NIWA
Taihoro Nukurangi

Freshwater dilution and transport in Canterbury Bight

Prepared for Environment Canterbury

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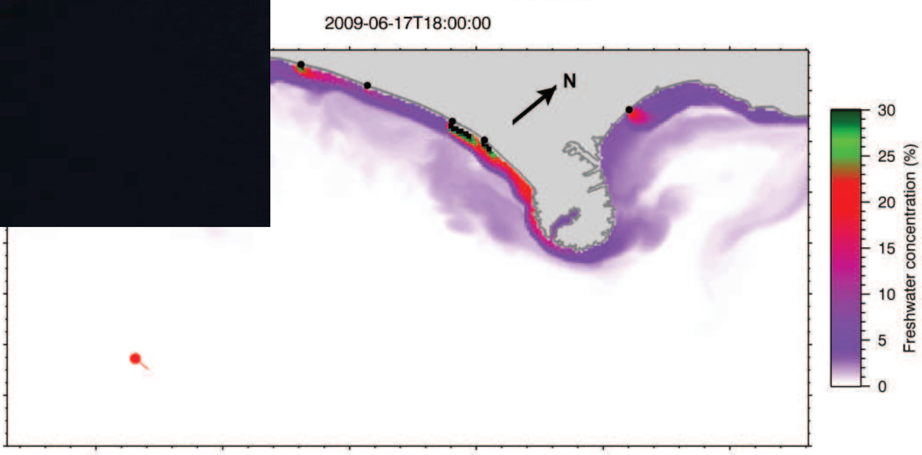

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Cover images:

- MODIS true-colour image 7 September 2004, (Schwarz et al. 2008, figure A10).
- False-colour graph of freshwater concentration from a ROMS simulation, 17 June 2009 (this report)
- Sontek ADP

Contents

Tables

Figures

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Executive summary

- A nested set of ocean and coastal hydrodynamic models was set up with the ultimate aim of simulating freshwater transport in Canterbury Bight and Pegasus Bay.
- A model of Canterbury Bight at 1 km resolution was run for a period of one year (April 2009–April 2010), forced with ocean currents, winds, tides and freshwater inputs from 10 rivers in Southland, Otago and Canterbury, along with Lake Ellesmere/Te Waihora. The freshwater sources in Canterbury were each labelled with a separate tracer, allowing the concentration of river-derived freshwater to be evaluated and attributed to the specific source.
- A programme of field measurements in Canterbury Bight has been carried out under the same project, involving acoustic Doppler profiler (ADP) time series at two locations and two surveys with conductivity-temperature-depth (CTD) instruments, in July and December 2011.
- The model produces freshwater plumes with behaviour that is physically plausible and qualitatively consistent with remote sensing results.
- The model verification confirms that the model is simulating currents in the area very well and that the behaviour of the surface freshwater layer is realistic, though it does not reproduce the small-scale variability on the in-shore transect during the CTD surveys.
- River plumes are initially confined very close to the surface (typically 1–3 m) and have freshwater concentrations of 10–30%, occasionally approaching 100%. The plumes are progressively diluted by vertical mixing and horizontal dispersion and form a coastal band ~10 km wide with surface freshwater concentrations typically 5–10%.
- The coastal freshwater band, and the river plumes within it, general move north-eastward but with substantial fluctuations that are largely wind driven. Under winds from the south or southwest, the coastal freshwater band can move quite quickly (within a few days) north-eastward along the coast of Canterbury Bight and around the end of Banks Peninsula.
- The model indicates substantially higher freshwater concentrations on the southern and eastern sides of Banks Peninsula than on the northern side.

1 Introduction

Environment Canterbury requires more information on the mixing and transport of freshwater—with its associated nutrients, sediments and contaminants—entering Canterbury Bight. A recent two-year study (Schwarz 2008,Schwarz et al. 2010) found that river plumes were frequently visible in satellite images and were generally constrained to within 6 km or so of the coastline. Water from Lake Ellesmere/Te Waihora was conspicuous because of its yellow-green colour and was seen up to 95 km northeast and 27 km southwest of the source, and up to 33 km from the coast. Plumes from the rivers and from Lake Ellesmere typically moved north-eastward along the coast, around Banks Peninsula and into Pegasus Bay.

The task, as specified by Dr Lesley Bolton-Ritchie ('Canterbury Bight water circulation and mixing'. ECAN pers. comm., January 2010) was to model the near shore water circulation and mixing processes in the Canterbury Bight with an emphasis on the fate of the freshwater inputs to the Bight. This modelling was to investigate

- the dilution and mixing of the freshwater inputs and
- the offshore and alongshore movement of lower salinity water (resulting from freshwater inputs).

The modelling must take into consideration the temporal variation in the volumes of freshwater discharged into the Canterbury Bight.

This report describes modelling of the dynamics of freshwater-affected coastal waters. The work has been accompanied by a programme of in-situ ocean observing for validation purposes. This approach capitalises on the reciprocal relationship between modelling and in-situ observation: the modelling allows prediction of the dynamics of freshwater-affected waters under various environmental scenarios (e.g., wind, river flow patterns) over broader time and space scales than can be achieved with in-situ observations, while the observations validate predictions of the modelling.

The programme of field measurements in Canterbury Bight has now been completed. They are described and compared with the model.

2 Methods: model setup

2.1 Nested domains

A nested set of hydrodynamic model domains was set up (Figure 1). The model used on all three domains was ROMS[1] (Haidvogel et al. 2008; MacCready et al. 2009), a widely used, open-source ocean/coastal model. Coupling between the nested domains was one-way and off-line: one-way because each domain influences any smaller-scale domains nested inside it, but not vice versa and off-line because the models are run separately.

[1] http://www.myroms.org/

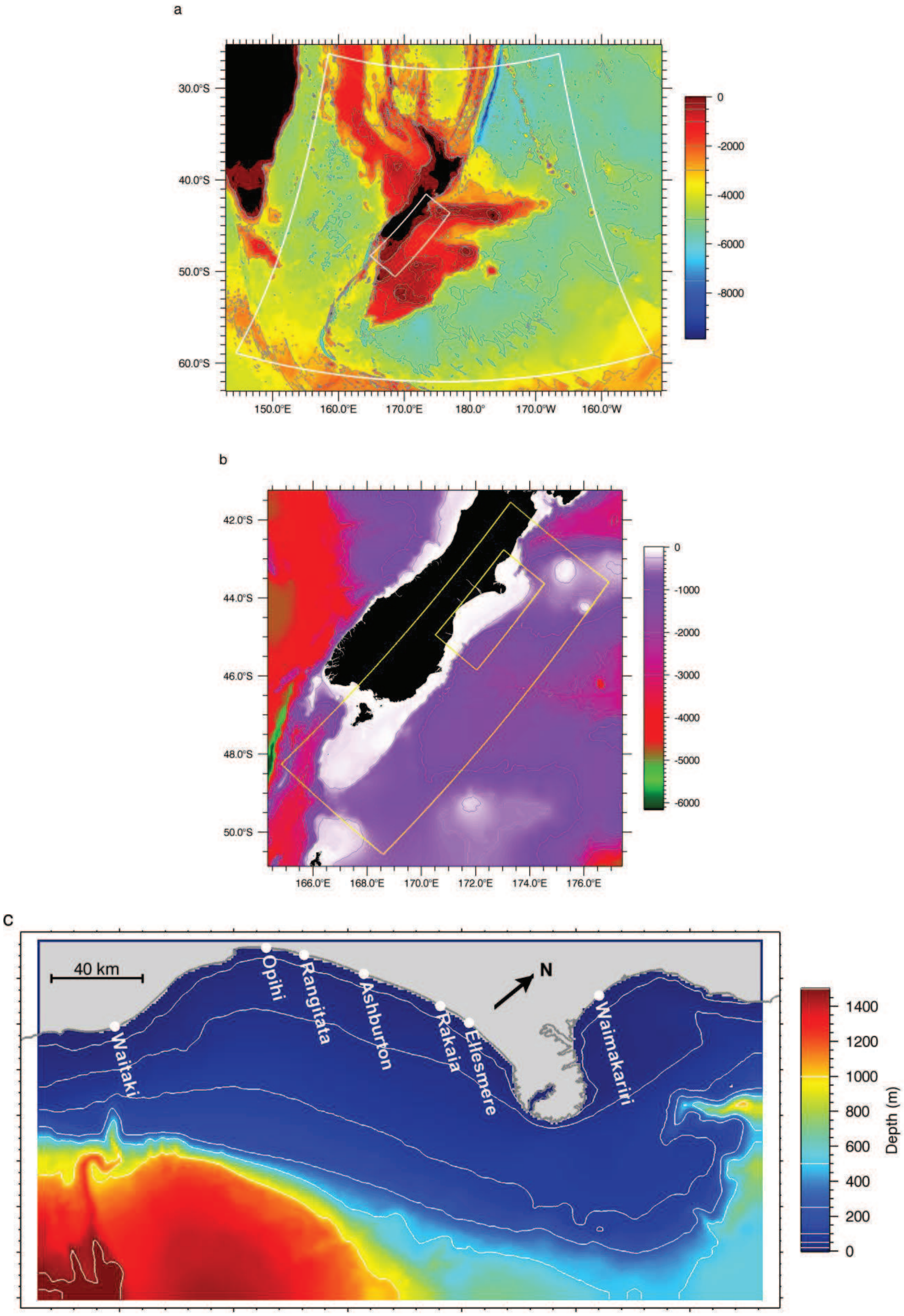


Figure 1: Model domains. (a) Outer and intermediate domains; (b) intermediate and inner domains; (c) inner domain with coastline (grey) and freshwater input locations (white symbols) shown over the land mask (light grey) and bathymetry (coloured) of the 1 km grid.

The outer domain covered an area somewhat larger than the New Zealand EEZ at 10 km resolution; the intermediate domain covered the continental shelf of the southeast South Island at 2.5 km resolution; the inner domain covered Canterbury Bight and Pegasus Bay. On the inner domain, model grids have been set up with two different resolutions: 1 km and 500 m; The simulations described here used 1 km grid and were run for a relatively long time, namely one year. Because it is expensive—in terms of processor time and storage space—to run simulations of comparable length with the 500 m grid, we intend in future to compare simulations on the 1 km and 500 m grids for selected shorter periods (perhaps 20–50 days) to establish whether the finer resolution changes the results significantly.

The outer model simulates the climatological[2] large-scale flows around the New Zealand landmass, essentially repeating the work of Rickard et al. (2005), but with a different model code and different forcing datasets. Boundary conditions along the 4 sides of the outer model grid were from a monthly climatology calculated from 10 years' output of a global ocean model (the SODA reanalysis, version 1.4.2, Carton and Giese 2008). The heat, momentum and freshwater fluxes through the sea surface were from the NCEP Reanalysis monthly climatology (Kalnay et al. 1996), with nudging of sea surface temperature (SST) towards a monthly climatology from the NOAA optimum interpolation SST analysis (Reynolds et al. 2002). Weak nudging towards the SODA climatology was applied in the interior of the model to prevent it drifting away from a realistic state. The outer model was spun up from rest for 3 years and then run for several more years, during which output was saved at 5 day intervals and interpolated spatially to provide lateral boundary data for the intermediate model.

The intermediate model simulates the Southland Current, a flow of subtropical and subantarctic water along the continental shelf of the south-eastern South Island (Sutton 2003). The Southland Current's mean flow and water mass properties are imposed by the outer model, and the intermediate model adds a much more accurate description of the bathymetry and the ability to generate finer-scale turbulent flow structures (both permitted by the finer grid) along with forcing by real-time winds. Freshwater sources representing the major rivers are also included in the intermediate domain, as described in more detail in Section 2.2.

The inner domain covers Canterbury Bight, Banks Peninsula and Pegasus Bay allowing the inner model to simulate the movement of freshwater plumes in reasonable detail. The Southland Current flows through this domain, imposed by the initialisation and lateral boundary data derived from the intermediate model. Tides were imposed at the boundaries of the inner domain in the form of 6 tidal constituents (M_2, S_2, N_2, O_1, K_1, & P_1) from the NIWA EEZ tidal model (Stanton et al. 2001; Walters et al. 2001).

Given that the wind is known to be a major driver of variability in currents on the South Island continental shelf (Chiswell 1996), the choice of wind data to drive the model is important. We used 3-hourly winds from the NIWA NZLAM regional atmospheric model, which is part of the EcoConnect[3] environmental forecasting system. The NZLAM data are available from May 2007 to the present and appear to be superior to other wind datasets in their representation of topographic effects by the New Zealand topography. Surface stresses were calculated from the NZLAM winds using a standard relationship (Smith 1988) and then multiplied by a

[2] There is an important distinction between climatological and real-time model forcing—see the glossary (Section 8).
[3] http://ecoconnect.niwa.co.nz/

factor of 1.2. This factor was adjusted to optimise the match between modelled and observed sub tidal velocities (Section 4.1); similar adjustments have been found to be necessary in other similar modelling exercises around New Zealand.

2.2 Freshwater input

The major rivers of the southern and eastern South Island, from the Oreti in Southland to the Waimakariri in Pegasus Bay were represented in the model as point sources of freshwater and also labelled with passive tracers, or "dyes", as explained below. The freshwater sources (the 10 rivers along with Lake Ellesmere) are listed in Table 1 column 1. The input locations (Table 1 column 2) were established by inspecting Google Maps and then converted into model grid locations, with adjustments to ensure each freshwater input lay on the model's land-sea boundary. Flow-rate time series were constructed for each source by multiplying daily data from a suitable flow gauge site (Table 1 column 3) by a factor (Table 1 column 4) representing the ratio between the total catchment area of the river (from the NIWA WRENZ[4] site) and the catchment area upstream of the flow gauge site. For Lake Ellesmere, a daily flow rate time series was constructed from opening/closing data for 2009–present supplied by Graeme Horrell of NIWA, using the model described by Horrell (2009). The tracers associated with each point source, or set of sources, are listed in Table 1 column 5. The four rivers in Otago and Southland were all labelled with the same tracer, dye_01. The remaining rivers, all in Canterbury, were labelled separately, with dye_02 to dye_08, giving a total of 8 tracers. Carrying this many tracers in the model simulations increases the resources required substantially, but allows the individual plumes to be distinguished. The value of each dye tracer was set to one in the water entering from its respective source(s) and zero elsewhere. Thus the dye concentration in the model represents the volume fraction of river-derived freshwater.

Table 1: Model freshwater point sources. See text for information on the construction of the time series.

Source	Source input location	Flow gauge	*Flow factor*	Tracer
Oreti	168.29318° E, 46.50395° S	78601 Oreti at Wallacetown	1.60	dye_01
Mataura	168.79735° E, 46.58187° S	77506 Mataura at Tuturau	1.23	
Clutha	169.81067° E, 46.34515° S	75207 Clutha at Balclutha	1.00	
Taieri	170.20257° E, 46.05358° S	74308 Taieri at Outram	1.21	
Waitaki	171.14284° E, 44.93710° S	71110 Waitaki below Waitaki Dam	1.20	dye_02
Opihi	171.34998° E, 44.28165° S	69607 Opihi at No1 SHB	1.36	dye_03
Rangitata	171.51421° E, 44.18596° S	69302 Rangitata at Klondyke	1.21	dye_04
Ashburton	171.80366° E, 44.05293° S	68801 Ashburton at SHBr	1.01	dye_05
Rakaia	172.20661° E, 43.90176° S	68526 Rakaia at Fighting Hill	1.14	dye_06
Waimakariri	172.71054° E, 43.39133° S	66401 Waimakariri at Old Highway Br	1.10	dye_07
Ellesmere	172.37753° E, 43.85625° S			dye_08

[4] http://wrenz.niwa.co.nz/webmodel/

The flow time series for the 8 tracers cover the years 2009 and 2010 (Figure 2), and will be extended to the end of the measurement period in late 2011 as soon as the data become available.

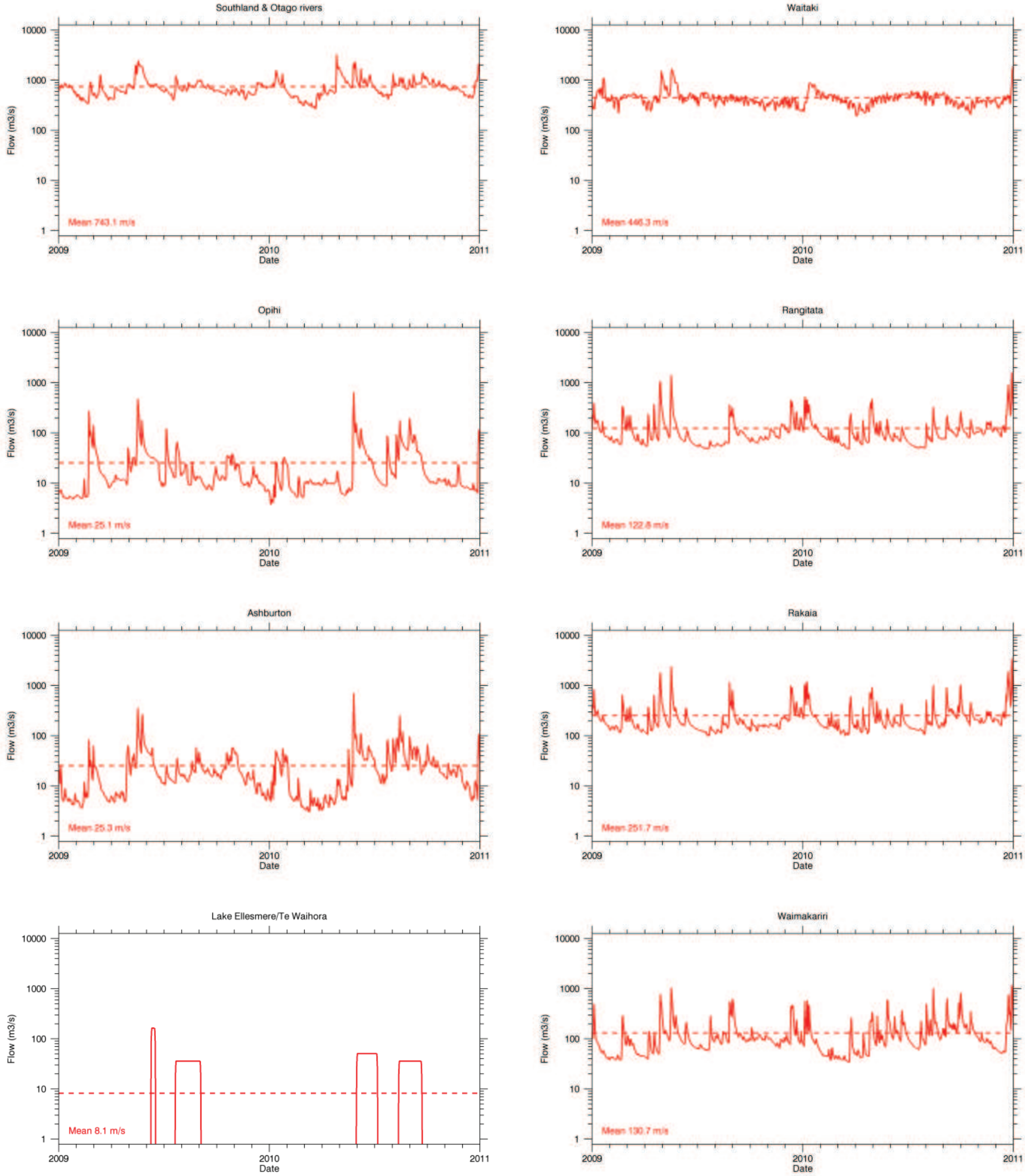


Figure 2: Freshwater flow rate time series.

The freshwater point sources were applied in the intermediate and inner domains only. (This means that seawater entering the intermediate domain may be slightly more saline than it should be, because the outer model is missing some freshwater inputs. However this is expected to be a very small effect.) In the intermediate model, all 11 sources in Table 1 were included. In the inner domain, the first 4 sources lie outside the domain and so were omitted, but the remaining 7 sources were included.

2.3 Simulations

Our strategy for simulations on the intermediate domain is to run a “base” simulation for a several-year period, saving restart files at regular intervals from which other simulations can be started as required. The base simulation in this case covered the years 2009–2011, with restart files saved every 25 days. From the base simulation’s restart files, two shorter period runs were conducted. The model output data from these runs comprised consecutive 0.5 day averages throughout and these were then interpolated in space to provide lateral boundary data for the inner model. The inner model was then run over the same periods.

The first inner model run was started at 100 days (relative to the beginning of 2009, so at 11 April 2009) and continued to 475 days (21 April 2010). This run provided the model output fields that are examined in the remainder of this report. The choice of this period of this run was rather arbitrary, but it covers a full seasonal cycle and includes several high-flow events (Figure 2). For comparison with the field data (Section 3) a similar inner model run was initialised at 900 days (20 June 2011) and continued to 1075 days (12 December 2011).

3 Methods: field measurements

A programme of field measurements was conducted in late 2011 to collect measurements for verification of the hydrodynamic model.

3.1 CTD survey

CTD (conductivity-temperature-depth) profiles were measured at 30 sites (Figure 3) on 4 July and 9 December 2011. Sites 1–25 were distributed along the coast from Akaroa Heads to the Waitaki River mouth, generally within 2 km of the shore. Sites 26-30 were distributed in the reverse direction along the 50 m depth contour in the middle of Canterbury Bight.

The CTD measures high-resolution profiles of temperature, conductivity and depth (from pressure) on the down-cast and again on the up-cast. The variable of most interest here is salinity, calculated from the measured variables. All the profiles are shown in comparison with modelled profiles in Appendix B.

3.2 Current measurements

Acoustic Doppler Profilers (ADPs) were installed at two locations (Figure 3) during the first CTD survery and recovered during the second. Because of battery life limitations (which were known in advance) the instruments stopped collecting data before they were recovered. The instrument at the inner site returned 77 days data and the instrument at the outer site returned 102 days.

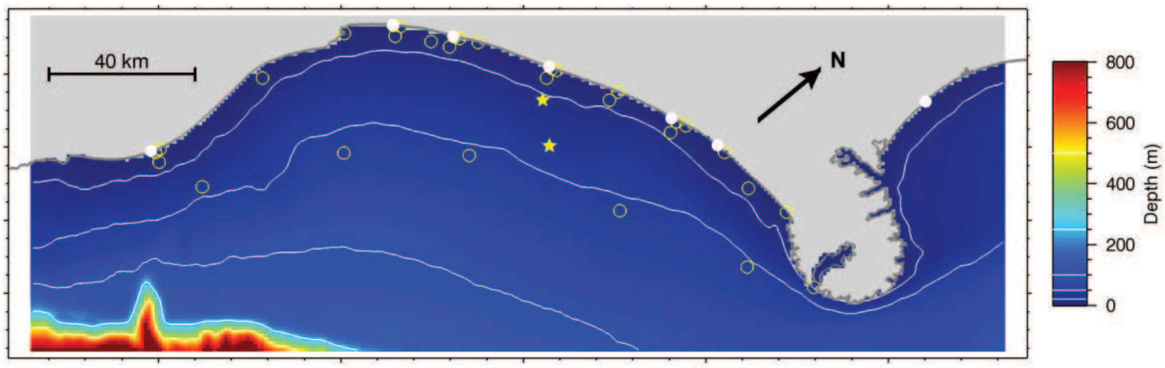


Figure 3: Field measurement sites. A portion of the inner model domain (cf. Figure 1c) with the locations of ADP sites (solid yellow stars), CTD sites (open yellow circles) and river mouths (solid white circles).

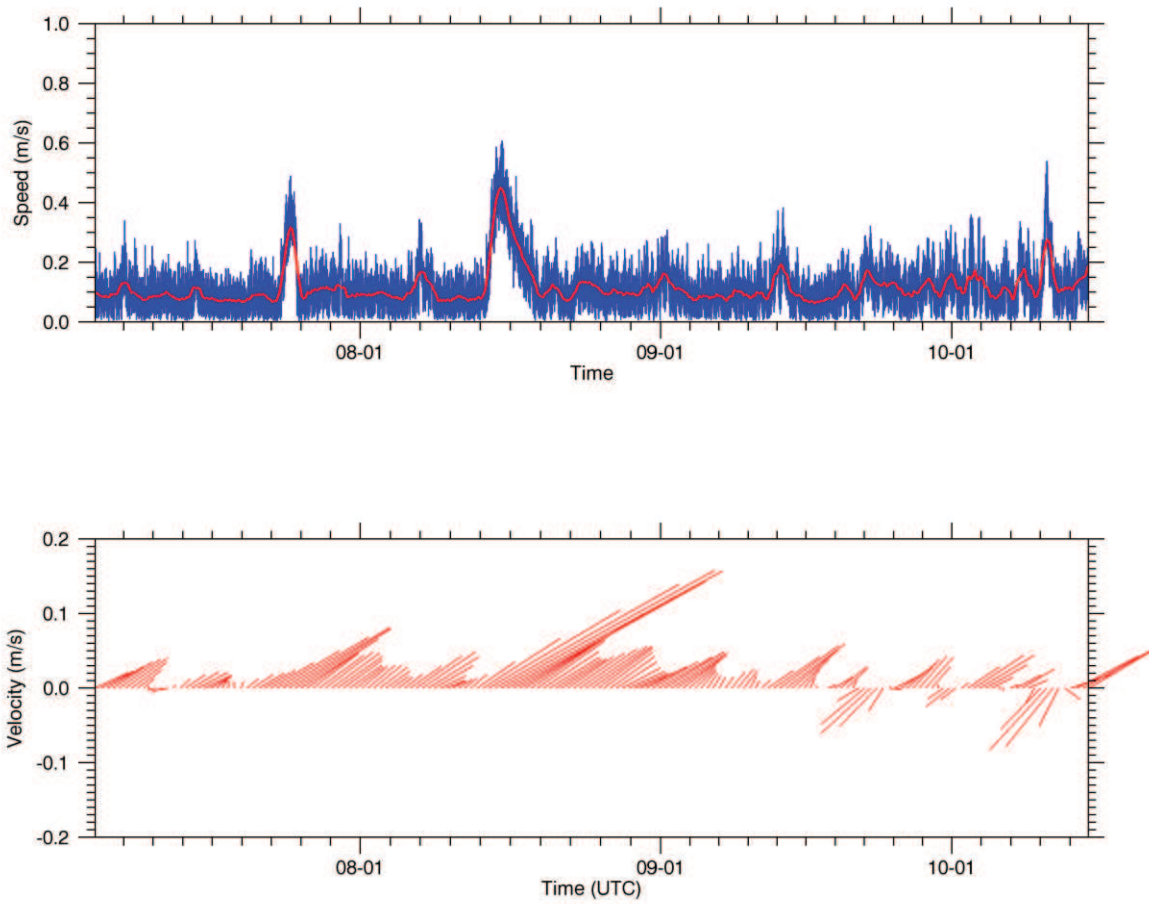


Figure 4: Currents at the outer ADP. a) .Current speed: 5-minute data in blue with 25-hour running average in red; b) De-tided velocity vector. All data are from the middle of the water column (19 m below the surface in a water depth of 39 m).

For an indication of the characteristics of the currents in Canterbury Bight, Figure 4 shows data from the outer ADP site, midway between the surface and the bottom. The mean current speed (Figure 4a) is usually around 0.1 m s^{-1}, with a few excursions as high as 0.6 m s^{-1}. The vector plot of sub tidal currents (Figure 4b) shows that there is a mean drift to the northeast at about 0.05 m s^{-1} and that the high-current periods correspond to periods of increased flow to the northeast (or in some cases to the southwest). Comparison with the model (Section 4.1) indicates that the subtidal variability in the currents is largely driven by the wind.

4 Model verification

4.1 Sub tidal velocity

The animations of the surface freshwater plumes in Canterbury Bight indicate (Section 5) that there is generally a drift to the northeast, frequently accelerated or reversed for periods of several days, and that the surface plumes sometimes spread into the bight and are sometimes confined close to shore. The correspondence between the surface plume pattern and the surface wind vector displayed on the animations suggests that much of the variability is associated with the winds. Before we can believe these aspects of the model we need verification that its variability is realistic.

As explained in Section 2.3, a model run was set up for the period from 20 June to 12 December 2011 specifically for comparison with the field measurements. Vertical profiles from the ADP and CTD sites were extracted from the model at a high temporal resolution (one-hourly) to facilitate this comparison. Data were then interpolated to a common hourly time series and smoothed with a 103-point filter (Thompson 1983) to remove the tides. Figure 5 to Figure 7 show various the comparisons of the filtered, or sub tidal, velocities at the Outer ADP site. With one exception (Figure 7b) the graphs show velocities at the middle of the water column (19 m below the surface in 39 m water depth).

The scatter plots in Figure 5 indicate that the mean and variability in velocity in the model agree in magnitude with the observations. The observed mean velocity over the measurement period is 0.051 m s^{-1} (modelled 0.041 m s^{-1}) towards 57°T (modelled 62°T), i.e. parallel to the coastline. For some perspective on these values, note that 0.05 m s^{-1} = 4.32 km d^{-1}. Ellipses (called “variance ellipses”) are drawn on Figure 5 to indicate the magnitude and direction of variability. In both cases the ellipse is highly elongated. The axis of greatest variability in the observed data is towards 57°T (modelled 53°T) and the length of this axis is 0.078 m s^{-1} (modelled 0.071 m s^{-1}).

In Figure 6 the along-shore velocity components (towards 60°T) are compared in time. The magnitudes agree (as one can see from Figure 5) and the correlation coefficient (*r*) is high at 0.92. Given that the only model input that is related to specific times is the surface stress, calculated from the wind, this agreement implies that the variability in along-shore velocity in the middle of the water column is predominantly wind-driven and that the model is representing this process well.

In Figure 7 the cross-shore velocity components (towards 330°T) are similarly compared in time. In the middle of the water column (Figure 7a) the magnitudes are similar but the correlation coefficient is low at 0.39. Nearer the surface (Figure 7b) the magnitudes are larger and the correlation coefficient somewhat higher at 0.57. The poorer agreement for cross-shore velocity than for along-shore velocity implies that cross-shore currents are not so strongly wind-driven, or possibly that they are, but the model is not representing this process so well.

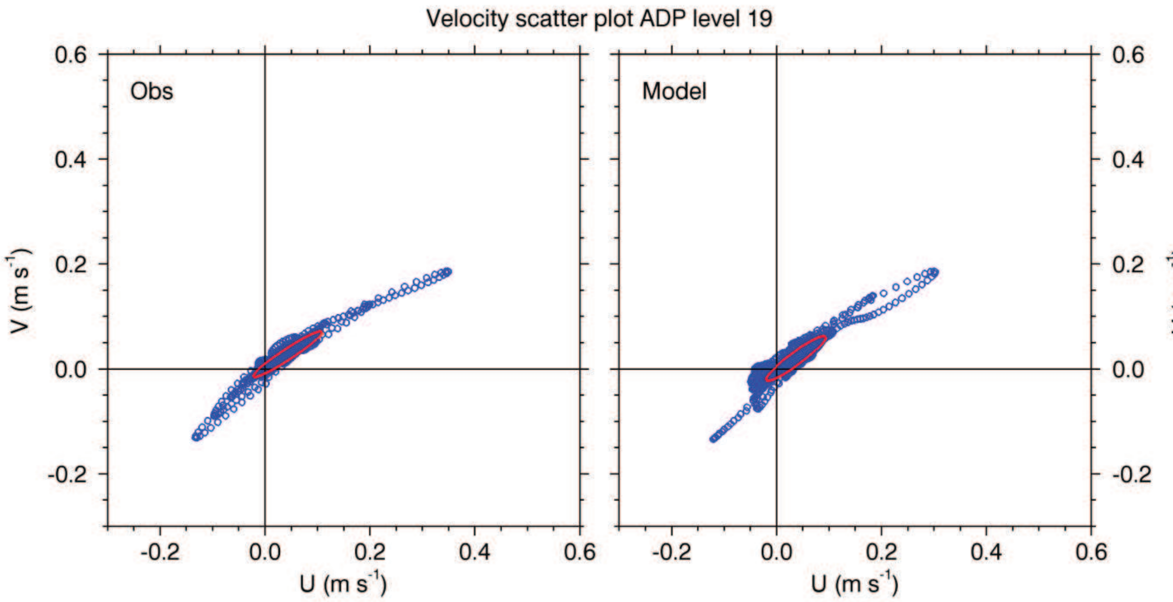


Figure 5: Velocity scatter plot comparison at the outer ADP site. Measured (left-hand panel) and modelled (right-hand panel) velocities in the middle of the water column (19 m below the surface).

The degree of agreement between the observed and modelled currents at the outer ADP site is similar to, or better than, what has been achieved with similar models elsewhere on the New Zealand continental shelf.

A similar set of comparisons has been done for the inner ADP site, with very similar results; it will not be shown here. One of the purposes of the inner ADP site was to detect any near-shore counter-current, directed opposite to the flow on the middle of the shelf. There is no sign of such counter-current in either the observations or the model.

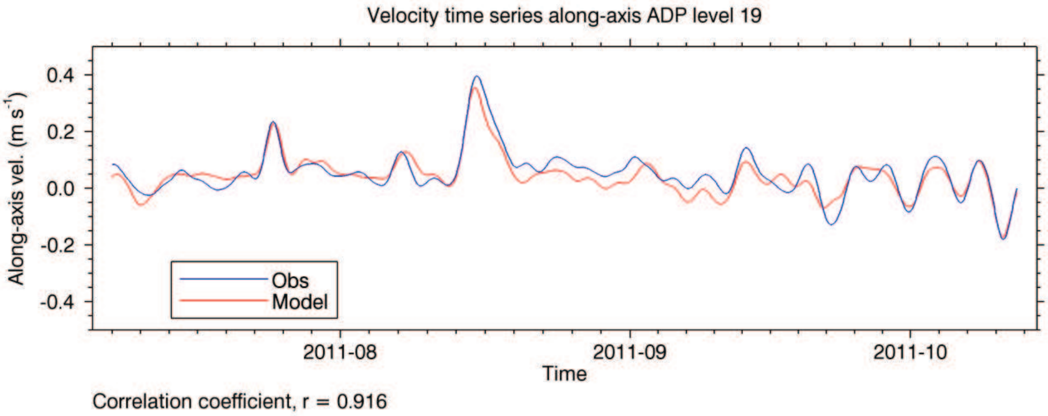


Figure 6: Along-shore (60°T) velocity component comparison at the outer ADP site. Measured (blue) and modelled (red) velocities in the middle of the water column (19 m below the surface).

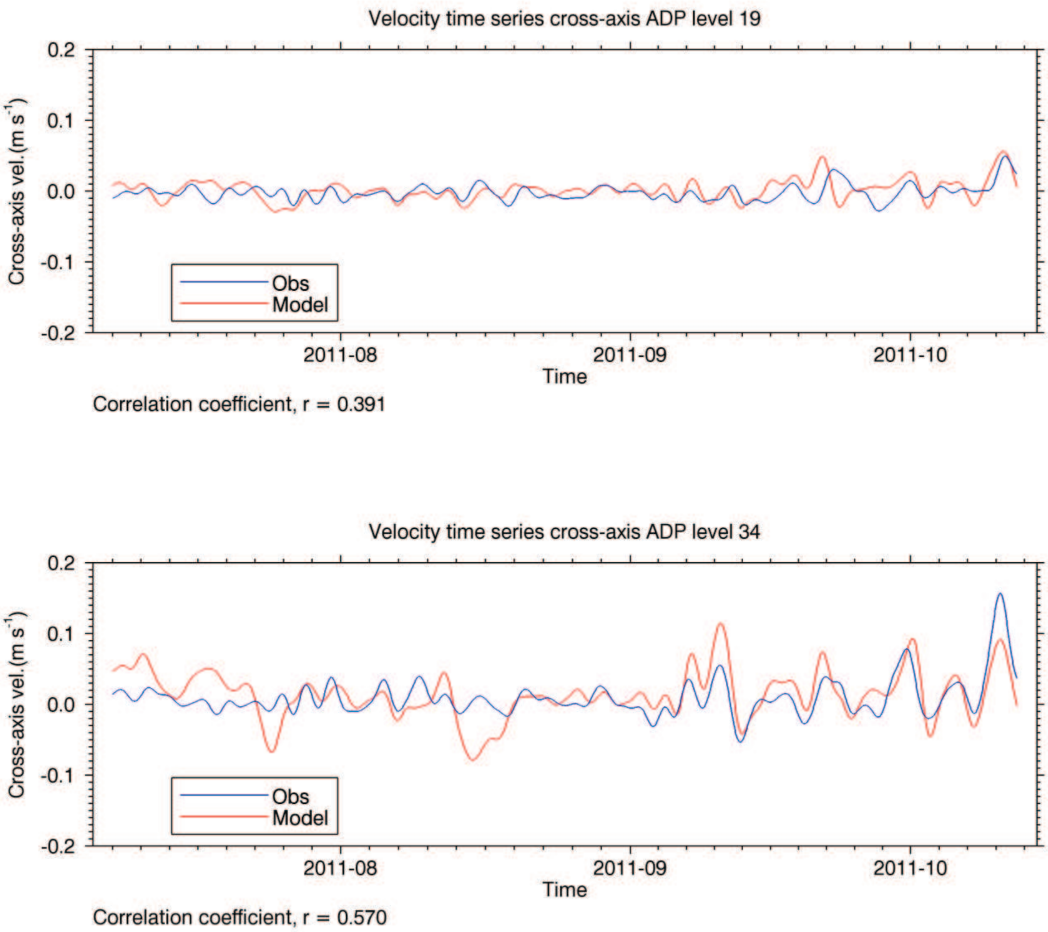


Figure 7: Cross-shore (330°T) velocity component comparison at the outer ADP site. Measured (blue) and modelled (red) velocities: a) in the middle of the water column (19 m below the surface); b) near the top of the water column (4 m below the surface)

4.2 Tidal velocity

An accurate treatment of tides is not crucial for the present application, but it is desirable as a test of model quality. Figure 8 shows the M2 (lunar, semi-diurnal) tidal constituent in the conventional ellipse. Over the course of a tidal cycle, the current vector traces out the elliptical path indicated on the graph, with the phase in time indicated by a line from the origin to the ellipse boundary. Agreement is very good at the outer site, but not quite so good at the inner site, where the model over-estimates tidal velocities by approximately 10%. The poorer agreement probably results from errors in the model's near-shore bathymetry, resulting from a lack of data at less than 20 m depth in Canterbury Bight.

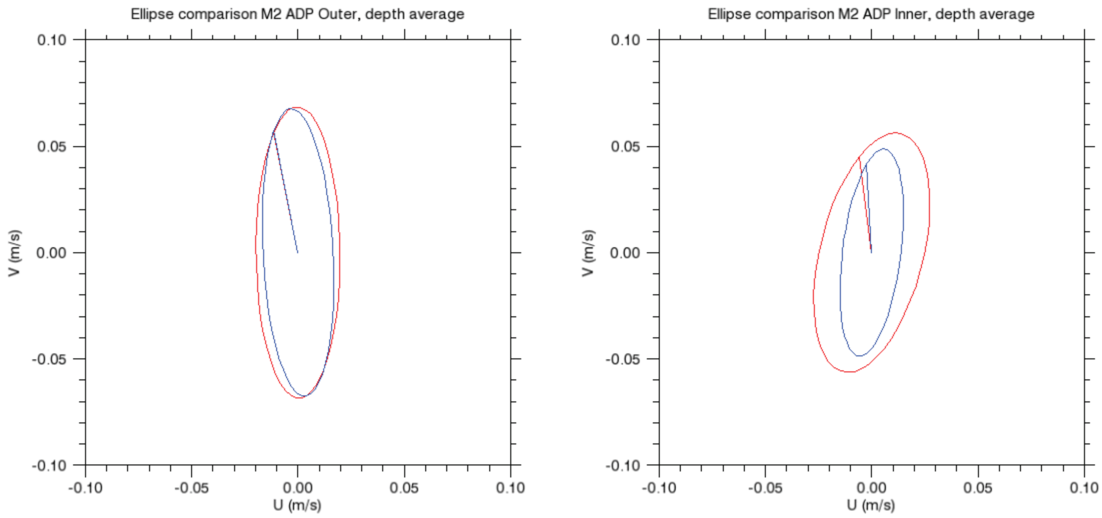


Figure 8: Tidal ellipse comparison for the outer (left) and inner (right) ADP sites. M2 tidal ellipses from measured (blue) and modelled (red) depth-average velocity data.

4.3 Salinity

There were two CTD surveys, each comprising 30 casts. The observed salinity profiles have been collocated with the modelled salinity; figures showing the 60 comparisons are shown in Appendix B.

Agreement between the observed and modelled salinity is variable. Some profiles (Survey 1, Site 3) match very well, some (Survey 1, Site 6) do not. In some cases (Survey 1, Site 5) the model agrees with one cast of the CTD but not with the other. Given that the spacing in time between the downcast and the upcast is typically 10 minutes, this indicates considerable short-term variability (and probably considerable small-scale spatial variability) in the freshwater layer.

The thickness of the observed surface freshwater layer on the inshore transect is typically 2–5 m and the model generally agrees with this, though the model never develops the very sharp salinity discontinuities that mark the base of the layer in the CTD casts. On the offshore transects, the salinity depression is smaller and the thickness of the freshwater layer, if it is apparent at all, is 5–7 m. Again the model reproduces this behaviour.

Overall the comparison indicates that the model does not match the small-scale variability that characterises the freshwater layer on the inshore transect, but tends to produce a freshwater layer with salinity depression and thickness of approximately the correct magnitude.

5 Results

Section 2.3 described a simulation on the inner domain (1 km grid) covering a period of slightly more than one year in 2009–2010. From this simulation were saved fields of temperature, salinity, velocity and freshwater dye concentration as averages over consecutive 12-hour intervals. Possibly the most instructive way to examine model output is by viewing animated graphs; several of these are included with the electronic version of this report, as described in Appendix A.

The animated graphs of surface velocity, temperature and salinity show some of the basic oceanography of the area. The Southland Current is evident as a region of persistent flow towards the northeast along the shelf break, following the 500 m depth contour (Figure 1c). On the continental shelf the surface water moves back and forth, mainly in response to forcing by the wind. Tides are included in this simulation and the 12-hour averaging filters out most, but not all, of the tidal motion: what remains is largely responsible for the “jittery” character of the velocity plot. Over periods of a week or more the surface water in Canterbury Bight generally drifts to the northeast and past Banks Peninsula. Along the coast of Canterbury Bight there is a band ~10 km wide in which the currents, temperature and salinity are quite variable, due to the effects of freshwater input from the rivers and also coastal upwelling and downwelling. The salinity is generally lowest (< 33.5 psu) near the coast, highest (~34.6 psu) in the subtropical water on the outer shelf and lower again (~34.3 psu) in the subantarctic water beyond the shelf break.

Animated graphs are also included of the freshwater tracers (Table 1) individually and of their sum. Looking first at the animation of the surface total freshwater concentration (dye_01+dye_02+dye_03+dye_04+dye_05+dye_06+dye_07+dye_08.avi):

- One can see a plume associated with each of the major rivers and a broader freshwater band attached to the coast.
- The surface freshwater concentration in the river plumes regularly exceeds 30% (the scale maximum) within a few kilometres of the source.
- The river plumes move back and forth, and the width of the coastal freshwater band fluctuates, on time scales of several days. The animations include a barb indicating the direction and magnitude of the surface stress. The relationship between plume behaviour and surface stress is not straightforward, but, broadly speaking, a stress directed to the S (a northerly wind) spreads the freshwater band away from the coast, whereas a stress directed to the NE (a south-westerly wind) produces a narrow freshwater band moving north-eastward along the coast.

The total freshwater concentration at 10 m depth (dye_01+dye_02+dye_03+dye_04+-dye_05+dye_06+dye_07+dye_08_10.0_m.avi) is much lower than at the surface, indicating that the plumes are generally shallow features.

In the animations of the individual tracers (dye_01 to dye_08), points to note include:

- Freshwater from the Southland and Otago rivers (dye_01) is periodically injected into Canterbury Bight and then tends to persist, at concentrations less than 1%. On other occasions, one can see pulses of this water moving past Canterbury Bight in the Southland Current.
- Waitaki River water (dye_02) forms an extensive plume that tends to move along the coast towards Timaru or be swept offshore, sometimes being picked up by the Southland Current and moved rapidly north-eastward.
- Plumes from the Opihi (dye_03), Rangitata (dye_04) and Ashburton (dye_05) Rivers move back and forth along the coast of central Canterbury Bight, with occasional rapid excursions towards Banks Peninsula. These excursions occurred during the first few months of the one-year simulation period and the most pronounced one was around 22–26 May 2009.
- The Rakaia River (dye_06) produced higher surface concentrations around Banks Peninsula than any other single source. Rakaia River water entered Pegasus Bay on several occasions, but at surface concentrations of no more than a few percent.
- Lake Ellesmere/Te Waihora (dye_08) was open twice during the simulation period. The plume affected northern Canterbury Bight and southern and eastern Banks Peninsula.
- The Waimakariri River (dye_07) plume was normally contained within Pegasus Bay, more often in the northern part.

Mean and maximum surface freshwater concentrations have been calculated from the tracer data and are shown in Figure 9 (surface) and Figure 10 (10 m depth). At the surface, the highest concentrations occur near the mouths of the major rivers (Waitaki, Rangitata, Rakaia and Waimakariri): the mean concentrations here are in excess of 30% and the maximum concentrations approach 100%. The lowest concentrations at the Canterbury coastline occur on northern Banks Peninsula (mean ~3%, maximum ~10%).

At 10 m depth the concentrations are much lower than at the surface and also more evenly distributed. The mean concentration in Canterbury Bight is typically 1–3% and the maximum is 2–6%.

Table 2: Sites for vertical profiles. See also Figure 11.

Site	Location	Description
A	171.209° E, 44.971° S	Waitaki River plume, 20 m contour
B	172.225° E, 43.948° S	Rakaia River transect, 20 m contour
C	172.317° E, 44.108° S	Rakaia River transect, 40 m contour
D	172.544° E, 44.392° S	Rakaia River transect, 100 m contour

Site	Location	Description
E	172.973° E, 43.913° S	Near Akaroa Harbour entrance
F	172.836° E, 43.578° S	Lyttleton Harbour/Port Levy entrance

To further elucidate the vertical variation in freshwater concentrations, six sites have been specified (Table 1, Figure 11) and vertical profiles extracted at each one from the 12-hour average model output. The mean and maximum concentrations at each site are shown in Figure 12 for the same one-year period as shown in Figure 9 and Figure 10.

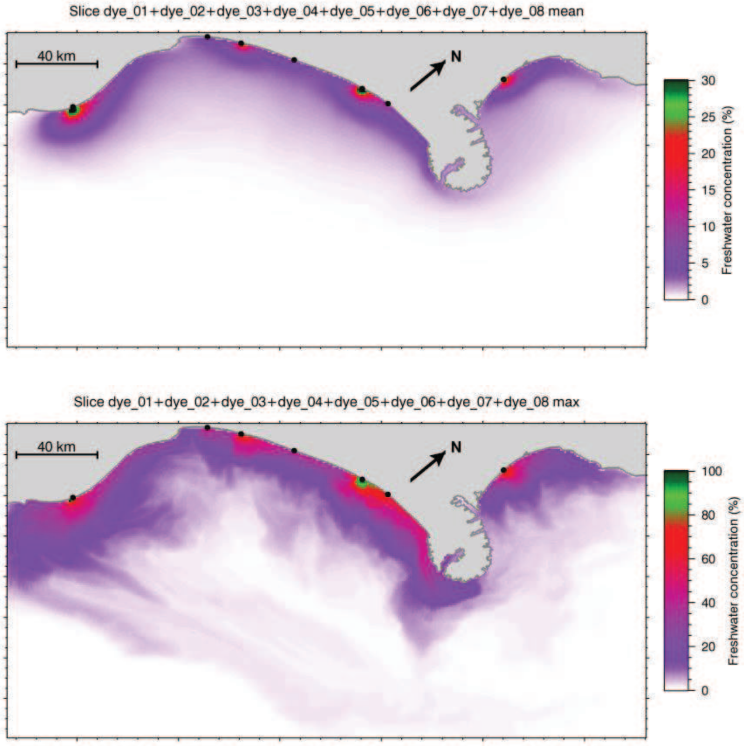


Figure 9: Mean (upper) and maximum (lower) surface freshwater concentration . Statistics calculated for the sum of the eight freshwater tracers over the 365 day period from 21 April 2009 to 21 April 2010.

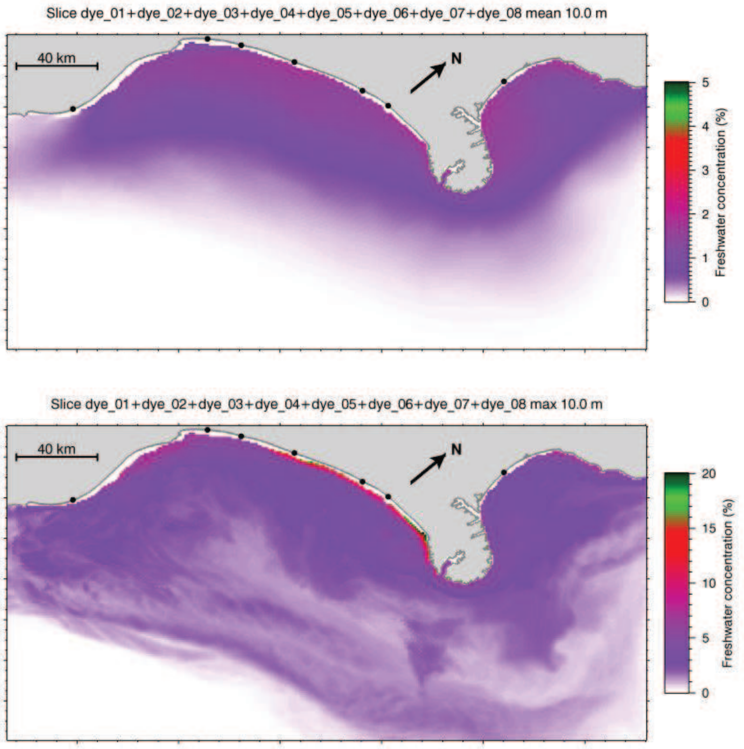


Figure 10: Mean (upper) and maximum (lower) freshwater concentration at 10 m depth. Statistics calculated for the sum of the eight freshwater tracers over the 365 day period from 21 April 2009 to 21 April 2010.

Two of the sites (A and B) are within a few kilometres of the largest rivers (Waitaki and Rakaia, respectively. Maximum concentrations there are 50–70% and mean concentrations ~20%. The concentrations drop off rapidly in the top 3 m of the water column and below 5 m are always less than 10%. Sites B, C and D form a transect out from the Rakaia River and Figure 12 clearly shows the drop-off in concentration with distance from the coast and/or depth. Site E, in relatively deep water at the entrance to Akaroa Harbour shows quite a high maximum concentration (~35%) associated with shallow plumes from the Rakaia River; Site F, in much shallower water at the entrance to Lyttleton Harbour and Port Levy, has much lower concentrations.

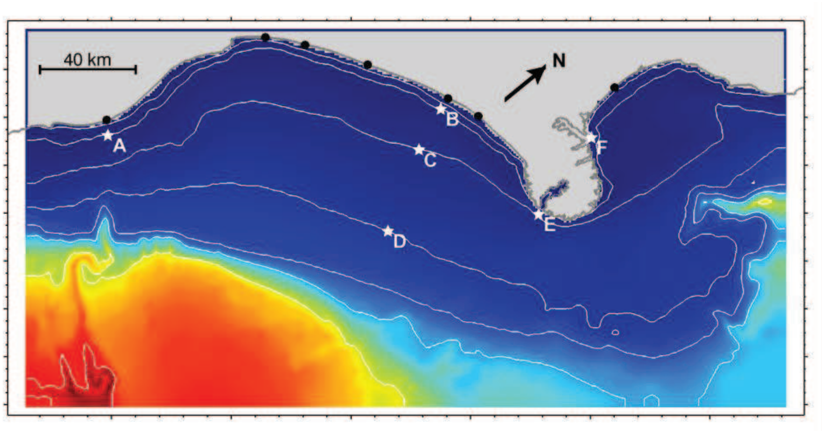
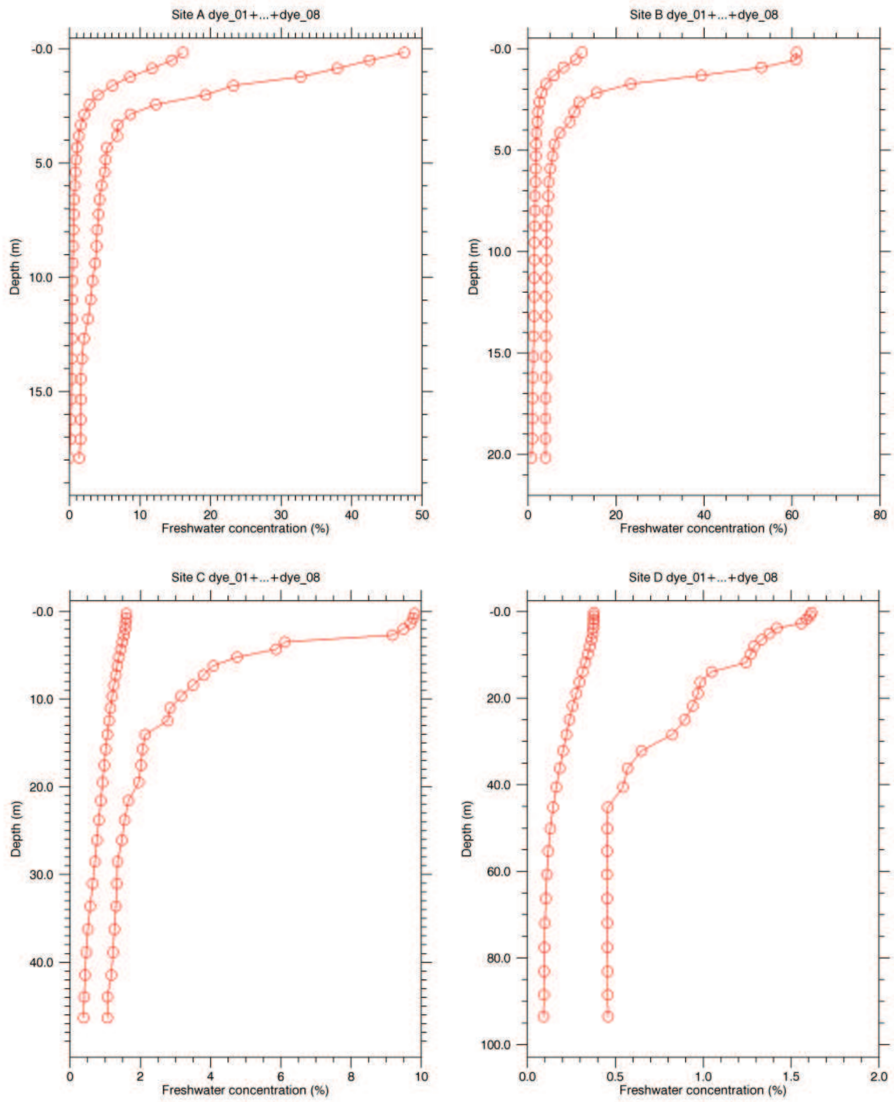


Figure 11: Sites for vertical profiles. See also Table 2 and Figure 12.



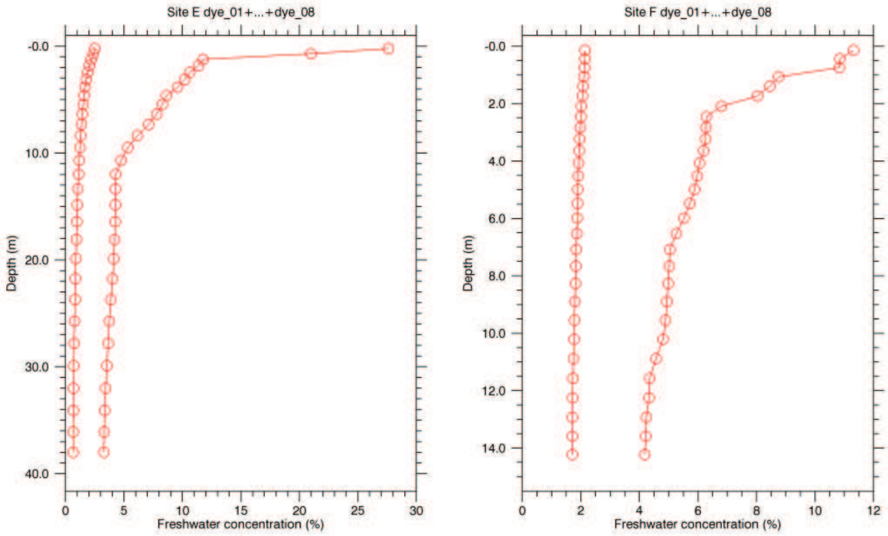


Figure 12: Profiles of mean and maximum freshwater concentration at six sites. See Table 2 and Figure 11.

6 Discussion

The model has produced freshwater plumes with behaviour that is physically plausible and qualitatively consistent with remote sensing results (Schwarz 2008,Schwarz et al. 2010). The model verification confirms that the model is simulating currents in the area very well and that the behaviour of the surface freshwater layer is realistic, though it does not reproduce the small-scale variability on the in-shore transect during the CTD surveys in July and December 2011. Plumes are initially confined very close to the surface (typically 1–3 m) and have freshwater concentrations of 10–30%, frequently more and occasionally approaching 100%. Such concentrated plumes can often be detected several kilometres from the source. The plumes are progressively diluted by vertical mixing and horizontal dispersion, forming a coastal band ~10 km wide with surface freshwater concentrations typically 5–10%. Further out in Canterbury Bight the surface freshwater concentrations are lower still (1–5%) and include a significant contribution from Southland and Otago rivers, notably the Clutha River.

The coastal freshwater band, and the river plumes within it, are transported by surface currents, which produce a general north-eastward drift but with fluctuations that are largely wind driven. When the wind is from the south or southwest, the coastal freshwater band becomes narrower and can move quite quickly (within a few days) north-eastward along the coast of Canterbury Bight and around the end of Banks Peninsula.

The model indicates substantially higher freshwater concentrations on the southern and eastern sides of Banks Peninsula than on the northern side (e.g. see Figure 9 and Figure 12). The concentrations on the northern side are relatively low because freshwater from rivers to the south (notably the Rakaia) tend to be diluted as they enter Pegasus Bay, while the Waimakariri plume tends to move northward and does not produce high concentrations adjacent to Banks Peninsula. Note that this finding depends on the model's representation of the circulation in Pegasus Bay, and there are not sufficient data to confirm that this representation is essentially correct.

7 Acknowledgements

River flow data were provided by Kathy Walter of NIWA and originated from Environment Southland, Otago Regional Council, Environment Canterbury and NIWA archives.

The field measurement programme was conducted by Warren Thompson of NIWA, who worked long hours to ensure high-quality data.

Thanks to Lesley Bolton-Ritchie of Environment Canterbury for her feedback on a preliminary version of the report.

8 Glossary of abbreviations and terms

climatological	In connection with model forcing, an adjective describing data (frequently at one-month intervals) with an annual cycle that is repeated indefinitely, thus representing generic conditions, cf. real-time.
real-time	In connection with model forcing, an adjective describing a dataset representing a sequence of actual dates and times, cf. climatological.

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Appendix A Animations

Several animations of model output are included with the electronic version of the report in a subdirectory called Animations. On Windows we recommend that you view them with a free media player called Imagen, available from the following Web page:

http://gromada.com/imagen/

Otherwise you can use Windows Media Player or QuickTime Player. The advantage of Imagen is that it allows fast & easy navigation, either forward or backward, through the animation with the computer's keyboard. (Use the space bar to pause or restart the animation, left and right arrow keys to step one frame, and the Home and End keys to move to the beginning and end of the animation.)

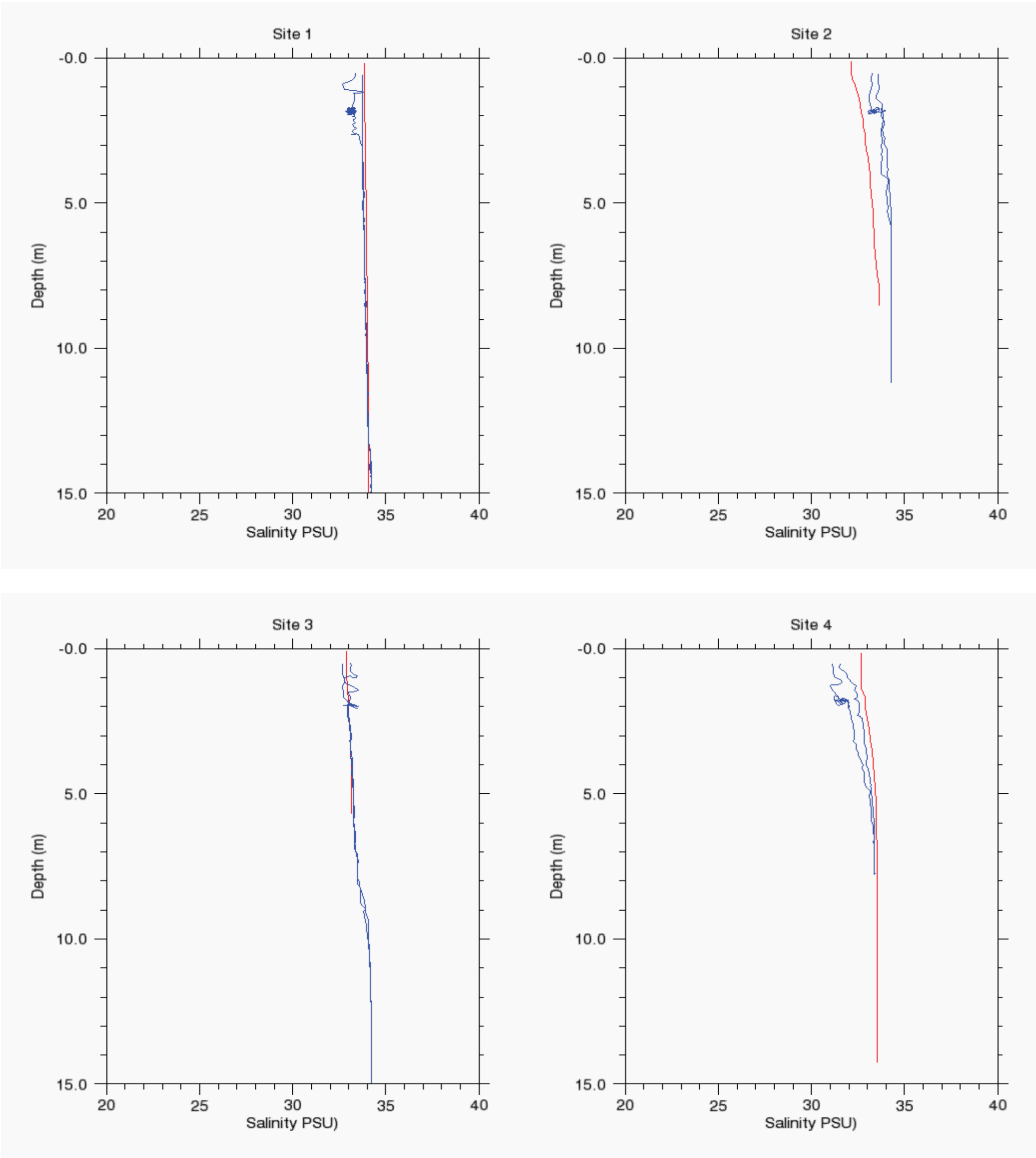
The Animations subdirectory includes an HTML document (index.html) with links to the animations, along with a brief description of each one. If the location of the Animations subdirectory relative to this report has been preserved, you *should* be able to open the index.html using the following relative link:

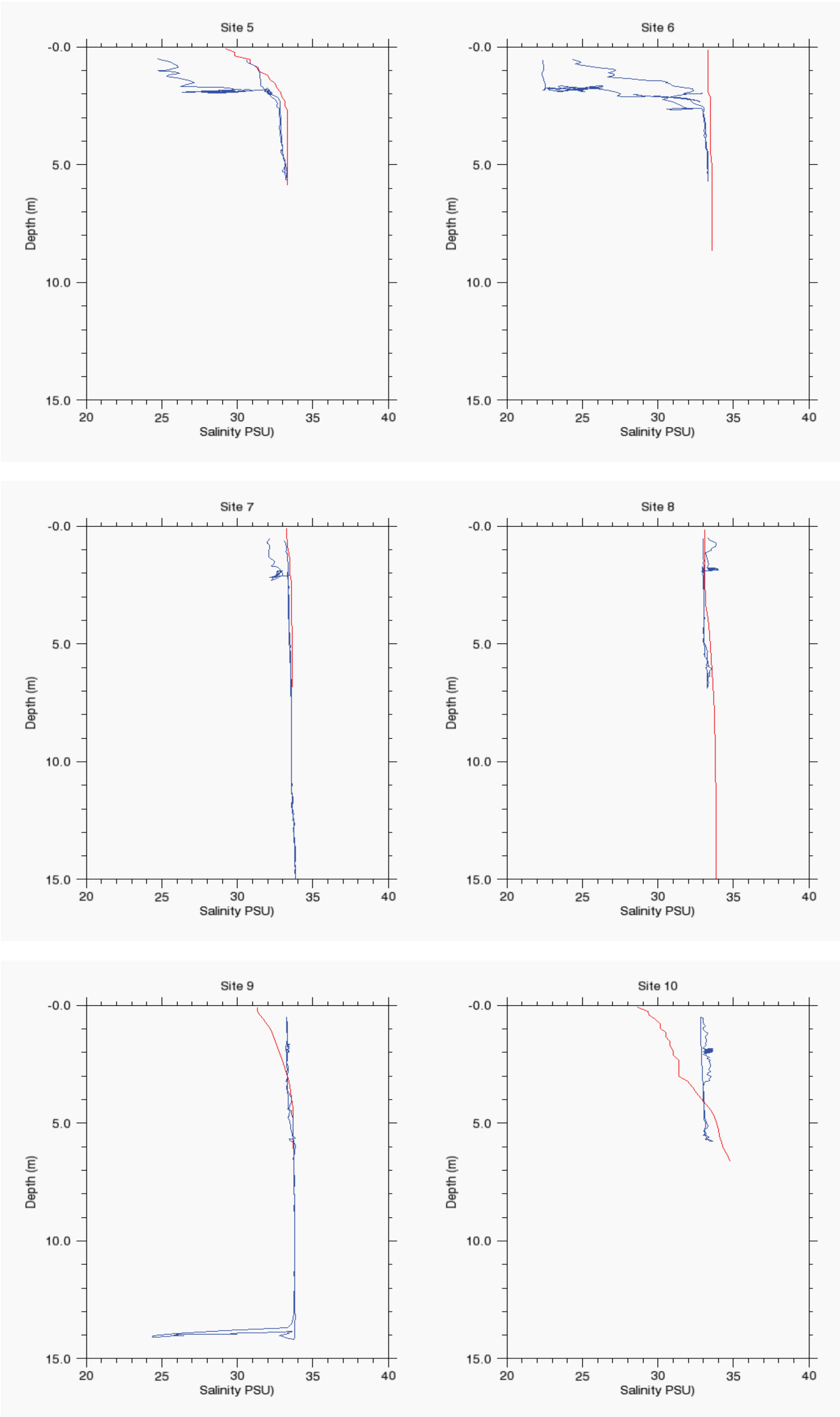
Animations/index.html

Alternatively, you can navigate to the Animations subdirectory and open index.html in a Web browser directly.

Appendix B CTD-model comparisons

Survey 1 (4 July 2011), near-shore transect (Sites 1 to 25)

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Site 6
Site 7
Site 8
Site 9
Site 10
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Salinity PSU)
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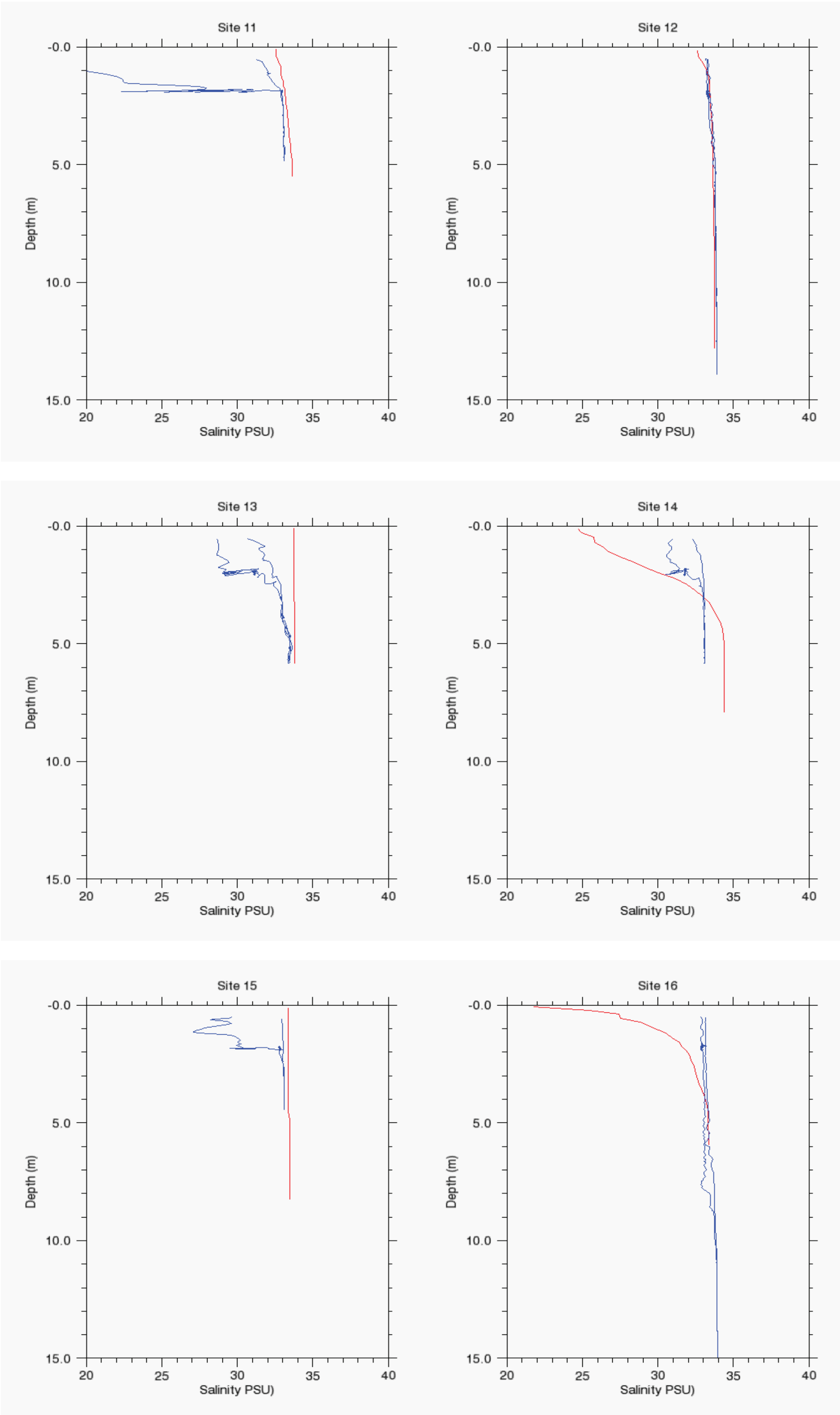
10.0
15.0
20
25
30
35
40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Site 12
Site 13
Site 14
Site 15
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Depth (m)
Salinity PSU)
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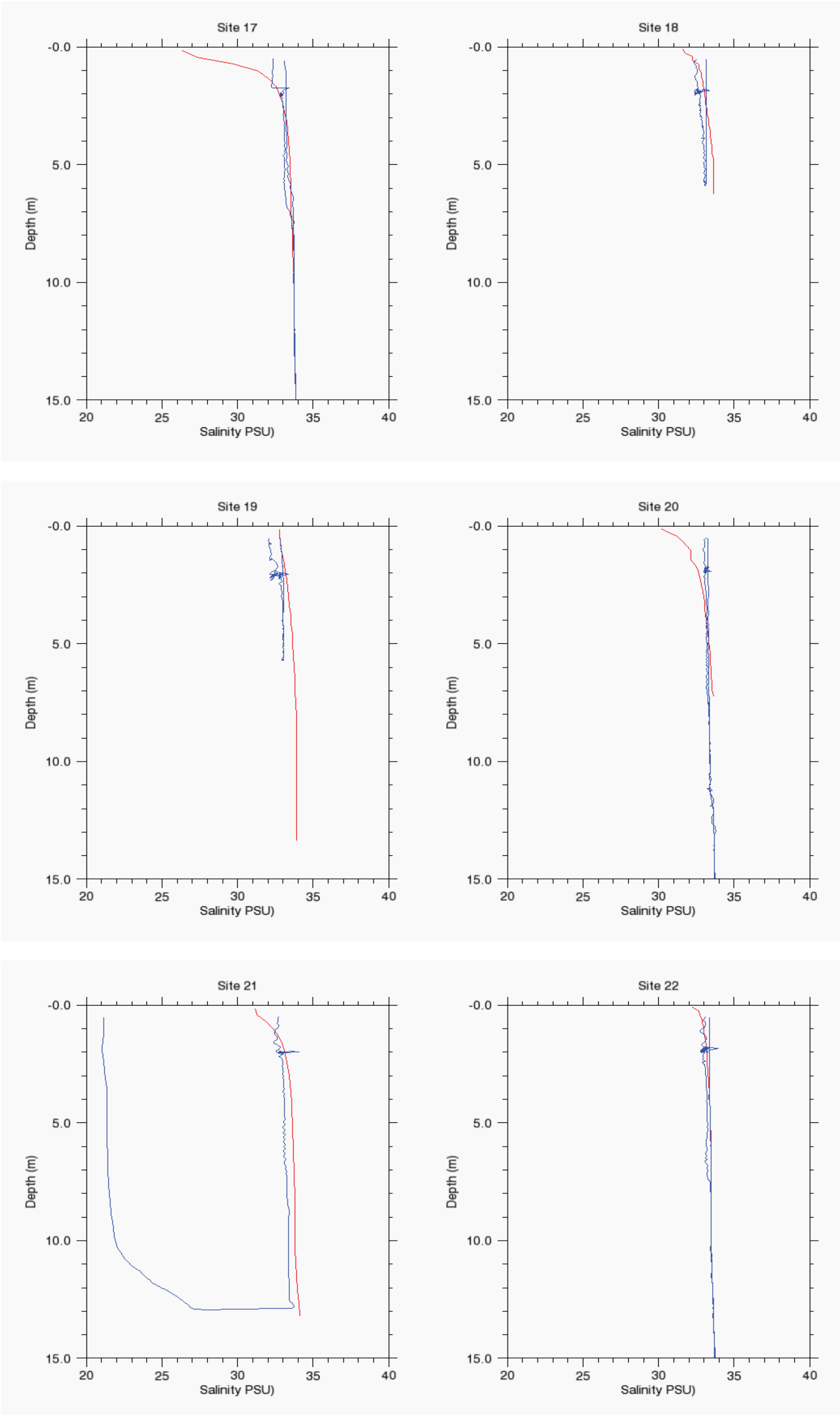
10.0
15.0
20
25
30
35
40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Site 18
Site 19
Site 20
Site 21
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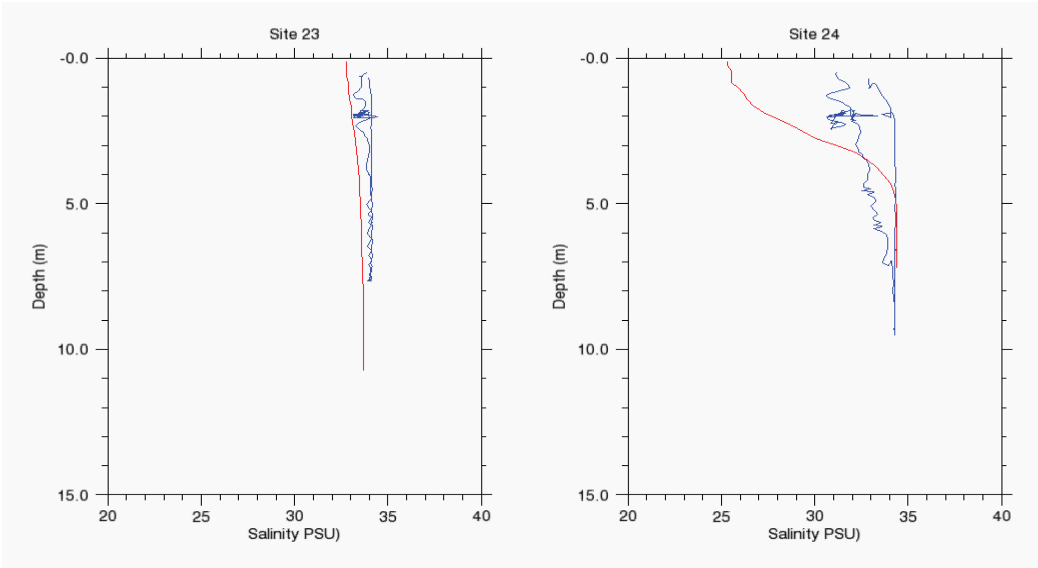
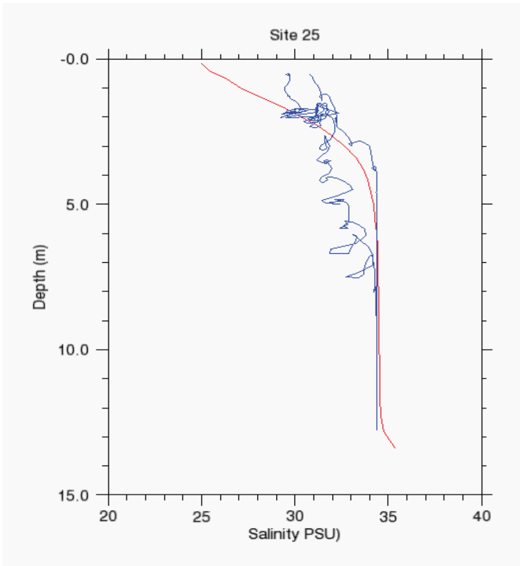
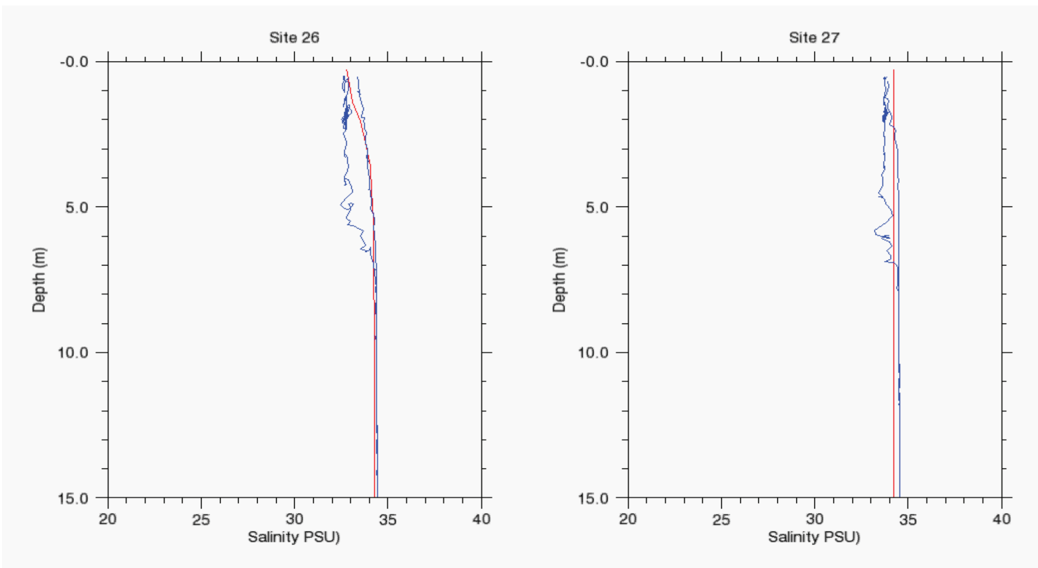
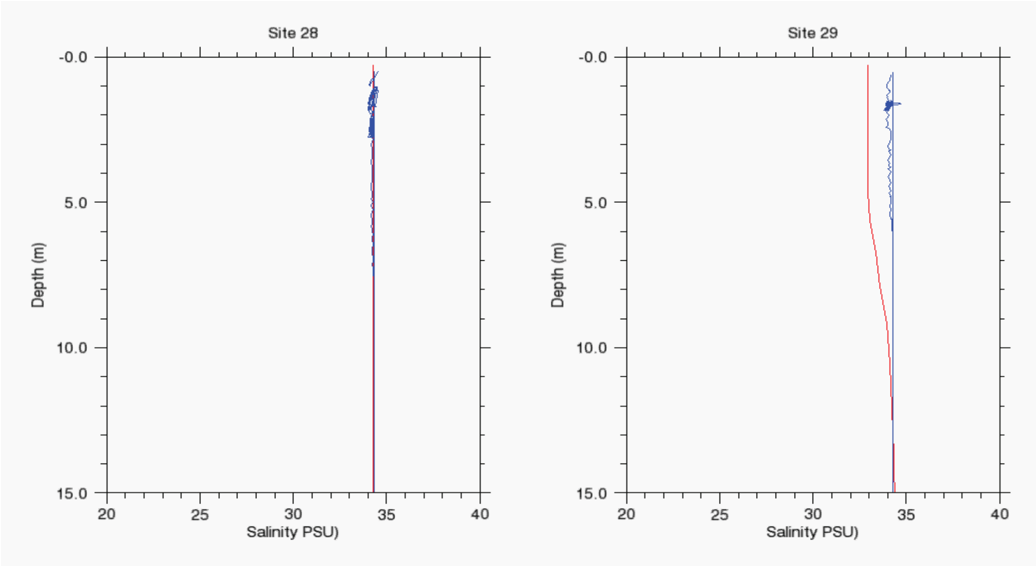
10.0
15.0
Depth (m)
20
25
30
35
40
Salinity PSU)

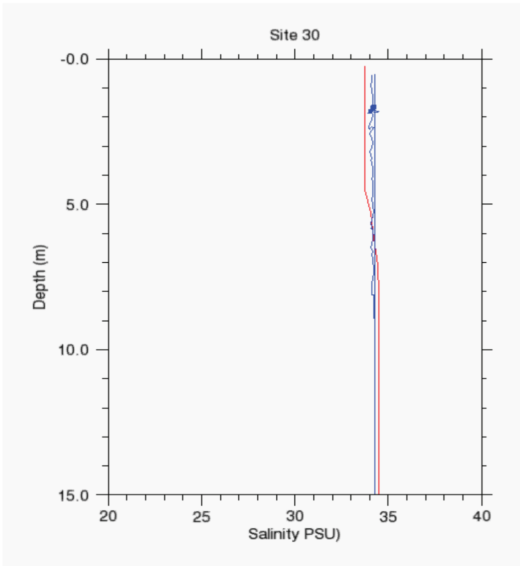




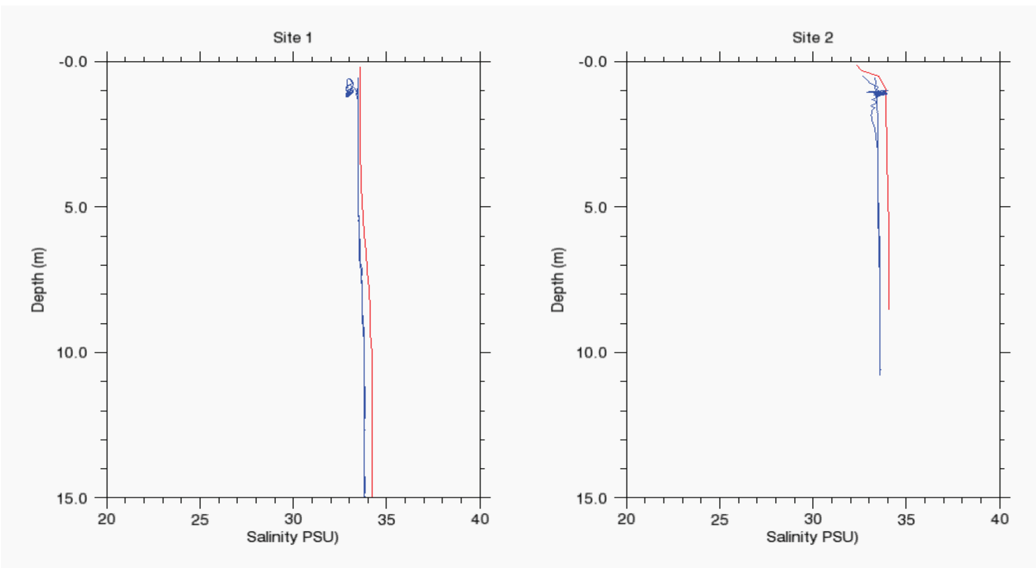
Survey 1 (4 July 2011), off-shore transect (Sites 26 to 30)

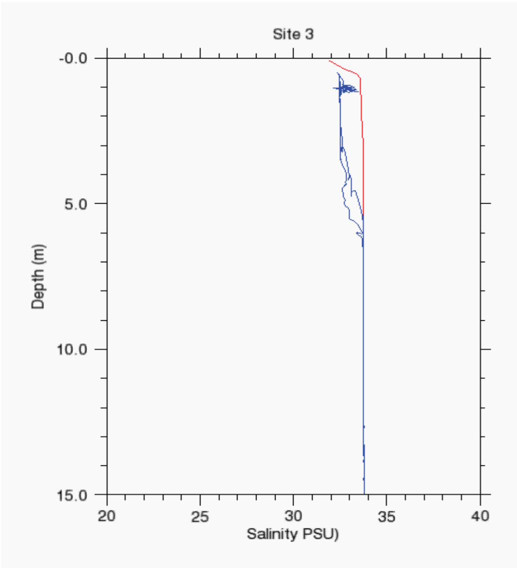






Survey 2 (9 December 2011), near-shore transect (Sites 1 to 25)

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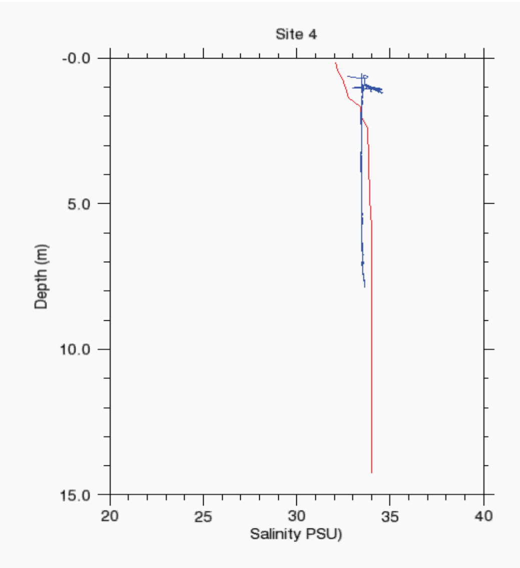
Salinity PSU)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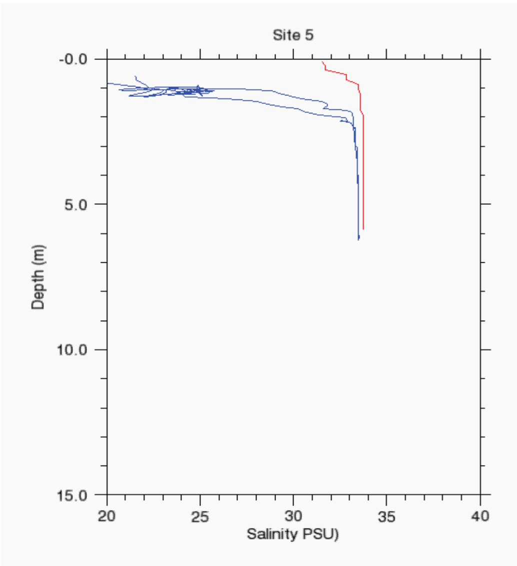
Salinity PSU)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Depth (m)
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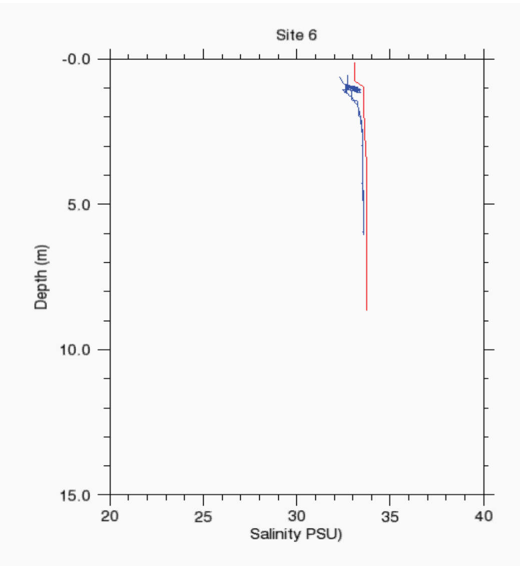
Salinity PSU)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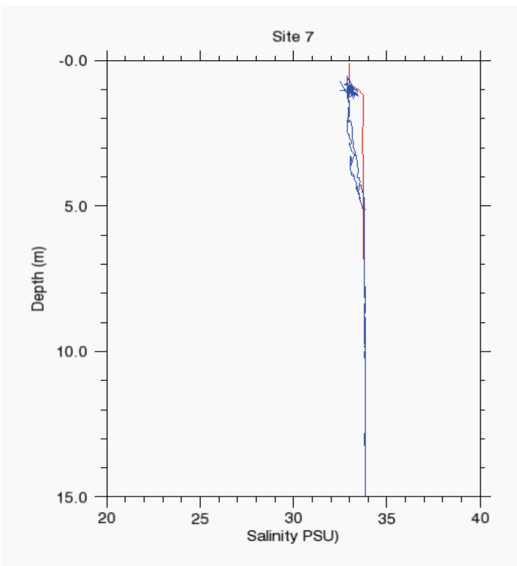
Salinity PSU)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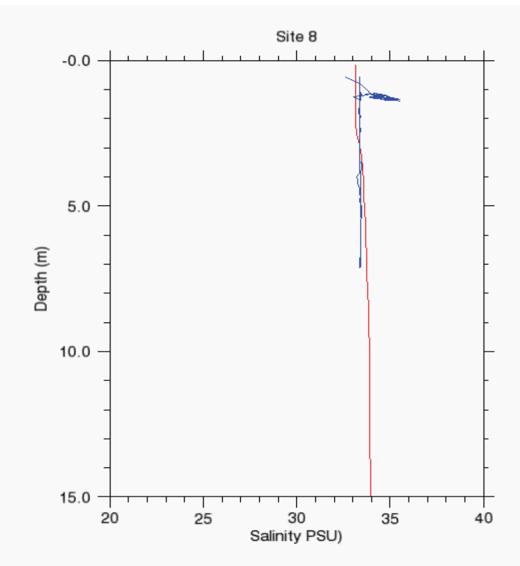
Salinity PSU)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Depth (m)
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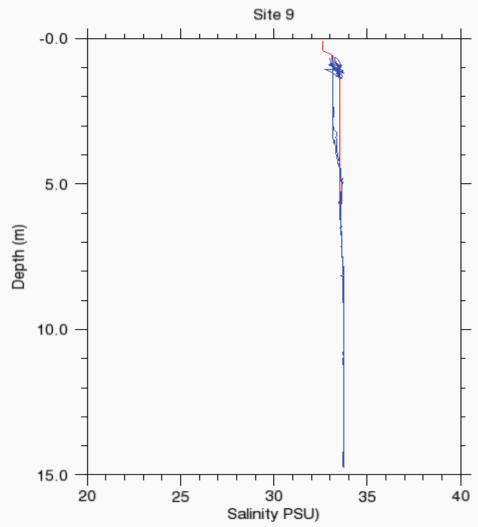
Salinity PSU)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Depth (m)
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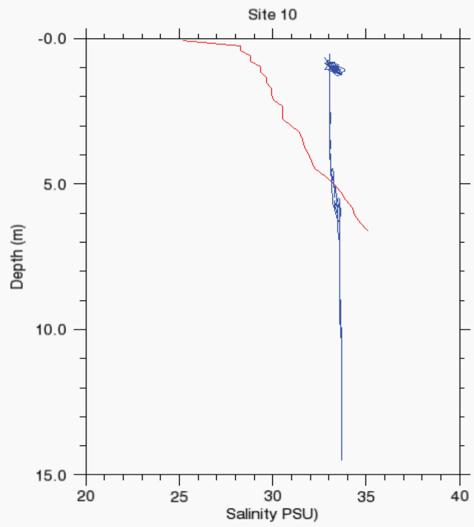
Salinity PSU)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Depth (m)
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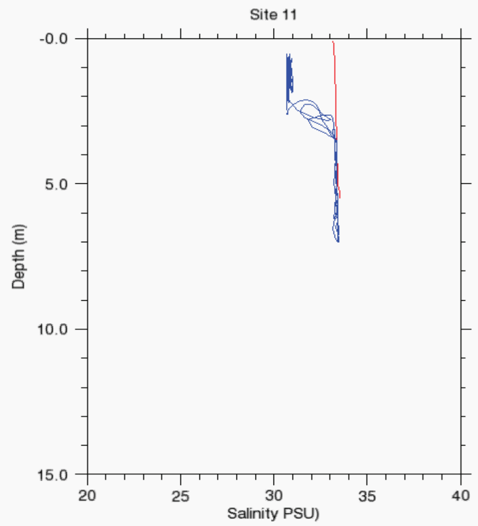
Salinity PSU)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Depth (m)
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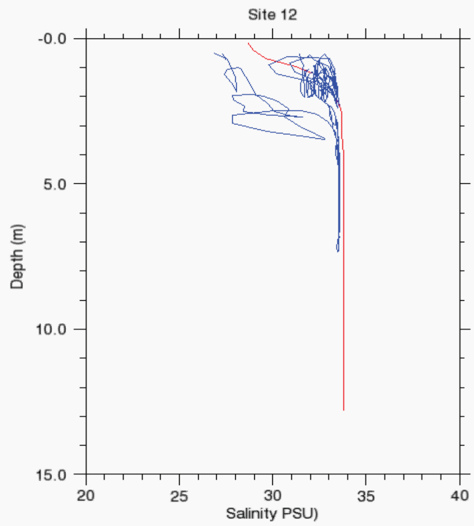
Salinity PSU)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Depth (m)
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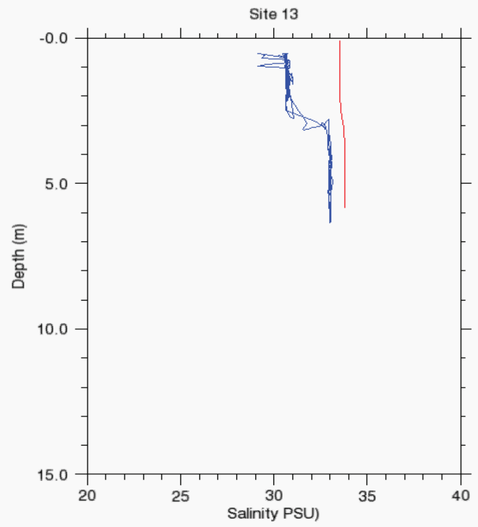
Salinity PSU)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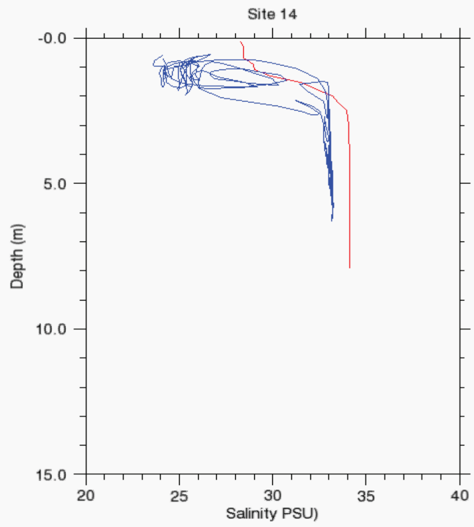
Salinity PSU)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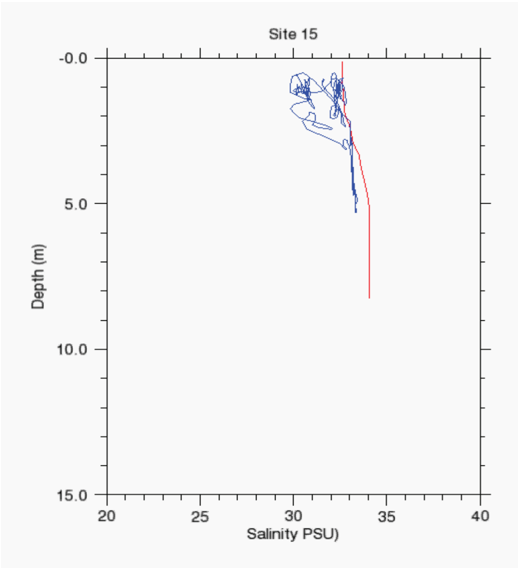
Salinity PSU)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Depth (m)
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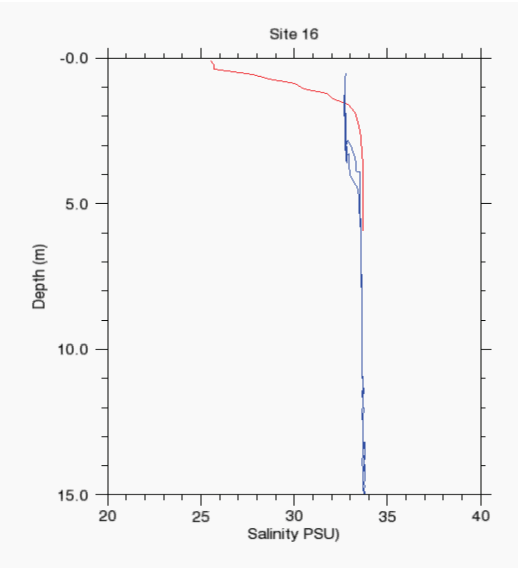
Salinity PSU)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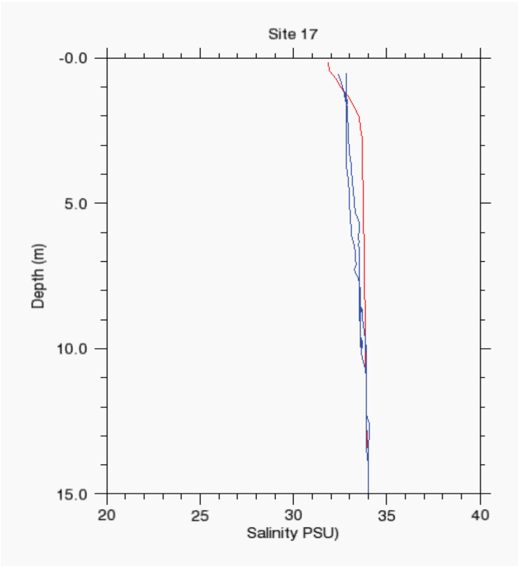
Salinity PSU)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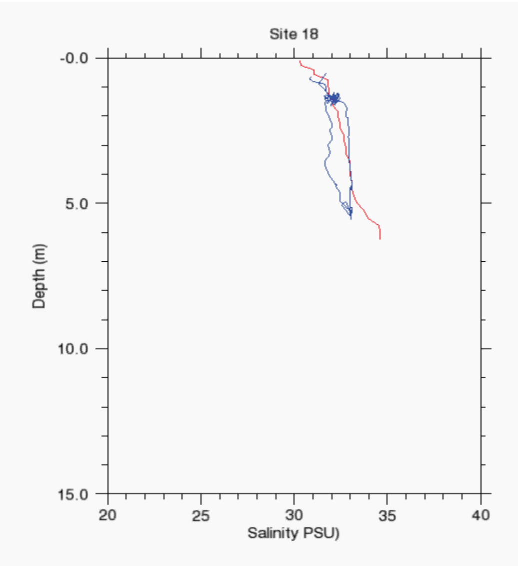
Salinity PSU)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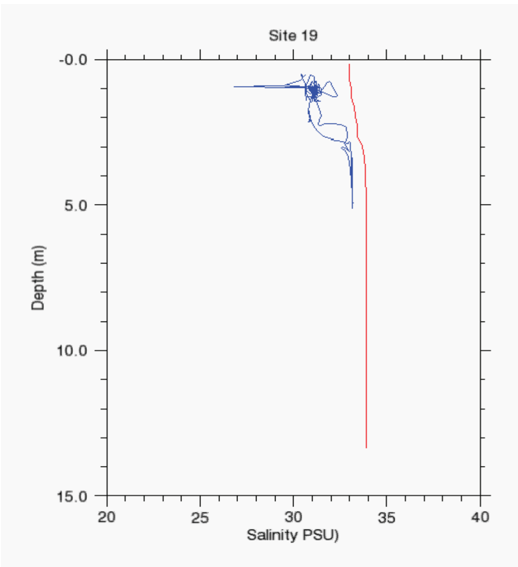
Salinity PSU)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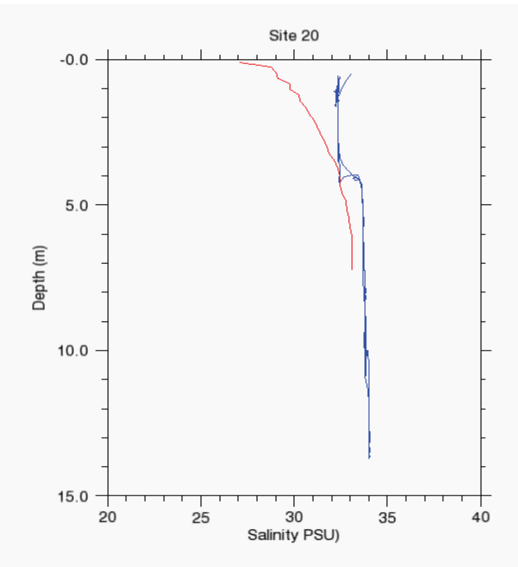
Salinity PSU)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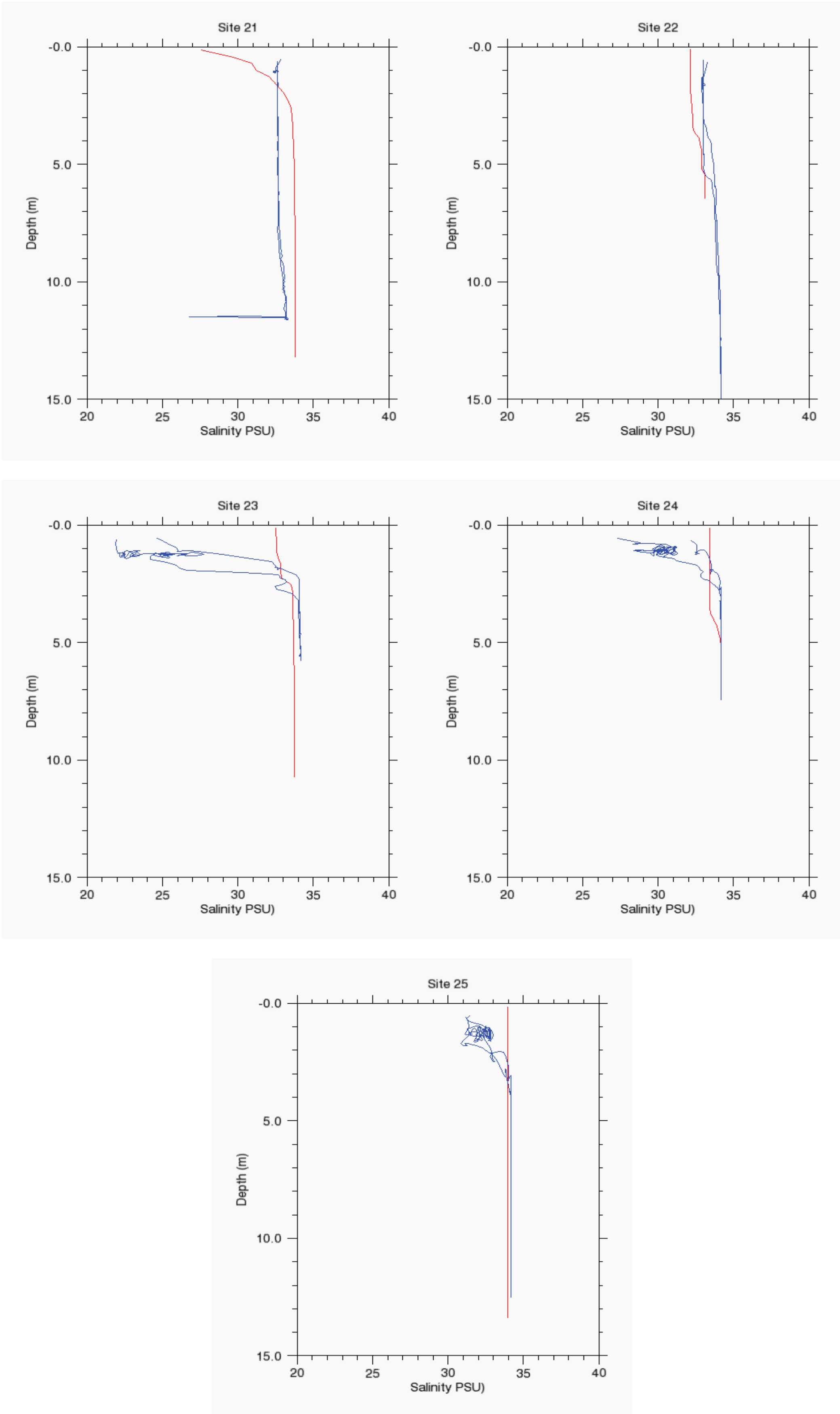
Salinity PSU)


Site 21
Site 22
Site 23
Site 24
Site 25
Depth (m)
Salinity PSU)
-0.0
5.0
10.0
15.0
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35
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Survey 2 (9 December 2011), off-shore transect (Sites 26 to 30)