River Plume Dynamics in the Coastal Marine Area

January 2020

NIWA Taihoro Nukurangi

horizons REGIONAL COUNCIL

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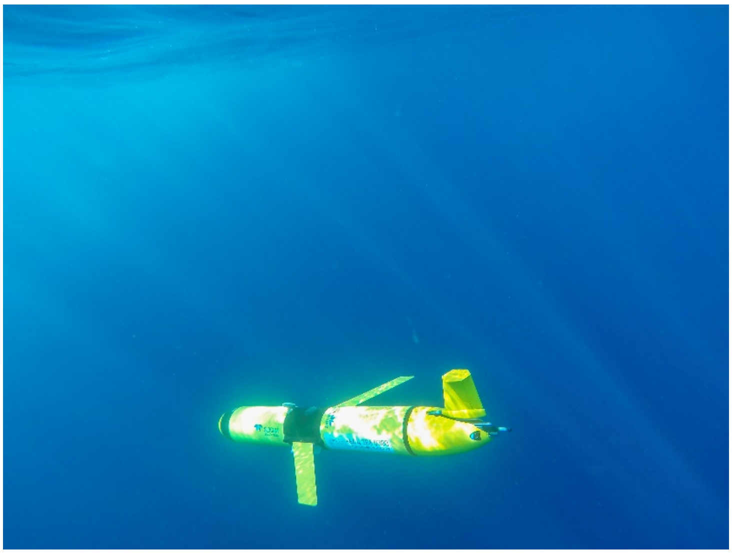

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Executive summary

Spatial and vertical distributions of biophysical ocean properties were observed in South Taranaki Bight during Spring 2019. An ocean glider collected 6196 profiles over the 4-week mission. Glider data provide an important link between the routinely available SST observations from satellites and subsurface physical properties. Profiles from the 32 days dramatically increased the available data in the South Taranaki Bight coastal marine area (CMA). River plumes with elevated organic matter concentrations were present offshore in two (of the three) major rivers in the Horizon Regional Council CMA.

The vertical extent of the low salinity water varied from between 5 to 35 m below the surface. Near-surface salinities decreased to a minimum of 32.8 psu. The horizontal extent of ROFI, identified by salinity less than 34. 6 psu, ranged between 3 and 11 km. ROFIs observed were both surface intensified features constrained to the upper 5m as well as features that occupied the full water column down to 35m.

The prevalence of higher CDOM in freshwater than the ocean makes it a good proxy for identifying the fate of rivers in the ocean. Although as CDOM and chlorophyll both absorb light in the same spectral range robust interrogation is needed to distinguish between them. Elevated CDOM was regularly collocated with the ROFI indicating that river water is present in the CMA. Small productive fronts (from higher chlorophyll) were observed at the outer boundary of the ROFI.

ROFIs were evident offshore from the Rangitīkei, Manawatū, Otaki and Waikanae rivers. Although the latter two rivers are outside the Horizon's CMA, these southeast ROFIs are likely to be influenced by rivers in the Horizon's CMA. Mean flow in South Taranaki Bight to the southeast and periods of strong wind mixing could, at times, enhance the horizontal transport through the region.

1 Introduction

1.1 Motivation

Buoyant river plumes transport massive quantities of river water, suspended detritus and energy into coastal seas after high intensity rainfall events. These river plumes are usually found as a very thin lens that occupies only a few metres at the ocean's surface. In many coastal areas, the strong signature from the freshwater disperses quickly into a feature known as a region of freshwater influence (ROFI). A ROFI acts as a critical interface between estuaries and the ocean, with interactions between stratification and tides dramatically affecting the transport of land-derived sediments and nutrients from degraded catchments.

Horizon's Regional Council is seeking advice on the vertical and horizontal extent of river plumes in regions of the coastal marine area (CMA) to the south and southeast of the Whanganui River. Satellite observations of turbid river plumes can be regularly seen in the Horizon's CMA. Figure 1-1 is an example satellite image with weak and strong ROFI signals.

Envirolink advice grant (Collins and Macdonald, 2019) examined oceanographic flow patterns and the transport and dispersal of particles in the South Taranaki Bight around the Manawatū-Whanganui Region using a numerical model. Riverine water from the three major rivers (Whanganui, Rangitīkei and Manawatū rivers) was tracked with particles in the model to evaluate the extent and scale of rivers in the Horizon's CMA. ROFI spreading was typically parallel to coastline in the CMA with an average flow of plumes from each river to the south. Tidal oscillations and wind patterns modulated plume mixing and spreading at the 1 - 5 day timescale. The longer term averaged transport of particles was to the southeast.

Limited observations of ROFI properties exist in the CMA due to the characteristic vertical scales being typically less than 5m. The common subsurface oceanographic moorings are not suitable for resolving scales of river plumes. An ocean glider can detect both the vertical plumes and offshore scales. It is anticipated that the advice will support the development of policies that better reflect the integrated land-sea connectivity. Improved understanding of the extent of ROFI will enable fit-for-purpose management of sediment, nutrients and organics, to achieve healthy coastal waters.

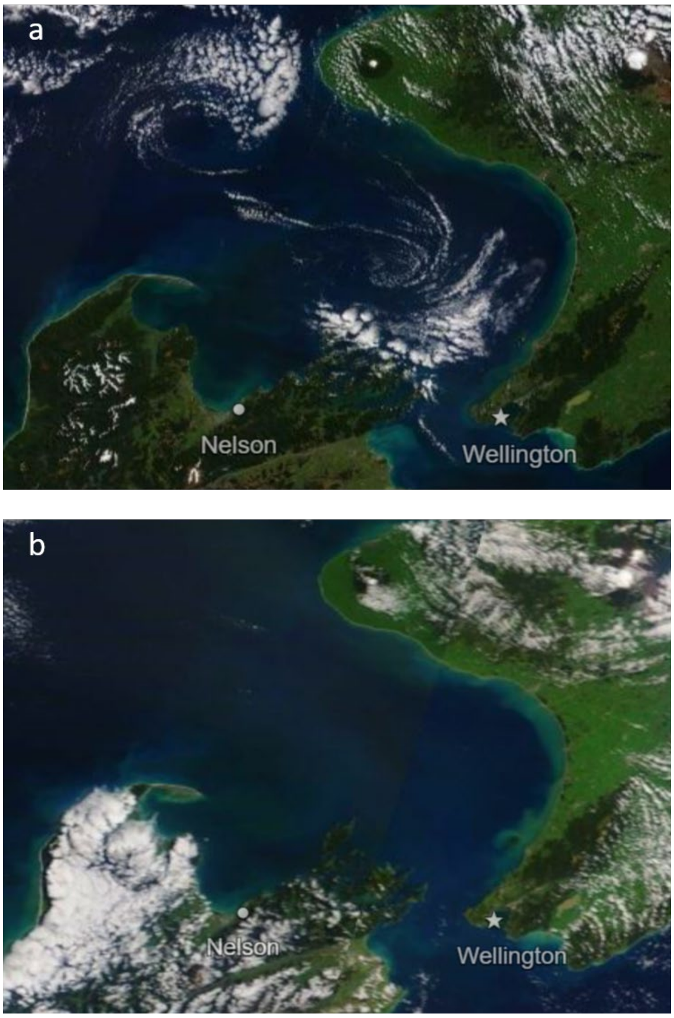

Figure 1-1: MODIS images from a) September 20 and b) October 6, 2019 showing the absence and presence of plumes in the Horizon's CMA during the glider mission. These two images had the least cloud cover. Images obtained from https://www.cawthron.org.nz/apps/cawthroneye/

1.2 Historic observations in Horizons CMA

There were very few observations of ocean stratification, turbidity and fluorescence in the coastal waters of Horizons CMA. Nearest and most recent data was from the coastal waters off from Whanganui as part of an environmental impact assessment undertaken by Trans-Tasman resources (MacDonald et al 2012a, MacDonald et al 2012b, MacDonald et al 2013). In the coastal waters (30-50m) outside of the 12 nm limit, tidal currents accounted for a significant proportion of current flows (MacDonald et al 2012a). Currents in the region were affected by wind conditions with near surface flows modified by the speed and direction of the wind. In particular, strong winds forced currents to flow in a constant direction for more than 24 hours. At timescales longer than wind stirring and tidal oscillations currents are dominated by the barotropic D'Urville current (Chiswell et al, 2016). The average flow of the D'Urville current is towards the southeast in South Taranaki Bight. Variability in currents by these three main processes will strongly influence the pathway of a ROFI through the Horizon's CMA.

While the majority of the effort was focused outside the coastal limit of 12 nm, there were several relatively shallow moorings deployed to resolve ocean stratification (MacDonald et al 2015). Well mixed conditions were indicated, except in the vicinity of major rivers. Higher suspended sediment concentrations occurred for increased river flows.

2 Methods

An ocean glider was deployed in Horizons CMA on September 20, 2019. The vehicle was deployed for 32 days travelling 633 km and performing 6196 profiles. The glider was deployed from the Whanganui Coastguard vessel at 40° 02.28' S, 174° 43.03' E and water depth of approximately 40 m. This deployment was carried out in collaboration with the Horizons Regional Council to look at regions of fresh water influence along the districts' coastline. Recovery was from RV Ikatere at 41° 16.06' S, 174° 33.01' E on October 22, 2019. Figure 3-2 and Figure 3-3 show the surface locations of the glider over the 32 days coloured by surface temperature and salinity, respectively.

At times during the mission, strong currents made it difficult to complete transects perpendicular to the three main river mouths in the CMA. An attempt to resample the Manawatū River and any likely dilution of salinity or turbidity were made part way through the mission. Moderate success was had, however, as the wind direction reversed for several days the ocean glider was difficult to pilot and sampled outside the CMA for 4 days.

A Teledyne Webb Research 200 m electric glider was used for the mission. Slocum gliders are buoyancy-driven autonomous underwater vehicles (AUVs) that provide high-resolution surveys of the physical and bio-optical properties of the water column. The 200 m glider `Betty', was equipped with a Seabird conductivity-temperature-depth (CTD) sensor and carried a WET Labs Environmental Characterization Optics (ECO) puck, that measured chlorophyll-a fluorescence, backscatter at 660 nm —and coloured dissolved organic matter (CDOM). Temperature, conductivity, and pressure data were collected at 0.5 Hz, and subsequently processed to remove spikes. Quality control (QC) procedures from the Balearic Islands Coastal Observing and Forecasting System (SOCIB) data processing toolbox was used for data (Troupin et al., 2016) and include salinity corrections for the thermal lag error for the un-pumped CTD data (Garau et al., 2011). Final profiles have an average horizontal along-track resolution of 0.5 km and vertical bins of 1 m.

3 Results

3.1 Background oceanographic conditions

Background temperature conditions in the coastal waters of south Taranaki Bight during the glider mission were close to average conditions. Figure 3-1 shows snapshots of sea surface temperature (SST) anomalies for the period of the glider deployment.

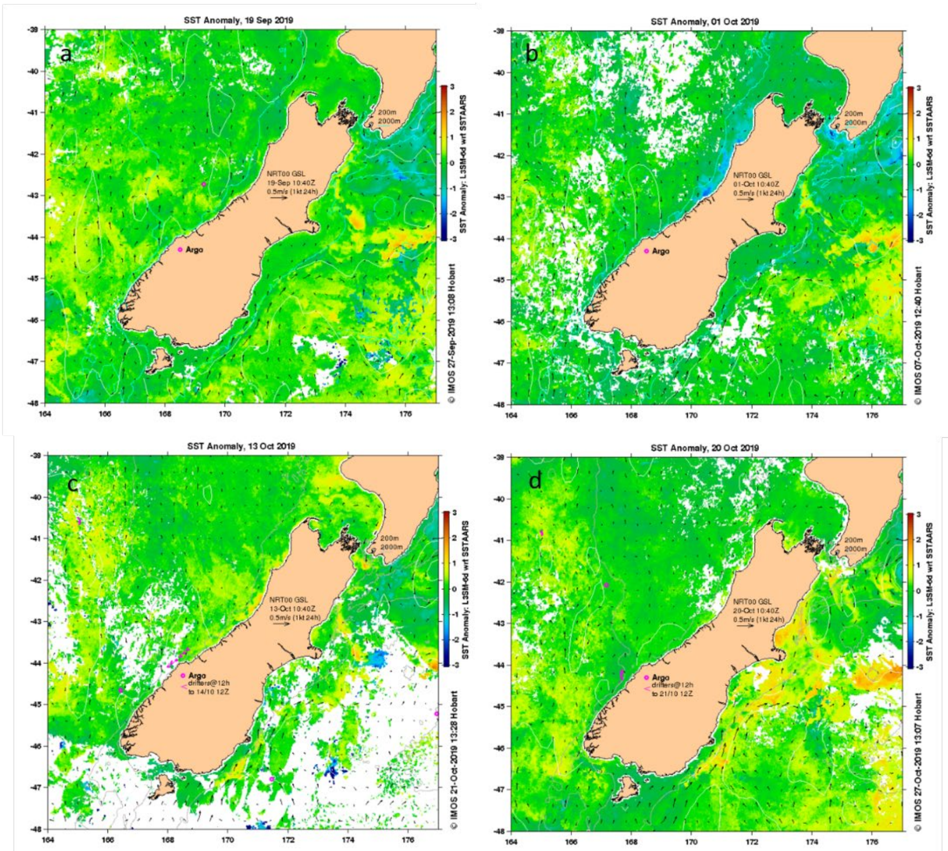

Figure 3-1: Sea surface temperature anomaly (SSTA) for (a) September 19, (b) October 1, (c) October 13 and (d) October 20 2019. Anomalies were neutral for the majority of the 32 day mission, with the exception being slightly warmer than average water being evident around October 13. The SSTA maps were obtained from http://oceancurrent.imos.org.au/product.php

3.2 Near surface temperature and salinity

An ocean glider collected 6196 profiles over the 4-week mission. Glider data provide an important link between the routinely available SST observations from satellites and subsurface physical properties. Near-surface temperatures (5 m) ranged from 12.2 to 14°C (Figure 3-2) throughout the mission from the Whanganui through to Cook Strait. At the beginning of the mission – offshore from the Whanganui River - near-surface temperatures were close to 13 °C. Further to the southeast (and around 1 week later), surface temperatures were 1 °C warmer. Near-surface water at, and south of, 40.5 S ranged between 13.6 and 14.0°C through to Cook Strait narrows at 41.5 S.

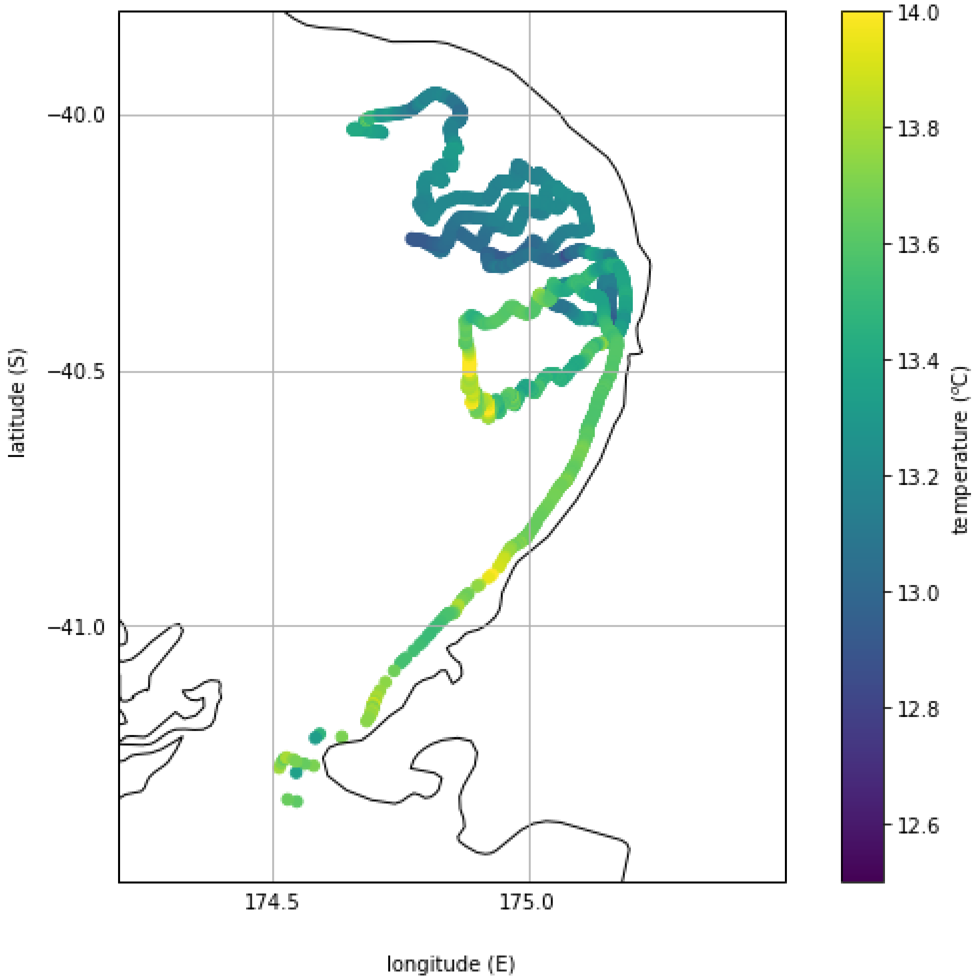

Figure 3-2: Temperature from 5 m below the surface from the 32-day glider mission in Taranaki Bight

Variability in salinity variations had a clearer signal offshore from major and minor rivers in the Horizon's CMA. Near-surface salinities maxima were 35.2 psu and primarily observed for the first week of the mission between Whanganui and Turakina Beach. Offshore from the Rangitīkei and Manawatū rivers salinity minima were 34.5 psu (Figure 3-3). Later in both time and space, salinity decreased to 33 psu in the coastal seas adjacent to the Otaki River.

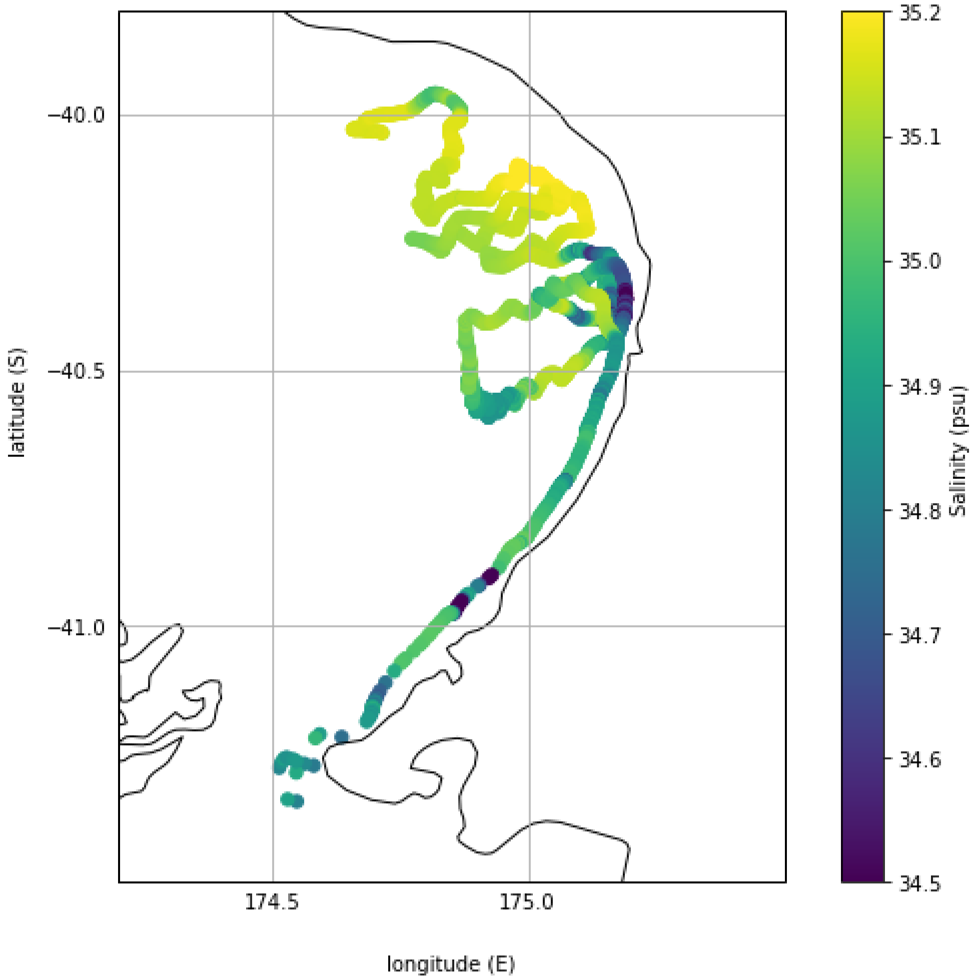

Figure 3-3: Salinity from 5 m below the surface from the 32-day glider mission in Taranaki Bight

3.3 Spatio-temporal glider observations

Subsurface glider observations over the 4-week times series are shown in Figure 3-4. Broadly, vertical gradients were weak with well mixed profiles extending from the surface to the seabed for the first half of the mission. Increased stratification was evident at inshore locations and from around October 3 and onwards in both time and space.

Water temperatures ranged from near-surface values of 14.5 °C down to 12.7 °C at the seabed. Warmest surface temperatures were observed at the start of the mission, September 20, and for the period October 10 to 16. The largest daily variations in temperature were seen over these six days as increases and decreases in temperature of 0.5-0.8 °C.

Lowest salinities (32.8 psu) over the glider mission were observed at the surface and, as expected, at locations closest to rivers (Figure 3 4). Riverine responses are provided in more detail in section 3.5. Maximum salinities of 35.3 psu were observed further offshore and below river plumes through south Taranaki Bight. High salinity around October 17 extended to the surface, however around 1-2 days later higher salinities were subsurface features once the glider was closer to shore again.

CDOM ranged from 0.5 to 1.2 ppb and was dominated primarily by vertical and horizontal salinity stratification. Higher CDOM of 0.6ppb or greater was observed for lower salinities and mainly in water depths of less than 40 m, or essentially the coastal waters of South Taranaki Bight. Lower CDOM concentrations were spatially constrained to deeper water north of Kapiti Island. Further south of Kapiti, and outside the Horizon's CMA, higher CDOM was observed through the full column down to 80m.

Vertical differences in dissolved oxygen were typically small in spring 2019. Minimum dissolved oxygen saturation was 95% near to October 15 while highest saturation concentrations were 115% several days earlier on October 9. It was over this period (9 -13 October) that vertical gradients in dissolved oxygen were highest in the Horizon's CMA. This high dissolved oxygen in the upper 25m, collocated with high chlorophyll-a fluorescence concentrations of 2.5 mgm^{-3} was indicative an algal bloom. This is an expected biophysical response during the spring months in coastal and shelf seas The collapse of the bloom and consumption of settling organic matter by bacteria was reflected in the dissolved oxygen decrease to 85% for 14-15 October.

Increased chlorophyll-a fluorescence (2 – 2.5 mgm^{-3}) was observed at the seaward margin of the river plume off from the Rangitīkei and Manawatū rivers. The glider sampled the river plumes twice with an offshore and onshore sampling strategy. Bands of higher chlorophyll-a fluorescence were close vertically uniform in water depths of 50m (e.g. September 30 and October 2).

Backscatter observed at 700nm was used as a proxy for turbidity. Largest backscatter concentrations occurred in water depths less than 40m and tended to be present through the whole water column from the surface to near bed. Highest backscatter was observed towards the southeast region of the mission from October 18 to 21. Better characterisation of particles – either organic or inorganic – can be derived from scattering relationships between optical observations from the ecotriplet data. It was, however, beyond the scope of this report.

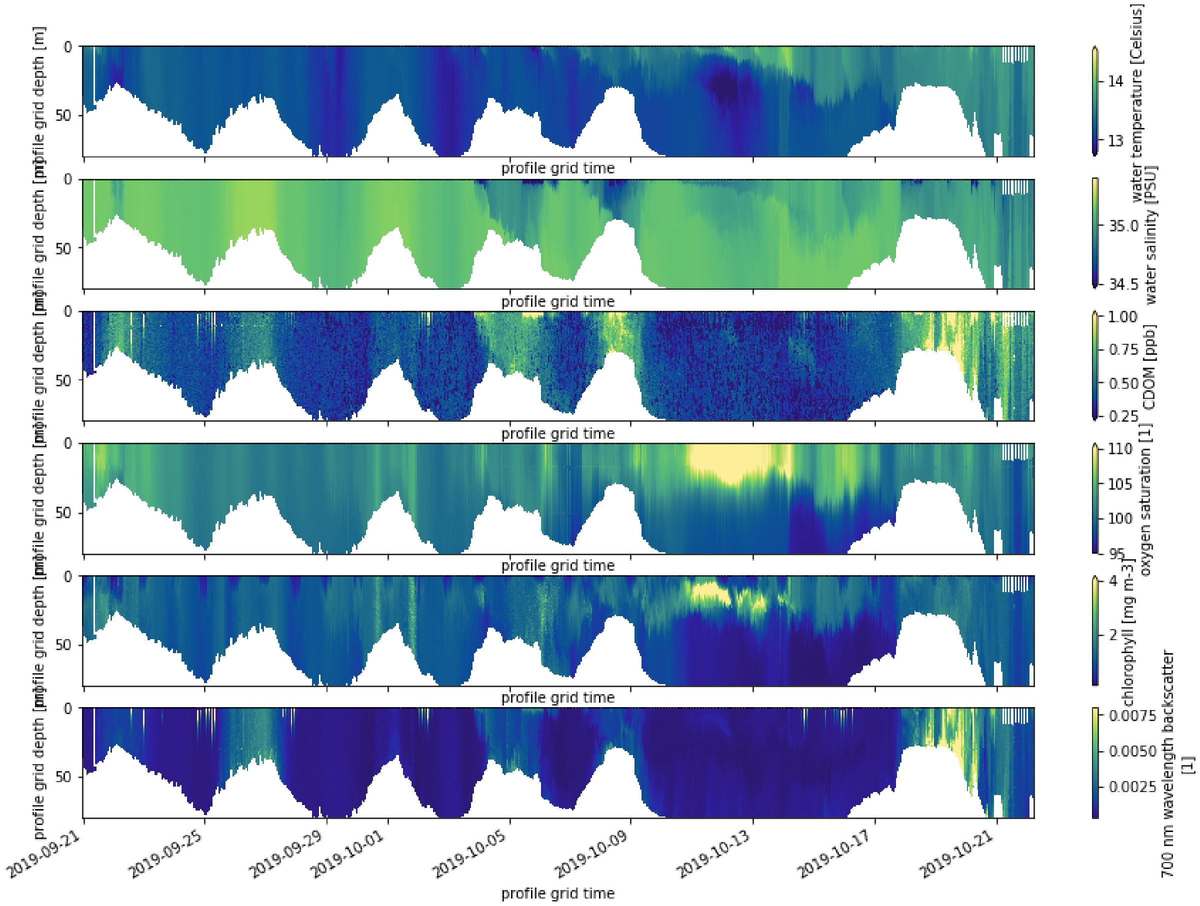

Figure 3-4: High resolution map of ocean properties from September 19 to October 20, 2019

3.4 Vertical structure of biophysics in South Taranaki Bight

Averaged-vertical profiles of all observations collected by the ocean glider are shown in Figure 3-5. Although averaging more than 6,000 profiles eliminates the substantial variability observed by the glider, it useful to get a broad description of ocean properties for South Taranaki Bight.

The timing of the glider mission in late September meant that weak vertical gradients were observed for salinity and temperature. Lowest salinity was observed at the surface and increased towards the seabed. Maximum vertical salinity difference of the mean was 0.2 psu. Larger vertical gradients of up to 2 -3 psu in salinity would be expected after substantial rainfall across the three major catchments. Vertical temperatures had a top-to-bottom difference of 0.3°C mean over the month-long sampling.

Dissolved oxygen saturation ranged from 102% at the surface down to 98% at 80m. At river-influenced water depths (~30m) and closer to land, oxygen saturation was 100% at the seabed. Weak top-to-bottom differences in CDOM were evident in the mean. Chlorophyll-a fluorescence had a subsurface maxima at 15 m 18m (~ 1.2 mg m^{-3}). Near-bed chlorophyll concentrations at 30-40m remained relatively high at 1 mg m^{-3}

Backscatter (as a proxy for turbidity) had small differences through the water column for averaged observations. Of note, is the 30% spread in the standard deviation of backscatter above 28m that highlighted the nearshore spatial constraint of elevated turbidity.

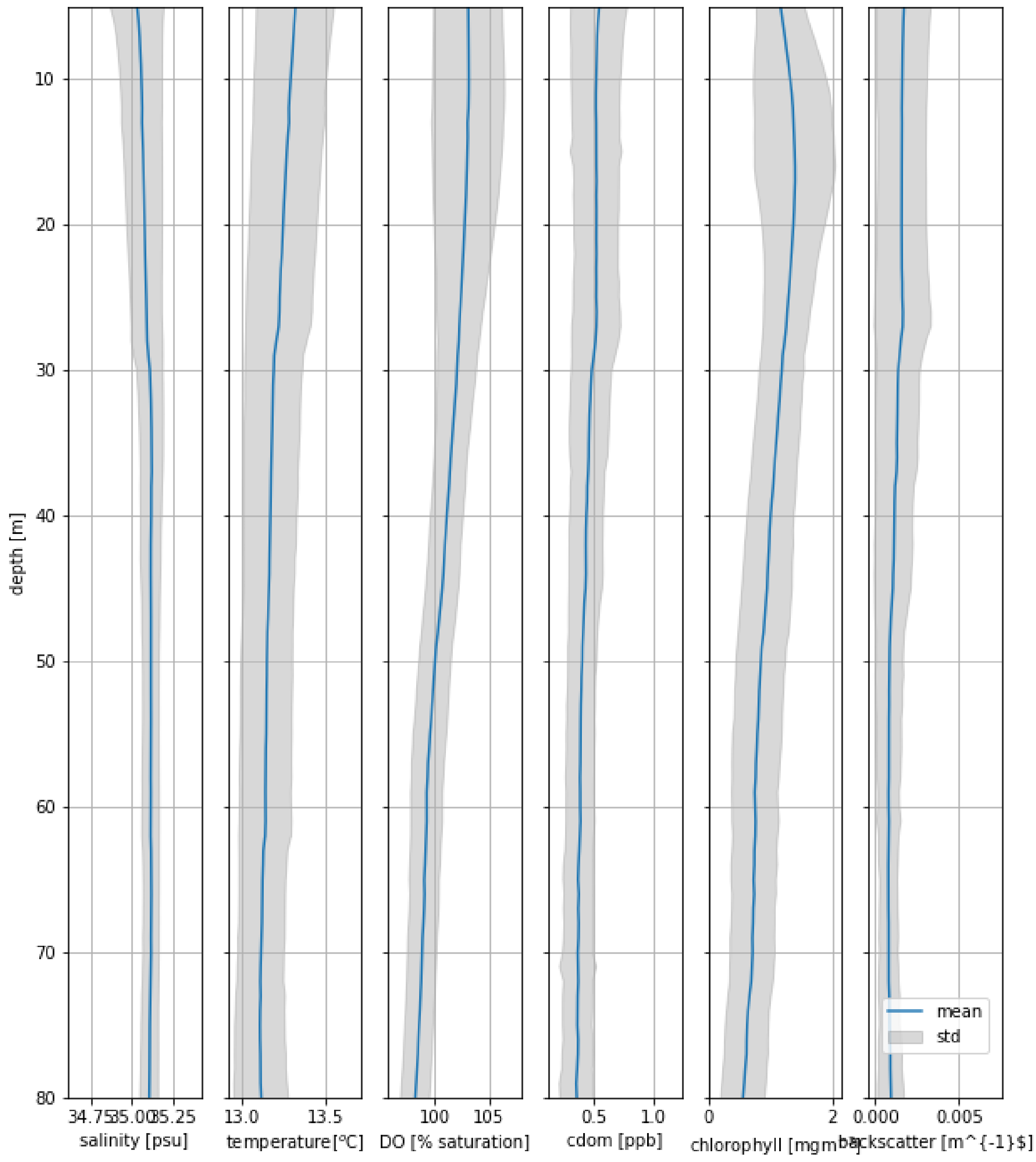

Figure 3-5: Mission-averaged profiles of salinity, temperature, dissolved oxygen, CDOM, Chlorophyll-a and Backscatter (700nm). Shaded regions are standard deviations.

3.5 ROFI signals in South Taranaki Bight

Distinct ROFI signals through the South Taranaki Bight region (and beyond) can be seen from MODIS satellite images (Figure 1-1). Initially, the brown turbidity signals indicative of river plumes was primarily observed close to land. By contrast on October 6 (Figure 1-1b), turbidity signals were widespread throughout South Taranaki Bight and ROFIs extended substantially further from river sources and through the Horizon's CMA. There were only two cloud-free MODIS images available during the spring 2019 mission to demonstrate the extent of ROFIs in coastal waters. However, the intensity of rainfall and catchment sizes of NZ rivers indicate that ROFIs will be regularly present in South Taranaki Bight.

Near surface turbidity and physical properties from the glider mission were extracted to examine characteristic ROFI responses in South Taranaki Bight. The vertical extent of the low salinity water varied from between 5 to 35 m below the surface. Time series from 5 m water depth showed that near-surface salinities decreased to a minimum of 32.8 psu (Figure 3-6a). This was at the southeast part of the mission close to the Otaki River. Offshore from the Rangitīkei and Manawatū rivers, the salinity minima were 33.8 and 33.5 psu, respectively. Near-surface salinity offshore from the Whanganui river was close to oceanic values (34.8 psu).

With distance from the freshwater source, observed salinity was diluted with ocean salinity and observed salinity increased to oceanic values (35.2 psu). Mixing was in both the vertical and horizontal directions. Vertical stirring by wind mixed and deepened the ROFI. Offshore from the Manawatū river, low salinity water that was distinct from the ambient occupied the majority of the water column (35 m).

Warmest near-surface temperatures early in the mission (September 21) were from the inflow of the D'Urville Current in South Taranaki Bight. Temperatures showed clear tidal oscillations from October 5to 14 but the tidal signal was not always evident (e.g. September 23 to October 1) and likely due to strong winds, a fast flowing D'Urville Current or both. Further examination would be needed to quantify the timing and signals quantitatively.

Peaks in CDOM that occurred concurrently with low near-surface salinity were observed on October 6-7, October 9 and October 18-20. These were offshore from Rangitīkei, Manawatū and Otaki rivers, respectively. The absence of a collocated CDOM and low salinity signal offshore from the Whanganui river does not mean that there is weaker riverine influence. Rather, sampling from the ocean glider platform was only a few days and missed the ubiquitous ROFI events seen from satellite around October 6.

Backscatter observations ranged between 1-2 m^{-1} with strong diel variability. Higher backscatter values were generally not located with low salinity ROFI. As noted above, particles present in the CMA would be better characterised by resolving the relationships between optical observations from glider observations.

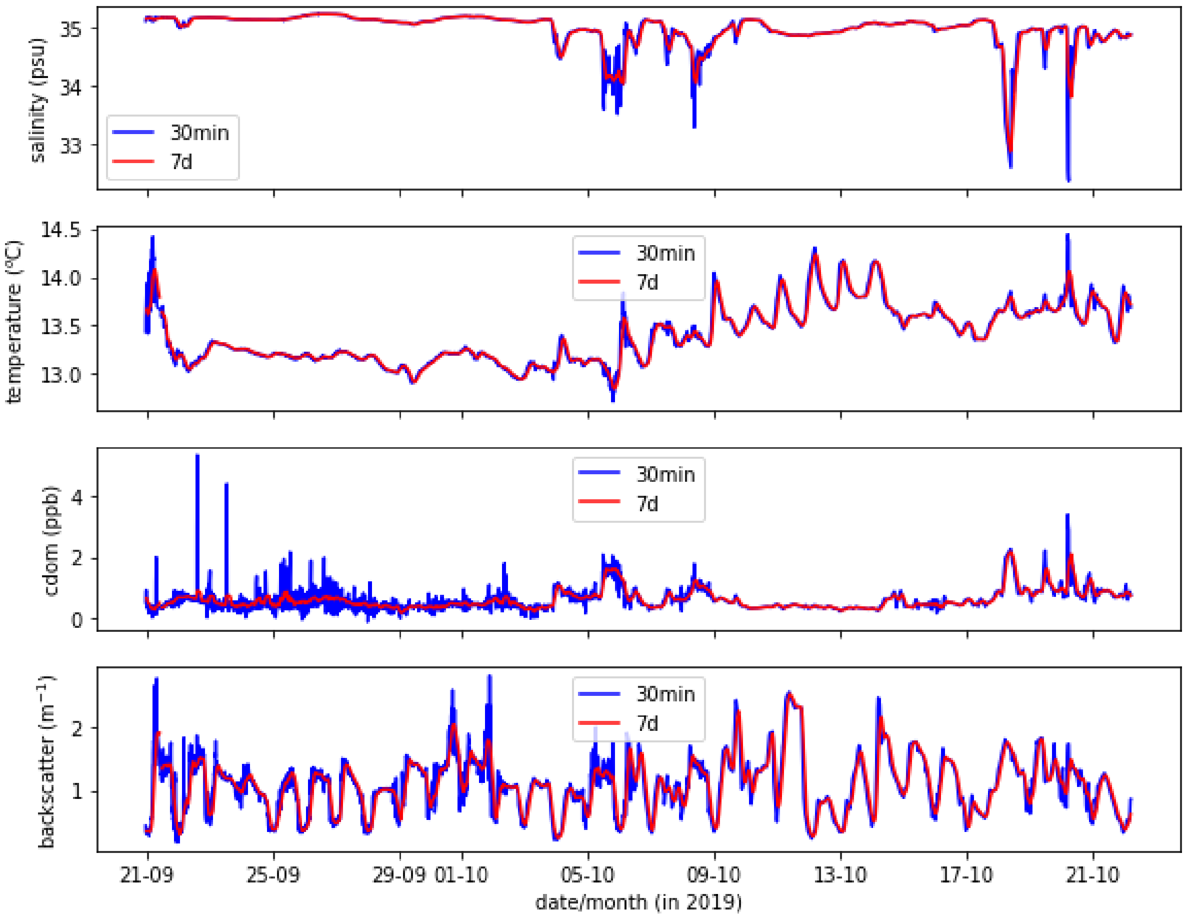

Figure 3-6: Time series of salinity, temperature, CDOM and backscatter for the 32-day mission with 30-minute and 7-day averaged data.

4 Summary

New ocean glider observations were obtained for Horizons Regional Council via an MBIE Envirolink grant. There were 6196 profiles collected over 32 days dramatically increasing the available subsurface biophysical ocean data in the Horizon's CMA. The Spring 2019 mission coincided with coastal SST being close to average climatological conditions for South Taranaki Bight.

Glider profiles were obtained with 3km of the shoreline. The maximum distance from land was 35km from the land-sea boundary. ROFIs were observed at least four times over the mission with signals observed from the Rangitīkei, Manawatū, Otaki and Waikanae rivers. The offshore extent of these ROFI, identified by salinity less than 34. 6 psu, ranged between 3 and 11 km. ROFIs observed were both surface intensified features constrained to the upper 5m as well as features that occupied the full water column down to 35m.

The prevalence of higher CDOM in freshwater than the ocean makes it a good proxy for identifying the fate of rivers in the ocean. Although as CDOM and chlorophyll both absorb light in the same spectral range robust interrogation is needed to distinguish between them. Elevated CDOM was regularly collocated with the ROFI indicating that river water is present in the CMA. Small productive fronts (from higher chlorophyll) were observed at the outer boundary of the ROFI. A spring bloom of scale approximately 5- 8km that lasted for 4 days was observed in glider observations. Broadly, the water column was well oxygenated throughout South Taranaki Bight.

ROFIs are common in coastal systems around New Zealand (O'Callaghan and Stevens, 2017, O'Callaghan, 2019). The offshore extent of a ROFI can be >100km from land after large discharge events from frontal weather systems or ex-tropical cyclones. As there were no significant rainfall events during September 2019 the observed ROFIs offshore between 3 to 11km from land is towards the minimum extent of ROFI extent in the Horizon's CMA. Larger ROFIs, to the 12nm and beyond, are expected for event-based discharges. Offshore wind stress would further enhance ROFI extent as was observed in Collins and Macdonald (2019) for particles located near the Whanganui river.

Evaluating the impact of ROFIs on coastal water quality and ecosystem health is difficult without baseline data of key water quality properties. This would require both in situ water sampling in the CMA and at downstream locations of the three main rivers to develop causal relationships. Additional bio-physical sampling after a large discharge event would provide the maximum offshore extent of a ROFI. Together, the annual cycle and event sampling would allow for CMA 'impact' to be measured, and ultimately managed in the freshwater domain.

ROFIs were evident offshore from the Rangitīkei, Manawatū, Otaki and Waikanae rivers. Although the latter two rivers are outside the Horizon's CMA, these southeast ROFI's are likely to be influenced by rivers in the Horizon's CMA. Maps of tracer concentrations from Collins and Macdonald (2019) demonstrated that the combined mean flow to the southeast and periods of strong wind mixing could, at times, enhance the horizontal transport of particles through the South Taranaki Bight region.

5 Acknowledgements

Many thanks to the Whanganui Coastguard support for the deployment and recovery of the ocean glider, in particular Mark Carson (skipper). Thank you to Fiona Elliott for all things glider related – planning, preparation, piloting and processing of the autonomous vehicles. Ocean glider Betty is operated as part of the NIWA Ocean Glider Facility and supported by NIWA SSIF and Capex funding.

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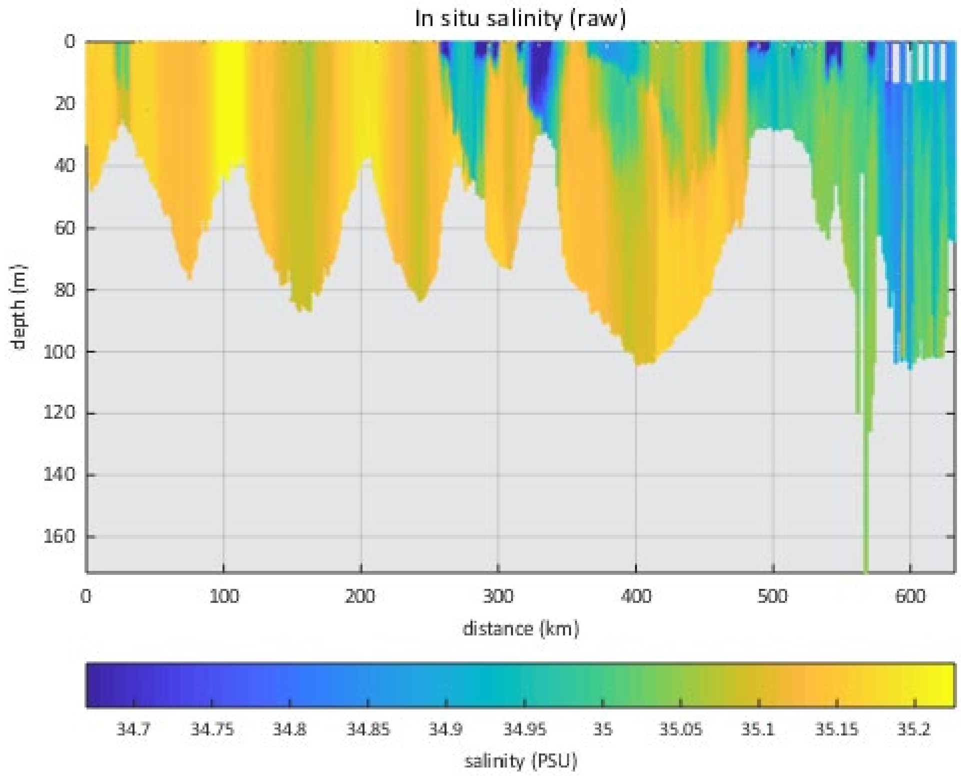
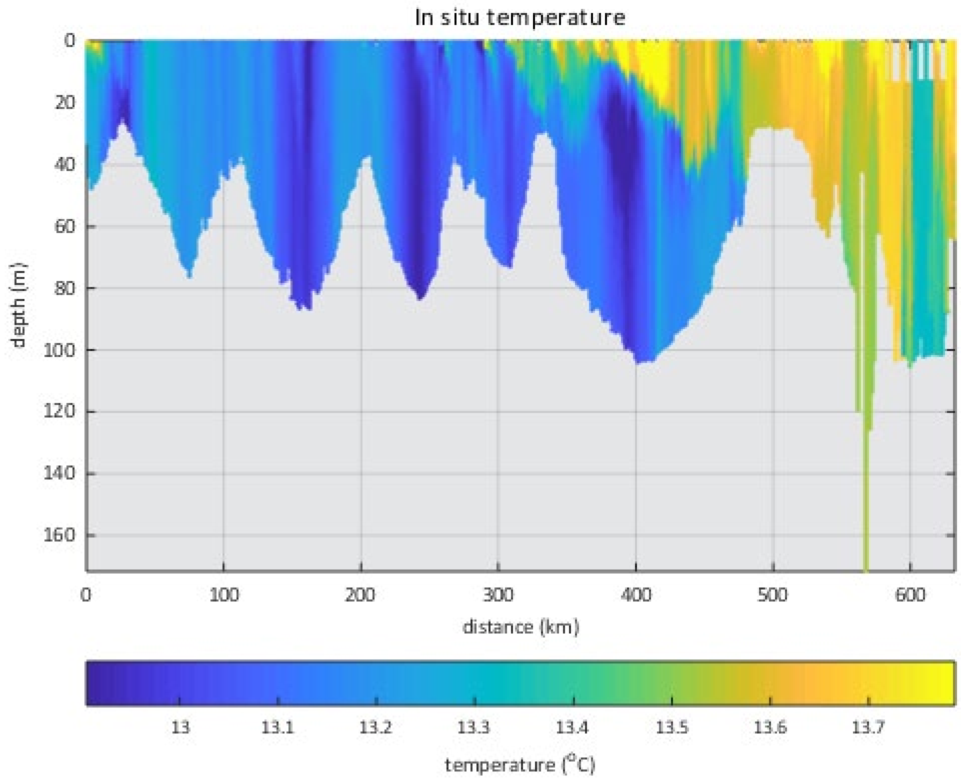
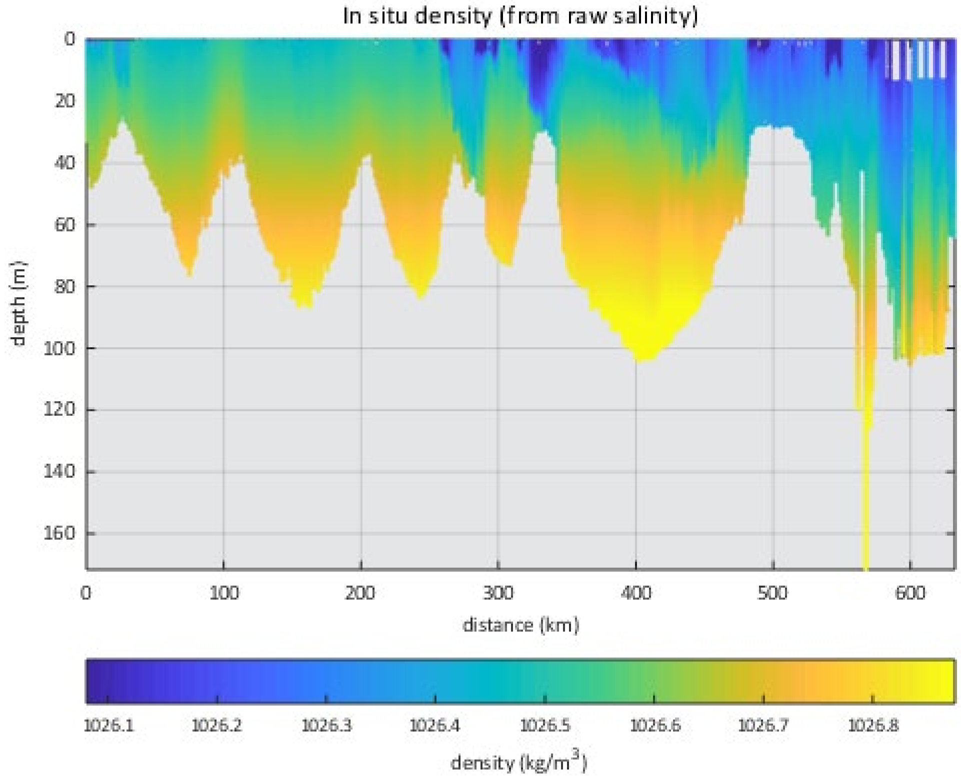
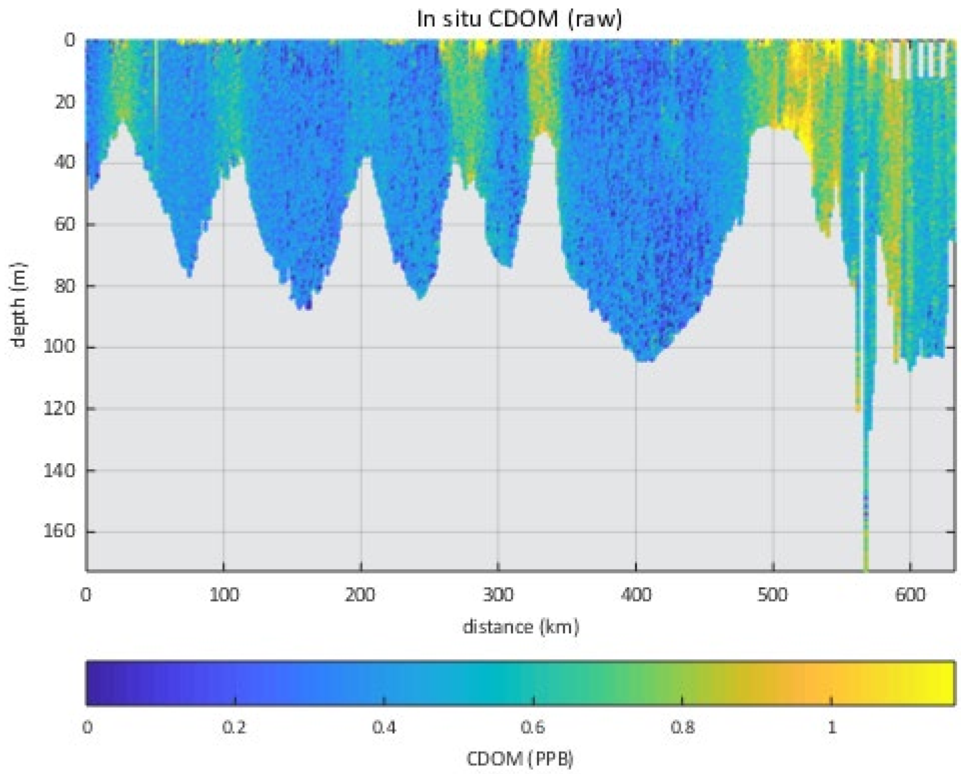
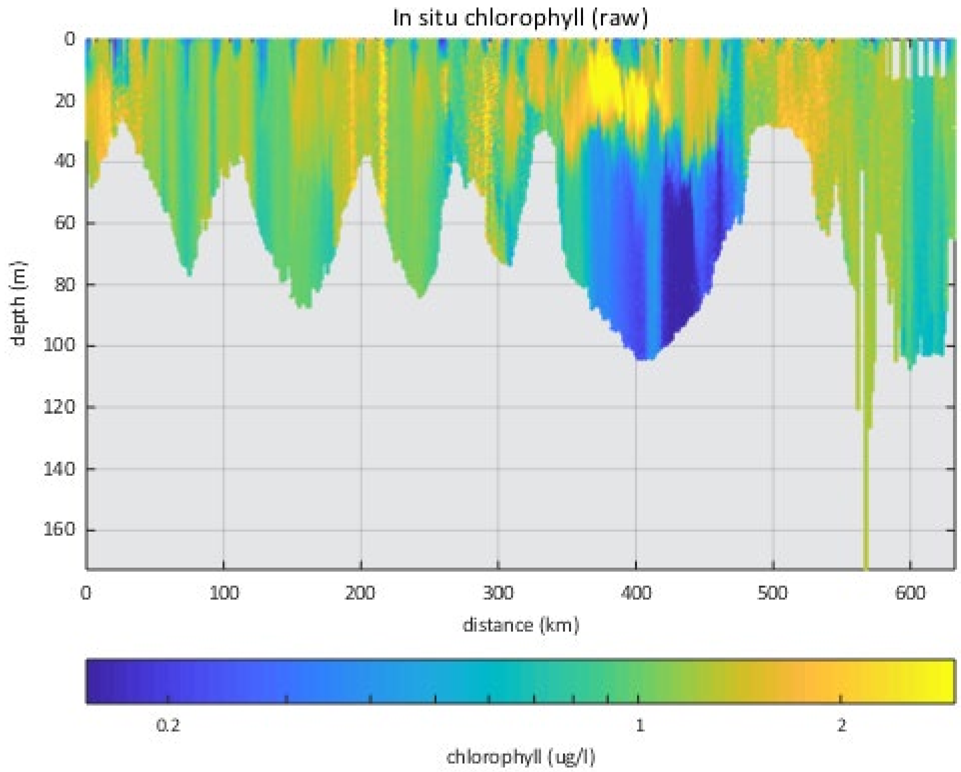
Appendix A Data plots from delayed mode processing

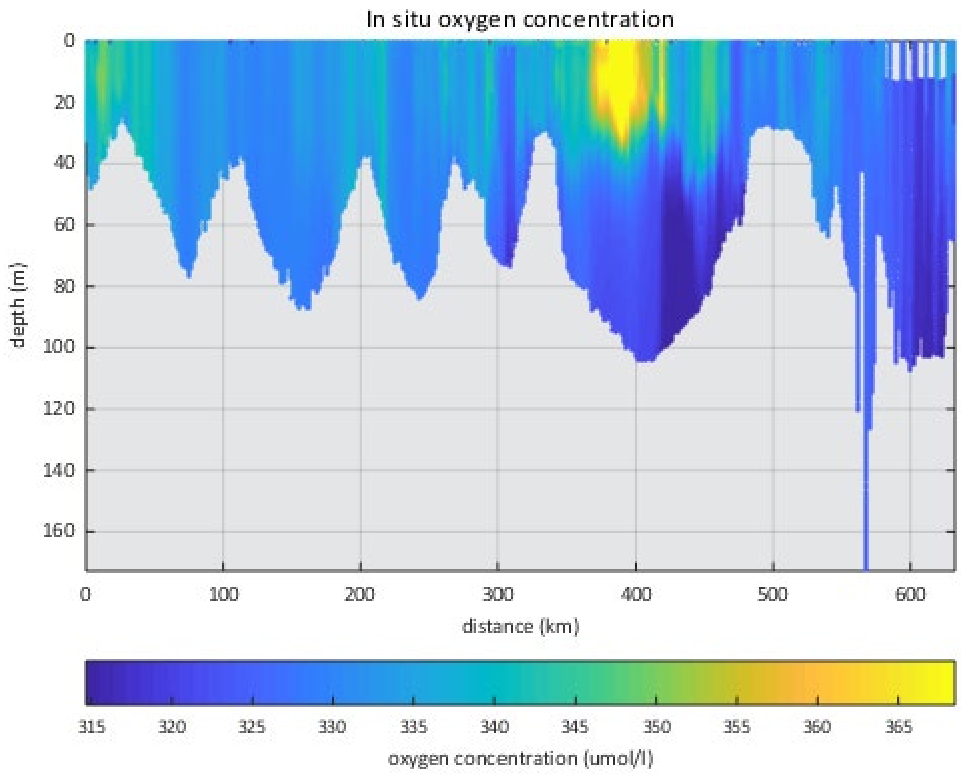


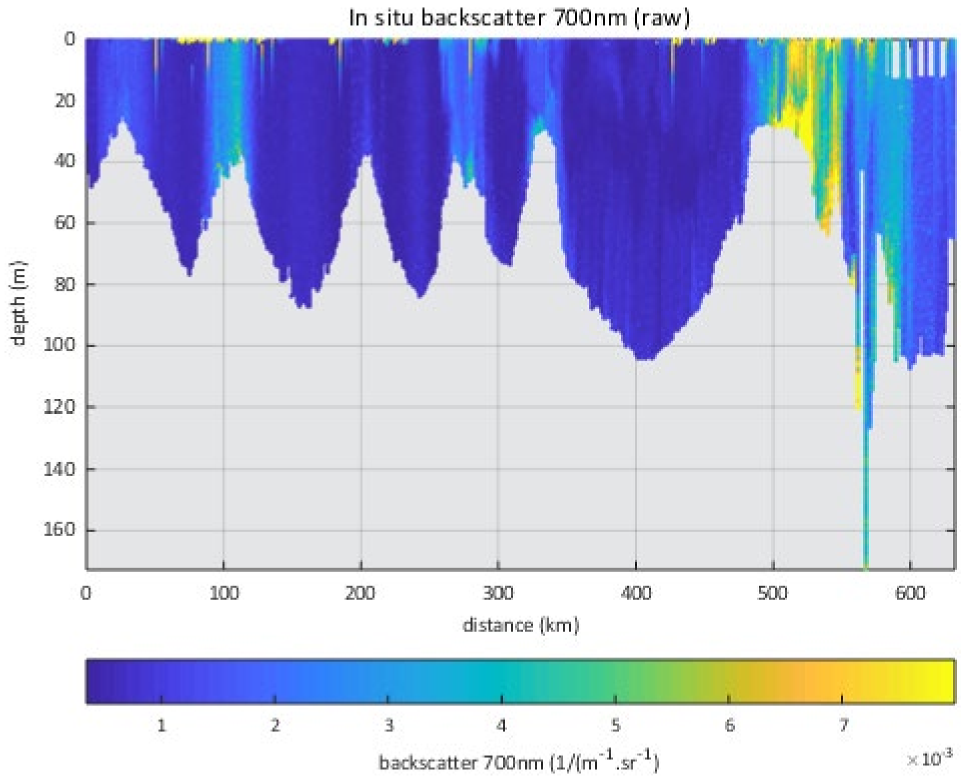


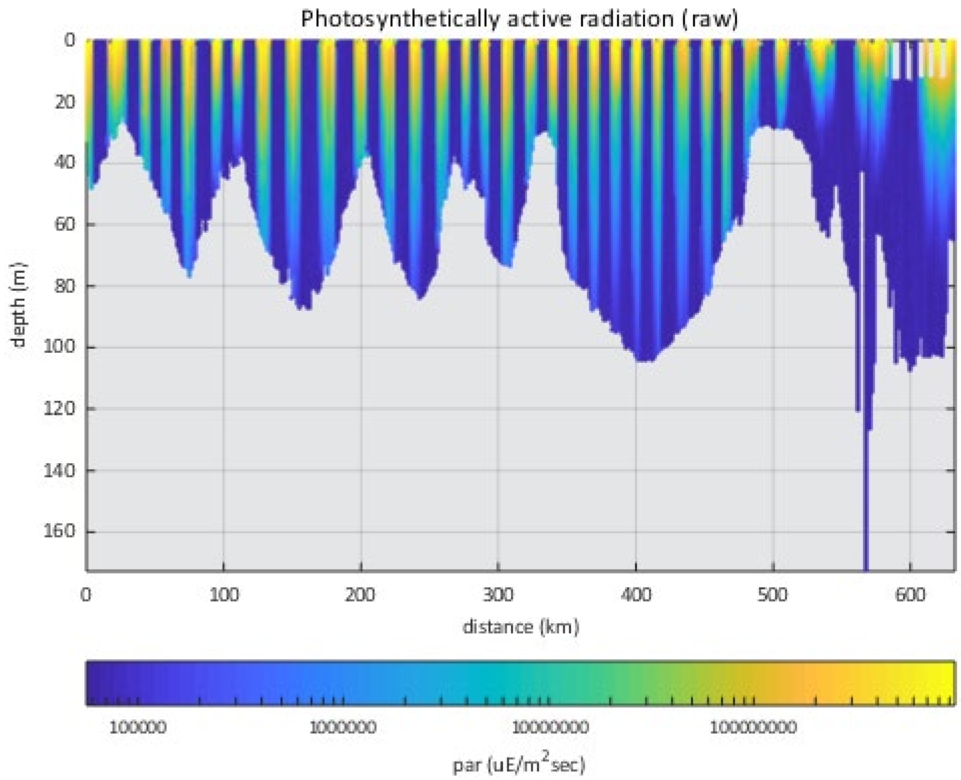

In situ density (from raw salinity)
depth (m)
0
20
40
60
80
100
120
140
160
0
100
200
300
400
500
600
distance (km)
1026.1
1026.2
1026.3
1026.4
1026.5
1026.6
1026.7
1026.8
density (kg/m³)


In situ CDOM (raw)
depth (m)
0
20
40
60
80
100
120
140
160
0
100
200
300
400
500
600
distance (km)
0
0.2
0.4
0.6
0.8
1
CDOM (PPB)


In situ chlorophyll (raw)
depth (m)
distance (km)
chlorophyll (ug/l)


In situ oxygen concentration
depth (m)
distance (km)
oxygen concentration (umol/l)


In situ backscatter 700nm (raw)
depth (m)
distance (km)
backscatter 700nm (1/(m-1.sr-1))
×10-3


Photosynthetically active radiation (raw)
depth (m)
distance (km)
par (uE/m2sec)

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