A study into the export of saline water from Hervey Bay, Australia

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Content

Abstract

Australia's climate is one of the world's driest and locally characterised by high year-to-year rainfall variability. Due to high evaporation and low river runoff many estuaries and embayments in the region are characterised by inverse conditions with salinity increasing toward the coast and river mouths. Such conditions were also found during the first comprehensive hydrographic survey of Hervey Bay located at the east coast of Australia in early spring 2004. The survey traced a subsurface salinity maximum that was found in earlier studies within the East Australia Current east of Hervey Bay to the shallow southwest regions of the bay. These are identified as the most likely source region for locally produced saline Hervey Bay Water. Utilising a simple box model, mean evaporation rates and historical river run-off data, it is demonstrated that inverse conditions are likely to dominate throughout the year. The negative circulation is a climatological feature of this estuary that is not limited to the dry season of the year. Due to persistent drought and declining rainfall in coastal eastern Australia, these conditions are likely to persist into the near future and need to be considered in coastal management strategies.

Key words: estuaries; estuarine dynamics; water masses; CTD observations; box model; climate change; Australia; East Australia Current; Hervey Bay Water

1. Introduction

The Australian estuaries and shelf seas are significantly impacted by high year-to-year rainfall variability, a dry climate in comparison to that of other continents, and the fact that about 80 % of Australia's population resides in coastal regions and uses estuaries and their catchments for commercial (e.g. farming, fishing, aquaculture, coastal development) and non-commercial (e.g. recreation, tourism) purposes. In dry climates or during drought conditions, estuaries and larger coastal embayments are often characterised by a negative circulation, with inflow at the surface and outflow of high salinity water at the bottom. Such systems have been found in Australia (e.g.

Wolanski 1986, Nunes and Lennon 1986, de Silva Samarasinghe and Lennon 1987, Burling et al. 1999, de Silva Samarasinghe et al. 2003) and studied in other parts of the world (e.g. Lavin et al. 1998; de Castro et al 2004). In this paper, first insight into the physical oceanographic conditions from an early spring hydrographic survey of Hervey Bay, located off the coast of central eastern Australia, and its physical settings is provided. Middelton et al. (1994) lacked observational evidence in support of their hypothesis that Hervey Bay potentially exports high salinity water formed through a combination of heat loss, high evaporation and weak freshwater input in shallow regions of the bay. The data presented in this paper together with the application of a simple model provide this evidence and support the notion that a local water mass formation process exists within Hervey Bay.

Systematic research into the circulation of Hervey Bay is lacking and most recent studies focus on aspects that underpin the importance of the Bay as a marine ecological system and whale sanctuary. Hervey Bay is a resting place for several thousand Humpback whales that migrate between the southern and tropical oceans annually (Chaloupka et al 1999). Moss and Kocovski (1998) implemented a long-term chlorophyll-a monitoring program within the bay during the whale watch season. The region is also home to a large number of dugongs and sea turtles that were listed as vulnerable to extinction by the International Council for the Conservation of Nature and Natural Resources. Severe weather events and extreme high river-runoff led to a major sea grass loss and impacted adversely upon the dugong population in the past (Preen 1995, Preen and Marsh 1995, Preen et al. 1995) highlighting the regions vulnerability to extreme physical climatic events. Sea grass recovery was monitored for several years (Campbell and McKenzie, 2004). The subtropical water of Hervey Bay is also a spawning region for temperate pelagic fish (Ward et al. 2003) and supports a fisheries industry that is worth several tenths of millions of dollars with aquaculture developing recently into a significant industry (ABARE 2004). Coastal population growth in the Hervey Bay region is exceptional and was one of the largest in Australia during the last 10 years (LPG 2004), placing further pressure on an important ecological system.

Many of the previous studies have in common that they were conducted without any or only limited consideration of the general physical, oceanographic or climatological conditions in the bay and the impact these might have upon sampling strategies and environmental monitoring programs. Yet, the physical conditions within a coastal embayment and estuaries are clearly 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 clearly unique.

2. Site characteristics and method

Hervey Bay (Figure 1) is situated just outside the southern boundary of the Great Barrier Reef Marine Park off the coast of sub-tropical southeast Queensland, Australia. It is bowl-shaped with an area of about 4000 km^2 and a main opening facing northward. At this location, the continental shelf is about 90-100 km wide and the eastward boarder separating the bay from the open ocean is formed by Fraser Island, the world largest sand island. Based upon its sedimentary environment, Boyd et al (2004) classified the bay as a shoreline divergent estuary expanding on the now well accepted classification of Australian estuaries introduced by Roy (1984) and updated by Roy et al. (2001).

[Insert Figure 1]

At its northern end, the Bay is about 80 km wide and its average depth is about 20 m. 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, and Burnett rivers drain into the Bay. The highly managed Mary and Burnett Rivers are the main sources for freshwater with the Burrum having only a small catchment area (see discussion below). 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 found in the north of the study area.

The climate of the region is classed as subtropical with no distinct dry period (Stern et al. 2000). Rainfall is at a maximum from about January to April with an approximate climatological average of 150 mm per month for this period, yet rainfall and correlated run-off are characterised by high interannual variability (EPA 2001) and since about 1950, rainfall in coastal Queensland declined with about 50 mm per decade (Manins et al. 2001).

A hydrographic survey of Hervey Bay was conducted from September 20th to September 26th, 2004 during which conductivity-temperature-depth profiles were recorded at 46 locations. The survey was conducted on-board the Queensland Department of Primary Industries and Fisheries (DPI&F) research vessel Tom Marshall. Sample locations are indicated in Figure 1 and were spaced at about 5 nautical mile intervals in both north to south and west to east direction. These data provide a first comprehensive insight into the physical settings of Hervey Bay complementing earlier oceanographic studies that were conducted outside the bay (e.g. Middelton et al. 1994).

3. Results and discussion

In this section, firstly the temperature and salinity observations recorded during the hydrographic survey are presented and discussed. Secondly, a simple model is presented that considers the balance between evaporation and river runoff in forcing a residual internal circulation driven primarily by the production of high salinity water in shallow coastal near-shore regions (Wolanski 1986; de Silva Samarasinghe and Lennon 1987). Other processes such as the inertial and frictional forces, winds, tides and Earth rotation are certainly important when investigating details of the three-dimensional circulation of estuaries and coastal embayments (e.g. Fischer 1976, Kasai et al. 2000). Yet, it is the observed salinity distribution, which is consistent with that of an inverse estuary and justifies in the first instance, the application of a simple two-layer box model to investigate some of the basic physical properties of the bay.

3.1 Observed temperature and salinity distribution

The depth-averaged distributions for temperature and salinity are shown in Figure 2 and Figure 3 respectively. Indicated are the sample locations. Lowest temperature values were found within the interior of the bay with temperature as low as 20.6 ^{o}C. Toward the coast as well as the open ocean temperature increased with higher values toward the edges of the bay, maximum values in the northeast closest to the open ocean region and the shallow coastal southwest with values of about 21.2 ^{o}C. The weekly averaged SST AVHRR data obtained from the CSIRO Marine and Atmospheric Research (courtesy of Dr. D. Griffin, but not shown here) reflect a similar pattern and is characterised by a temperature minimum within the interior of the bay increasing toward the edges of the bay.

[Insert Figure 2]

The depth-averaged salinity distribution (Figure 3) exhibits a gradient of about 0.8 across the bay; from a minimum value of about 35.7 in the northeast of the bay (outer shelf and open ocean region) to values larger than 36.5 in the southwest. The highest depth averaged salinity values were found in the shallow regions of the bay with water depth decreasing from about 15 m to less than 5 m toward the coastline. This salinity distribution already provides some first indication of a hydrographic structure for the bay that is consistent with that of an inverse estuary and is discussed further below.

[Insert Figure 3]

In the following section, the distribution of temperature and salinity with depth along individual daily cruise tracks is displayed. Figures 4 to 7 are joined, north to south and west to east, quasi-synoptic daily section plots along the cruise track. During the first day of sampling (Figure 4a and Figure 4b), the track commenced in the southern part of the bay leading to the north along 152^{o} 45’ E before turning to the east and covering the northeast region of the survey area. In the northeast part of the survey region warm, low-salinity water extends to depth of about 6-7 m. The surface layer resides above colder but saltier water. An increase of salinity through the water column and toward the most southern part of the survey during day one was observed with salinity lower in the surface layer than in the bottom layer throughout the bay. The structure of a two layer system, with salinity high in the bottom layer, is consistent with that of an inverse estuary.

[Insert Figure 4a]
[Insert Figure 4b]

During the 2nd day of the survey (Figure 5a and Figure 5b), locations in the northeast quadrant of the bay were sampled. The northern area (stations 19-22 in particular) is again characterized by warmer and less salty water ($T > 21.1\ ^{o}C$, $S < 35.9$) overlaying cool and saltier water ($T < 21.1\ ^{o}C$, $S > 35.9$).

[Insert Figure 5a]
[Insert Figure 5b]

Sampling during the 3rd day of the survey was confined to the southern part of the bay obtaining data from both the eastern and western region. The western domain is clearly characterized by warmer ($T > 21.1\ ^{o}C$) and more saline water ($S > 36.2$) than the eastern areas (Figure 6a and Figure 6b). The highest salinity values encountered during the survey were found within the shallower region (< 10 m) of the bay at stations 31-33. Values were as high as about 36.9. Lowest salinity values were found during day 1 at location 8 with minimum values of about 35.6.

[Insert Figure 6a]
[Insert Figure 6b]

The distribution of temperature (Figure 7a) and salinity (Figure 7b) observed during the 4th and final day of the survey revealed a pattern that was consistent with those observed during the previous days. The survey was conducted primarily in the northwest quadrant of the bay, with a few final locations along the northern boundary of the survey region. Temperature was largest in the south and in proximity of the coastline and toward the open ocean of the surveyed region. Salinity clearly exhibited a trend of increasing values throughout the water column and toward the southwest of the region with largest values encountered at locations 34, 35 and 36.

[Insert Figure 7a]
[Insert Figure 7b]

It is interesting to take note again of the subsurface salinity maximum (S > 36.5) that extends toward the northeast (location 34 and 35) and which is associated with a lower temperature. This is interpreted as an indication of an outflow away from the shallow regions of the bay and driven by high salinity and possible cooling. This is also observed during day 1 (location 2, 3, 4) and day 3 (location 31, 32, and 33). It is this supply of salt to the subsurface layer of the Bay which raises salinity above the values observed at the open shelf and ocean. Wind and tidal mixing within the bay homogenises salinity further throughout the bay, but are not sufficient to fully mix the water column.

This high salinity water, i.e. Hervey Bay Water was earlier observed by Middelton et al. (1994) being supplied to the open ocean, albeit their observations were made during May at the begin of the southern hemisphere winter season and within the open ocean, while the data reported here were recorded at the end of winter in coastal water. It should be noted that Middelton et al. (1994) stated their hypothesis without any support from observation of temperature and salinity taken within the bay. The data reported here, however, provide some strong support of their hypothesis. The shallow regions of the bay seem to be the source for a particular regional water mass, i.e. Hervey Bay Water, that enters the open ocean to the north of Fraser Island producing a localised subsurface salinity maximum within the East Australia Current system east of Fraser Island.

Due to a lack of observations in Hervey Bay and off the central Queensland continental shelf, it is difficult to assess how the September 2004 survey compares to average seasonal conditions in the region. In addition to the survey reported by Middelton et al. (1994), other data available comes from the weekly averaged SST AVHRR (courtesy of Dr. D. Griffin, see above but not show here). The 10-year record (1994-2004) indicates that SST can vary from year to year and for any particular month by about 3-4 ^{o}C. Since river runoff and precipitation is highly variable, mean monthly sea surface salinity may vary as well, particularly, in near shore regions. However, no detailed information is available and future research should focus upon seasonal observations carried out over a period of years.

3.2 A simple model

The balance between evaporation (E) and river runoff (F) determines the inverse nature of an estuary (Wolanski 1986; de Silva Samarasinghe and Lennon 1987). Since Australia’s climate and rainfall is highly variable, changes in the E-F balance could frequently lead to a reorganisation of the mean circulation within embayments such as Hervey Bay and smaller estuaries, in particular during the dry season. In the following sections a simple box model, similar to that used by Wolanski (1986), is applied in order to discuss physical characteristics of Hervey Bay and estimate salt production, flushing time and mixing. In order to assess likely changes in the inverse nature and physical characteristics that were observed during the September 2004 cruise, the balance equations for water (1) and salt (2) were employed:

$$F + Q_1 = E + Q_2 \tag{1}$$

$$Q_1 \cdot S_1 = Q_2 \cdot S_2 \tag{2}$$

F is the river runoff in ($m^{3\cdot}s^{-1}$), Q_1 is the surface inflow in ($m^{3\cdot}s^{-1}$), Q_2 is the bottom outflow in ($m^{3\cdot}s^{-1}$), E is the rate of water loss due to evaporation in ($m^{3\cdot}s^{-1}$), S_1 is the open ocean salinity (~35.7, depth averaged), S_2 is the salinity of the maximum zone in the southwest region of the bay (~36.5, depth averaged). The balance equations (1) and (2) yield the condition for an inverse circulation when E > F (Wolanski, 1986), i.e. saltier and denser water flows toward the ocean below a fresher surface layer. Middelton et al. (1994) already argued this to be the case.

The evaporation rate in the Hervey Bay (A ~ 4000 km^2) region is about e = 0.5 $cm^{\cdot}day^{-1}$ during September (data are available from the Australian Bureau of Meteorology), which is equivalent to the annual mean and compares to a minimum of about 0.3 $cm^{\cdot}day^{-1}$ in June and a maximum value of about 0.7 $cm^{\cdot}day^{-1}$ in December.

This yields an estimated loss of water by evaporation ($E = e \cdot A$) in the order of about $E = 232\ m^{3} \cdot s^{-1}$, or using the minimum and maximum values for evaporation, it ranges from about $E = 139\ m^{3} \cdot s^{-1}$ in June to $E = 324\ m^{3} \cdot s^{-1}$ in December.

Both rainfall and river runoff in the Hervey Bay region of subtropical Queensland are at a minimum during the winter/early spring period often approaching zero. The mean monthly average freshwater discharge via the Mary/Burnett rivers into Hervey Bay for the July to September 2004 period, i.e. the period prior the September survey, was very low and estimated to be less than 5 $m^{3} \cdot s^{-1}$. This is well below the climatological mean value for that period which is about 12 $m^{3} \cdot s^{-1}$ (data not shown, but are available from the Queensland Department of Mines and Natural Resource, no data for the Burrum River are available, but since the Burrum River catchment is significantly smaller than that of the other two, the contribution would be very minimal). Based upon the simple evaporation-runoff balance, an inverse circulation within Hervey Bay is clearly most likely during this low rainfall, runoff period.

Furthermore, the balance between evaporation and runoff indicates that the inverse circulation may not be restricted to the low rainfall, runoff winter/early spring months, but may persist throughout the year. Taking into account the historical record of mean monthly freshwater discharges from the Mary/Burnett Rivers for the period January 1950 to December 2004, only 10 % of all discharges were larger than 201 $m^{3} \cdot s^{-1}$, 15 % were larger than 122 $m^{3} \cdot s^{-1}$, and 20 % were larger than 88.9 $m^{3} \cdot s^{-1}$. Over the same period, rainfall trends in parts of eastern Australia were negative. Southeast coastal Queensland was and still is characterised by a ‘drying’ trend (Manins et al. 2001). This contributes to a decline in freshwater discharges over the same period. For example, during the period January 1980 to December 2004, only 10 % of all monthly mean discharges were larger than 122 $m^{3} \cdot s^{-1}$, 15 % were larger than 87 $m^{3} \cdot s^{-1}$, and 20 % were larger than 65 $m^{3} \cdot s^{-1}$, which is a significant reduction if compared to the period 1950 to 2004. Flows above the 10 % cut-off were due to single climatic events that reflect in high monthly mean values, of which the year 1999 major flooding one is an example (Campbell and McKenzie, 2004). In particular, for the period 1980-2004, freshwater discharges were mostly well below the minimum evaporation rate of $E = 139\ m^{3} \cdot s^{-1}$ in June which in turn would lead to persistent hypersaline conditions throughout most of the period.

With a mean evaporative water flow of about E = 232 $m^{3}\cdot s^{-1}$, the amount of salt ejected into the bay is about $Q_s = E\cdot S_1$ = 8306 $kg\cdot s^{-1}$ which is transported via the mean-subsurface circulation out into the open ocean. Using the minimum and maximum evaporation rates the amount of salt ejected potentially ranges from about 5000 to 11500 $kg\cdot s^{-1}$. If no flushing of the bay would occur, salinity of the bay would rise by about 3 over the period of one year (using a volume of about $V = 8\cdot 10^{10}$ m^3 and the mean value for the amount of salt ejected).

The residence time τ for the excess salt discharged into the bay due to evaporation can be defined as the ratio of the excess salt content over a background (i.e. the oceanic level) to the salt outflow from the bay (Wolanski 1986, de Silva Samarasinghe and Lennon 1987). It follows that:

$$\tau = \frac{S_2 - S_1}{S_1 \cdot (e/H)} \qquad 3$$

This yields a value of about τ = *89 days* using the mean evaporation rate. A range *of* τ *= 64 days* to τ *= 149 days* is computed using the minimum and maximum values for e. This is in the order of 3-5 months and similar to the mean residence times that were estimated by Wolanski (1986) and de Silva Samarasinghe and Lennon (1987) for several other Australian inverse estuaries from which quasi steady-state conditions for the period of the Hervey Bay survey follow. The eddy diffusivity coefficient is estimated following the procedure used by Wolanski (1986). It yields a coefficient which is smaller than that found by Wolanski (1986), but of similar order of magnitude, i.e. $\sim 10^3$, i.e. the internal circulation provides a measurable contribution to the flushing of Hervey Bay during low runoff periods. The historical relationship of the evaporation and runoff record indicates that these conditions may prevail for most of the time. It is likely that these have been enhanced in the last 2-3 decades due to a decline in rainfall and persistent drought conditions in the region.

4. Conclusion

The analysis of data from a four-day field survey of Hervey Bay during September 2004, allowed tracking the possible source for locally produced high salinity water to the shallow southwest coastal region of the bay. This water is supplied to the East Australia Current (EAC) system off Fraser Island and was observed initially by Middelton et al. (1994). Middelton et al. (1994) lacked observational data to support their argument. The Hervey Bay survey found salinity to be highest in the southwest of the Bay. The observed temperature and salinity distribution resembles that of an inverse albeit three-dimensional estuary. Salinity increased in the upper layer away from the open ocean and toward the head of the bay. This increase was observed throughout the water column. In addition to Boyd et al’s (2004) new classification of Hervey Bay from sedimentary data as a shoreline divergent estuary, this survey proposes the classification of Hervey Bay from hydrographic principals as an inverse laterally inhomogeneous estuary.

Inverse conditions in the bay seem to prevail throughout the year and are only reversed briefly during climatic extreme events. This follows from an analysis of the historical runoff - evaporation budget. In particular, since 1980 runoff declined and was only larger than the minimum evaporation rate for the region in less than 10 % of all instances. The out-flowing locally produced water supplied to the EAC is referred to as Hervey Bay Water. The one-time survey highlights the importance of local physical mechanisms that operate in Hervey Bay and should be considered in the future for management purposes of an important marine ecological system.

Current rainfall trends in southeast Queensland have led to persistent drought conditions, i.e. below average rainfall (e.g. see also Murphy and Ribbe 2004). It is likely that the inverse circulation characteristics found for Hervey Bay will not revert in the future but continue to be more persistent throughout the year. Long-term monitoring and detailed three-dimensional modelling of the bay is suggested to study the physical conditions within the bay, the response of that circulation to variable freshwater input, and to assess the impact of continued and possible increasing salinity discharges upon marine environmental conditions through, for example, the associated reduction in dissolved oxygen (e.g. Davies and Kalish 1994)

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Figure 8: A simple box model of the bay.

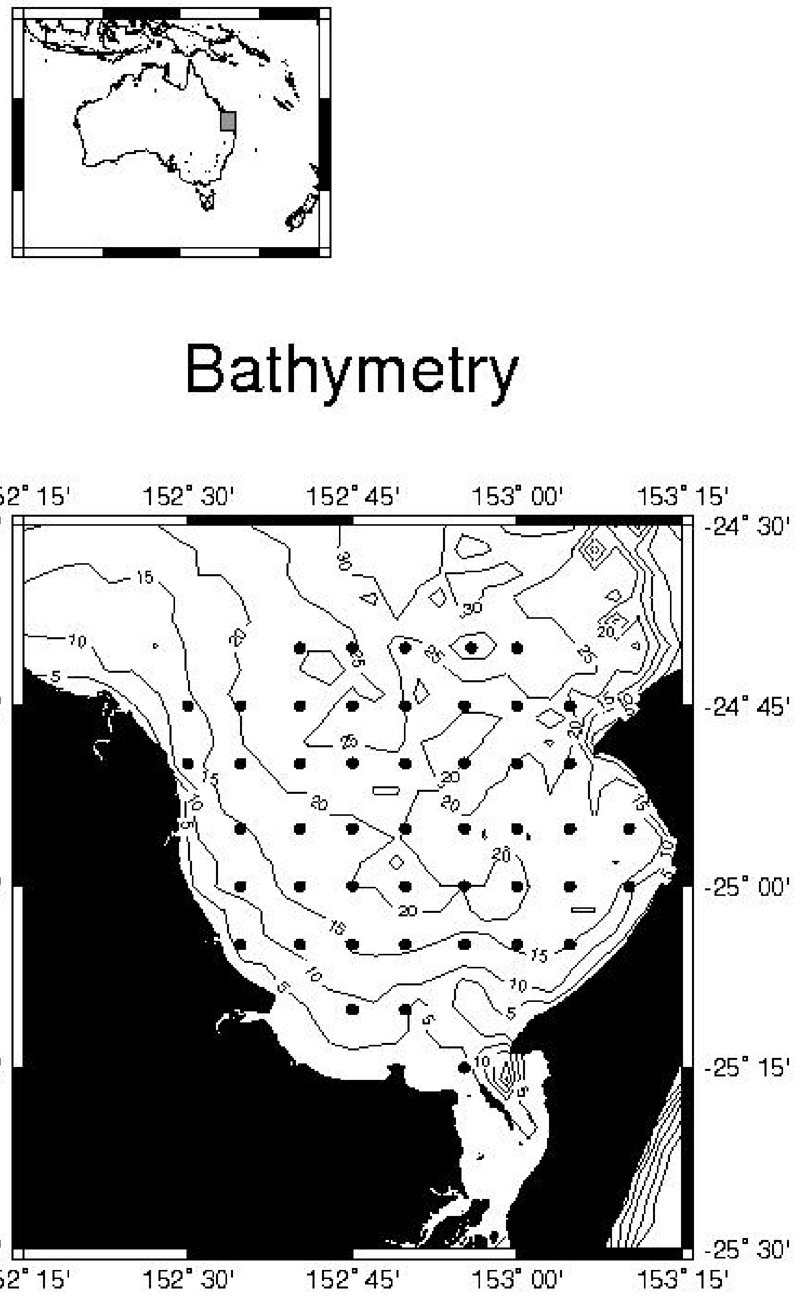


Figure 1: Location and bathymetry (m) of Hervey Bay surveyed during an early southern hemisphere spring cruise in September 2004.

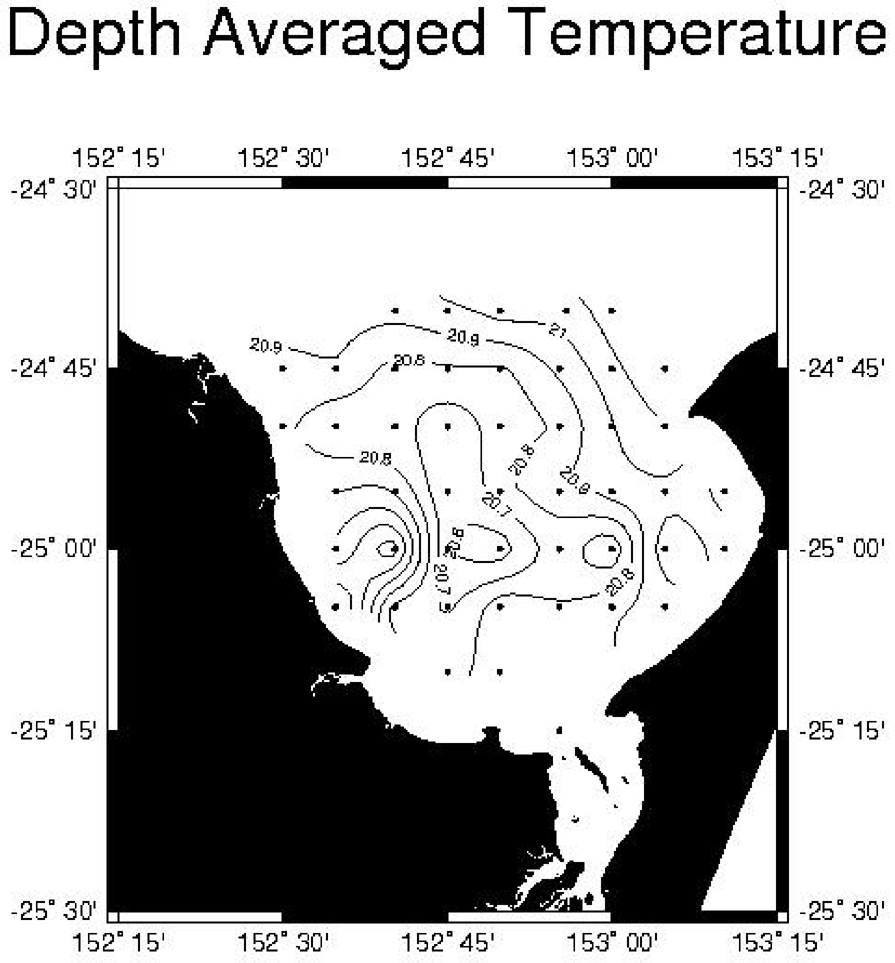


Figure 2: Depth averaged temperature distribution (^{o}C).

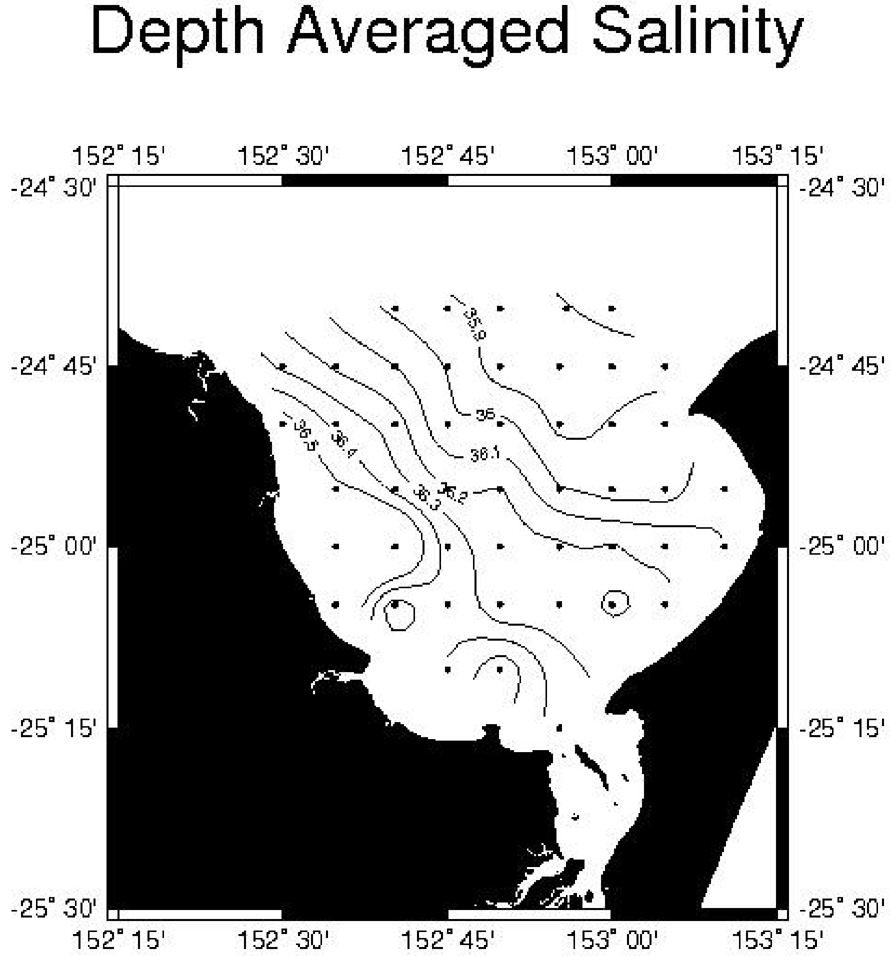


Figure 3: Depth averaged salinity distribution.

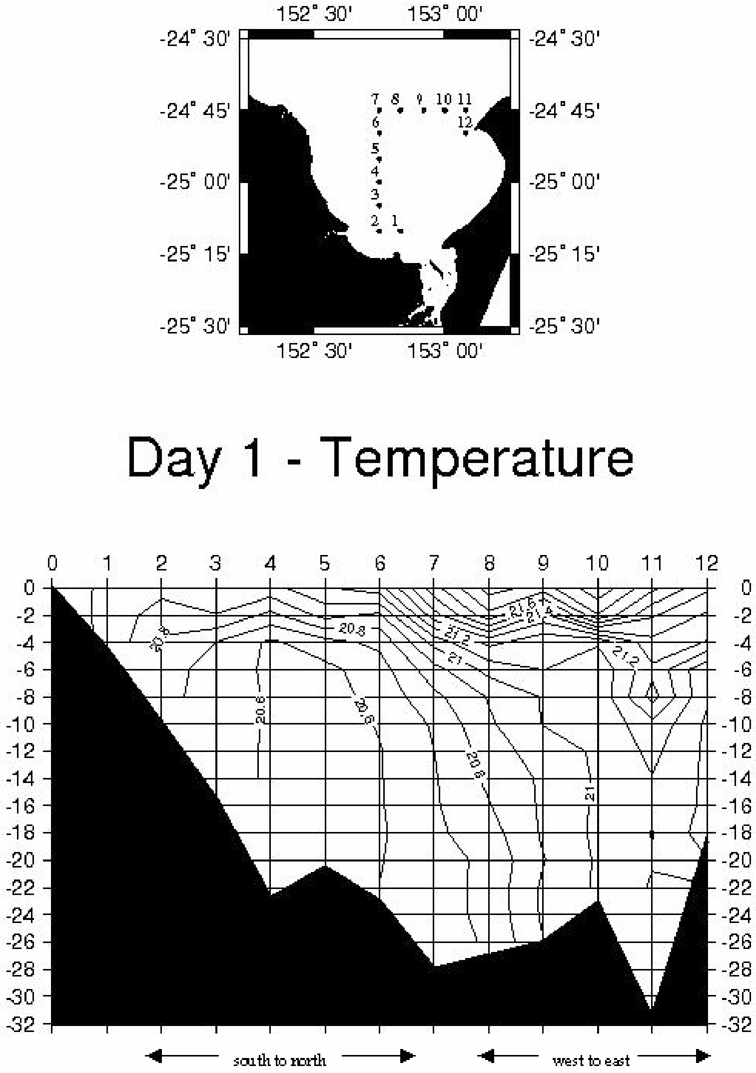
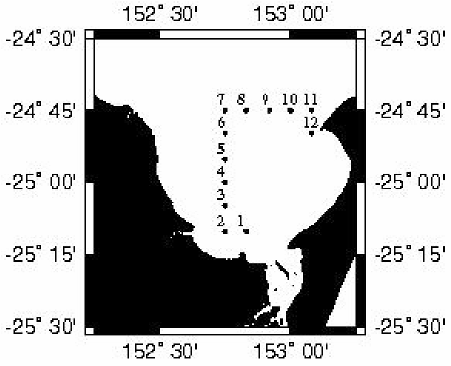


Figure 4: Survey day 1 locations, (a) temperature (°C) and (b) salinity profiles recorded on September 20, 2004. Locations are about 5 nautical miles apart. Changes in the predominant direction of the cruise track are indicated at the bottom of the panel.



Day 1 - Salinity

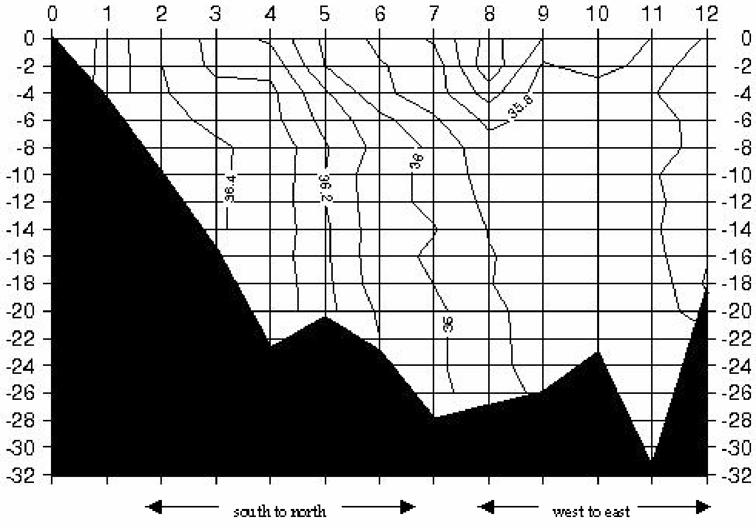


Figure 4: continue

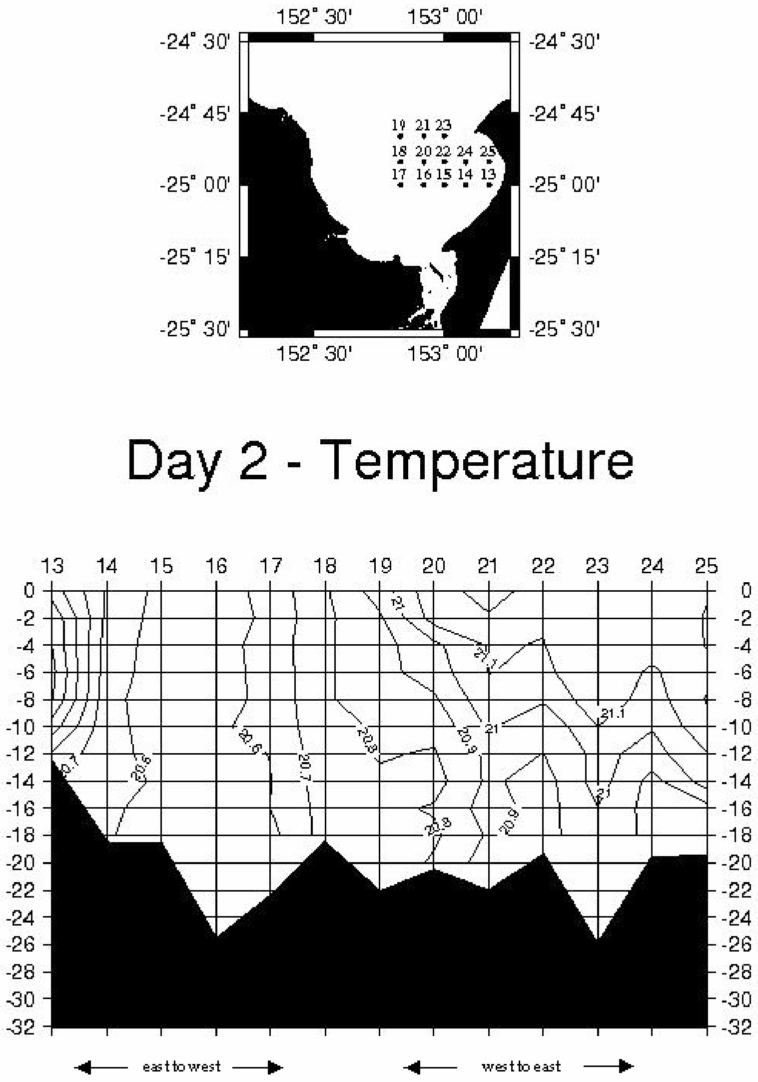


Figure 5: Survey day 2 locations, (a) temperature (^{o}C) and (b) salinity profiles recorded on September 21, 2004. Locations are about 5 nautical miles apart. Changes in the predominant direction of the cruise track are indicated at the bottom of the panel.

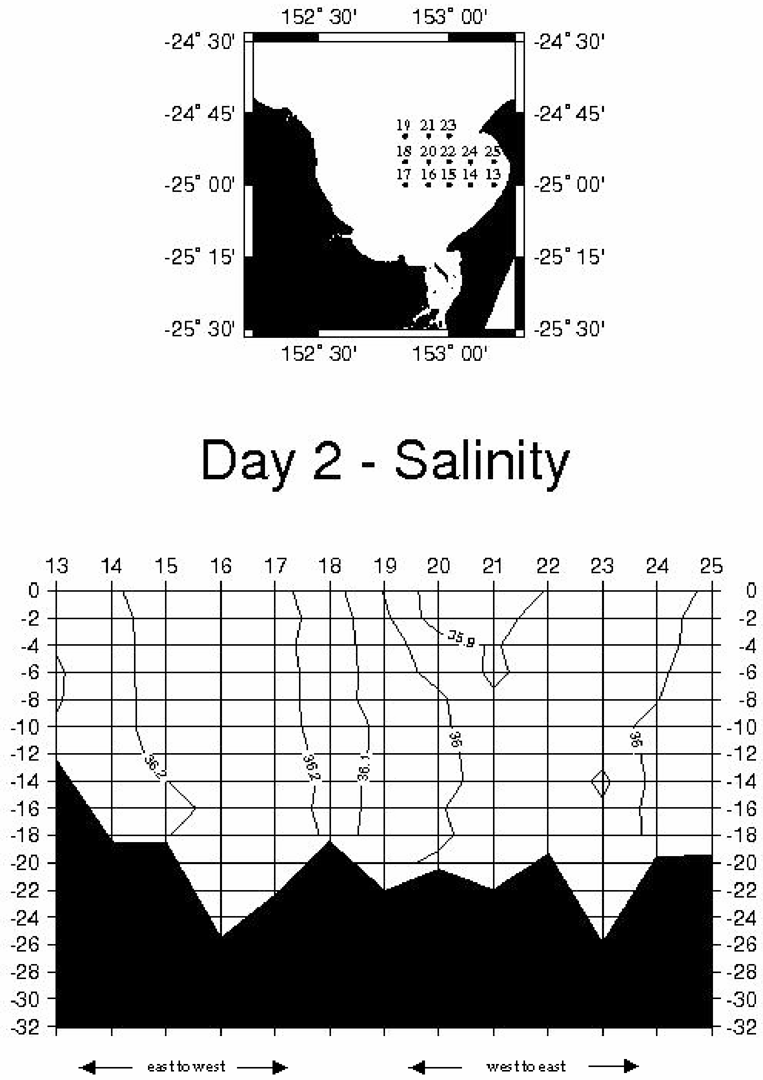


Figure 5: continue

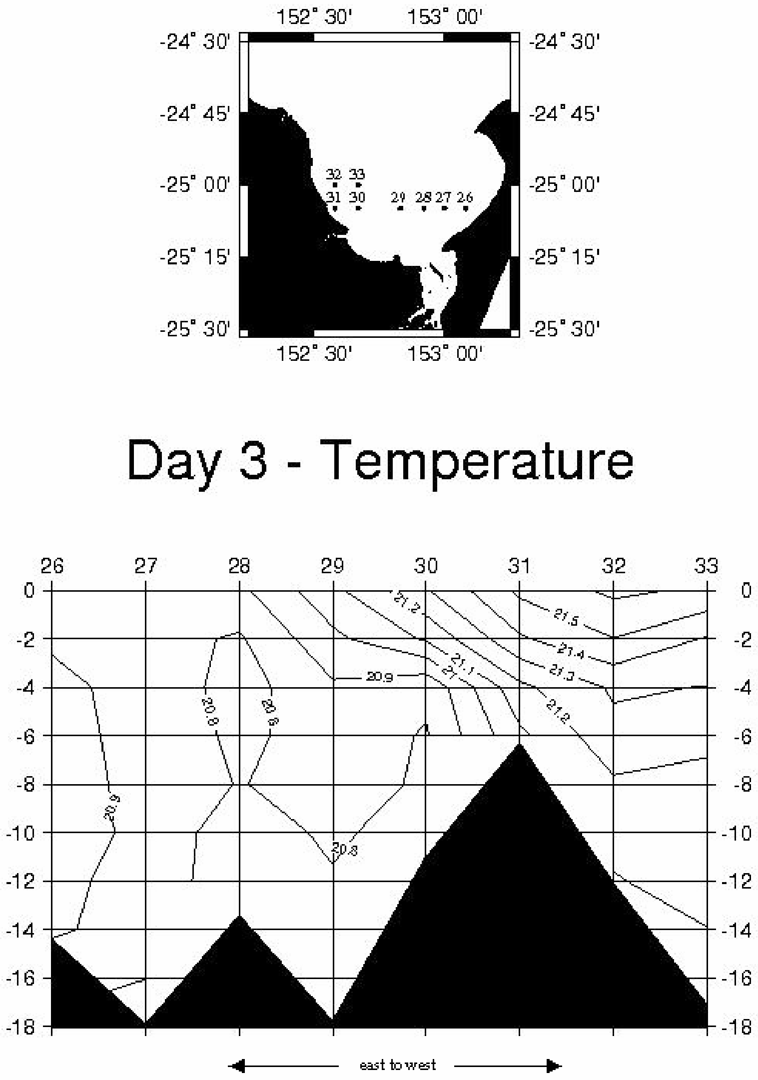
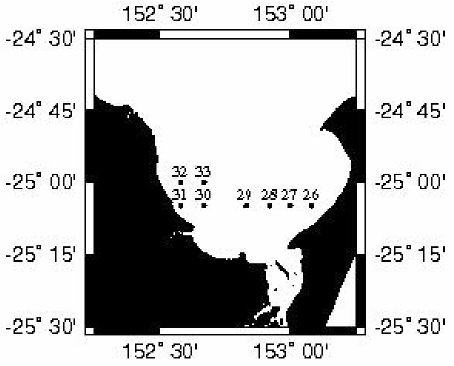


Figure 6: Survey day 3 locations, (a) temperature (^{o}C) and (b) salinity profiles recorded on September 22, 2004. Locations are about 5 nautical miles apart. Changes in the predominant direction of the cruise track are indicated at the bottom of the panel.



Day 3 - Salinity

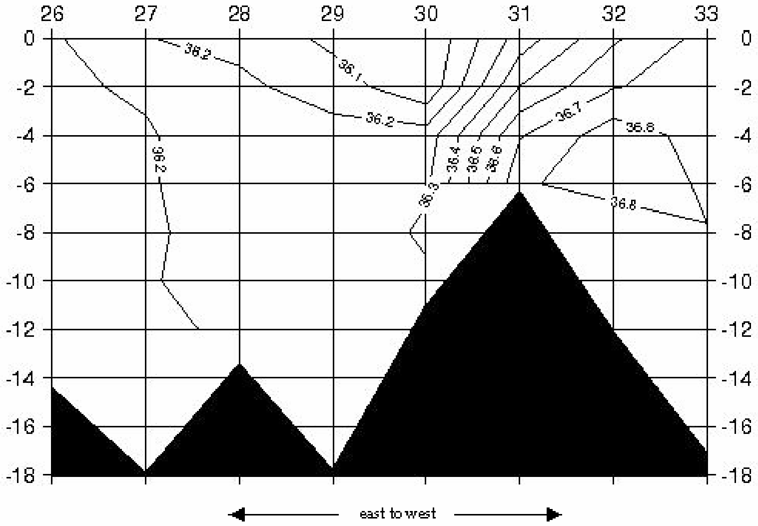


Figure 6: continue

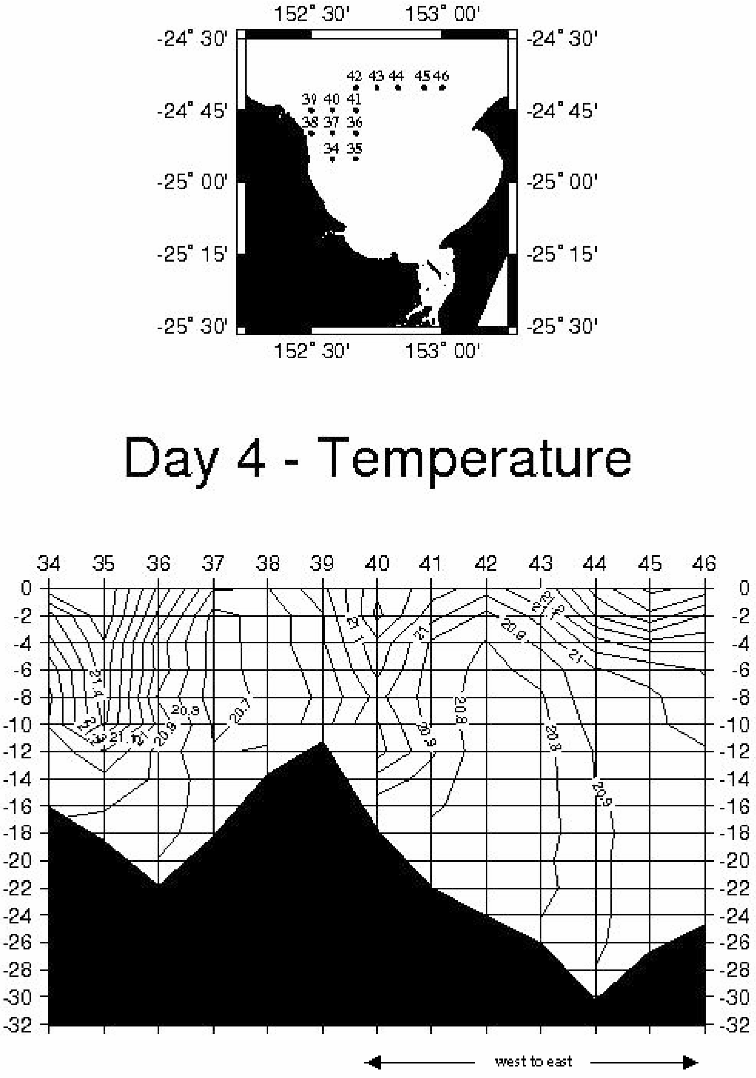


Figure 7: Survey day 4 locations, (a) temperature (^{o}C) and (b) salinity profiles recorded on September 23, 2004. Locations are about 5 nautical miles apart. Changes in the predominant direction of the cruise track are indicated at the bottom of the panel.

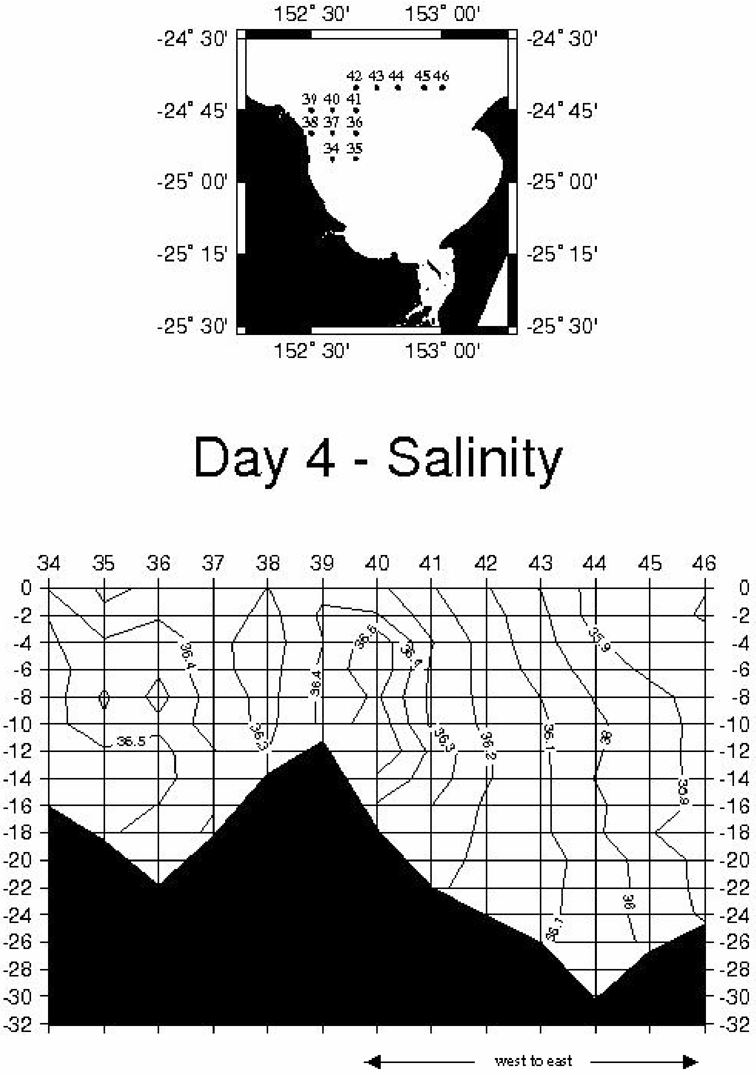


Figure 7: continue

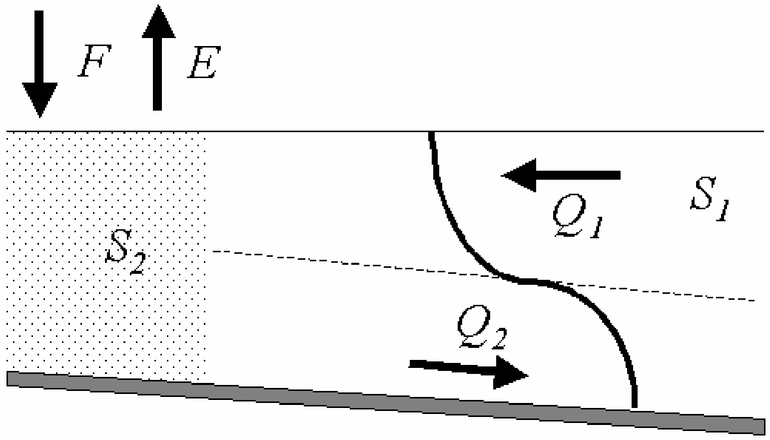


Figure 8: A simple box model of the bay.