiler and in one instance with an Falmouth Scientific Instrument CDT. These snapshots of the hydrographic characteristics of Hervey Bay provide a first comprehensive overview of the physical conditions that determine to a large degree the environmental health of a unique marine ecosystem.

The data supports previous findings reported by Ribbe (2006) and Ribbe et al. (2008) and inform the future development and application of ocean models for this region. The previous findings are briefly reviewed in the following Section 2 describing the background to this report. This is followed by a discussion of each of the hydrographic surveys in Section 3, a discussion of the findings in Section 4, and a brief summary in Section 5.

All the data recorded and discussed in this report are provided in electronic format via CD-Rom in the annex to this report.

Of particular interest to the region is the impact of variable freshwater supplies into the bay from precipitation and river-run-off, primarily via the Mary River in the south and the Burnett River in the north. Changes of freshwater supply result from natural climate variability, which is documented as high for the study region (e.g. Murphy and Ribbe 2004), and from utilisation of rainfall and river flows in catchments. Consumption may be due to agricultural usage or supply of freshwater to meet the needs of a growing population in southeast Queensland. The variability in freshwater discharges is potentially linked to changes in the hydrographic structure of the bay which in turn may be associated with changes in the marine ecosystem and impacts on fisheries. For example, there is well documented evidence of the relationship between freshwater supplies and fisheries for a number of marine and estuarine species but the exact mechanisms are poorly understood (Staunton-Smith et al. 2004; Loneragan and Bunn, 1999). A direct link between freshwater supplies and impact on fisheries is not established for the study site; however, the Hervey Bay region is an important spawning region for fisheries (Ward et al. 2003). It is contributing to a Queensland commercial fishery that is valued at about $300 million (ABARE 2008) and attracts in recent years significant investments in expanding aquaculture.

In this report, the hydrographic properties temperature, salinity and density sampled during five field surveys (four directly funded through this project) are being discussed and the physical response of Hervey Bay to changes in the freshwater balance addressed. The key results documented in this report include:

- The climatological freshwater balance between precipitation, evaporation, and runoff for Hervey Bay indicates that the hydrographic structure of the bay is likely to resemble that of an inverse estuary;
- In four out of five surveys evidence of a hypersalinity zone along the western shore is found confirming that Hervey Bay could be classed as an inverse estuary;

- A significant wide-spread rainfall event during May/June 2008 and a survey prior and after that event documents significant changes in the hydrographic structure of the bay;
- Significant Mary River discharge lowered salinity along the western coast of Hervey Bay during June 2008;
- The June 2008 survey documented remnants of a hypersalinity zone that was eroded due to high river run-off and precipitation but is potentially the cause of elevated densities within the interior of Hervey Bay; and
- The data indicates the existence of density driven or gravity current outflow from Hervey Bay into the open ocean.

2. Background

Although Hervey Bay has been recognised as an important marine system and is part of the Great Sandy Marine Park, little is known about the physical processes that drive marine environmental conditions in the bay. The only assessment of the physical conditions within the bay prior to this report is published by Ribbe (2006). This paper reports data and the analysis of an early spring 2004 survey. The survey traces a subsurface salinity maximum that was found in earlier studies within the East Australia Current east of Fraser Island to the shallow southwest regions of Hervey Bay (Middleton et al. 1994). These regions are identified as the most likely source region for locally produced dense and saline Hervey Bay Water.

The hydrographic conditions reported by Ribbe (2006) are characteristic for inverse estuaries and bays. In these situations, saline and dense water exits the system below an incoming layer of less dense and saline surface water flowing toward the coast. It is in particular the balance between freshwater (precipitation, river-runoff) and evaporation that leads to inverse estuarine circulations. By utilising a simple box model, mean evaporation rates and historical river run-off data, Ribbe (2006) demonstrated that the inverse conditions are likely to dominate throughout the year and are a climatological feature of this estuary that is not limited to the dry season of the year. It may even persist due to long-lasting drought, declining rainfall observed in coastal eastern Australia for the last decade, and continued climatic changes impacting upon ocean circulations (e.g. Cai et al. 2006).

Ribbe (2006) also provides a first assessment of the water residence time for Hervey Bay. This is defined as the time it takes to replace all water within the bay with new incoming ocean water. It can also be referred to as a flushing time scale. A mean evaporation rate results in a time scale of about 90 days and using climatological maximum and minimum values for evaporation yields a range of 64 days to 149 days. Subsequent simulations carried out with a three-dimensional coastal ocean circulation model confirmed the range of residence times but also provided insight into the spatial variability of this time scale (Ribbe et al. 2008). For example, with predominate easterly wind, water in the eastern part of the bay is renewed very quickly within the first 2-3 days, in the western part within about the first two weeks and in the interior of the bay only after several weeks. A significant limitation of these modelling studies is the idealised conditions that were assumed for model forcing and validation but are addressed in future model developments and applications.

The data in this report confirm the previous finding reported by Ribbe (2006), but also allow for significant new insight in particular in regards to the response of the bay to severe rainfall events. One such event is the significant storm and rainfall event at the end of May 2008. A survey in progress during that time had to be aborted due to adverse weather conditions in the Bay. However, this event provided a unique opportunity to observe the response of the Bay to a significant freshwater input. A follow-up survey about two weeks after the storm event documents a complete reversal of the climatologically characteristic inverse conditions.

The description in the following section is a summary of the research that has been published by Ribbe (2006) and Ribbe et al (2008) providing a framework for the data represented in this report.

2.1 Hervey Bay

Hervey Bay (Figure 1) is located on the continental shelf and situated to the south of Great Barrier Reef Marine Park off the coast of sub-tropical southeast Queensland, Australia. It covers an area of about 3000 km^2 and its average depth is about 20 m (Figure 1). The main exchange of water with the open shelf and ocean occurs in the north where the shelf is about 90-100 km wide. In the east, the bay is separated from the open ocean by Fraser Island which is the world‘s largest sand land. In the south, it is connected with the open ocean via a narrow, about 90 km long and shallow system of channels, the Great Sandy Strait and an eastward facing gap of about 2 km width south of Fraser Island. The Mary, Burrum, Elliott, and Burnett rivers drain into the Bay. The Mary and Burnett Rivers are the main sources for river water discharges with the Burrum and Elliott having only a small catchment area. The Mary River mouth is located at the northern end of the Great Sandy Strait and freshwater is drained into the southern parts of Hervey Bay and southward into the Strait itself. The mouth of the Burnett River is at the north of the study area. The bay came into existence about 7000-8000 years ago with the flooding of the coastal regions due to global sea level rise after the termination of the last ice.

The climate of the Hervey Bay region is subtropical with predominantly high *monsoonal* summer and low winter rainfall. Climate is also characterised by significant interannual variability in rainfall (e.g. Murphy and Ribbe 2004). Climatological information in terms of mean precipitation, evaporation, and total river run-off is shown in Table 1. These are averages from three rainfall observation locations, i.e. Bundaberg and Sandy Cape in the north, and Urangan in the south of the Bay. This data is presented since it contributes to the freshwater balance of the bay and impacts upon its general circulation. The mean or climatological data is compared to that recorded during the surveys reported in this document. Recent observations indicate that the climate of the region is rapidly changing and is characterised by significant downward trends in rainfall (Shi et al. 2008), upward trend in surface air temperature (Beer et al. 2006) and shifts in ocean climate zones (Lough 2008). The key climate drivers controlling the rainfall delivering weather systems are primarily the Austral Asian Monsoon circulation and the Easterly Trade winds.

Systematic research into the circulation and hydrographic characteristics of Hervey Bay is lacking. Many of the previous studies support its status as an important marine ecosystem, whale sanctuary, focus upon its sedimentary history, and its importance for fisheries (Preen 1995; Preen et al. 1995; Preen and Marsh 1995; Moss and Kocovski 1998; Chaloupka et al 1999; Campbell and McKenzie 2004; Boyd et al 2004; Ward et al. 2003). The studies report little if anything at all about physical conditions of the bay that are clearly the key determinants of marine ecological systems and interact with biological, chemical and sedimentary processes. Clear knowledge of the physical marine processes, the estuarine classification of the bay in oceanographic terms and the impact of natural climatic variability and climatic trends through changes in rainfall, river runoff, sea temperature and wind, for example, is lacking for a marine environment that is so unique.

2.2 Hydrographic survey in September 2004

The survey reported by Ribbe (2006) provided an overview of the temperature and salinity distribution from sampling the hydrographic properties at 46 locations throughout the bay (see Figure 2-5).

Temperature is larger toward the northern open ocean, western and eastern boundary region of the bay, and cooler water occupies the interior of the bay (Figure 3). Temperature ranges from northern surface values of about 21.6 ^oC to southern subsurface values of about 20.4 ^oC. Salinity is found to be higher in the south eastern region of the Bay (> 36.9 ppt) and decreases toward the centre and open ocean of the bay (<35.6 ppt). Density increases with depth with larger values in the south (> 25.8 $kg \cdot m^{-3}$) and decreases toward the north (<25.0 $kg \cdot m^{-3}$). There is some indication of a gravity or density-driven flow away from the western boundary and toward the interior north of Hervey Bay. At 24^o 50′ S, for example, a distinct density (and salinity) gradient is observed that close to the seafloor decreases in density (and salinity) from the western boundary toward the open ocean. This indicates that the mechanical energy input from tides and winds, which tends to mix shallow coastal regions uniformly, is not sufficient in eroding a density stratification that is likely to be maintained by buoyancy changes due to heat and freshwater fluxes. Basin averages for temperature, salinity and density are shown in Figure 6. Salinity and density decrease from south to north (Figure 6, left column) and west to east (Figure 6, right column). Temperature is slightly higher in the north (Figure 6, left column) and east (Figure 6, right column).

A more detailed analysis of the data recorded during September 2004 is presented by Ribbe (2006) linking the observed hydrographic structure to the hydrological cycle in the region. It identifies the Bay as an inverse estuary which is characterised by a maximum salinity zone along the western shoreline of the Bay. This high salinity water is discharged into Hervey Bay and the open ocean along the sea floor. The production of high salinity water is directly linked to the Burnett/Mary catchments and freshwater discharges due to river runoff, since it is the balance between freshwater runoff, precipitation and evaporation over the Bay that drives the production of saline water and the maintenance of a hypersalinity zone. The exact role of thermal forcing due to cooling in shallow coastal regions during winter or night time is not clear but should contribute to the formation of the density gradient with depth, possibly aiding in driving a gravity current toward the open ocean.

The September 2004 situation informed the planning and design of the hydrographic surveys described in the following sections of this report. Hydrographic conditions within the Bay at large and in the near-shore regions are highly variable undergoing significant variations in salinity, temperature, circulation and other environmental variables that define the marine environment. These changes are due to natural (climate) and anthropogenic factors (agriculture, constructions, etc.). In particular, further data are required to document the production of saline near shore water in a low rainfall, 'drying' climate which is further exacerbated by reduced river run off and the utilisation of water in the catchments (agricultural use, dams, etc).

2.3 Experimental modelling studies

The production of high salinity Hervey Bay water due to the particular regional freshwater balance is aided by the slow water renewal time scale that characterises the bay. A prolonged residence of water within the bay allows salinity to increase when evaporation is larger than the freshwater gain. This residence time is controlled by the tidal and wind driven exchange between Hervey Bay and open ocean water and the bathymetry of the bay itself. A basin average time scale of 90 days was estimated by Ribbe (2006).

A first assessment of this spatially varying time scale is provided by Ribbe et al. (2008) from simple hydrodynamic modelling. An example of typical water renewal time scales using a model with idealised westerly and easterly wind forcing is presented in Figure 7. Water renewal time scales range from 10-15 days along the near-shore region to about 70-80 days within the interior of the Bay. See Ribbe et al (2008) for more detail about the model and its application. The model is currently being developed further and the data from this BMRG funded survey project will aid its continued development.

2.4 Objectives of activity

The overall objective of the activity is to provide new insight into the variable hydrographic structure of Hervey Bay and possibly monitor the response to changing freshwater flows. In some detail this includes:

- conducting and monitoring hydrographic conditions in Hervey Bay during several surveys,
- providing an assessment of marine climatological conditions, and
- establishing an environmental database aiding future impact assessment and policy making processes.

The project delivers

- a comprehensive database of hydrographic observations consisting of about 310 CTD profiles which is available to the public;
- a report that links the database with other climatological information (e.g. rainfall, river discharges);
- an assessment of the impact of climate variability and change (i.e. through rainfall and river discharges); and
- a database that will potentially support the continued development of a comprehensive ecosystem model for Hervey Bay.

Some of the findings presented in this report have already been presented to the public and a full list of outcomes in terms of seminars and presentations and national and international conferences is presented in the appendix to this report. In the following section 3, all the surveys and data recorded are discussed in detail. This followed by a discussion in Section 4 that compares field trips and places the data into the climatological context. A summary concludes the report in Section 5.

3. Hydrographic Surveys

A total of four surveys were conducted during the period of this project and are reported in this document. All cruises commenced and terminated in Bundaberg Port and utilised the fisheries research vessel FRV Tom Marshall which is managed by the Queensland Department of Primary Industries and Fisheries (DPI&F). The FTV Tom Marshall is a research catamaran cruising with an average speed of about 17-18 kn between sample locations which allows for a fast survey of the bay. The distance between sample locations in all surveys reported here is about 5 nm in both longitudinal and latitudinal direction. The surveys took place during late winter (August 28-30) and early summer (December 4-7) in 2007 and during later autumn (May 26-27) and winter (June 16-18) in 2008. This is a total of 12 observing days during which a total of 269 CTD profiles were recorded. Including the September 2004 survey, results in a temperature, salinity, and density data base of 319 profiles.

Data recorded during individual surveys are presented and discussed in the following sections of this report. The data was recorded using a Sea-Bird Electronics SBE 19plus SEACAT Profiler and Falmouth Scientific Instrument CTD in August 2007. For this report the raw data has been quality controlled and erroneous data has been removed. All data on standard depth levels is provided as text files with the report and can readily be graphed using any common data spreadsheet.

For better scientific visualisation, presentation and the analysis documented in this report, the data has also been converted into data common data format referred to as NetCDF. This is a set of software libraries and machine-independent data formats. It supports the creation, access, and sharing of array-oriented scientific data and is documented by Rew et al (1997). The software is available via the world wide web from the following webpage http://www.unidata.ucar.edu/software/netcdf/. The data has then been visualised and analysed using the scientific data visualisation and analysis tool referred to as FERRET. It is developed and maintained by staff at the NOAA Pacific Marine and Environmental Laboratory in Seattle, USA, and the software is available via http://ferret.wrc.noaa.gov/Ferret/.

In the following sections, data from individual cruises are presented and discussed. For completeness all data are shown as latitudinal sections (i.e. east to west) across the Bay. This is complemented with longitudinal and latitudinal basin averages that in particular in the case of salinity and density identify the inverse nature of the bay and the indication of a possible density driven or gravity outflow from the Hervey Bay. This section is then followed in Section 4 by a discussion of depth averaged data comparing the individual cruises.

3.1 Survey August 2007

This survey follows the only other one completed for the study region in September 2004 and which is documented by Ribbe (2006).

3.1.1 Overview

Table 3 summarises the locations sampled during August 28-30, 2007. A total of 65 temperature, salinity and density profiles were collected (note this includes 8 repeat profiles) at 57 locations (see Figure 8 for sample locations; locations 47-53 and 21 were surveyed twice). The locations sampled are identical to those sampled in September 2004; however, the sections across the bay in the north and south have been expanded to the west and east in order to better trace the existence of a possible salinity maximum zone. Prior to the cruise a major rainfall event took place but affected only the very southern part of the Bay where rainfall was larger than 181 mm for the month of August. Rainfall in the Bundaberg and Sandy Cape location was only 59 and 57 mm respectively, giving a Hervey Bay region average of about 99 mm (see Table 1).

3.1.2 Temperature distribution

The observed temperature distribution along latitudinal cross-sections of the bay is shown in Figure 9. Temperature is decreasing from the north east of the Bay (larger than 21.2 ^{o}C) to the south west (lower than 19.4 ^{o}C). This equates to horizontal temperature change across the bay of about 1.8 ^{o}C near the surface. In the vertical, a temperature stratification is indicated throughout most of the western section of the Bay, while the western stratification is not as evident.

3.1.3 Salinity distribution

The most striking feature of the salinity distribution throughout Hervey Bay is the presence of a high salinity or hypersalinity zone (Figure 10) that was already alluded to by Ribbe (2006) and is shown in Figure 4. It should be noted that this survey took place after a very dry July and some major rainfall events in August, but which only affected the very south of the region. This is further discussed in Section 5, however, the observed salinity structure very clearly reveals the presence of a hypersalinity zone with higher salinity in the west and lower salinity in the east. Salinity increases from north to south and surface to bottom throughout the bay. Within the hypersalinity zone, salinity increases from a northern minimum of about 35.9 ppt at 24^{o} 40′ S to a maximum surface level value of larger than about 36.3 ppt in the central western part of the bay at 24^{o} 45′ S. It then decreases within the salinity maximum zone to about 35.9 ppt in the southern region. This zone is further more characterised by vertical stratification to about 152.7 ^{o}E at 24^{o} 50′ S. East of that longitude, the water column appears to be vertically mixed with only weak vertical gradients in temperature and salinity. The salinity gradient across the bay is about 1.4 ppt, i.e. from a minimum of about 35.1 ppt in the northeast to a maximum of about 36.5 within the southwest of the salinity maximum zone.

3.1.4 Density distribution

The densest surface and subsurface water is found within the hypersalinity zone along the western region of the bay (Figure 11). Density is larger than 25.9 kg·m^{-3}

at 24^{o} 50′ S which compares to surface density of about 25.5 kg·m^{-3} to the north and south of the western hypersalinity zone. There is evidence of a clear vertical density stratification which persists throughout the bay but most evident within the salinity maximum zone. Density in the bottom layer is larger than 25.9 kg·m^{-3} and 25.8 kg·m^{-3} in the west at latitude 24^{o} 50′ S and 24^{o} 55′ S. The across-bay density gradient is about 1.3 kg·m^{-3}, i.e. from a minimum of about 24.6 kg·m^{-3} in the north east to a maximum within the salinity maximum zone of about 25.9 kg·m^{-3}.

3.1.5 Basin averages

The longitudinal and latitudinal basin averaged hydrographic structure of the bay is shown in Figure 12. While salinity is rather uniform, density decreases from the southern part of the bay toward the north, while temperature increases from colder water in the south to the warmer water in the north (Figure 12, left column). In longitudinal direction, the higher salinity and density associated with the hypersalinity zone of the bay is evident. This water is also cooler than water outside the hypersalinity zone. Both high salinity and low temperature drive density and possibility a density-driven or gravity current toward the northern opening of the bay. The across the bay mean latitudinally (north to south averaged values) averaged salinity, temperature, and density difference is about 0.7 ppt, 0.9 ^{o}C, and 0.8 kg·m^{-3}. Mean longitudinal differences (west to east averaged values) are about 0.1 ppt, 0.2 ^{o}C and 0.2 kg·m^{-3}.

3.2 Survey December 2007

Both previous hydrographic surveys documented in this report where carried out during the month of August (2007) and September (2004) and both clearly documented the existence of a hypersalinity zone. The December survey was extended by about 10 nautical miles northward to further trace the possible presence of a hypersalinity zone. Climatological rainfall is generally low and evaporative loss about twice as large during late winter and early spring in this region (see Table 1). The resulting local freshwater balance (evaporation minus precipitation) is in favour of conditions that are prone to support the formation of a hypersalinity zone with in the Bay.

Total evaporative freshwater loss for August to September is about 211 mm compared to a gain of only 87 mm. Climatological river runoff during this period is about 56820 ML which would be equivalent to an additional rainfall of about 20 mm if spread across the Bay. In December evaporation outweighs precipitation by about 63 mm and run-off is about 78112 ML (i.e. 26 mm if spread across the bay), only marginally larger than during the August/September period.

3.2.1 Overview

All sample locations are shown in Figure 13. At total of 96 CTD profiles were taking at 87 locations. A summary of sampled locations is provided in Table 4.

3.2.2 Temperature distribution

The northern part of the bay is strongly stratified with a warm shallow surface layer overlaying colder water (Figure 14). Within the surface, temperature is larger than 25.9 ^{o}C in the west of the Bay decreasing to about 24.8 ^{o}C in the east along the northern region. From north to south, temperature decreases to a minimum of about 24.7 ^{o}C at 24^{o} 50′ S. It then increases to larger than 25.8 ^{o}C toward the south west of the bay. An interesting feature to note is the sub-surface temperature minimum of less than 23.8 ^{o}C along the most northern section, the coldest temperature observed during this survey.

3.2.3 Salinity distribution

Salinity is found to be at a minimum along the most northern section (Figure 15) where salinity values are as low as 35.5 ppt. The minimum in sub-surface salinity is located in the same region that is characterised by the lowest temperature observed during the survey (Figure 14). Some indication of a salinity maximum zone with values of larger than 36.2 ppt is evident in the west of the Bay. This salinity maximum zone increases further southward and salinity is increasing throughout the whole of Hervey Bay. It is at a maximum near the shallow western boundary of the Bay and in the south with values of larger than 36.2 ppt. The latitudinal surface salinity gradient is about 0.7 ppt. Clearly, Hervey Bay is again characterised by a hypersalinity zone which has been observed in previous surveys. Since water is supplied primarily from the north of the Bay, salinity can only increase due to the access of evaporation over precipitation. There is also an indication of slightly increased salinity along the eastern boundary of Hervey Bay at 24^{o} 55′ S and 24^{o} 50′ S and sample locations 31 and 47, i.e. within Platypus Bay just to the west of Fraser Island.

3.2.4 Density distribution

A shallow layer of low density water overlies a layer of denser water in the north leading to a vertically stratified water column (Figure 16). The primary driver of this low density seems to temperature (see Figure 14). Density is increasing toward the south and Hervey Bay is clearly occupied by saline and high density water compared to the lighter, fresher water that is flowing into the Bay along the north. Density ranges from less than about 23.5 kg·m^{-3} in the northwest to about 24.1 kg·m^{-3} in the south, i.e. a gradient of about 0.6 kg·m^{-3}. An interesting feature to note is the high density water that occupies the deeper layers at the northern end of the Bay. Here density is larger than 24.0 kg·m^{-3}. This maximum coincides with the minimum in temperature and salinity identified above (Figure 14 and 15).

3.2.5 Basin averages

Temperature, salinity and density have been averaged in longitudinal and latitudinal direction to obtain basin averages (Figure 17). Note that Hervey Bay's longitudinal locations range from about 152.5 ^{o}E to 154.1 ^{o}E (right column of Figure 17). The region within those bounds is occupied by dense, saline and cool water compared to the regions surveyed outside of the Bay. In latitudinal direction (north to south), dense, saline, and warmer water occupies the southern region of the bay. The north south differences are about 4 ppt, 0.2 ^{o}C and 0.2 kg·m^{-3} for surface salinity, temperature and density respectively.

In summary, a zone of hypersalinity is found along the western boundary of the surveyed region with salinity increasing toward the south leading to elevated salinity throughout Hervey Bay.

3.3 Survey May 2008

During May 28-29, 2008, a planned four day survey of the region had to be terminated after only two days due to adverse weather conditions. A significant and unexpected storm event took place which resulted in the delivery of about 260 mm (averaged across the region) in just four days, i.e. the combined total monthly falls (Table 1) for May (179 mm) and June (58 mm) were delivered within the last days of May and early June. This was the only rainfall event for the month of May and June. The May survey, together with a follow-up survey in June, documents the response of Hervey Bay to a significant rainfall event. A key difference of the May 2008 rainfall event compared to the August 2007 one is the widespread delivery of rainfall across the region. Rainfall of similar magnitude was recorded for Bundaberg, Sandy Cape and Hervey Bay Airport/Urangan in May which is indicative of the wide spread impact upon the whole of the Bay. During August 2007 only Hervey Bay Airport/Urangan documents a 180 mm rainfall event.

3.3.1 Overview

Prior the onset of the storm, a total of 49 CTD profiles were obtained at 49 locations in the northern region of the survey domain (Figure 18). A summary of sample locations, time and charted depths is presented in Table 5. For this field survey, the study domain was expanded to the north of Hervey Bay in order to chart the size of the expected hypersalinity zone. This was observed during all previous cruises into the region with an indication of a continuation further to the north.

Although the May 2008 survey had to be terminated earlier than expected, an extensive hypersalinity zone was found along the western shore line. Unfortunately, it was not possible to trace this zone all the way into the southern sections of Hervey Bay. However, the two most southern sections of this survey overlap with the two most northern sections during the follow-up survey in June 2008 which is described below. It is these two surveys that document the reversal of an inverse system to a full mixed system or homogenised Bay in terms of its hydrographic structure. It is characterised by the absence of a hypersalinity zone during June which is largely due to wide-spread precipitation, high freshwater discharges primarily from the Mary river into the southern bay and along the western regions northward, and mixing throughout the bay due to tides and winds.

3.3.2 Temperature distribution

The northern part of the Bay region is characterised by a horizontal temperature gradient with temperature decreasing toward the west from about 22.6 ^{o}C - 23.6 ^{o}C to less than about 20.4 ^{o}C - 20.6 ^{o}C (Figure 19). Vertically the water column is mostly mixed and only weak stratification indicated at depth in the eastern and southern region of the survey. Temperature along the two southern sections is lower than along the two northern ones and temperature ranges from about 21.8 ^{o}C (southern region) and 22.2 ^{o}C (northern region) in the east to about 19.2 ^{o}C (southern region) and 20.4 ^{o}C (northern region) in the west.

3.3.3 Salinity distribution

A hypersalinity zone is observed in the west of the surveyed region. Salinity increases from about 35.3 ppt in the east to larger than 35.7 ppt along the most northern sections (Figure 20). A maximum salinity within the Hervey Bay hypersalinity zone of larger than 36.0 ppt is observed along latitude 24^{o} 35′ S. The salinity maximum zone increases in size southward with the high salinity area (red shading) expanding eastward. Some indication of salinity stratification with depths is evident in the west along each of the sections.

3.3.4 Density distribution

Density is at a maximum within the hypersalinity zone reaching values of about 25.3 kg·m^{-3} at 24^{o} 35′ S and 25.4 kg·m^{-3} at 24^{o} 40′ S (Figure 21). A weak stratification is evident along all sections and close to the seafloor, which possibly is indicative of a density driven gravity flow of saline water away from the zone of hypersalinity.

3.3.5 Basin averages

The basin averages in longitudinal (north to south average) and latitudinal (west to east average) direction are shown in Figure 22. The hypersalinity zone is clearly identifiable with higher salinity and density in the south (Figure 22, left column) and west (Figure 22, right column). In the south water is colder than in the north toward the open ocean water.

3.4 Survey June 2008

The June 16-18, 2008 hydrographic survey of Hervey Bay followed a major storm and rainfall event in the Hervey Bay region. This event resulted in the erosion of the hypersalinity zone observed in May 2008. The June 2008 survey documents the hydrographic structure of Hervey Bay which resembles that of a typical estuary or coastal bay with salinity at a minimum near the western coast and throughout Hervey Bay and increasing towards the open shelf and ocean in the north.

3.4.1 Overview

A total of 59 CTD profiles (Table 6) were recorded at 59 stations throughout Hervey Bay (Figure 23). The two most northern sections from this survey overlapped with the two most southern sections surveyed during the May field trip.

3.4.2 Temperature distribution

Temperature is high along the northern sections across the bay and decreases from a maximum of about 21.4 ^{o}C to a value of less than 20.4 ^{o}C in the south of the bay (Figure 24). Temperature is generally higher in the east than in the west of the bay establishing an east to west temperature gradient of about 2 ^{o}C at 24^{o} 40′ S, of less than 0.4 ^{o}C at 24^{o} 55′ S and none along 25^{o} 10′ S, where the bay is shallow and appeared to be homogenised horizontally and vertically.

3.4.3 Salinity distribution

The most striking feature observed in the salinity distribution is the absence of a hypersalinity zone in the west of the bay (Figure 25). Instead, the salinity gradient is reversed if compared to previous surveys and salinity increases away from the coast and toward the open ocean. A sharp horizontal gradient is observed in coastal regions with near coast salinity decreasing to values of less than 34.0 ppt at 24^{o} 40′ S. Throughout Hervey Bay, the water column appeared homogenised in salinity with a value of about 35.15 ppt. Only along the most southern section located at 25^{o} 10′ S, values of about 34.1 ppt are recorded.

3.4.4 Density distribution

Density along the two most northern sections is at a minimum near the northwest coast with values of less than 24 - 24.5 $kg{\cdot}m^{-3}$ - 25.4 $kg{\cdot}m^{-3}$ (Figure 26). Along the most southern section surveyed similar low density values were observed. Throughout the bay the water column appeared to be homogenised with density of about 24.6 $kg{\cdot}m^{-3}$ to 24.7 $kg{\cdot}m^{-3}$. There is an indication of a density maximum zone with density above 24.7 $kg{\cdot}m^{-3}$ located at about 152.6 ^{o}E and 24^{o} 50′ S which extends through the water column. This can also be seen in salinity with values larger than 31.15 ppt (Figure 25). In both directions, i.e. west- and eastward, density as well as salinity decreases. Low density in coastal areas is most likely a result of high river discharges. The slightly elevated levels in both density and salinity (Figure 25) could be interpreted as the remnants of a hypersalinity zone that has characterised Hervey Bay during previous surveys. See discussion of this feature in the following Section 4.

3.4.5 Basin averages

The basin averages in longitudinal (north to south average) and latitudinal (west to east average) direction are shown in Figure 27. Lower temperature, salinity, and density clearly characterises the south and west of the bay. Both the minima in density and salinity are likely to be a result of the entry of freshwater in the northwest from the Burnett River (although very small) and in the south from the Mary River.

3.5 Climatological Data

In this section, the wind, precipitation and river-discharges are briefly reviewed for the period January 2003 to June 2008. Both precipitation and river-discharge control together with evaporation the local freshwater balance, while both wind and tides influence the circulation within the Bay (see e.g. Ribbe 2006, Ribbe et al. 2008)

3.5.1 Precipitation

Climatological precipitation data are summarised in Table 1. Total monthly rainfall is high during the southern hemisphere summer months and low during winter. Some of the data has already been discussed above. The annual net freshwater balance (evaporation minus precipitation) favours inverse conditions within the bay with evaporation exceeding precipitation by about 392 mm. Climatological gain by river run-off is about 1116791 ML or if spread across the bay would equal to about 370 mm.

Year-to-year rainfall variability is high and total monthly rainfalls are primarily delivered over a period of just a few days. An example is the May to June 2008 rainfall event already referred to above. In Figure 28, monthly total rainfall for the Hervey Bay region is shown during the period 2003 – 2008. This is obtained as the average from the rainfall recorded at Sandy Cape, Bundaberg and Urangan. It documents falls that are high during summer and low during the winter months and that are characterised by significant variability. This applies to yearly totals as well as to monthly values. For example, total falls for the summer/autumn season (December – May) of the years 2003 – 2008 are about 956 mm, 640 mm, 570 mm, 389 mm and 920 mm, i.e. the seasons of 2003/2004 and 2007/2008 are particularly wet compared to the dry years 2005 – 2007

(Figure 27). An example of variations in monthly falls is September. Falls range from a low of only 8 mm in 2003 to a high of 134 mm in 2007 at Sandy Cape (individual rainfall data not shown here).

Hydrographic surveys were conducted for the month of September 2004, August 2007, December 2007, May 2008 and June 2008. During those months, the area average rainfalls for the Hervey Bay region were about 48 mm, 99 mm, 112 mm, 179 mm, and 58 mm respectively (see Table 1). Compared to the climatological mean falls (also Table 1), rainfall was close to the average of 44 mm in September 2004, about twice the average of 46 in August 2007, close to the average of 110 in December 2007, about twice the average of 92 in May 2008, and slightly larger than the average of 81 in June 2008. The larger than climatological averages are due to severe storm and rainfall events that in August 2007 and May/June 2008 occurred prior to the field surveys.

3.5.2 River discharges

Run-off data are available for four rivers discharging into Hervey Bay. These are the Burnett, Burrum, Elliott and Mary rivers. The data are provided by the Queensland Government Department of Natural Resources and Water. For all the main tributaries, inflow data are most consistent from 1980 onwards and provide a climatological (Table 1) view of likely river discharges into the Bay. Data for individual and total river discharges during the field surveys are shown in Figure 29 and Figure 30.

The 20 year-average monthly total inflow into Hervey Bay reveals that peak inflows are recorded during the months of about February to March (Table 1). These then decline to a minimum discharges during September and October. The month of February shows a very large climatological mean inflow. This is primarily due to two very heavy rainfall events that occurred in February 1992 and 1999 when in both cases more than 2,000,000 ML entered the bay. These two events are well documented in the literature since they have been associated with significant impacts on the marine environment, in particular the loss of sea grasses (Preen, 1995, Preen et al, 1995).

Figure 29 (individual river flows) and Figure 30 (total discharge) show the total monthly inflows into Hervey Bay from January 2004 to June 2008. This is the period for which hydrographic information is now available. During this period, the inflows are in general highly variable with significant departures from climatological mean values. Main flows are recorded during the summer rainfall period (Figure 29). In March 2004, a total Hervey Bay inflow of about 500,000 ML exceeds the 20-year average inflow of about 152,000 by more than a factor of three (Figure 30). Similarly total inflows during the hydrographic survey month of June 2008 and August 2007 exceed the climatological value. During the survey months of December 2007 and May 2008 total inflows are well below the climatological total monthly average.

Most of the freshwater is delivered by the Burnett River in the north and the Mary River in the south of the Bay (Figure 29). The period from about May 2004 to August 2007 is characterised by small river discharges with extreme low flows until about August 2007. Only the month of December 2005 has a total inflow of about 200,000 ML, all other flows are well below 100,000 ML during this 2004 to 2007 period.

4. Discussion

The climate of the Hervey Bay region is characterised by low winter and high summer rainfall and an annual total rainfall of about 1146 mm (Table 1). This ranges from 1265 mm at Sandy Cape, 1100 mm at Bundaberg to 1074 mm at Urangan. In addition to significant year-to-year changes in rainfall, recent climatic trends along the east Australian coast have led to a continued decline in rainfall. Average annual trends in total rainfall for the Hervey Bay region are in the order of more than 40 mm per decade or a total of more than 200 mm in the last 50 years (Figure 31). This is about 20% of the climatological annual rainfall for the region and impacts on the freshwater balance for Hervey Bay.

The climatological balance between freshwater gain due to precipitation and losses due to evaporation for the Hervey Bay region (Table 1) is negative (Table 1). This indicates that salinity within the Bay should be elevated in comparison to those measured in the open ocean and shelf area of the region. This would lead to hypersalinity within the Bay that may persist throughout the year.

In fact, all the surveys conducted in September 2004, August 2007, December 2007, May 2008 and June 2008, clearly support the concept that hypersalinity is a climatological feature of Hervey Bay's marine environment. Only wide-spread precipitation, major river discharge, and strong mixing of the water column during significant storm events could lead to the erosion of the hypersalinity zone. The impact of such an event was observed during the May to June 2008 period. The elevated salinity observed in May 2008 was found to be eroded due storm activity in the following June survey. Yet, the hydrographic survey in June still detected remnants of elevated salinity and density away from the western coast and within the bay.

A comparison of depth-average temperature, salinity, and density between the individual cruises is shown in Figure 32 to Figure 34. Temperature ranges from 20.6 ^{o}C – 21.2 ^{o}C in September 2004, 19.4 ^{o}C – 20.8 ^{o}C in August 2007, 24.4 ^{o}C - 25.6 ^{o}C in December 2007, 20.4 ^{o}C - 23.0 ^{o}C in May 2008 and 19.8 ^{o}C – 21.4 ^{o}C in June

2008 (Figure 32). September 2004 is characterised by a cold water region within the interior of the bay and warm water along the boundary of the bay. In all other cases, an across the bay gradient is observed with warm water dominating the northeast part of the bay with the exception of December 2007, where warm water dominates the western and southern shallow regions of the bay. This is most likely a result of the strong warming the bay experiences during summer which rapidly warms the shallow areas of the bay. In all other seasons rapid cooling overnight may dominate the heat gain during the day in shallow water. In contrast, the deeper ocean regions heat capacity prevents rapid cooling.

In four out of five surveys conducted, a hypersalinity zone within the bay extending toward the western shore characterises Hervey Bay (Figure 33). Maximum depths-averaged salinity is about 36.8 ppt in September 2004, 36.3 ppt in August 2007, 36.2 ppt in December 2007, and 35.9 ppt in May 2008. In June 2008, no hypersalinity zone within the bay is found. Depth-averaged salinity is lower throughout the bay with values smaller than 34.8 ppt along the western boundary. Although these are depth-averaged salinity values, actual observed salinity within the hypersalinity zone reaches values of similar magnitude since the zones are vertically well mixed (see Figures 4, 10, 15, 20, and 25).

The distribution of density observed in all five surveys is characterised by a high density region that in four out of five is linked with zones of hypersalinity (Figure 34). In all these cases, depth-averaged density maximum values are about 25.8 $kg{\cdot}m^{-3}$ in September 2004, 25.8 $kg{\cdot}m^{-3}$ in August 2007, 24.1 $kg{\cdot}m^{-3}$ in December 2007, 25.3 $kg{\cdot}m^{-3}$ and in May 2008. In June, depth-averaged density is largest in what could be referred to as a transition zone between lower density regions toward the west and the open ocean. Maximum depth averaged density within this transition zone is larger than about 24.75 $kg{\cdot}m^{-3}$ (see also Figure 26, second most southern latitudinal section). This transition region is likely to be a remnant of a hypersalinity zone found in May and seemingly to extend into the bay along the western region of the bay. This region is now dominated by low density water resulting from freshwater river run-off that is entering the bay as a result of the end May/early June 2008 storm event.

It should also be noted that during periods the surveys took place, the balance between evaporation and precipitation (Table 1) favoured the establishment or maintenance of a hypersalinity zone. Only two rainfall events occurred with falls well above the climatological mean, but only during the late May/early June 2008 storm event, precipitation was significantly larger than evaporation. In addition, river discharges were well below the climatological mean in three cases but significantly larger in the case of August 2007 and June 2008 (Table 1). Yet, the hypersalinity zone was only absent during the June 2008 cruise.

It is interesting to note the different response of Hervey Bay to the high river run-off events in August 2007 and June 2008. Total discharges into Hervey Bay from all tributaries were very similar during both the August 2007 and June 2008 events (Table 1) with almost all of the total discharges being contributed to by the Mary River (Figure 30) in both cases. During the August event, the hypersalinity zone continued to persist with salinity only slightly reduced in the far southern region of the Bay. However, during the June 2008, the hypersalinity zone was fully eroded and a zone of low salinity spread across the western region of the Bay. The different response of the hydrographic structure of the Bay due to the Mary river run-off is most likely a result of the pre-conditioning of the Bay by wide-spread precipitation. In August 2007, only the southern end of Hervey Bay received significant rainfall but during the June event, rainfall was high across the Bay. In this case, surface water salinity would have been already lowered throughout the Bay by precipitation with the Mary River discharge being important in reducing salinity in the western region of the bay further.

Considering a Hervey Bay surface area of about 3000 km^2, a Mary River discharge of about 300,000 ML (Table 1) distributed across Hervey Bay would equate to an additional 100 mm of rainfall.

The basin wide averages for the bay characterising properties (Table 7) reveal that temperature was at a maximum with 24.8 ^{o}C during the summer month of December 2007 survey driving overall density to a low of 23.92 $kg \cdot m^{-3}$. Lowest salinity is obtained for the month of June 2008 with a value of about 35.09 ppt which is most likely the basin-wide response to high river discharges (Figure 29) and high basin-wide precipitation (Figure 28).

5. Summary

The report summarises the hydrographic observations made during five cruises into Hervey Bay, four of those directly supported by the Burnett Mary Regional Group. The most prominent feature observed during all but one cruise is the existence of a hypersalinity zone along the western region of the Bay. The existence of this zone is a clear response of the system to a freshwater balance that is dominated throughout most of the year by the excess of evaporation over precipitation. The annual climatological values for Hervey Bay indicate that evaporation exceeds the gain of freshwater from precipitation by about 30-35 %. The bathymetry and shape of the bay together with associated slow water exchange times (Ribbe et al. 2008) aid the formation of the hypersalinity zone. Salinity is generally elevated throughout the bay if compared to the open shelf and ocean with values largest in the western region. Mary River water discharges play an important role in contributing to the hydrographic structure of the bay. During a period of high river run-off in June 2008, the hypersalinity was eroded and the salinity gradient across the bay reversed. Salinity was low in the southwest and west and increased toward the north and northeast.

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Figure 22: Basin average salinity [ppt] (top), temperature [T in °C] (middle), and density [σ_t in kg·m^{-3}] (bottom) in latitudinal (left column) and longitudinal (right column) direction during May 28-29, 2008.

Figure 23: Hydrographic sample location surveyed during June 16-18, 2008.

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Figure 25: Salinity [S in ppt] distribution during June 16-18, 2008, at latitude (a) 24° 40′ S, (b) 24° 45′ S, (c) 24° 50′ S, (d) 24° 55′ S, (e) 25° 00′ S, (f) 25° 05′ S and (g) 25° 10′ S. Top left to top right.

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Figure 33: Depth-averaged salinity [ppt] distribution from observations in (a) September 2004, (b) August 2007, (c) December 2007, (d) May 2008 and (e) June 2008. Contour interval is 0.05 ppt and high salinity water regions are shaded in red.

Figure 34: Depth-averaged density [$kg{\cdot}m^{-3}$] distribution from observations in (a) September 2004, (b) August 2007, (c) December 2007, (d) May 2008 and (e) June 2008. Contour interval is 0.05 $kg{\cdot}m^{-3}$ and high density regions are shaded in red.

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Table 1: Hervey Bay Climatological Data for Evaporation, Precipitation and Runoff

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Annual
Evaporation (mm/month)	183	146	133	104	85	132	82	95	116	134	157	173	1538
Precipitation (mm/month)	167	166	139	97	92	81	64	46	41	64	79	110	1146
Runoff (ML)	73100	268080	152768	163572	132306	87462	57061	33981	22839	18505	40903	78112	1116791
Precipitation during surveys (mm/month)					179	58		99	49			112	
Run-off during surveys (ML/month)					9496	294316		295932	2288			17839	

Table 2: Summary of sample locations surveyed in September 24-29, 2004

		Start	Longitude		Start Latitude		
Station	**Date**	**Time**	**Degree**	**Min**	**Degree**	**Min**	**Depth**
Day 1							
2	20/9/04	8:00	152.00	50.00	25.00	10.00	4.50
1	20/9/04	8:40	152.00	45.00	25.00	10.00	9.80
5	20/9/04	9:25	152.00	45.00	25.00	5.00	15.50
12	20/9/04	10:05	152.00	45.00	25.00	0.00	22.80
20	20/9/04	10:57	152.00	45.00	24.00	55.00	20.50
29	20/9/04	11:38	152.00	45.00	24.00	50.00	23.00
37	20/9/04	12:24	152.00	45.00	24.00	45.00	28.00
38	20/9/04	13:26	152.00	50.00	24.00	45.00	27.10
39	20/9/04	14:28	152.00	55.00	24.00	45.00	26.30
40	20/9/04	15:14	153.00	0.00	24.00	45.00	23.00
41	20/9/04	15:58	153.00	5.00	24.00	45.00	31.60
33	20/9/04	16:58	153.00	5.00	24.00	50.00	18.40
Day 2							
17	21/9/04	6:33	153.00	10.00	25.00	0.00	12.70
16	21/9/04	7:09	153.00	5.00	25.00	0.00	18.60
15	21/9/04	7:47	153.00	0.00	25.00	0.00	18.70
14	21/9/04	8:27	152.00	55.00	25.00	0.00	25.70
13	21/9/04	9:10	152.00	50.00	25.00	0.00	22.50
21	21/9/04	9:55	152.00	50.00	24.00	55.00	18.60
30	21/9/04	10:42	152.00	50.00	24.00	50.00	22.20
22	21/9/04	11:55	152.00	55.00	24.00	55.00	20.50
31	21/9/04	13:02	152.00	55.00	24.00	50.00	22.10
23	21/9/04	14:01	153.00	0.00	24.00	55.00	20.50
32	21/9/04	14:47	153.00	0.00	24.00	50.00	26.10
24	21/9/04	15:55	153.00	5.00	24.00	55.00	19.70
25	21/9/04	16:44	153.00	10.00	24.00	55.00	19.50
K1	22/9/04	14:46	152.00	54.70	25.00	14.72	11.70
Day 3							
9	22/9/04	7:15	153.00	5.00	25.00	5.00	13.90
8	22/9/04	7:55	153.00	0.00	25.00	5.00	17.30
7	22/9/04	8:32	152.00	55.00	25.00	5.00	13.40
6	22/9/04	9:22	152.00	50.00	25.00	5.00	17.90
4	22/9/04	10:27	152.00	40.00	25.00	5.00	11.50
3	22/9/04	11:10	152.00	35.00	25.00	5.00	6.40
10	22/9/04	11:51	152.00	35.00	25.00	0.00	12.20
11	22/9/04	12:28	152.00	40.00	25.00	0.00	17.20

Day 4							
18	23/9/04	6:55	152.00	35.00	24.00	55.00	16.20
19	23/9/04	7:32	152.00	40.00	24.00	55.00	18.80
28	23/9/04	8:15	152.00	40.00	24.00	50.00	22.10
27	23/9/04	8:48	152.00	35.00	24.00	50.00	18.30
26	23/9/04	9:35	152.00	30.00	24.00	50.00	13.80
34	23/9/04	10:11	152.00	30.00	24.00	45.00	11.40
35	23/9/04	10:45	152.00	35.00	24.00	45.00	17.70
36	23/9/04	11:32	152.00	40.00	24.00	45.00	22.20
42	23/9/04	12:59	152.00	40.00	24.00	40.00	24.20
43	23/9/04	14:10	152.00	45.00	24.00	40.00	25.70
44	23/9/04	14:34	152.00	50.04	24.00	40.03	30.40
45	23/9/04	15:20	152.00	55.94	24.00	40.04	27.20
46	23/9/04	16:10	153.00	0.03	24.00	40.00	24.70
Day 5							
33B	24/9/04	5:58	153.00	4.99	24.00	49.99	19.30
32B	24/9/04	6:34	152.00	59.99	24.00	49.97	27.10
22B	24/9/04	7:26	152.00	55.00	24.00	55.00	20.10

Table 3: Summary of sample locations surveyed during August 28-30, 2007

		Start	End	Start Longitude		End Longitude		Start Latitude		End Latitude		
Station	Date	Time	Time	Degree	Min	Degree	Min	Degree	Min	Degree	Min	Depth
Day 1												
1	28/08/07	7:42	7:44	152.00	24.99	152.00	24.95	24.00	44.99	24.00	44.97	3.9
2	28/08/07	8:14	8:19	152.00	29.98	152.00	29.97	24.00	44.99	24.00	44.94	13
3	28/08/07	8:46	8:52	152.00	35.00	152.00	35.00	24.00	44.99	24.00	44.92	18.9
4	28/08/07	9:17	9:23	152.00	40.02	152.00	40.03	24.00	44.99	24.00	44.93	22.9
5	28/08/07	9:40	9:46	152.00	44.98	152.00	44.99	24.00	44.98	24.00	44.89	28
6	28/08/07	10:04	10:10	152.00	49.98	152.00	49.97	24.00	44.98	24.00	44.87	26.9
7	28/08/07	10:29	10:33	152.00	55.00	152.00	54.01	24.00	44.95	24.00	44.87	21.7
8	28/08/07	10:51	10:58	152.00	59.98	152.00	59.95	24.00	44.98	24.00	44.83	22.5
9	28/08/07	11:16	11:25	153.00	5.00	153.00	5.03	24.00	44.97	24.00	44.80	29.8
10	28/08/07	11:44	11:49	153.00	10.00	153.00	9.97	24.00	45.00	24.00	45.98	5.6
11	28/08/07	13:28	13:31	153.00	4.98	153.00	4.94	24.00	49.99	24.00	49.98	17.5
12	28/08/07	13:58	14:03	152.00	59.95	152.00	59.88	24.00	50.00	24.00	49.99	24
13	28/08/07	14:25	14:28	152.00	54.95	152.00	54.91	24.00	50.01	24.00	50.02	19.6
14	28/08/07	14:47	14:53	152.00	49.99	152.00	49.94	24.00	50.01	24.00	50.04	20.4
15	28/08/07	15:11	15:17	152.00	44.97	152.00	44.92	24.00	50.01	24.00	50.04	21.4
16	28/08/07	15:35	15:42	152.00	39.95	152.00	39.87	24.00	50.01	24.00	50.04	21.5
17	28/08/07	16:00	16:05	152.00	34.95	152.00	34.89	24.00	50.01	24.00	50.06	18.5
18	28/08/07	16:24	16:30	152.00	29.95	152.00	29.93	24.00	50.03	24.00	50.08	13.8
19	28/08/07	16:55	17:02	152.00	35.00	152.00	34.97	24.00	55.03	24.00	55.11	16.3
20	28/08/07	17:22	17:28	152.00	40.00	152.00	39.94	24.00	55.03	24.00	55.10	19.2
21	28/08/07	17:48	17:54	152.00	44.98	152.00	44.91	24.00	55.05	24.00	55.12	20.4
21b	28/08/07	18:04	18:10	152.00	46.34	152.00	46.29	24.00	55.19	24.00	55.26	21.2
22	28/08/07	18:25	18:30	152.00	49.99	152.00	49.96	24.00	55.04	24.00	55.09	19.7
Day 2												
23	29/08/07	7:33	7:37	153.00	4.98	153.00	4.96	25.00	5.00	25.00	5.01	15.5
24	29/08/07	8:00	8:06	152.00	59.98	152.00	59.97	25.00	5.00	25.00	4.98	19.2
25	29/08/07	8:27	8:31	152.00	59.99	152.00	59.99	25.00	10.01	25.00	10.02	5.5
26	29/08/07	8:56	9:02	152.00	55.00	152.00	55.01	25.00	9.99	25.00	9.99	13.2
27	29/08/07	9:23	9:33	152.00	54.99	152.00	54.98	25.00	4.97	25.00	4.85	15.2
28	29/08/07	9:52	9:55	152.00	49.99	152.00	49.96	25.00	4.99	25.00	4.49	19.5
29	29/08/07	11:09	11:11	152.00	49.98	152.00	49.96	25.00	9.96	25.00	9.92	9
30	29/08/07	10:42	10:46	152.00	44.96	152.00	44.93	25.00	9.96	25.00	9.91	10.6
31	29/08/07	11:41	11:50	152.00	44.96	152.00	44.90	25.00	4.89	25.00	4.73	15.9
32	29/08/07	12:09	12:12	152.00	39.97	152.00	39.94	25.00	4.97	25.00	4.92	11.2
33	29/08/07	12:38	12:38	152.00	40.01	152.00	40.00	25.00	9.98	25.00	9.01	1.4
34	29/08/07	13:51	13:54	152.00	34.99	152.00	34.96	25.00	4.98	25.00	4.96	5
35	29/08/07	14:35	14:38	152.00	34.99	152.00	34.96	25.00	0.01	24.00	60.00	10.4
36	29/08/07	14:57	15:01	152.00	39.96	152.00	39.92	24.00	60.00	24.00	59.97	15.2
37	29/08/07	15:20	15:26	152.00	45.04	152.00	44.98	24.00	59.99	24.00	59.94	20.6
38	29/08/07	15:47	15:50	152.00	49.99	152.00	49.97	24.00	59.99	24.00	59.97	21.2

39	29/08/07	16:09	16:15	152.00	54.98	152.00	54.93	25.00	0.00	25.00	0.00	24.9
40	29/08/07	16:34	16:37	152.00	60.00	152.00	59.97	25.00	0.01	25.00	0.03	18.3
41	29/08/07	16:56	16:58	153.00	4.96	153.00	4.93	25.00	0.02	25.00	0.04	18.6
42	29/08/07	17:19	17:22	153.00	9.97	153.00	9.93	25.00	0.04	25.00	0.05	13.3
43	29/08/07	17:41	17:47	153.00	10.01	153.00	10.00	24.00	55.99	24.00	55.99	19.5
44	29/08/07	18:21	18:26	153.00	4.97	153.00	4.96	24.00	55.05	24.00	55.09	19.9
45	29/08/07	18:44	18:47	152.00	59.99	152.00	59.97	24.00	55.99	24.00	55.09	20.6
46	29/08/07	19:06	19:09	152.00	54.98	152.00	54.96	24.00	55.02	24.00	55.05	20.7
Day 3												
47	30/08/07	8:40	8:46	152.00	40.01	152.00	39.97	24.00	45.01	24.00	45.01	22.7
48	30/08/07	9:06	9:12	152.00	44.99	152.00	44.94	24.00	45.01	24.00	45.02	28.4
49	30/08/07	9:36	9:41	152.00	49.89	152.00	49.94	24.00	44.99	24.00	44.98	27.6
50	30/08/07	10:02	10:09	152.00	55.00	152.00	54.96	24.00	44.99	24.00	44.90	26.7
51	30/08/07	10:33	10:38	152.00	60.00	152.00	59.96	24.00	44.97	24.00	44.88	23.6
52	30/08/07	10:59	11:09	153.00	5.00	153.00	4.98	24.00	44.95	24.00	44.72	29.5
53	30/08/07	11:51	11:53	153.00	10.00	153.00	9.98	24.00	44.97	24.00	44.94	6.7
54	30/08/07	13:05	13:06	153.00	14.18	153.00	14.17	24.00	40.13	24.00	40.10	9.6
55	30/08/07	13:27	13:28	153.00	16.11	153.00	16.09	24.00	38.17	24.00	38.16	5.6
56	30/08/07	13:54	13:58	153.00	9.95	153.00	9.89	24.00	39.99	24.00	39.96	16.5
57	30/08/07	14:17	14:28	153.00	4.96	153.00	4.89	24.00	39.99	24.00	39.93	20.5
58	30/08/07	14:42	14:48	152.00	59.83	152.00	59.74	24.00	40.00	24.00	39.96	22.7
59	30/08/07	15:05	15:09	152.00	54.97	152.00	54.90	24.00	40.00	24.00	39.98	24.1
60	30/08/07	15:28	15:34	152.00	49.84	152.00	49.71	24.00	40.02	24.00	39.98	26.8
61	30/08/07	16:11	16:15	152.00	44.96	152.00	44.87	24.00	40.01	24.00	40.02	24
62	30/08/07	16:33	16:38	152.00	39.96	152.00	39.89	24.00	40.01	24.00	40.03	22.8
63	30/08/07	17:00	17:03	152.00	34.04	152.00	34.80	24.00	40.04	24.00	40.07	18.7
64	30/08/07	17:22	17:26	152.00	29.99	152.00	29.93	24.00	40.00	24.00	40.04	17.3
65	30/08/07	17:44	17:47	152.00	24.97	152.00	24.94	24.00	40.02	24.00	40.03	14.3

Table 4: Summary of sample locations surveyed during December 4-7, 2007

		Start	End	Start Longitude		End Longitude		Start Latitude		End Latitude		
Station	**Date**	**Time**	**Time**	**Degree**	**Min**	**Degree**	**Min**	**Degree**	**Min**	**Degree**	**Min**	**Depth**
Day 1												
1	04/12/07	7:07	7:09	152.00	25.01	152.00	25.02	24.00	39.97	24.00	39.96	14.6
2	04/12/07	7:26	7:29	152.00	30.23	152.00	30.11	24.00	39.99	24.00	39.97	17.7
3	04/12/07	7:45	7:50	152.00	34.99	152.00	35.01	24.00	40.00	24.00	39.95	20.3
4	04/12/07	8:07	8:11	152.00	40.01	152.00	40.04	24.00	39.99	24.00	39.94	23.9
5	04/12/07	8:28	8:32	152.00	45.03	152.00	45.07	24.00	39.97	24.00	39.92	24.9
6	04/12/07	9:14	9:20	152.00	50.02	152.00	50.03	24.00	39.98	24.00	39.92	29.2
7	04/12/07	9:37	9:43	152.00	55.00	152.00	55.03	24.00	39.99	24.00	39.92	25.3
8	04/12/07	10:00	10:06	153.00	0.12	153.00	0.14	24.00	39.99	24.00	39.92	22.7
9	04/12/07	10:24	10:29	153.00	5.06	153.00	5.06	24.00	39.97	24.00	39.94	22.8
10	04/12/07	10:46	10:51	153.00	10.05	153.00	10.04	24.00	39.98	24.00	39.99	16.7
11	04/12/07	11:18	11:21	153.00	14.99	153.00	14.95	24.00	39.25	24.00	39.27	8.1
12	04/12/07	11:32	11:35	153.00	16.21	153.00	16.14	24.00	37.75	24.00	37.76	6.1
13	04/12/07	12:07	12:10	153.00	10.03	153.00	10.01	24.00	44.99	24.00	45.02	5.5
14	04/12/07	13:30	13:36	153.00	5.00	153.00	4.97	24.00	45.01	24.00	45.10	31.8
15	04/12/07	13:53	13:59	153.00	0.01	152.00	59.99	24.00	45.01	24.00	45.09	22.7
16	04/12/07	14:17	14:23	152.00	55.00	152.00	54.99	24.00	45.00	24.00	45.07	26.1
17	04/12/07	15:00	15:05	152.00	49.97	152.00	49.95	24.00	45.01	24.00	45.05	27
18	04/12/07	15:23	15:29	152.00	45.01	152.00	45.09	24.00	45.02	24.00	45.01	27.8
19	04/12/07	15:47	15:53	152.00	40.00	152.00	39.99	24.00	45.02	24.00	45.07	23.1
20	04/12/07	16:10	16:14	152.00	34.97	152.00	34.97	24.00	45.02	24.00	45.07	18.7
21	04/12/07	16:31	16:34	152.00	30.01	152.00	29.98	24.00	45.03	24.00	45.06	12.7
22	04/12/07	17:03	17:05	152.00	24.99	152.00	54.05	24.00	45.01	24.00	45.05	3.8
Day 2												
23	05/12/07	6:58	7:02	152.00	30.02	152.00	30.30	24.00	50.01	24.00	50.05	15.2
24	05/12/07	7:18	7:23	152.00	34.99	152.00	35.02	24.00	49.99	24.00	50.00	19.3
25	05/12/07	7:40	7:44	152.00	40.02	152.00	40.04	24.00	50.01	24.00	50.02	22.9
26	05/12/07	8:01	8:07	152.00	45.00	152.00	45.03	24.00	50.00	24.00	50.00	22
27	05/12/07	8:23	8:29	152.00	50.01	152.00	50.04	24.00	50.00	24.00	49.99	21.9
28	05/12/07	8:45	8:50	152.00	55.00	152.00	55.02	24.00	50.00	24.00	49.99	21.1
29	05/12/07	9:07	9:12	153.00	0.00	153.00	0.01	24.00	50.01	24.00	49.99	24.9
30	05/12/07	9:27	9:34	153.00	5.01	153.00	5.01	24.00	49.99	24.00	49.96	18.4
31	05/12/07	10:11	10:17	153.00	10.03	153.00	10.06	24.00	55.01	24.00	55.07	19.2
32	05/12/07	10:34	10:38	153.00	4.99	153.00	4.02	24.00	55.01	24.00	55.99	18.5
33	05/12/07	10:56	11:02	153.00	0.01	153.00	0.02	24.00	55.00	24.00	55.01	19.1
34	05/12/07	11:19	11:24	152.00	54.99	152.00	55.00	24.00	55.00	24.00	55.03	18.9
35	05/12/07	11:41	11:46	152.00	49.99	152.00	49.99	24.00	54.99	24.00	55.01	17.8
36	05/12/07	12:12	12:19	152.00	47.98	152.00	48.02	24.00	54.71	24.00	54.77	39.5
37	05/12/07	12:32	12:38	152.00	45.00	152.00	45.99	24.00	55.01	24.00	55.07	19
38	05/12/07	12:54	12:59	152.00	40.00	152.00	40.01	24.00	55.02	24.00	55.01	18.4
39	05/12/07	13:17	13:21	152.00	35.00	152.00	35.00	24.00	55.02	24.00	55.08	15.9

40	05/12/07	14:00	14:03	152.00	35.00	152.00	35.01	25.00	0.04	25.00	0.11	11.2
41	05/12/07	14:34	14:39	152.00	40.00	152.00	39.99	24.00	60.00	25.00	0.07	16.6
42	05/12/07	14:56	15:01	152.00	45.01	152.00	45.02	25.00	0.01	25.00	0.08	22.2
43	05/12/07	15:18	15:24	152.00	49.99	152.00	50.00	25.00	0.01	25.00	0.10	22.9
44	05/12/07	15:41	15:46	152.00	55.01	152.00	55.02	25.00	0.01	25.00	0.08	25.5
45	05/12/07	16:02	16:07	152.00	60.00	153.00	0.02	24.00	60.00	25.00	0.06	19.7
46	05/12/07	16:22	16:26	153.00	4.99	153.00	5.02	25.00	0.01	25.00	0.05	19.8
47	05/12/07	16:43	16:48	153.00	9.99	153.00	10.03	24.00	59.99	25.00	0.02	14.2
48	05/12/07	17:15	17:19	153.00	5.01	153.00	5.01	25.00	5.02	25.00	5.06	14.9
49	05/12/07	17:37	17:43	153.00	0.00	152.00	59.99	25.00	5.00	25.00	5.07	18.3
50	05/12/07	18:01	18:03	152.00	60.00	152.00	59.99	25.00	10.00	25.00	10.02	5
Day 3												
51	06/12/07	8:19	8:22	152.00	54.95	152.00	54.91	25.00	4.99	25.00	4.99	14.6
52	06/12/07	8:37	8:42	152.00	49.97	152.00	49.95	25.00	5.00	25.00	5.00	18.8
53	06/12/07	8:58	9:03	152.00	45.01	152.00	44.98	25.00	5.00	25.00	5.00	15.5
54	06/12/07	9:16	9:25	152.00	39.99	152.00	39.95	25.00	5.00	25.00	5.00	12
55	06/12/07	9:42	9:45	152.00	34.98	152.00	34.95	25.00	4.99	25.00	4.98	6.4
56	06/12/07	10:24	10:26	152.00	39.95	152.00	39.95	25.00	9.99	25.00	9.98	2.5
57	06/12/07	10"43	10:46	152.00	44.99	152.00	44.99	25.00	9.99	25.00	9.99	9.4
58	06/12/07	11:03	11:05	152.00	49.99	152.00	49.99	25.00	10.00	25.00	9.98	5.5
59	06/12/07	11:23	11:27	152.00	55.00	152.00	55.01	25.00	9.98	25.00	9.93	11
60	06/12/07	13:26	13:29	153.00	5.08	153.00	4.98	24.00	40.02	24.00	40.08	24
61	06/12/07	14:19	14:24	152.00	59.96	152.00	59.95	24.00	40.04	24.00	40.14	23
62	06/12/07	14:41	14:47	152.00	55.00	152.00	54.69	24.00	40.01	24.00	40.08	25.5
63	06/12/07	15:03	15:08	152.00	49.98	152.00	49.95	24.00	40.00	24.00	40.09	29.2
64	06/12/07	15:42	15:29	152.00	45.00	152.00	44.98	24.00	40.01	24.00	40.08	24.9
65	06/12/07	15:46	15:51	152.00	39.89	152.00	39.88	24.00	40.03	24.00	40.10	23.7
66	06/12/07	16:07	16:11	152.00	35.01	152.00	35.00	24.00	40.00	24.00	40.08	20
67	06/12/07	16:28	16:33	152.00	30.00	152.00	29.99	24.00	40.01	24.00	40.07	18
68	06/12/07	16:49	16:54	152.00	25.01	152.00	25.00	24.00	40.01	24.00	40.06	14.7
Day4												
69	07/12/07	736	7:40	152.00	30.02	152.00	30.04	24.00	35.00	24.00	35.03	19.8
70	07/12/07	7:59	8:03	152.00	35.01	152.00	35.03	24.00	34.99	24.00	35.00	24.1
71	07/12/07	8:21	8:26	152.00	39.98	152.00	40.01	24.00	35.01	24.00	35.03	27.8
72	07/12/07	8:42	8:47	152.00	45.02	15.00	45.06	24.00	35.00	24.00	34.99	29.5
74	07/12/07	9:05	9:12	152.00	49.98	152.00	50.00	24.00	35.00	24.00	35.00	34.5
75	07/12/07	9:27	9:33	152.00	54.99	152.00	54.98	24.00	35.00	24.00	34.96	35.8
76	07/12/07	9:50	9:57	152.00	59.99	152.00	0.02	24.00	35.00	24.00	34.96	27.8
77	07/12/07	10:14	10:19	153.00	4.99	153.00	4.99	24.00	34.98	24.00	34.90	22
78	07/12/07	10:37	10:43	153.00	10.00	153.00	10.00	24.00	34.99	24.00	34.92	24.5
79	07/12/07	11:20	11:25	153.00	10.01	153.00	9.99	24.00	29.97	24.00	29.90	23
80	07/12/07	11:45	11:52	153.00	4.98	153.00	4.90	24.00	30.00	24.00	29.93	29.3
81	07/12/07	12:08	12:14	152.00	59.99	152.00	59.96	24.00	30.00	24.00	29.94	34.7
82	07/12/07	12:33	12:39	152.00	54.02	152.00	54.99	24.00	30.00	24.00	29.99	37.5
83	07/12/07	12:56	13:03	152.00	49.99	152.00	49.96	24.00	30.01	24.00	29.98	42.3
84	07/12/07	13:21	13:27	152.00	45.00	152.00	44.96	24.00	30.01	24.00	29.99	31.2
85	07/12/07	14:04	14:09	152.00	40.01	152.00	39.98	24.00	30.03	24.00	30.04	25.8
86	07/12/07	14:27	14:33	152.00	34.99	152.00	34.94	24.00	30.00	24.00	30.02	26.2

87	07/12/07	14:51	14:56	152.00	29.99	152.00	29.97	24.00	30.01	24.00	30.04	22.6
88	07/12/07	15:13	15:17	152.00	24.99	152.00	24.94	24.00	30.00	24.00	30.03	22.3
89	07/12/07	15:35	15:40	152.00	20.00	152.00	20.00	24.00	30.01	24.00	30.06	21.1
90	07/12/07	15:57	16:02	152.00	14.99	152.00	14.96	24.00	30.00	24.00	30.06	18.6
91	07/12/07	16:18	16:22	152.00	9.99	152.00	9.96	24.00	30.00	24.00	30.04	18.6
92	07/12/07	16:40	16:43	152.00	5.01	152.00	5.03	24.00	29.98	24.00	30.03	9.9
93	07/12/07	17:20	17:23	152.00	10.00	152.00	9.98	24.00	35.00	24.00	34.03	9.9
94	07/12/07	17:40	17:44	152.00	15.00	152.00	14.97	24.00	35.01	24.00	35.05	12.3
95	07/12/07	18:01	18:04	152.00	20.02	152.00	19.99	24.00	35.01	24.00	35.05	15.1
96	07/12/07	18:20	18:24	152.00	24.99	152.00	24.95	24.00	35.01	24.00	35.04	16.3

Table 5: Summary of sample locations surveyed during May 28-29, 2008

		Start	End	Start Longitude		End Longitude		Start Latitude		End Latitude		
Station	**Date**	**Time**	**Time**	**Degree**	**Min**	**Degree**	**Min**	**Degree**	**Min**	**Degree**	**Min**	**Depth**
Day 1												
1	26/05/08	8:03	8:07	152.00	4.96	152.00	4.90	24.00	29.99	24.00	29.90	10.3
2	26/05/08	8:31	8:34	152.00	0.20	152.00	0.17	24.00	24.98	24.00	24.96	7.8
3	26/05/08	8:52	8:58	152.00	4.98	152.00	4.96	24.00	24.99	24.00	24.96	14.5
4	26/05/08	9:13	9:17	152.00	10.04	152.00	10.03	24.00	25.00	24.00	24.97	18.6
5	26/05/08	9:34	9:38	152.00	15.01	152.00	15.99	24.00	25.00	24.00	24.96	22
6	26/05/08	9:57	10:01	152.00	20.01	152.00	19.98	24.00	24.99	24.00	24.96	23.6
7	26/05/08	10:19	10:22	152.00	25.80	152.00	24.96	24.00	25.00	24.00	24.95	27.2
8	26/05/08	10:44	10:47	152.00	30.01	152.00	29.98	24.00	25.00	24.00	24.96	27
9	26/05/08	11:05	11:12	152.00	35.05	152.00	35.02	24.00	25.01	24.00	24.96	24.4
0	26/05/08	11:31	11:37	152.00	40.03	152.00	39.99	24.00	25.02	24.00	24.97	22.6
11	26/05/08	12:02	12:07	152.00	45.00	152.00	44.99	24.00	25.00	24.00	24.96	27.7
12	26/05/08	12:24	12:36	152.00	50.03	152.00	50.01	24.00	24.99	24.00	24.87	48.6
13	26/05/08	12:52	13:00	152.00	55.01	152.00	55.03	24.00	25.00	24.00	24.93	37.1
14	26/05/08	13:18	13:29	153.00	0.00	152.00	59.96	24.00	24.99	24.00	24.83	41.6
15	26/05/08	13:46	13:50	153.00	5.02	153.00	5.02	24.00	25.00	24.00	24.93	19
16	26/05/08	14:06	14:15	153.00	10.03	153.00	10.04	24.00	24.99	24.00	24.81	38
17	26/05/08	14:57	15:01	153.00	9.99	153.00	9.97	24.00	29.97	24.00	29.90	22
18	26/05/08	15:17	15:24	153.00	4.99	153.00	4.92	24.00	30.00	24.00	24.90	30.2
19	26/05/08	15:41	15:46	153.00	0.01	152.00	59.96	24.00	29.99	24.00	29.88	34
20	26/05/08	16:03	16:15	152.00	54.75	152.00	54.62	24.00	30.11	24.00	29.97	43.5
21	26/05/08	16:30	16:37	152.00	49.99	152.00	49.91	24.00	30.00	24.00	29.91	42.8
22	26/05/08	16:53	17:01	152.00	44.98	152.00	44.89	24.00	30.00	24.00	29.92	31.4
23	26/05/08	17:17	17:22	152.00	39.98	152.00	39.91	24.00	30.00	24.00	29.95	25.9
24	26/05/08	17:37	17:44	152.00	35.00	152.00	34.89	24.00	30.00	24.00	29.99	26.8
Day 2												
25	27/05/08	7:25	7:29	152.00	29.99	152.00	29.93	24.00	29.95	24.00	29.89	22
26	27/05/08	7:47	7:53	152.00	24.95	152.00	24.91	24.00	29.98	24.00	29.91	20.3
27	27/05/08	8:10	8:14	152.00	19.97	152.00	19.94	24.00	29.97	24.00	29.93	20.7
28	27/05/08	8:31	8:37	152.00	14.98	152.00	14.94	24.00	30.00	24.00	29.93	18.3
29	27/05/08	8:53	8:56	152.00	9.98	152.00	9.96	24.00	30.00	24.00	29.97	14,8
30	27/05/08	9:41	9:45	152.00	14.98	152.00	14.98	24.00	40.02	24.00	39.99	7.3
31	27/05/08	10:03	10:08	152.00	20.02	152.00	20.01	24.00	40.00	24.00	39.97	9.8
32	27/05/08	10:25	10:32	152.00	24.98	152.00	24.94	24.00	40.00	24.00	39.97	
33a	27/05/08	11:54	11.59	152.00	29.95	152.00	29.90	24.00	39.99	24.00	39.95	17.7
33b	27/05/08	12:35	12:42	152.00	34.44	152.00	34.38	24.00	39.83	24.00	39.77	23.7
34	27/05/08	12:46	12:51	152.00	34.99	152.00	34.95	24.00	39.99	24.00	39.96	20.7
35	27/05/08	13:10	13:14	152.00	40.00	152.00	39.98	24.00	39.99	24.00	39.96	24.5
36	27/05/08	13:32	13:39	152.00	45.00	152.00	44.98	24.00	39.99	24.00	39.92	25.1
37	27/05/08	13:57	14:03	152.00	50.00	152.00	49.97	24.00	39.99	24.00	39.93	30
38	27/05/08	14:20	14:27	152.00	54.98	152.00	54.94	24.00	39.98	24.00	39.91	25.9

39	27/05/08	14:45	14:49	153.00	0.01	152.00	59.99	24.00	39.99	24.00	39.93	23.6
40	27/05/08	15:08	15:15	153.00	4.97	153.00	4.87	24.00	39.97	24.00	39.91	25.6
41	27/05/08	15:35	15:42	153.00	4.99	153.00	4.94	24.00	44.99	24.00	44.93	31.6
42	27/05/08	16:38	16:45	152.00	59.99	152.00	59.92	24.00	44.98	24.00	44.90	22.6
43	27/05/08	17:01	17:08	152.00	54.98	152.00	54.89	24.00	45.00	24.00	44.92	24.6
44	27/05/08	17;23	17:30	152.00	49.98	152.00	49.89	24.00	44.99	24.00	44.91	26.3
44B	27/05/08	17:37	17:45	152.00	48.24	152.00	48.16	24.00	44.92	24.00	44.83	31.9
45	27/05/08	17:59	18:06	152.00	44.99	152.00	44.91	24.00	44.99	24.00	44.93	27
46	27/05/08	18:25	18:31	152.00	39.97	152.00	39.90	24.00	45.00	24.00	44.95	22
47	27/05/08	18:51	18:56	152.00	34.92	152.00	34.91	24.00	45.00	24.00	44.97	17.5
48	27/05/08	19:14	19:23	152.00	29.96	152.00	29.81	24.00	44.99	24.00	44.90	11.4
49	27/05/08	19:38	19:41	152.00	25.20	152.00	25.18	24.00	45.00	24.00	45.00	4

Table 6: Summary of sample locations surveyed during June 16-18, 2008

		Start	End	Start Longitude		End Longitude		Start Latitude		End Latitude		
Station	Date	Time	Time	Degree	Min	Degree	Min	Degree	Min	Degree	Min	Depth
Day 1												
1	16/06/08	14:53:00	14:57:00	152.00	29.99	152.00	29.98	24.00	50.01	24.00	50.04	14.1
2	16/06/08	15:13:00	15:19:00	152.00	34.98	152.00	35.01	24.00	50.01	24.00	50.03	18.8
3	16/06/08	15:34:00	15:39:00	152.00	40.00	152.00	40.01	24.00	50.01	24.00	50.04	22.4
4	16/06/08	15:55:00	15:58:00	152.00	45.01	152.00	45.01	24.00	50.02	24.00	50.04	21.8
5	16/06/08	16:15:00	16:19:00	152.00	50.02	152.00	50.01	24.00	50.01	24.00	50.04	22.1
6	16/06/08	16:35:00	16:39:00	152.00	55.01	152.00	55.02	24.00	50.01	24.00	50.03	21.7
7	16/06/08	16:54:00	16:58:00	153.00	0.04	153.00	0.04	24.00	50.02	24.00	50.03	25.6
8	16/06/08	17:13:00	17:16:00	153.00	4.99	153.00	5.02	24.00	50.02	24.00	50.03	19.4
9	16/06/08	17:41:00	17:46:00	153.00	10.00	153.00	10.02	24.00	55.00	24.00	54.99	20.5
10	16/06/08	18:02:00	18:05:00	153.00	5.01	153.00	5.00	24.00	54.99	24.00	54.99	20.2
11	16/06/08	18:21:00	18:26:00	152.00	59.99	152.00	59.98	24.00	55.01	24.00	55.00	20.8
12	16/06/08	18:42:00	18:46:00	152.00	55.00	152.00	54.99	24.00	55.00	24.00	54.99	20.8
13	16/06/08	19:02:00	19:07:00	152.00	49.98	152.00	49.95	24.00	54.99	24.00	54.98	19.7
14	16/06/08	19:22:00	19:27:00	152.00	44.99	152.00	44.95	24.00	54.99	24.00	54.97	20.9
15	16/06/08	19:44:00	19:49:00	152.00	39.96	152.00	39.93	24.00	55.00	24.00	54.99	20.2
16	16/06/08	20:05:00	20:08:00	152.00	34.99	152.00	34.95	24.00	54.98	24.00	54.97	17.6
Day 2												
17	17/06/08	8:00:00	8:27:00	153.00	3.72	153.00	3.72	25.00	9.30	25.00	9.30	7.8
18	17/06/08	9:44:00	9:49:00	152.00	59.99	153.00	0.00	25.00	9.95	25.00	9.88	4.2
19	17/06/08	10:07:15	10:13:26	152.00	54.47	152.00	54.95	25.00	9.94	25.00	9.76	10.8
20	17/06/08	10:30:46	10:36:20	152.00	49.98	152.00	49.96	25.00	9.99	25.00	9.90	8.6
21	17/06/08	10:51:28	10:58:44	152.00	44.98	152.00	44.95	25.00	9.99	25.00	9.88	9.6
22	17/06/08	11:16:28	11:22:00	152.00	39.98	152.00	40.00	25.00	9.99	25.00	9.94	2
23	17/06/08	11:48:06	11:54:10	152.00	34.99	152.00	34.94	25.00	5.00	25.00	4.96	5.6
24	17/06/08	12:11:48	12:16:48	152.00	40.01	152.00	39.99	25.00	4.99	25.00	4.94	10.6
25	17/06/08	12:35:58	12:43:22	152.00	45.02	152.00	44.99	25.00	4.99	25.00	4.91	14.4
26	17/06/08	13:00:50	13:07:07	152.00	50.97	152.00	50.00	25.00	4.99	25.00	4.91	17.5
27	17/06/08	13:24:46	13:32:10	152.00	55.02	152.00	55.00	25.00	4.99	25.00	4.92	13.1
28	17/06/08	13:49:58	14:00:00	152.00	59.99	152.00	59.97	25.00	4.99	25.00	4.90	17.6
29	17/06/08	14:16:46	14:23:32	153.00	5.01	153.00	4.95	25.00	5.01	25.00	4.99	13.9
30	17/06/08	14:47:56	14:54:20	153.00	10.02	153.00	10.00	24.00	59.99	24.00	59.93	13.1
31	17/06/08	15:12:46	15:21:02	153.00	4.98	153.00	4.95	24.00	59.99	24.00	59.94	18.5
32	17/06/08	15:38:58	15:45:56	152.00	60.00	152.00	59.96	25.00	0.01	24.00	59.99	19.2
33	17/06/08	16:02:52	16:11:14	152.00	54.99	152.00	54.96	25.00	0.00	24.00	59.95	25.4
34	17/06/08	16:28:30	16:37:38	152.00	50.00	152.00	49.95	25.00	0.00	24.00	59.97	22.9
35	17/06/08	16:54:52	17:03:02	152.00	44.95	152.00	44.89	24.00	60.00	25.00	0.01	23
36	17/06/08	17:21:24	17:29:26	152.00	39.99	152.00	39.93	24.00	60.00	24.00	60.00	17.4
37	17/06/08	17:45:16	17:52:14	152.00	34.95	152.00	34.90	25.00	0.01	25.00	0.02	13.1
Day 3												
38	18/06/08	8:23:16	8:27:56	152.00	14.97	152.00	14.93	24.00	39.95	24.00	39.89	8.6
39	18/06/08	8:45:14	8:51:22	152.00	20.00	152.00	19.98	24.00	40.00	24.00	39.93	10.9
40	18/06/08	9:08:14	9:15:36	152.00	25.14	152.00	25.12	24.00	39.99	24.00	39.89	14.7
41	18/06/08	9:32:14	9:38:06	152.00	30.00	152.00	29.98	24.00	39.99	24.00	39.89	19

42	18/06/08	9:54:58	10:01:58	152.00	35.01	152.00	35.00	24.00	39.97	24.00	39.84	22.8
43	18/06/08	10:19:12	10:24:46	152.00	39.99	152.00	39.99	24.00	39.99	24.00	39.99	23.9
44	18/06/08	10:45:24	10:54:26	152.00	44.97	152.00	44.97	24.00	39.97	24.00	39.77	25.2
45	18/06/08	11:12:58	11:22:02	152.00	50.07	152.00	50.08	24.00	39.99	24.00	39.77	28.8
46	18/06/08	11:38:34	11:47:12	152.00	54.99	152.00	55.00	24.00	40.10	24.00	39.91	25.7
47	18/06/08	12:16:50	12:23:12	152.00	59.97	152.00	59.95	24.00	39.84	24.00	39.71	23.5
48	18/06/08	12:40:08	12:48:42	153.00	4.99	153.00	4.97	24.00	40.10	24.00	39.98	24.7
49	18/06/08	13:04:12	13:10:52	153.00	10.07	153.00	10.00	24.00	40.01	24.00	39.98	17
50	18/06/08	13:58:04	14:03:14	153.00	9.96	153.00	9.90	24.00	45.08	24.00	45.08	5.3
51	18/06/08	14:18:22	14:27:10	153.00	5.00	153.00	4.89	24.00	45.00	24.00	45.05	30.1
52	18/06/08	14:43:48	14:51:48	152.00	59.97	152.00	59.90	24.00	45.01	24.00	45.04	22.2
53	18/06/08	15:07:06	15:14:10	152.00	54.99	152.00	54.91	24.00	45.01	24.00	45.02	25.5
54	18/06/08	15:30:30	15:38:24	152.00	50.00	152.00	49.95	24.00	45.01	24.00	45.03	26.3
55	18/06/08	15:54:00	16:01:50	152.00	44.99	152.00	44.92	24.00	45.01	24.00	45.03	27.4
56	18/06/08	16:17:50	16:26:44	152.00	39.98	152.00	39.89	24.00	45.01	24.00	45.04	22.5
57	18/06/08	16:42:48	16:49:46	152.00	34.98	152.00	34.92	24.00	45.02	24.00	45.05	18.4
58	18/06/08	17:05:42	17:12:34	152.00	30.01	152.00	29.96	24.00	45.01	24.00	45.06	12.6
59	18/06/08	17:27:52	17:32:16	152.00	24.99	152.00	24.95	24.00	45.01	24.00	45.01	3.7

Table 7: Basin Average Temperature, Salinity and Density

	09/2004	08/2007	12/2007	05/2008	06/2008
T [^{o}C]	20.91	20.04	24.80	22.05	20.79
S [ppt]	36.10	35.65	35.69	35.48	35.09
D [kg·m^{-3}]	25.45	25.29	23.92	24.56	24.62

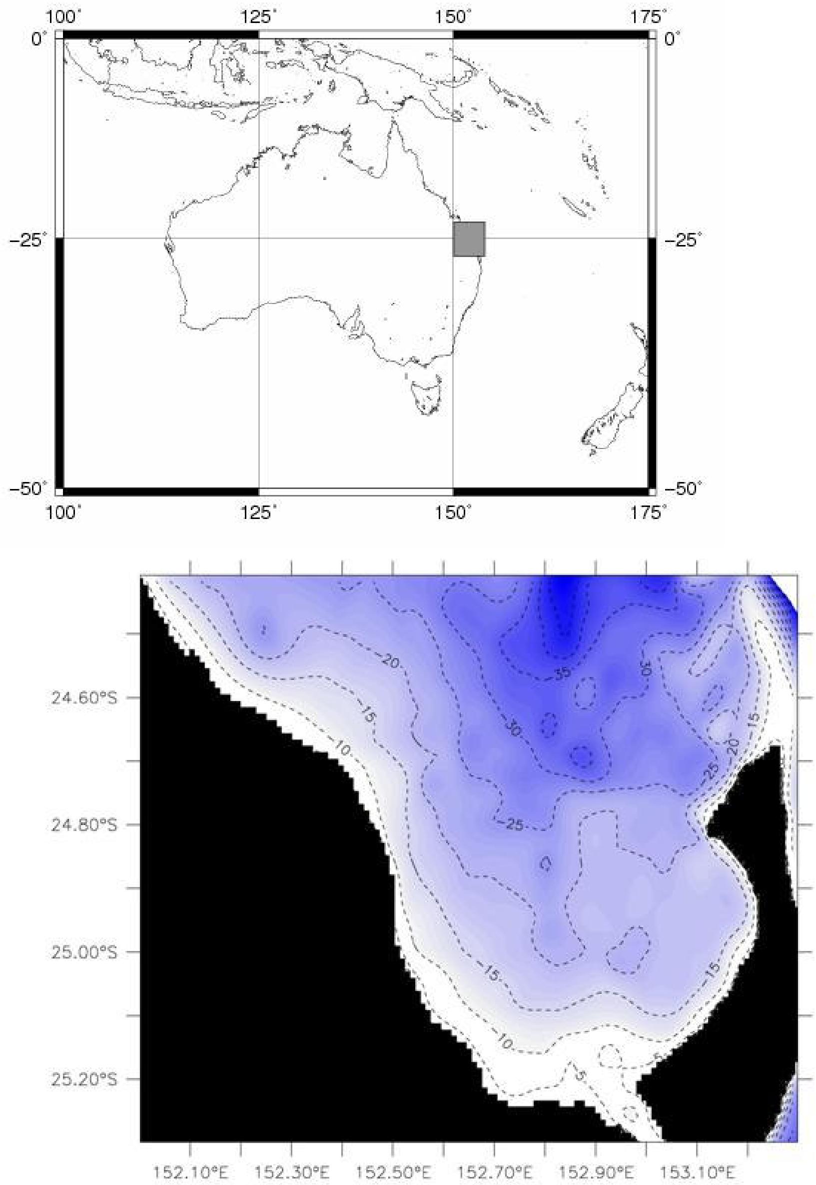

Figure 1: (a) Map of Australia indicating the study region and (b) bathymetry of Hervey Bay.

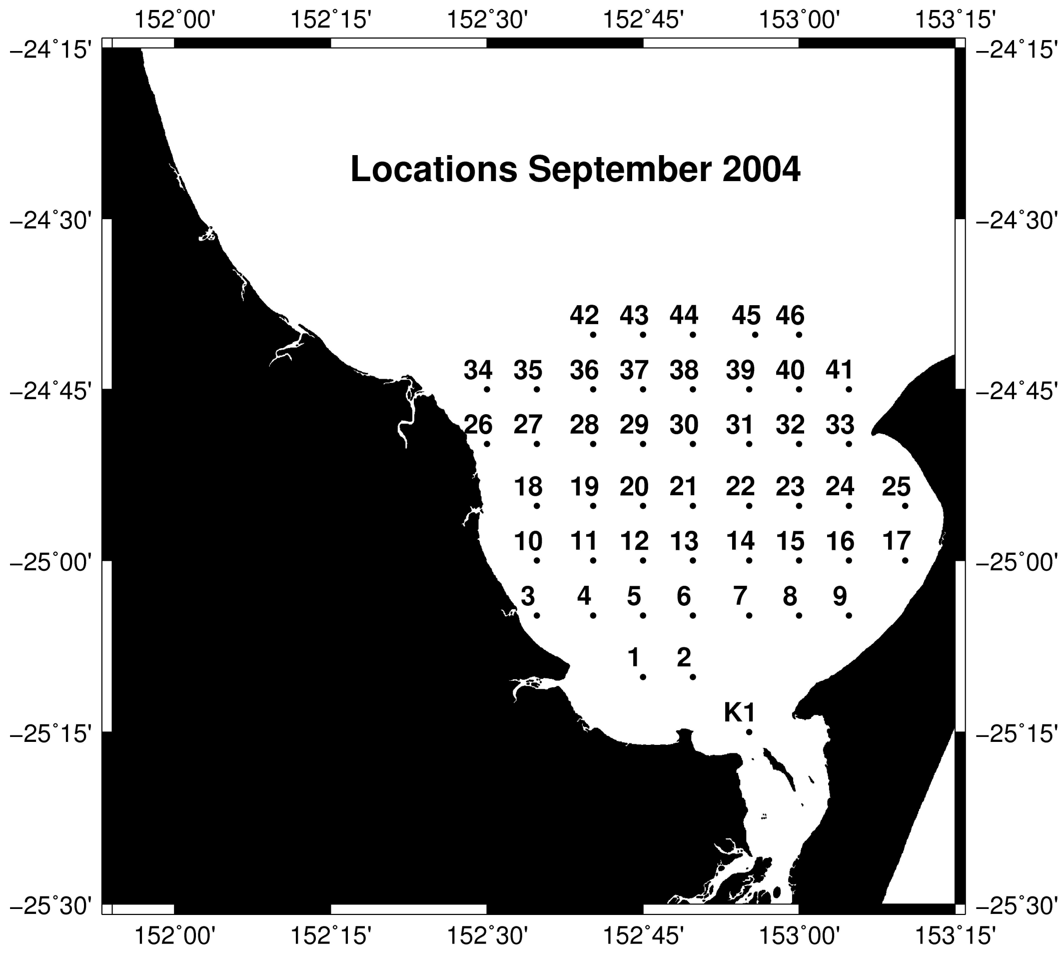

Figure 2: Hydrographic sample location surveyed during September 2004.

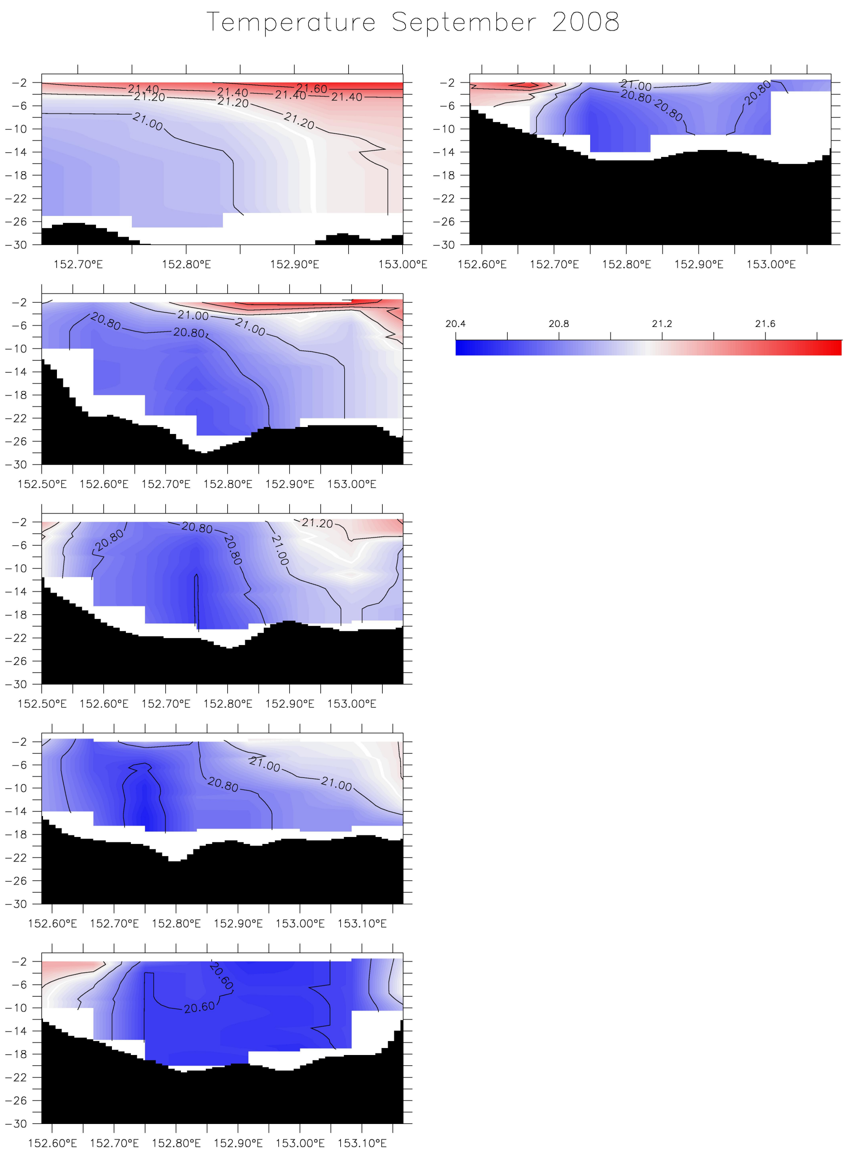

Figure 3: Temperature [T in ºC] distribution during September 2004, at latitude (a) 24º 40′ S, (b) 24º 45′ S, (c) 24º 50′ S, (d) 24º 55′ S, (e) 25º 00′ S and (f) 25º 05′ S. Top left to top right. High temperature is shaded in red and low temperature in blue.

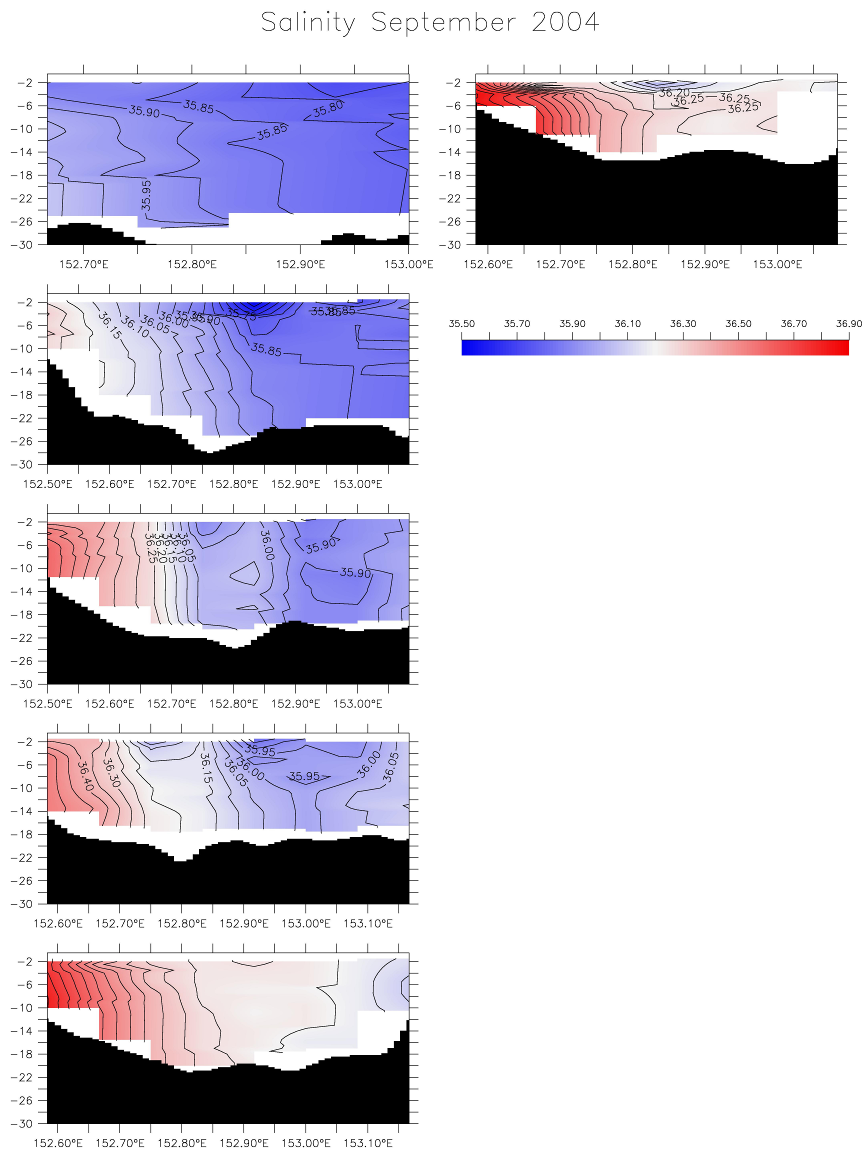

Figure 4: Salinity [S in ppt] distribution during September 2004, at latitude (a) 24º 40′ S, (b) 24º 45′ S, (c) 24º 50′ S, (d) 24º 55′ S, (e) 25º 00′ S and (f) 25º 05′ S. Top left to top right. High salinity is shaded in red and low salinity in blue.

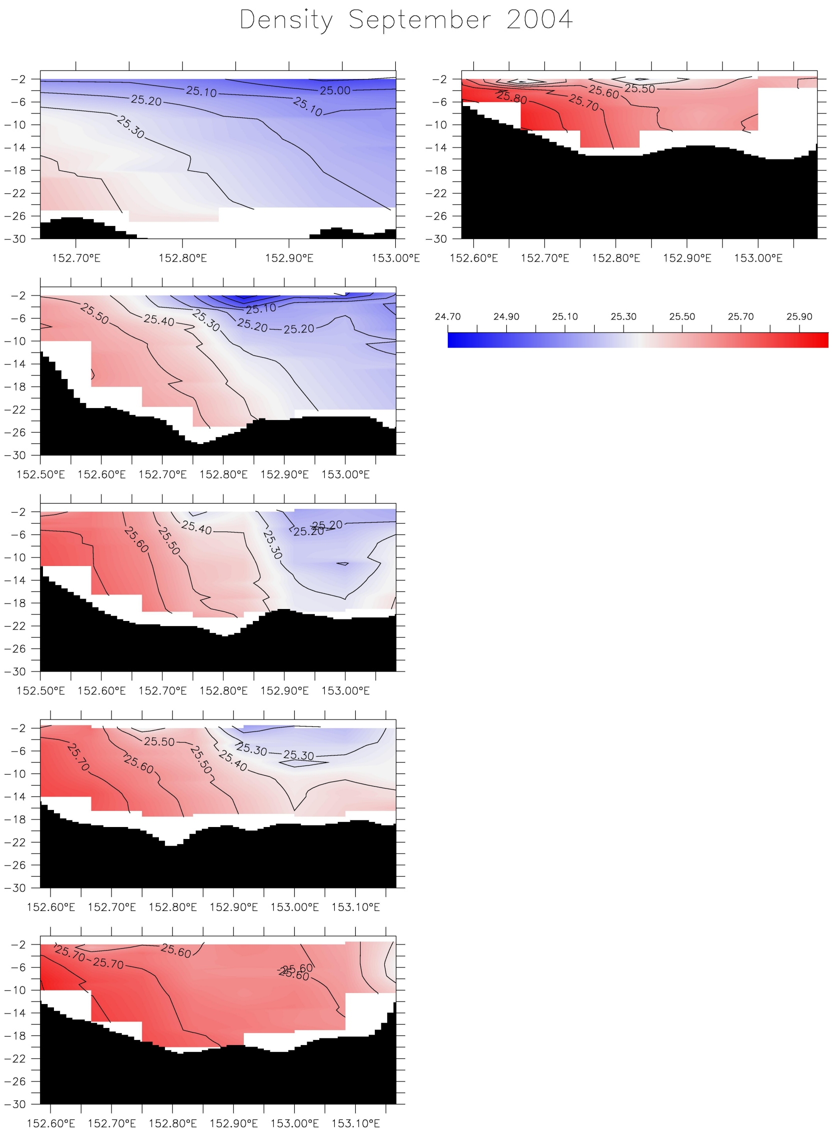

Figure 5: Density [σ_t in kg·m^{-3}] distribution during September 2004, at latitude (a) 24º 40′ S, (b) 24º 45′ S, (c) 24º 50′ S, (d) 24º 55′ S, (e) 25º 00′ S and f) 25º 05′ S. Top left to top right. High density is shaded in red and low density in blue.

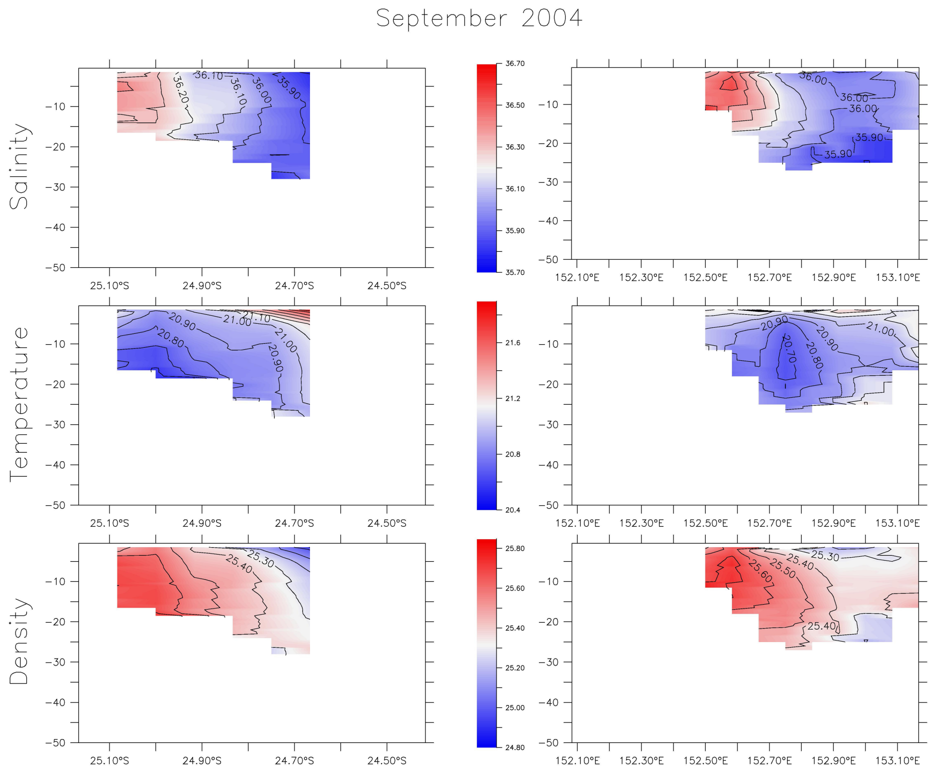

Figure 6: Basin average salinity [ppt] (top), temperature [T in °C] (middle), and density [σ_t in kg·m^{-3}] (bottom) in latitudinal (left column) and longitudinal (right column) direction during September 2004.

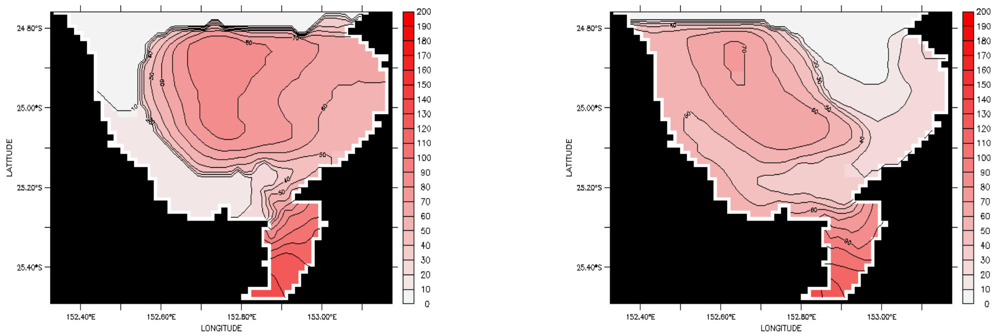

Figure 7: Bay flushing time scales [in days] for westerly (left panel) and easterly (right panel) wind with idealised quasi-semidiurnal tidal forcing. The model was integrated for a total period of 180 days. Water renewal time scales range from 10-15 days along the near-shore region to about 90 days within the interior of the Bay. See Ribbe et al (2008) for more detail about the model and its application.

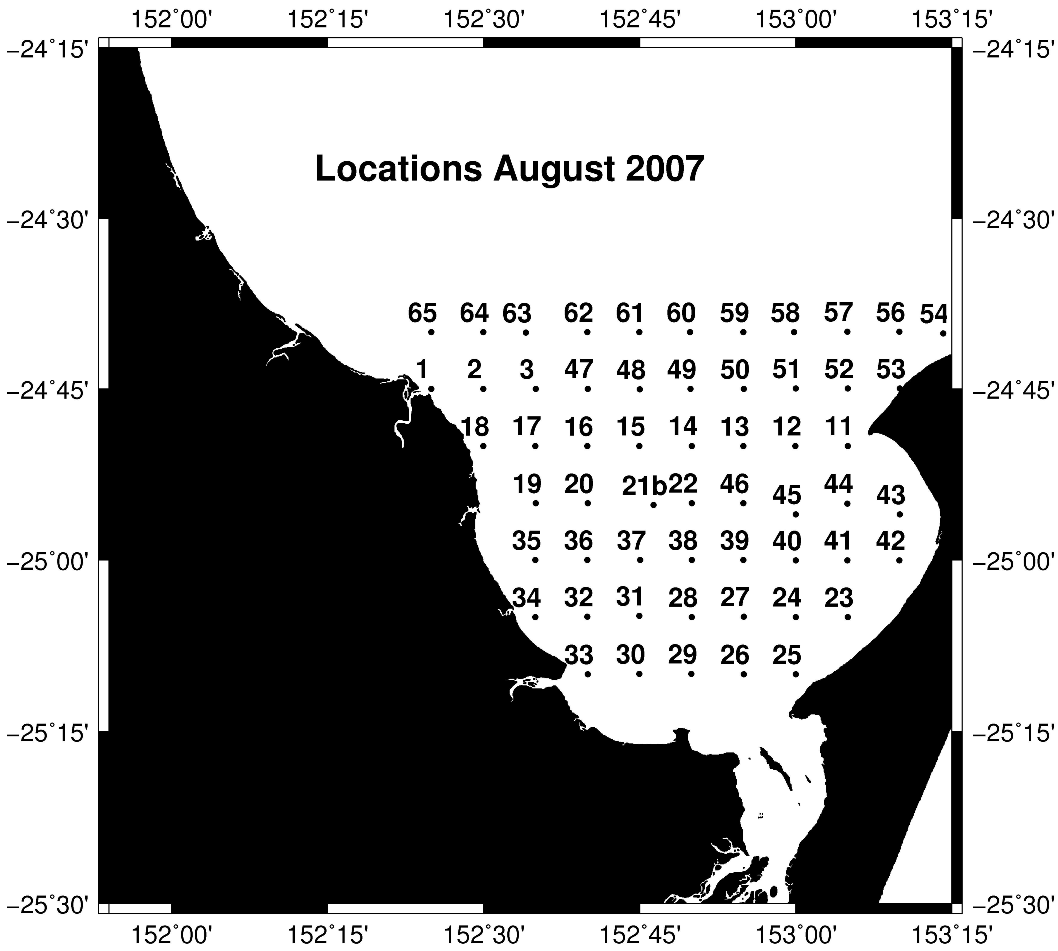

Figure 8: Sample locations surveyed during August 28-30, 2007. CTD profiles were recorded at a total of 65 locations.

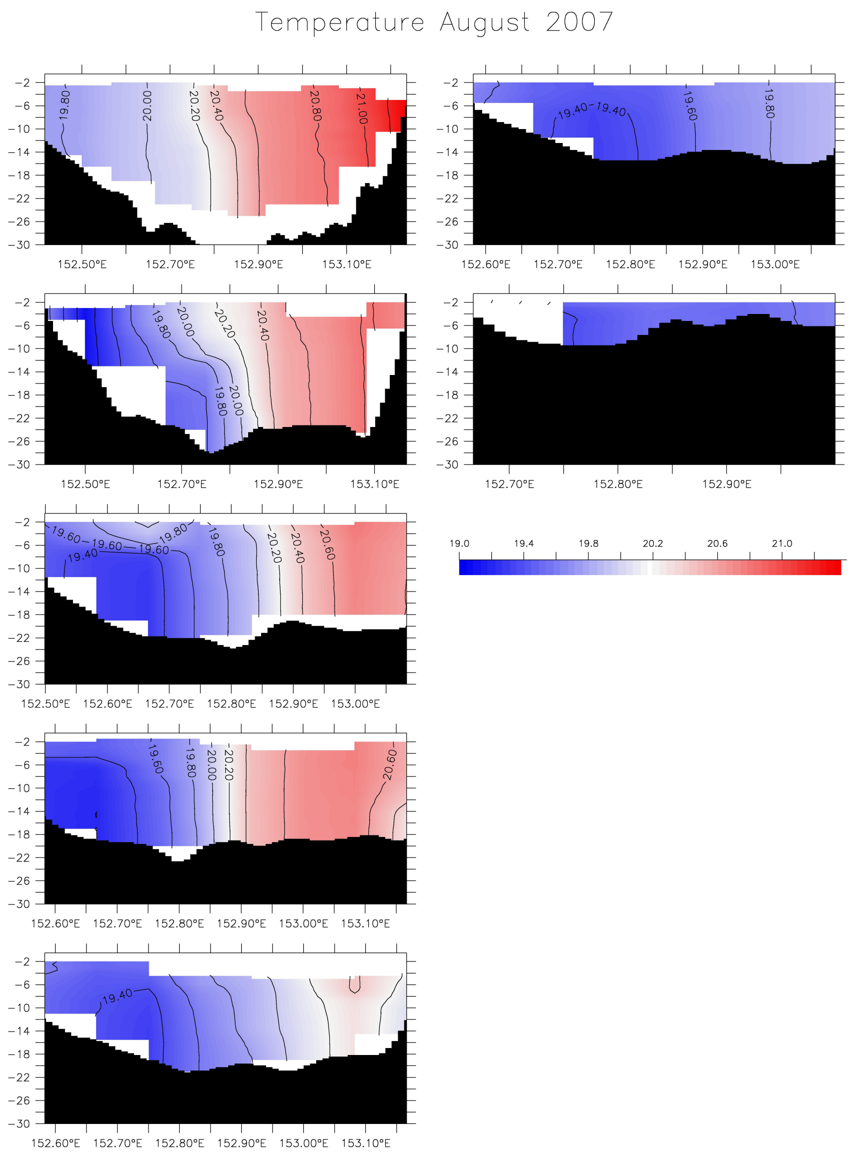

Figure 9: Temperature [T in °C] distribution during August 28-30, 2007, at latitude (a) 24° 40′ S, (b) 24° 45′ S, (c) 24° 50′ S, (d) 24° 55′ S, (e) 25° 00′ S, (f) 25° 05′ S and (g) 25° 10′ S. Top left to top right.

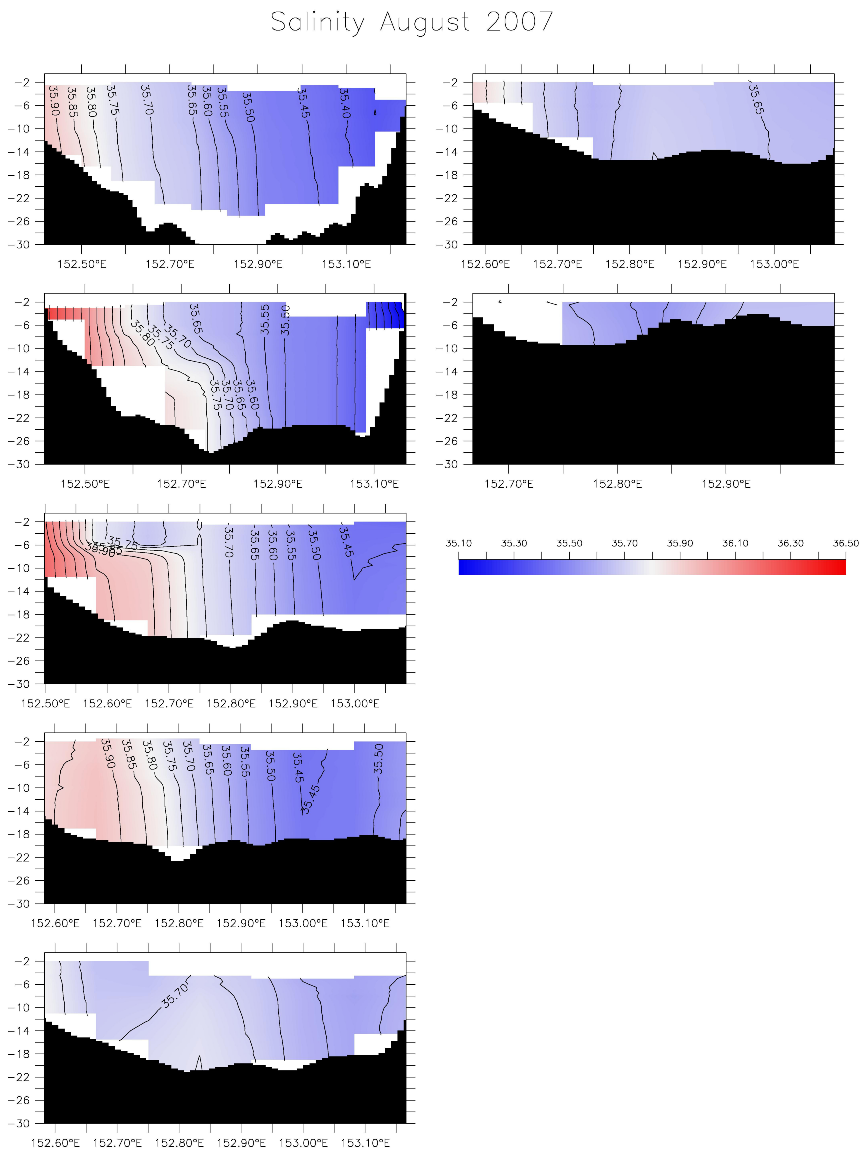

Figure 10: Salinity [S in ppt] distribution during August 28-30, 2007, at latitude (a) 24° 40′ S, (b) 24° 45′ S, (c) 24° 50′ S, (d) 24° 55′ S, (e) 25° 00′ S, (f) 25° 05′ S and (g) 25° 10′ S. Top left to top right.

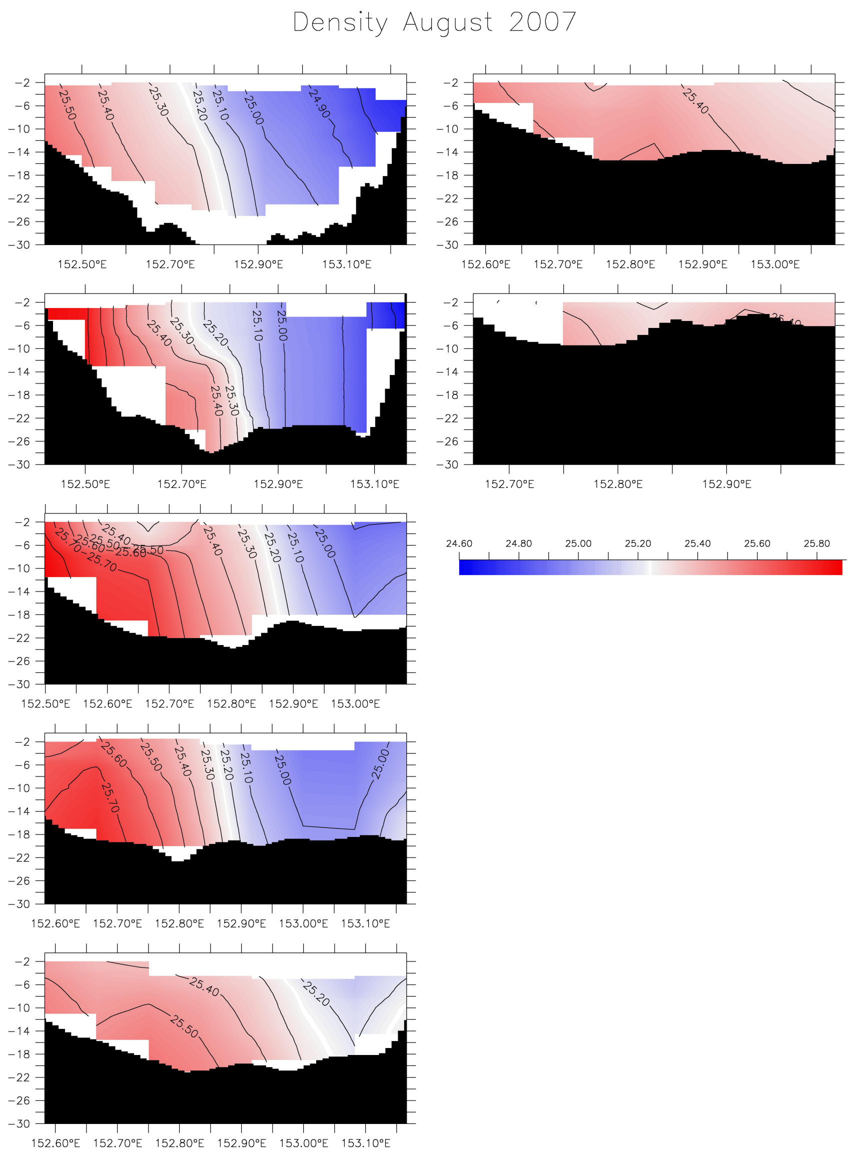

Figure 11: Density [σ_t in kg·m^{-3}] distribution during August 28-30, 2007, at latitude (a) 24° 40′ S, (b) 24° 45′ S, (c) 24° 50′ S, (d) 24° 55′ S, (e) 25° 00′ S, (f) 25° 05′ S and (g) 25° 10′ S. Top left to top right.

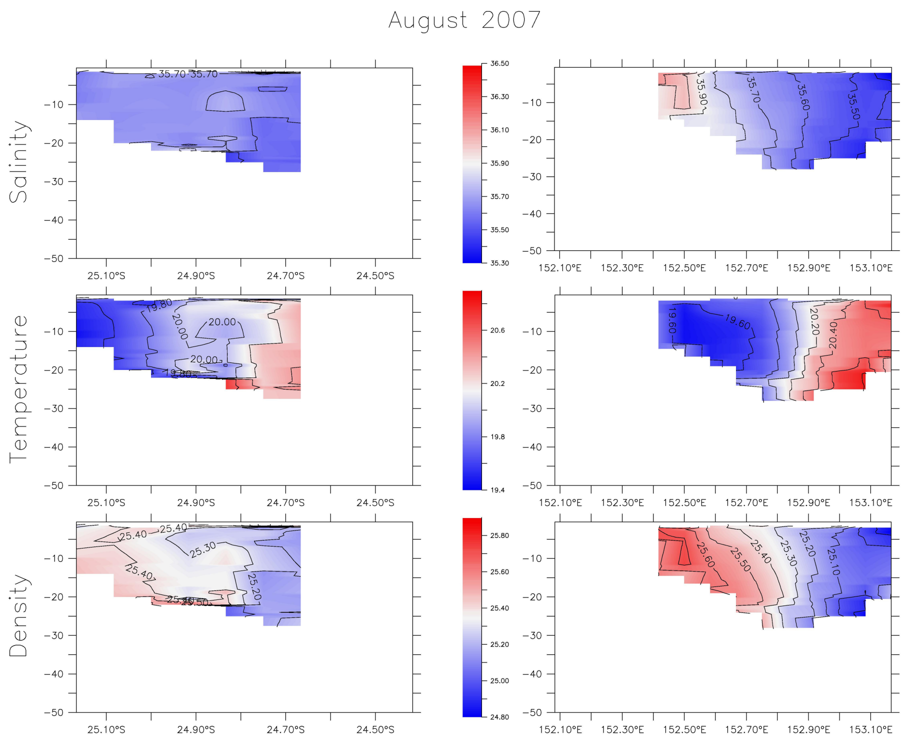

Figure 12: Basin average salinity [ppt] (top), temperature [T in °C] (middle), and density [σ_t in kg·m^{-3}] (bottom) in latitudinal (left column) and longitudinal (right column) direction during August 28-30, 2007.

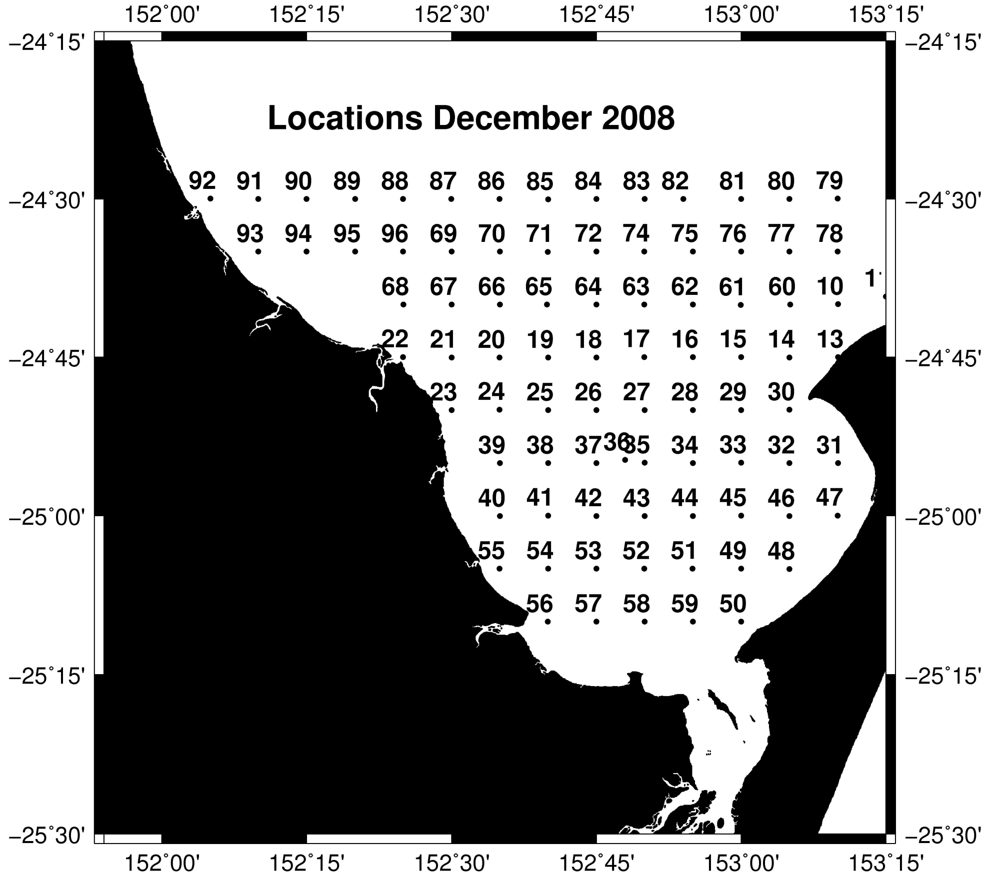

Figure 13: Hydrographic sample location surveyed during December 4-7, 2007.

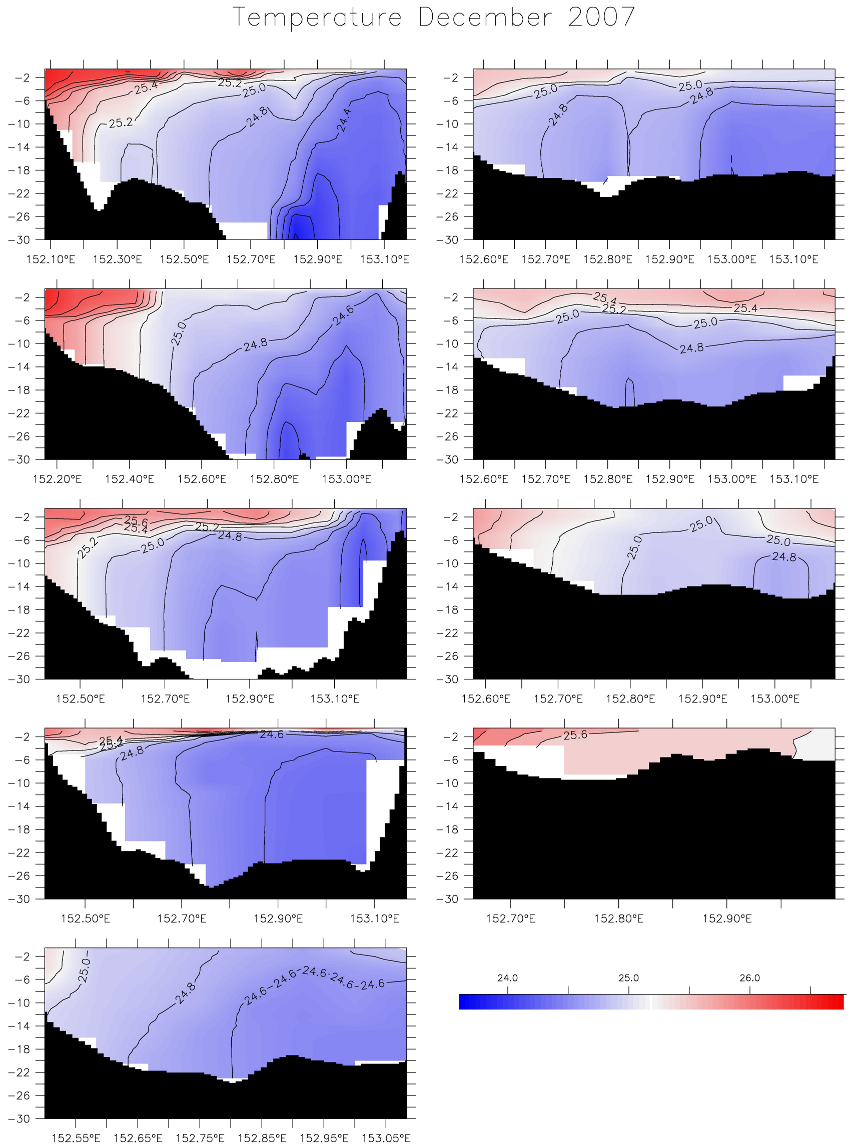

Figure 14: Temperature [T in °C] distribution during December 4-7, 2007, at latitude (a) 24° 30′ S, (b) 24° 35′ S, (c) 24° 40′ S, (d) 24° 45′ S, (e) 24° 50′ S, (f) 24° 55′ S, (g) 25° 00′ S, (h) 25° 05′ S and (i) 25° 10′ S. Top left to top right.

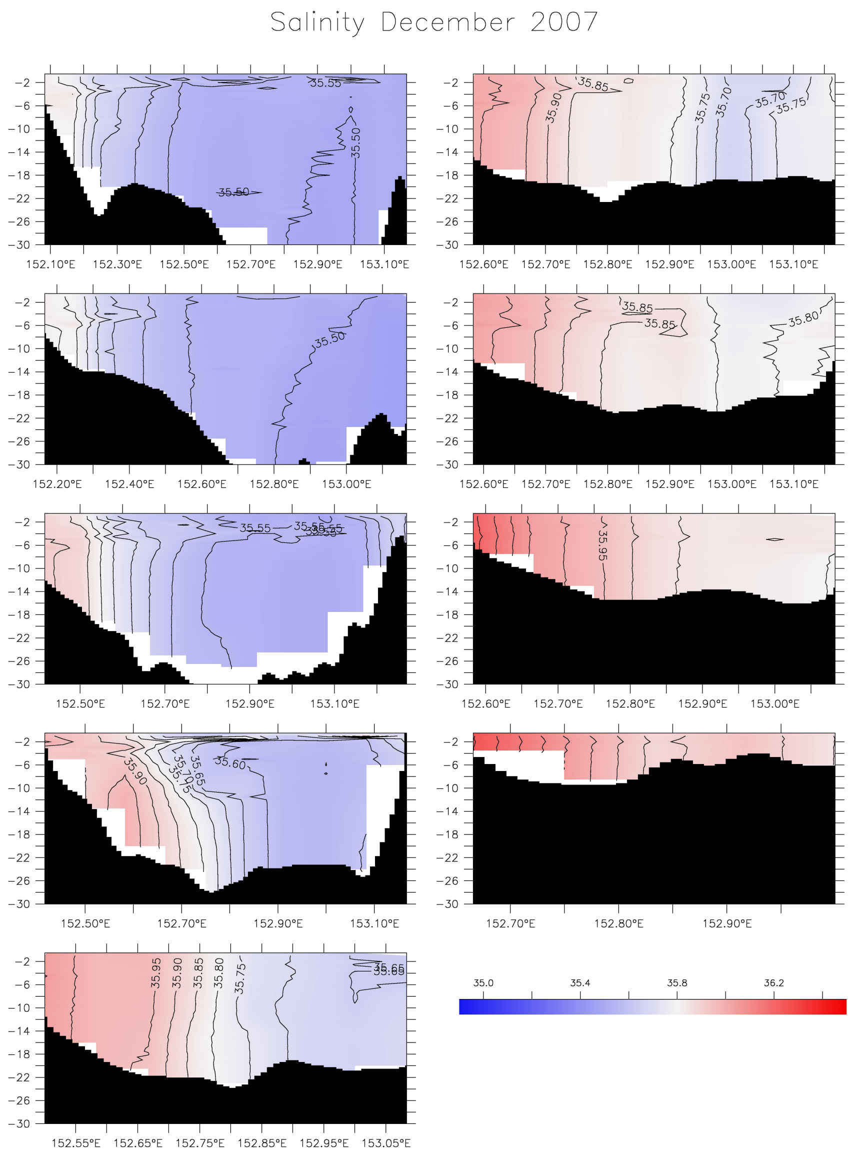

Figure 15: Salinity [S in ppt] distribution during December 4-7, 2007, at latitude (a) 24° 30′ S, (b) 24° 35′ S, (c) 24° 40′ S, (d) 24° 45′ S, (e) 24° 50′ S, (f) 24° 55′ S, (g) 25° 00′ S, (h) 25° 05′ S and (i) 25° 10′ S. Top left to top right.

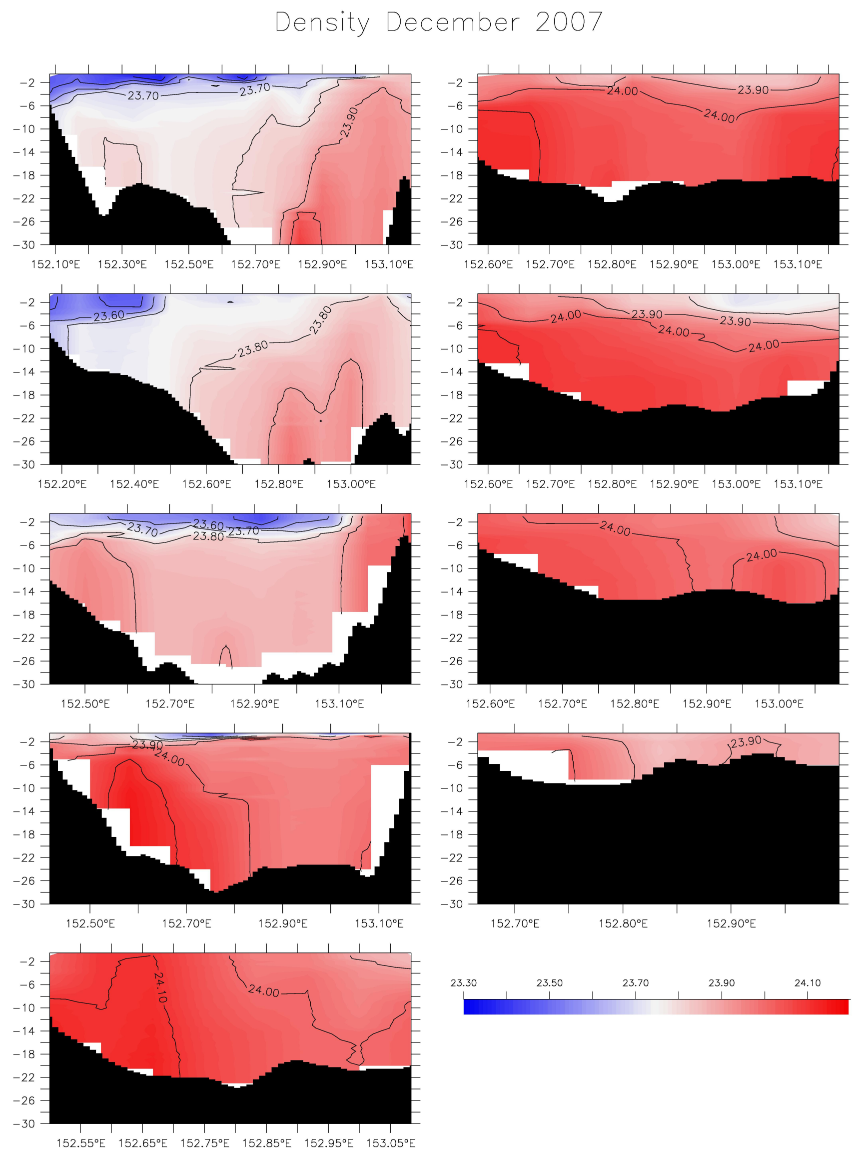

Figure 16: Density [σ_t in kg·m^{-3}] distribution during December 4-7, 2007, at latitude (a) 24° 30′ S, (b) 24° 35′ S, (c) 24° 40′ S, (d) 24° 45′ S, (e) 24° 50′ S, (f) 24° 55′ S, (g) 25° 00′ S, (h) 25° 05′ S and (i) 25° 10′ S. Top left to top right.

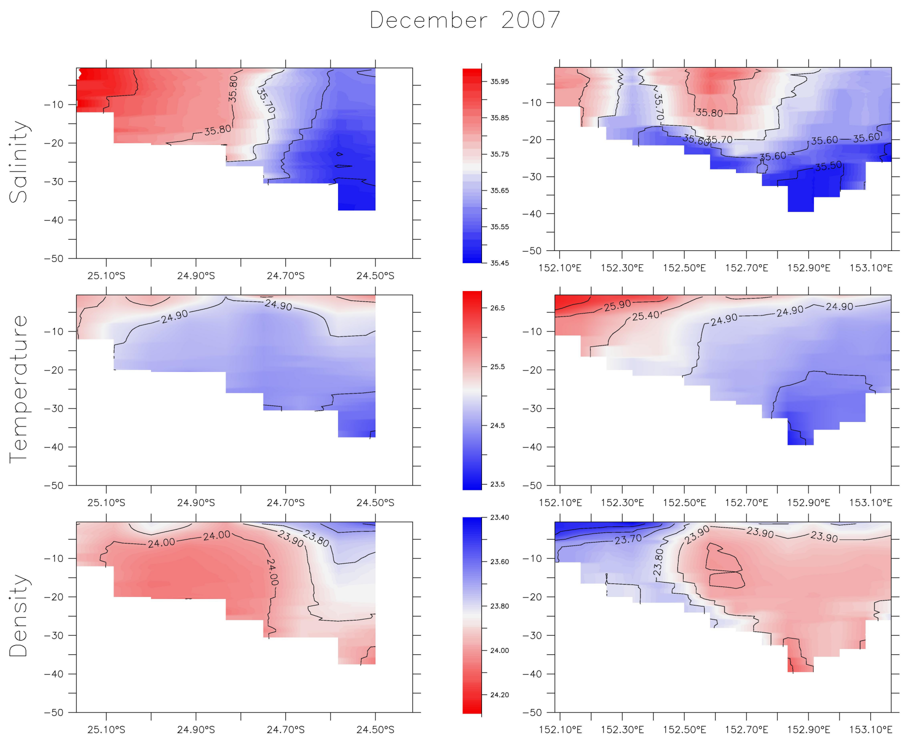

Figure 17: Basin average salinity [ppt] (top), temperature [T in °C] (middle), and density [σ_t in kg·m^{-3}] (bottom) in latitudinal (left column) and longitudinal (right column) direction during December 4-7, 2007.

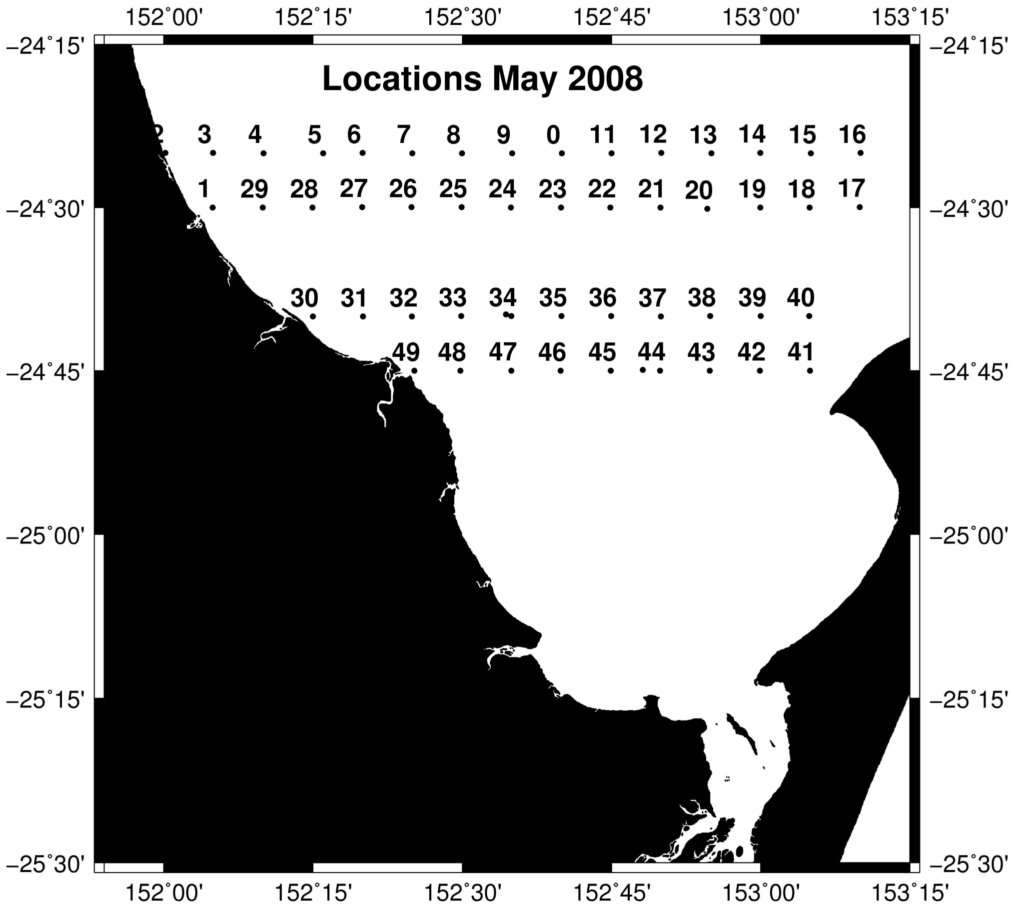

Figure 18: Hydrographic sample location surveyed during May 28-29, 2008.

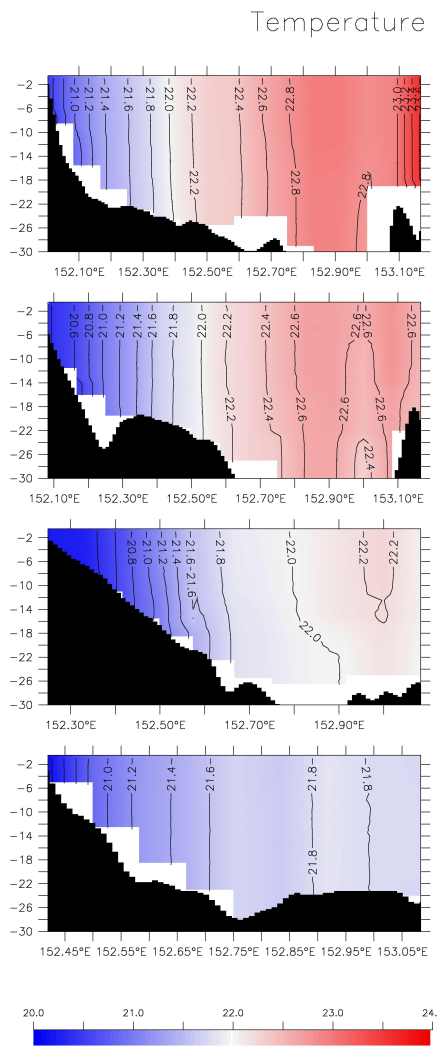

Figure 19: Temperature [T in °C] distribution during May 28-29, 2008, at latitude (a) 24° 25′ S, (b) 24° 30′ S, (c) 24° 40′ S and (d) 24° 45′ S. Top left to top right.

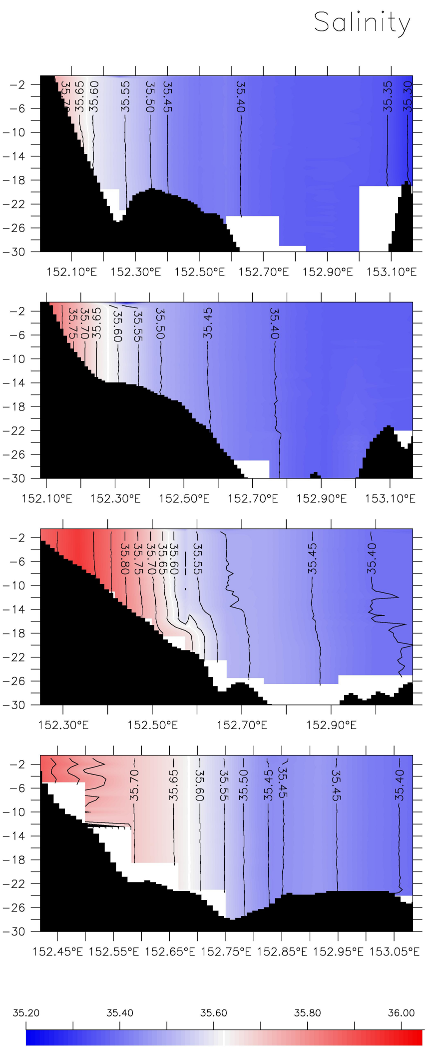

Figure 20: Salinity [S in ppt] distribution during May 28-29, 2008, at latitude (a) 24^{o} 25′ S, (b) 24^{o} 30′ S, (c) 24^{o} 40′ S and (d) 24^{o} 45′ S. Top left to top right.

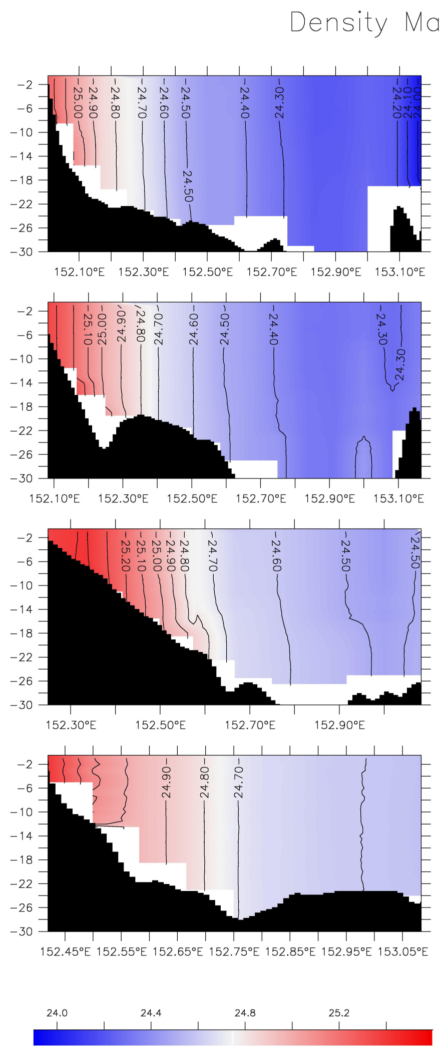

Figure 21: Density [σ_t in kg·m^{-3}] distribution during May 28-29, 2008, at latitude (a) 24º 25′ S, (b) 24º 30′ S, (c) 24º 40′ S and (d) 24º 45′ S. Top left to top right.

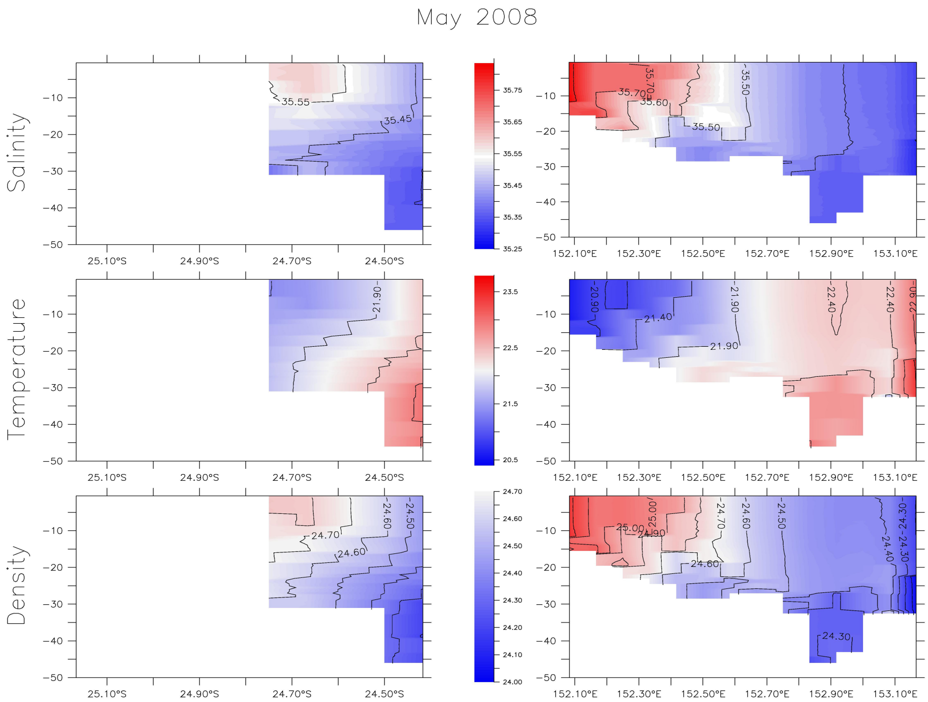

Figure 22: Basin average salinity [ppt] (top), temperature [T in °C] (middle), and density [σ_t in kg·m^{-3}] (bottom) in latitudinal (left column) and longitudinal (right column) direction during May 28-29, 2008.

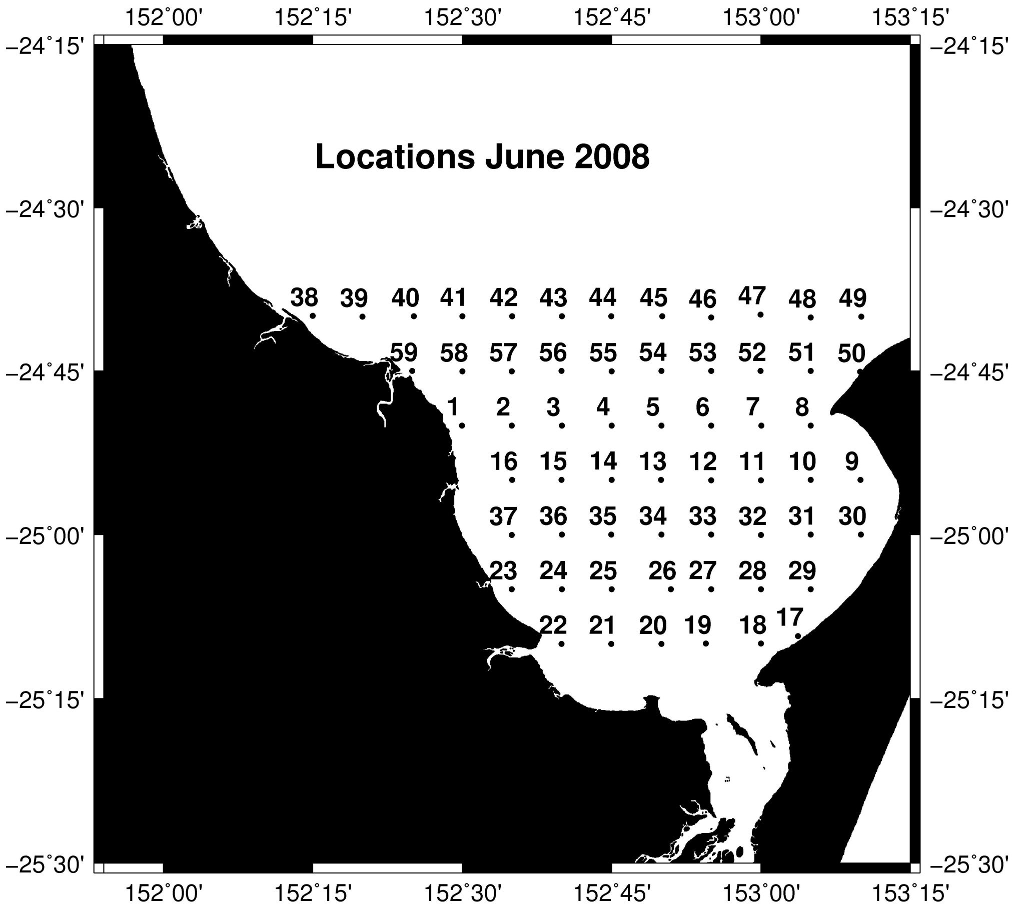

Figure 23: Hydrographic sample location surveyed during June 16-18, 2008.

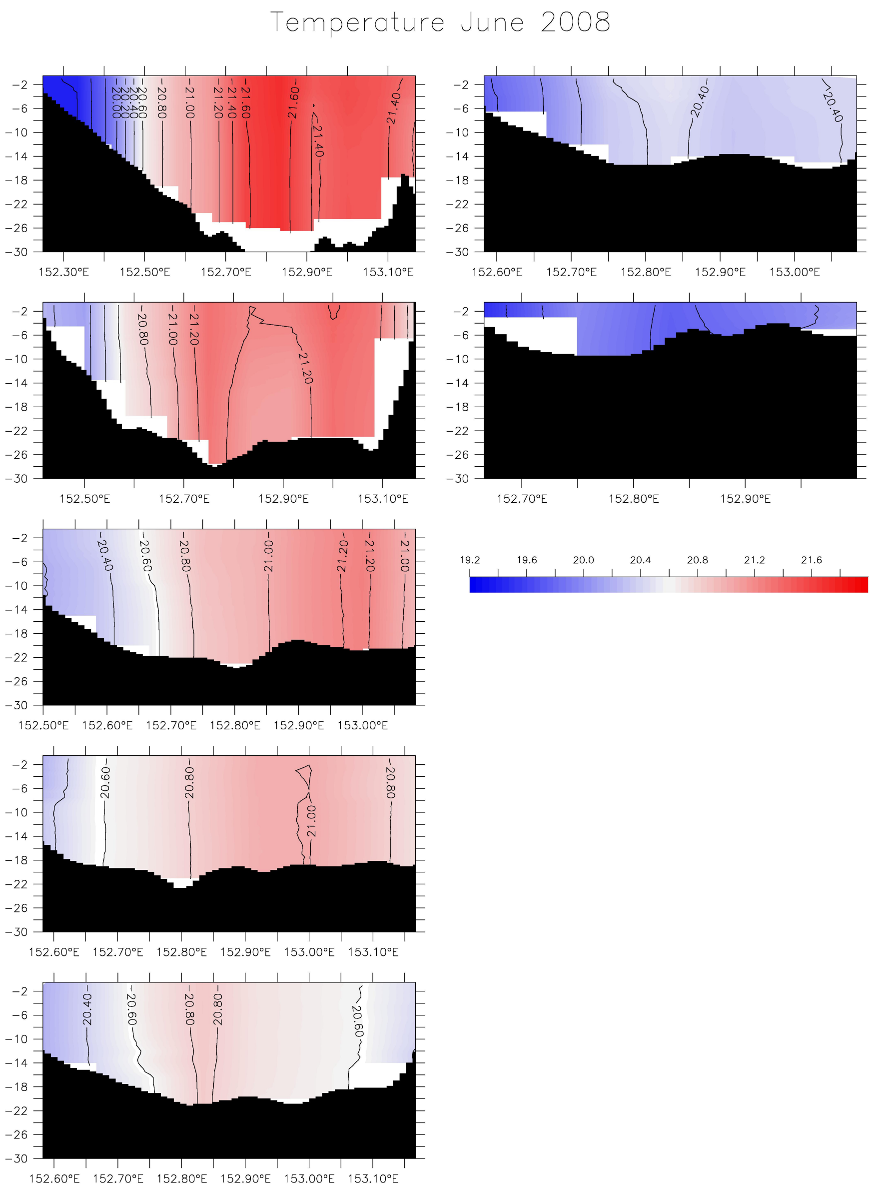

Figure 24: Temperature [T in °C] distribution during June 16-18, 2008, at latitude (a) 24° 40′ S, (b) 24° 45′ S, (c) 24° 50′ S, (d) 24° 55′ S, (e) 25° 00′ S, (f) 25° 05′ S and (g) 25° 10′ S. Top left to top right.

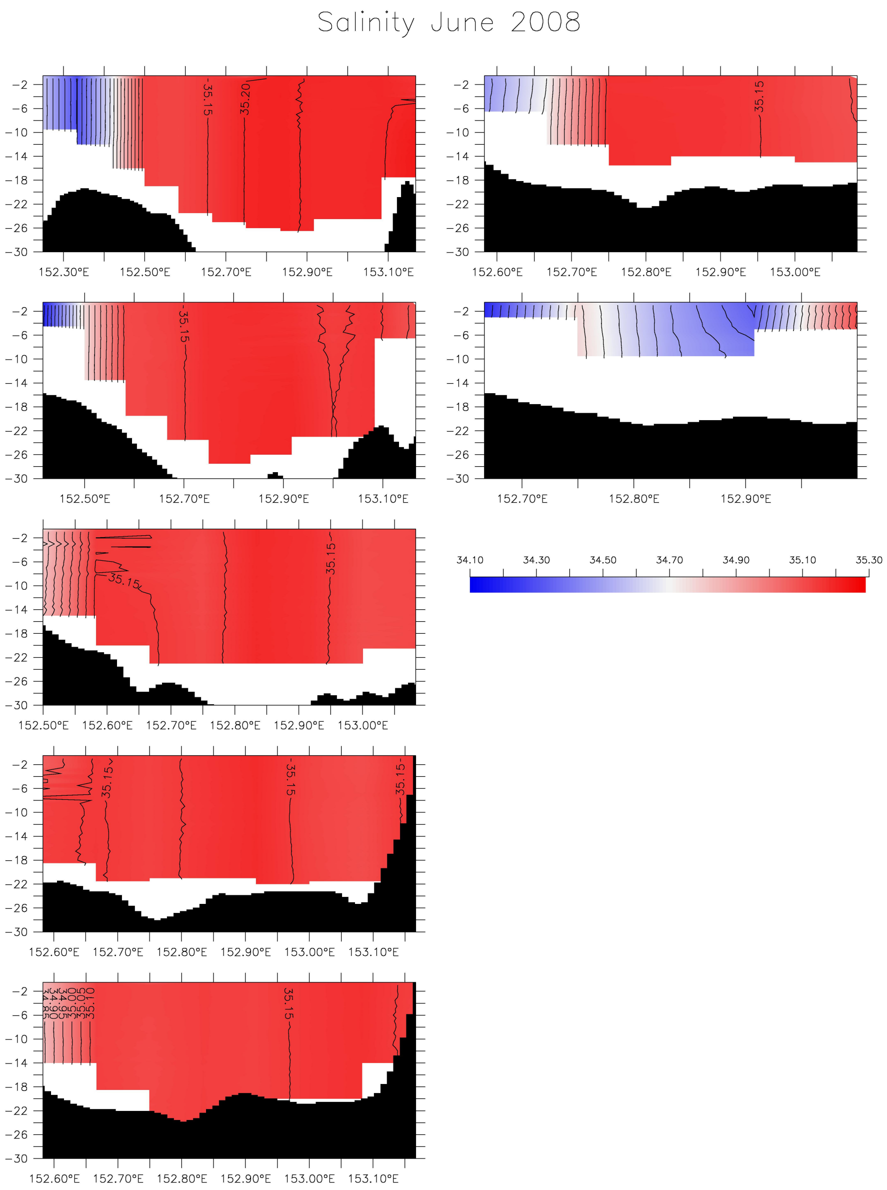

Figure 25: Salinity [S in ppt] distribution during June 16-18, 2008, at latitude (a) 24° 40′ S, (b) 24° 45′ S, (c) 24° 50′ S, (d) 24° 55′ S, (e) 25° 00′ S, (f) 25° 05′ S and (g) 25° 10′ S. Top left to top right.

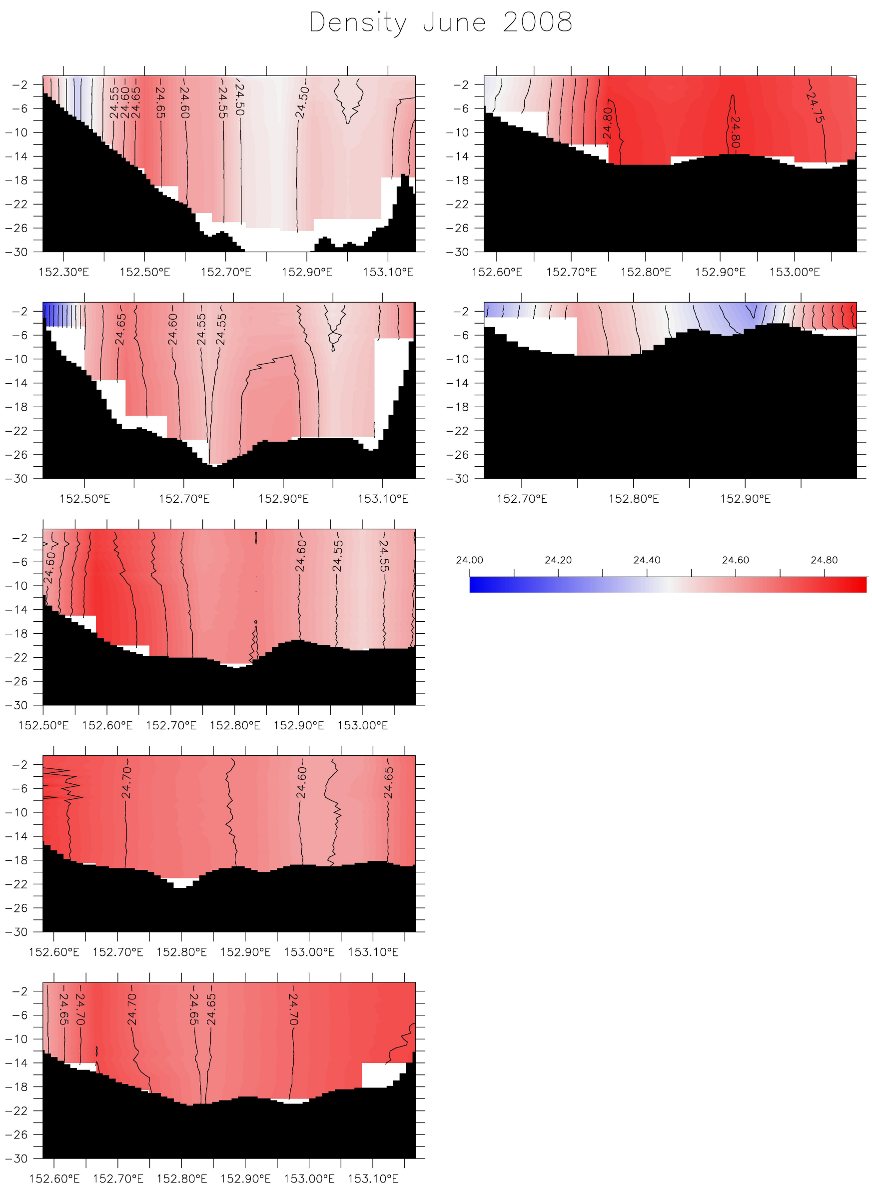

Figure 26: Density [σ_t in kg·m^{-3}] distribution during June 16-18, 2008, at latitude (a) 24° 40′ S, (b) 24° 45′ S, (c) 24° 50′ S, (d) 24° 55′ S, (e) 25° 00′ S, (f) 25° 05′ S and (g) 25° 10′ S. Top left to top right.

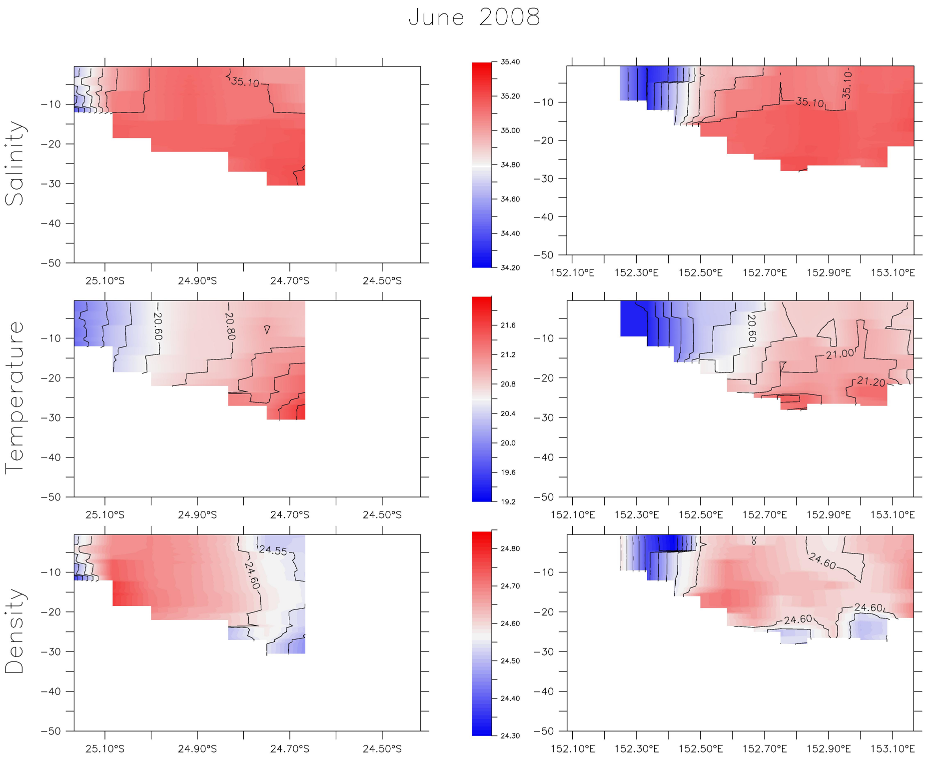

Figure 27: Basin average salinity [ppt] (top), temperature [T in °C] (middle), and density [σ_t in kg·m^{-3}] (bottom) in latitudinal (left column) and longitudinal (right column) direction during June 16-18, 2008.

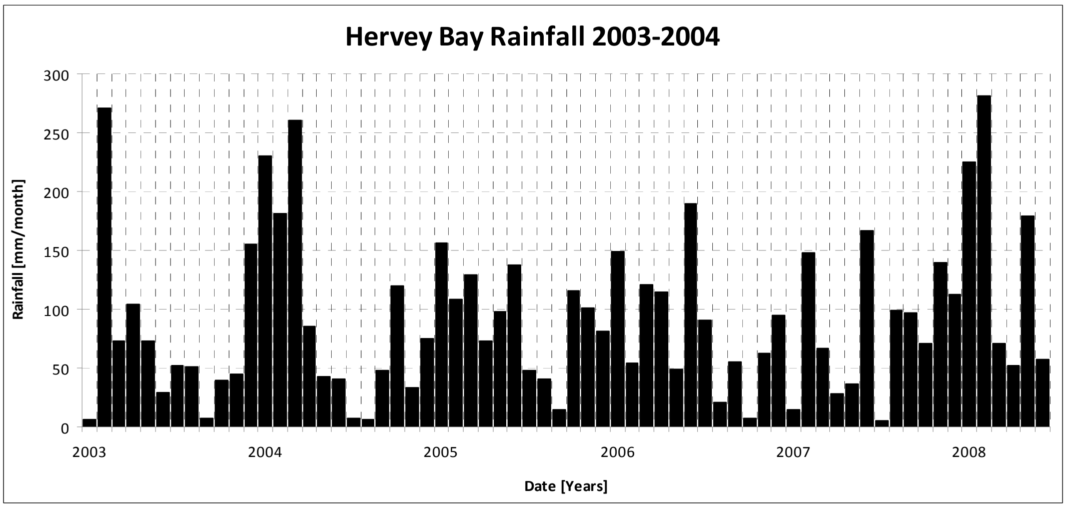

Figure 28: Total monthly precipitation for the Hervey Bay region as a composite for rainfall record at Bundaberg, Sandy Cape, and Urangan. Data provided by State of Queensland (Queensland Department of Primary Industries and Fisheries).

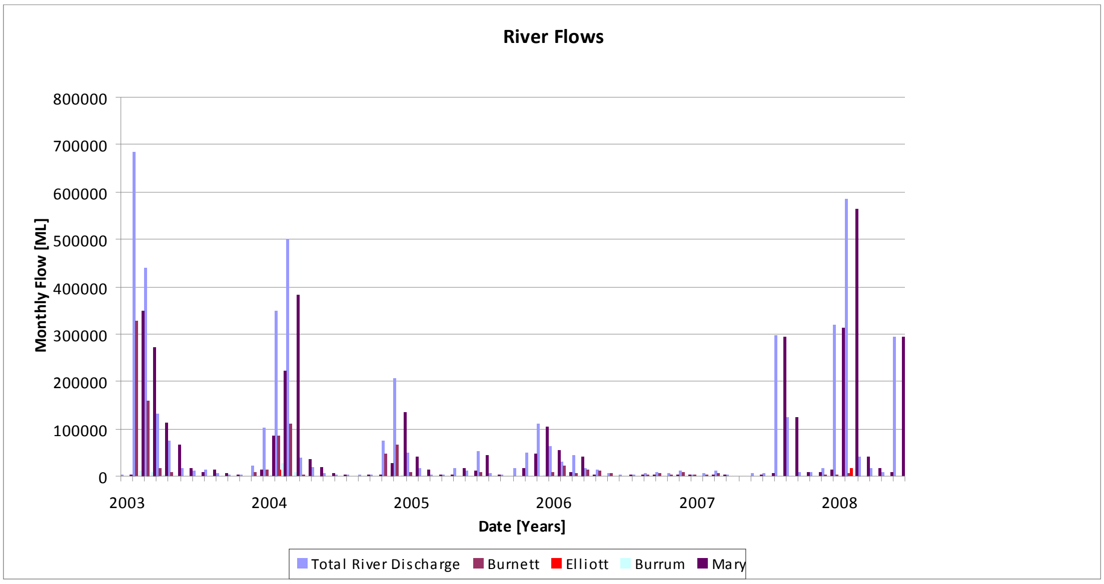

Figure 29: River discharges [ML] from the four main rivers into Hervey Bay. Data provided by State of Queensland (Department of Natural Resources and Water).

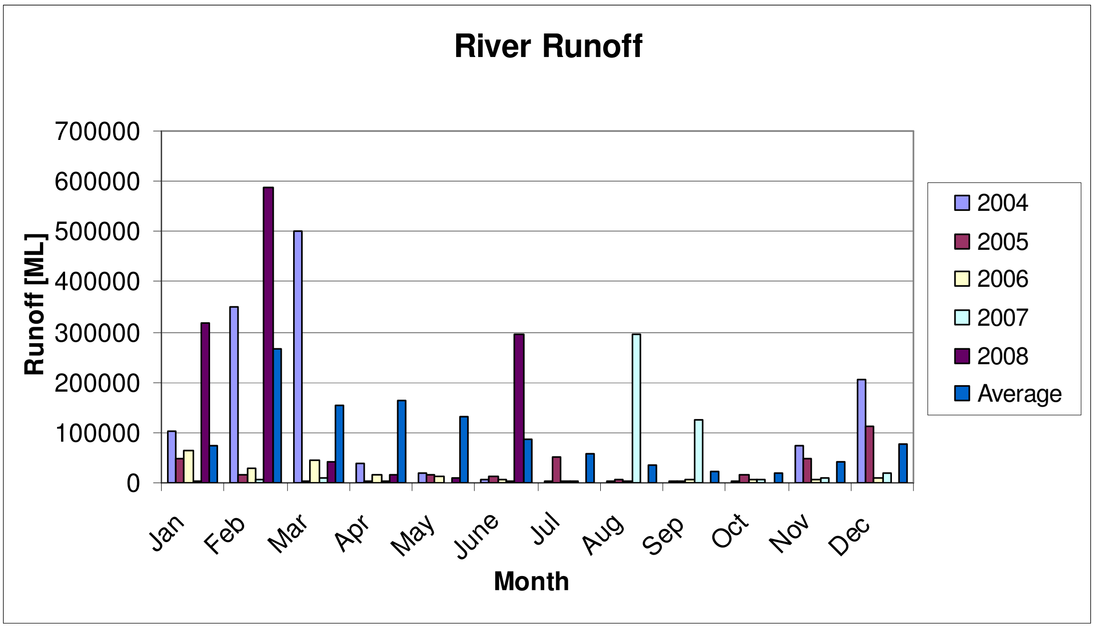

Figure 30: Total river discharges [ML] into Hervey Bay during survey period 2004-2008. Data provided by State of Queensland (Department of Natural Resources and Water).

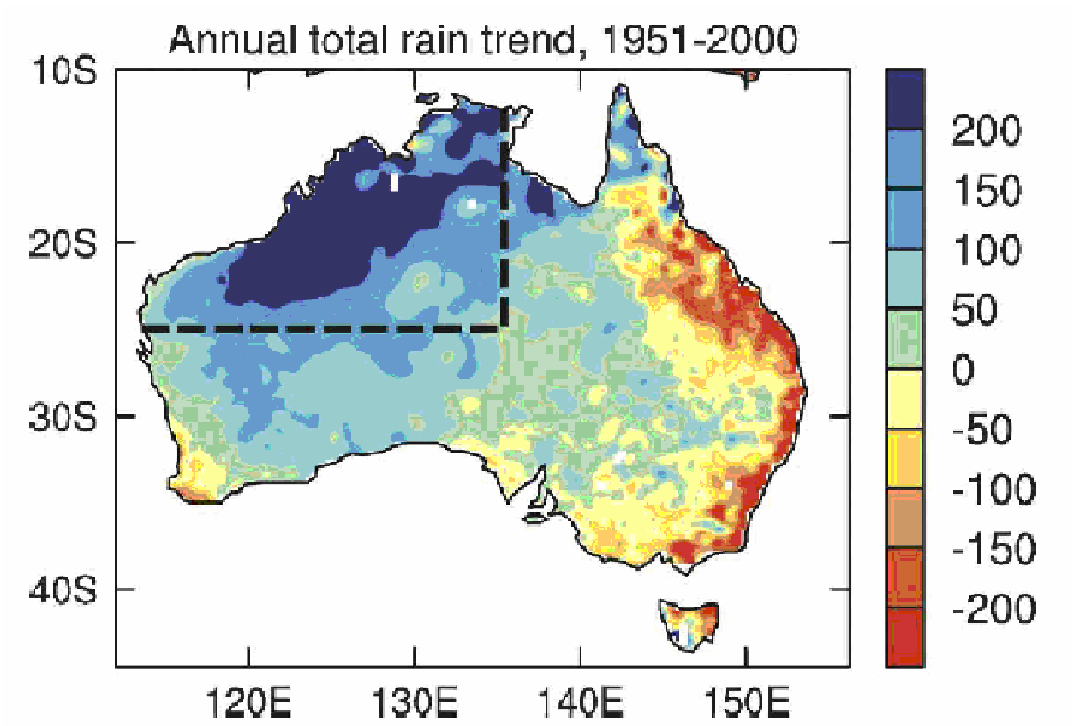

Figure 31: Observed annual rainfall trends based on BMRC rainfall from 1951-2000 (Source: Shi et al. 2008).

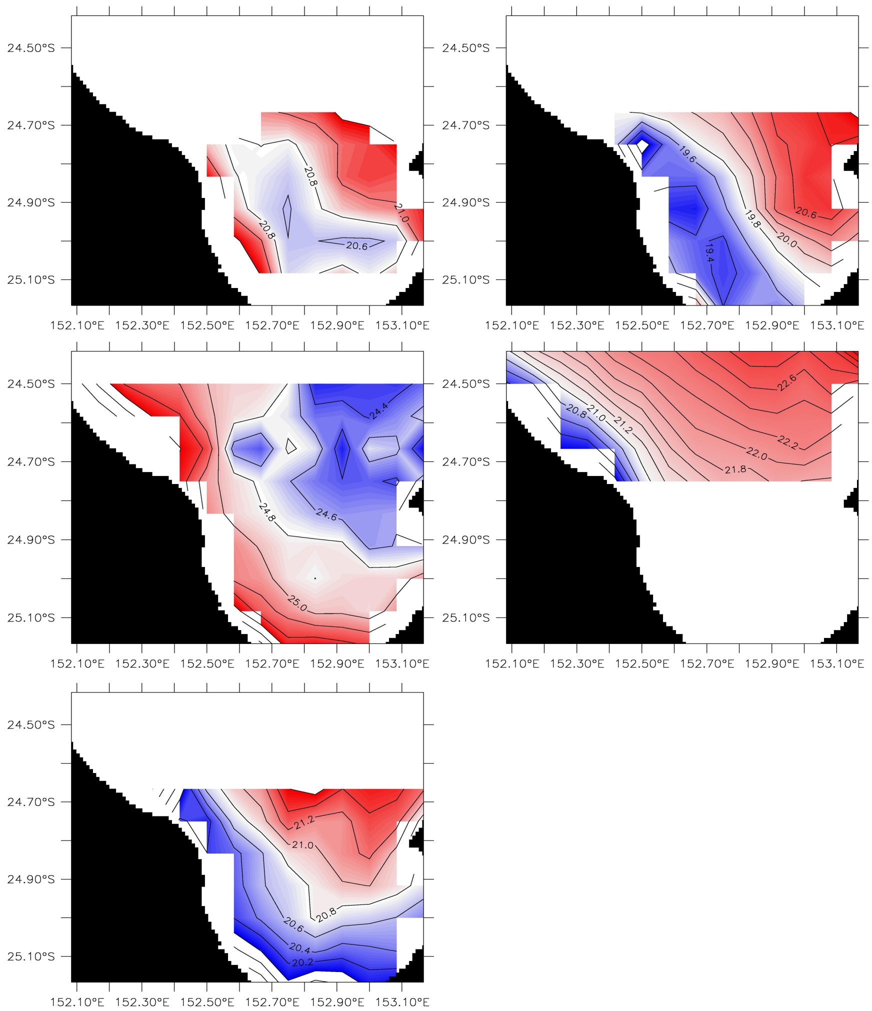

Figure 32: Depth-averaged temperature [ºC] distribution from observations in (a) September 2004, (b) August 2007, (c) December 2007, (d) May 2008 and (e) June 2008. Contour interval is 0.2 ºC and warm water regions are shaded in red.

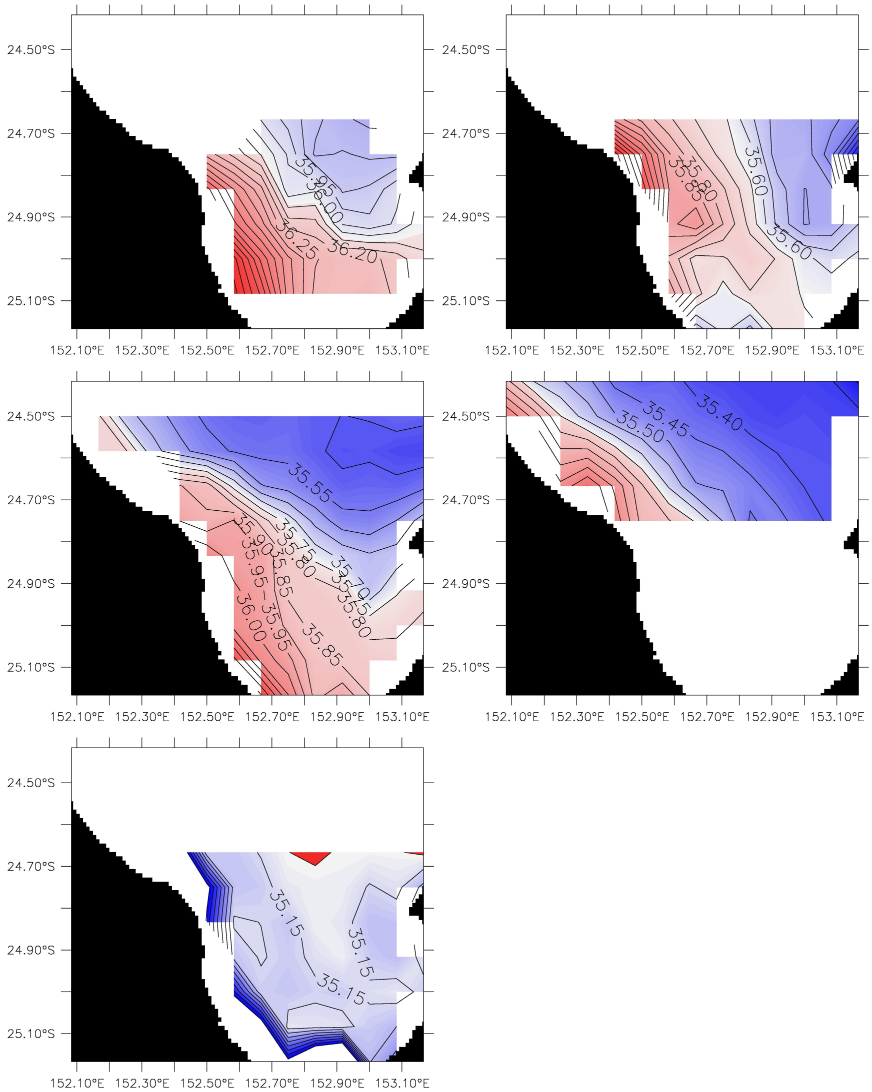

Figure 33: Depth-averaged salinity [ppt] distribution from observations in (a) September 2004, (b) August 2007, (c) December 2007, (d) May 2008 and (e) June 2008. Contour interval is 0.05 ppt and high salinity water regions are shaded in red.

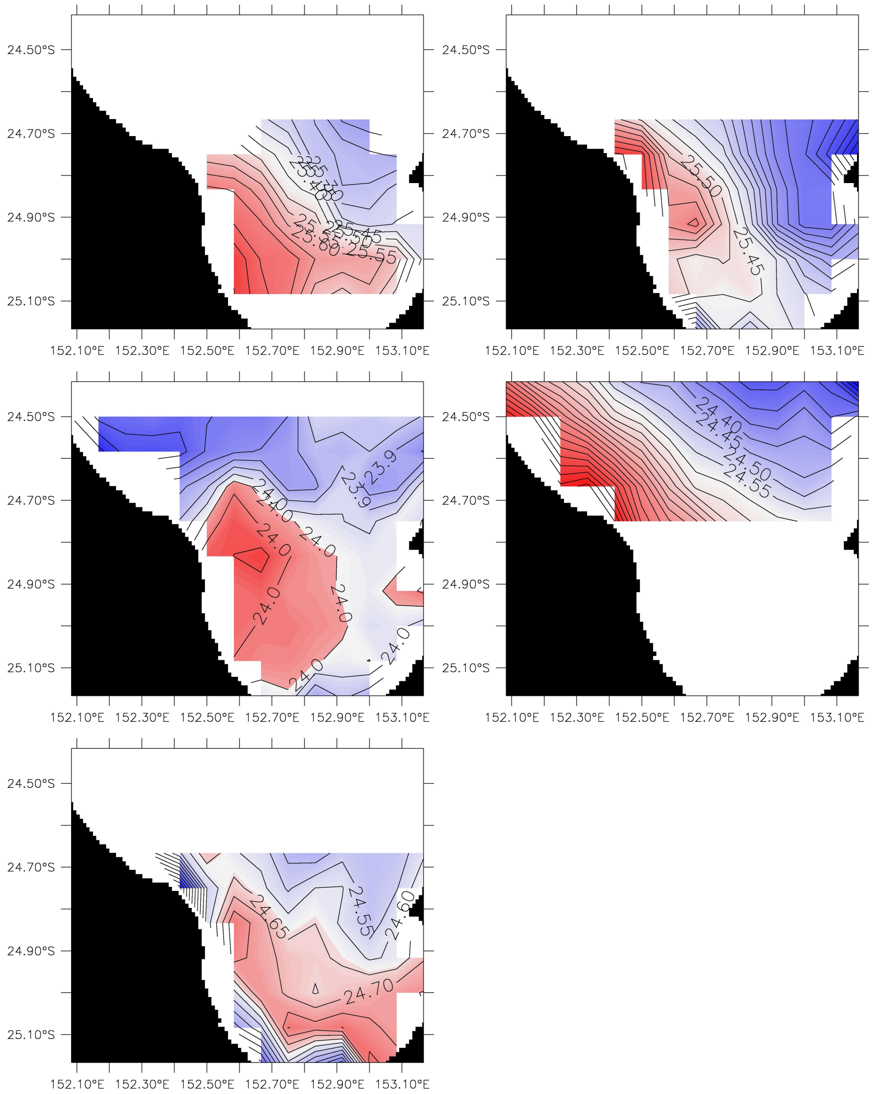

Figure 34: Depth-averaged density [kg·m-3] distribution from observations in (a) September 2004, (b) August 2007, (c) December 2007, (d) May 2008 and (e) June 2008. Contour interval is 0.05 kg·m-3 and high density regions are shaded in red.