Cross- and Along-Shelf Exchange Processes on the Great Barrier Reef

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Dear Sir,

It is with great pleasure that I submit this thesis, entitled “Cross- and Along-Shelf Exchange Processes on the Great Barrier Reef”, as a partial fulfillment of the requirements for the degree of Bachelor of Engineering (Environmental).

Sincerely,

Blake Edmunds

Cover Photo: An outcrop of corals on the Great Barrier Reef, Australia

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Acknowledgements

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Abstract

Cross- and along-shelf exchange processes are important to the health and viability of the Great Barrier Reef (GBR). The GBR is the largest and best-known coral reef system containing 10 percent of global coral and also supports over 1,500 species of fish and provides habitat for endangered loggerhead turtles, dugongs and humpback whales.

The GBR is frequently subjected to development initiatives and the results from this study provide key information required to properly assess the vulnerability of the GBR reef systems to future commercial developments.

This project has investigated cross- and along-shelf exchange processes on the GBR, including comparing regions of varying density along the GBR shelf edge. Model output has indicated that the East Australian Current (EAC) has a highly influential role on the shelf exchange of the reef as currents up to 0.5m/s along-shore move on and off the shelf at various stages (Between the 3rd-28th January 2011).

A strong spring neap tidal system is evident in this project and results have indicated an influence on volume fluxes along and across the GBR. Results have been achieved through examining the output of a 3-dimensional baroclinic model of the entire GBR, the Sparse Hydrodynamic Ocean Code (SHOC) model developed by CSIRO’s Marine research department. This model resolves the spatio-temporal variability of the thermocline. This provided an ideal tool to investigate shelf exchange processes.

The results of this study have contributed to the further understanding of physical relationships on the GBR by quantifying exchange over the GBR shelf.
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<table>
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<th>Description</th>
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<tbody>
<tr>
<td>2D</td>
<td>Two Dimensional</td>
</tr>
<tr>
<td>3D</td>
<td>Three Dimensional</td>
</tr>
<tr>
<td>AIMS</td>
<td>Australian Institute of Marine Science</td>
</tr>
<tr>
<td>BOM</td>
<td>Bureau of Meteorology</td>
</tr>
<tr>
<td>CSIRO</td>
<td>Commonwealth Scientific and Industrial Research Organisation</td>
</tr>
<tr>
<td>EAC</td>
<td>East Australian Current</td>
</tr>
<tr>
<td>ENSO</td>
<td>El Niño/La Niña -Southern Oscillation</td>
</tr>
<tr>
<td>GBR</td>
<td>Great Barrier Reef</td>
</tr>
<tr>
<td>GBRMPA</td>
<td>Great Barrier Reef Marine Park Authority</td>
</tr>
<tr>
<td>MSL</td>
<td>Mean Sea Level</td>
</tr>
<tr>
<td>NCJ</td>
<td>North Caledonian Jet</td>
</tr>
<tr>
<td>NJV</td>
<td>North Vanuatu Jet</td>
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<td>NQC</td>
<td>North Queensland Current</td>
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<td>SCJ</td>
<td>South Caledonian Jet</td>
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<tr>
<td>SEC</td>
<td>South Equatorial Current</td>
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<tr>
<td>SESE</td>
<td>School of Environmental Systems Engineering</td>
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<tr>
<td>SHOC</td>
<td>Sparse Hydrodynamic Ocean Code</td>
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1 Introduction

1.1 Motivation

This project has for the first time, compared in high resolution the variation in physical dynamics between sparse and dense reef regions. The results from this study are of significant importance to the hydrodynamic understanding of the region and can aid the ecological management of the region. Well-informed management of the GBR is essential to preserve the ecological and heritage value of the region. An understanding of the regional circulation is a vital component of this management because many of the ecological processes are intrinsically linked to the physical dynamics (e.g., recruitment patterns and nutrient dynamics).

The application of the SHOC model in this project provides quantitative insight into the influence of reef density in the cross- and along-shelf exchange on the GBR. This work thus facilitates future studies in verifying the influence of the physical oceanography on the greater ecology in the area. The GBR is frequently subjected to development initiatives and the results from this study provide key information, to assess the vulnerability of the reef systems to future commercial developments (e.g., vessel grounding and contaminant spills). This also helps to assess how susceptible the ecology of the area is to climate change (e.g., resulting in changes to ocean temperatures, cross- and along-shore shelf nutrient fluxes).

The GBR was one of Australia’s first World Heritage properties; described as an outstanding example representing the major stages in the earth’s evolutionary history and as an outstanding example of ongoing ecological and biological processes (Great Barrier Reef Marine Park Authority, 2011).

The GBR provides habitat for over 1,500 species of fish, over 360 species of hard corals (that help construct the reef). The GBR also provides habitat for dugongs, the endangered loggerhead turtle and humpback whales.

This project serves as a reference tool to help support ongoing research on the GBR. The project outcomes contribute to the greater understanding of the effects of physical exchange on the environment. The GBR is said to attract 6.9 billion dollars annually from eco-tourism (Harriott, 2001), which highlights the importance financially for the preservation of this resource.
The GBR is an area of much research and study; however, no one has assessed the variation in physical dynamics between dense and sparse reef systems at high resolution. Understanding the exchange processes on the GBR is necessary for informed management of the area. The use of model output in this project, for the first time, provide quantitative insight into the influence of cross- and along-shelf exchange on the GBR. This work provides a valued resource for future detailed studies involving the influence of physical oceanography on the greater ecology in the region. This project helps to improve current understanding of the GBR for effective management of habitat and biodiversity, as well as helping to assess how susceptible the ecosystem is to changes to its physical environment.

1.2 Aims

This thesis aimed to compare and contrast the hydrodynamic processes occurring at different regions along the GBR. To achieve this, output was analysed from the Sparse Hydrodynamic Ocean Code (SHOC) finite difference hydrodynamic model developed by the environmental modelling group at the CSIRO Division of Marine Research (Herzfeld, 2006). Using the SHOC model output this thesis aimed to:

1) Compare and contrast cross- and along-shelf exchange processes between northern and southern reef assemblages on the GBR focusing on the physical differences between sparse and dense reef systems.

2) Investigate the influence of seasonal changes in forcing on the physical dynamics on the GBR, including changes in the residence times at different locations on the GBR.

3) Discuss the ramifications of (1) and (2) on the transport of nutrients and contaminants at the GBR.
2 Literature review

2.1 Coral Reefs

Coral reefs cover 1% of the planet and are vital for the maintenance of biodiversity, preservation of fisheries, coastal protection from erosion and for tourism. The economic net benefits of Global coral reefs are quantified at $30 billion/yr (Cesar et al. 2003). Corals are modular organisms capable of calcification that form reef structures. Coral reefs are found in tropical to temperate waters in shallow areas (light permitting) displayed in Figure 1.

![Figure 1: Global Distribution of Coral Reefs (Henkel, 2010)](image)

2.2 The Great Barrier Reef

The GBR is the largest and best-known coral reef system in the world, largely due to the extensive research conducted in the area. The GBR was one of Australia’s first World Heritage sites (inscribed in 1981); described as an “outstanding example representing the major stages in the earth’s evolutionary history” and as an outstanding example of “ongoing ecological and biological processes” (Great Barrier Reef Marine Park Authority, 2011). This recognition highlights the international significance of the GBR and carries an obligation to conserve the region. Today the GBR possesses some of the richest biological diversity found globally, providing habitat for over 1,500 species of fish and over 360 species of hard corals (Great Barrier Reef Marine Park Authority, 2011), as well as providing habitat for dugongs (sea cows), endangered loggerhead turtles and humpback whales. This ecology being distributed between three major biological environments, the lagoon, reefal area and continental slope displayed geographically in Figure 2.
2.2.1 Cultural and Spiritual Significance

The GBR also serves cultural and spiritual significance to around 70 Aboriginal and Torres Strait Islander clans who are recognised as traditional owners of various regions (Kemp, 2003). To western establishment there are various reefs of particular historical significance such as Endeavour Reef where Captain Cook ran aground and was obliged to discard his ship’s cannons.

2.2.2 Economic Value

Today the GBR is a multiple use marine park and along with traditional usage the GBR also supports commercial marine tourism, fishing, shipping, recreation and scientific research. The GBR is said to contribute around $6.9 billion annually to the Australian economy and supports more than 53,800 jobs (Harriott, 2001) (Access Economics Pty Ltd, 2008).

2.2.3 Management of the Great Barrier Reef

The GBR is managed by the Great Barrier Reef Marine Park Authority (GBRMPA), who is a subsidiary organisation of the Australian Federal Government. The management priorities include; biodiversity protection, climate change, coastal development, commercial marine tourism, fishing, ports and shipping, recreation, water quality and traditional use of marine resources. In addition, the GBRMPA also conduct extensive
research to ensure the preservation of the GBR for future generations (Great Barrier Reef Marine Park Authority, 2007).

2.3 Physical Description

Found in the Coral Sea, the GBR extends more than 2000 km from Torres Strait along the northeast coast of Queensland, Australia and extends to just North of Fraser Island (25°S) (Great Barrier Reef Marine Park Authority, 2011). The GBR is composed of over 3000 reefs that together account for 10% of coral reef area globally (Spalding et al., 2001).

2.3.1 Bathymetry

The many reefs on the GBR that breach the ocean surface and create a complex topography which influences circulation and mixing on the Continental shelf (Pickard et al., 1977). The GBR has isobaths that run roughly parallel to the Australian coast which create a physical barrier which guides the transport of water. The shelf width (defined by the distance of the continental slope from the mainland) and water depths are both variable over the GBR, in the Northern region the shelf width is mostly 50-70 km. However at Princess Charlotte Bay (14°S) and near the Torres Strait (10°S) the shelf widens to over 150km (Steinberg, 2008). In the Northern region the water depth is relatively shallow and deepens to 40-60 m toward the shelf edge. Below 18°S the shelf widens to around 120km and the water depths is around 100m. The Southern region of the GBR (21°S) has the largest shelf width reaching over 250km (Pickard et al., 1977).

2.3.2 Reef Density

The many reefs that make up the GBR (>3000) create physical 'barriers' that can limit exchange between the offshore and inshore water. These 'barriers' are porous and variable, blocking off between 10%-90% of the shelf length (Pickard et al., 1977). The reef matrix is less dense in the Southern extent of the GBR and regions of high density are predominantly in the northern regions. In these dense areas long 'ribbon' reefs can cover up to 90% of the outer shelf leaving only narrow channels for oceanic and tidal flows (Wolanski & Van Sended, 1983). The central region of the GBR is also composed of a sparse reef matrix that follows the change in orientation of the shelf (North-South to South-South East) at a latitude 19° S. This allows for the southward flowing East Australian Current (EAC) to penetrate directly into the GBR lagoon (Brinkman et al., 2002).
2.4 Applicable Oceanography

The global ocean functions as a vast reservoir of heat, the top three meters of the ocean stores all the equivalent heat energy contained within the atmosphere (Gill 1982-29). Due to the high specific heat of water, the ocean has by far the largest heat capacity and therefore the largest energy retention capability of any other climate system component. Ocean currents play a major role in redistributing the earth's heat energy around the globe by transporting it from the tropical regions poleward principally via western boundary currents such as the EAC (Steinberg 2008). The energy of the resulting large-scale motions is transmitted progressively to smaller scales of motion down to molecular vibrations where energy is finally dissipated as heat (Mann & Lazier 1996). This temperature distribution of the ocean plays an important role in climate control and change.

2.4.1 Heat absorption

In the ocean, warming water forms a buoyant surface layer and mixing can disperse this heat throughout the water column. Naturally varying solar radiation can influence the prevalence of this warmer surface layer. However, climate change is altering the Earth's atmospheric composition and irradiative balance (Steinberg 2008). In response, the Earth system is absorbing excess heat where global oceans take up much of this. The greatest amount of warming occurs near the surface because 75% of the total short-wave radiation energy (from infrared to ultraviolet radiation) is absorbed in the top 5 meters of ocean water (Mann & Lazier, 1996).

2.4.2 Heat fluxes

Heat fluxes that occur across the air-sea interface include short and long wave radiation, sensible and latent heat fluxes. Tropical oceans such as the Coral Sea tend to have a net gain of heat each year although evaporation, wind, nighttime back radiation and cold air temperatures can cause periods of heat loss (Mann & Lazier, 1996).

2.4.3 Stratification

The cumulative result of these fluxes results in Ocean stratification. This is caused by surface heating and subsequent thermal expansion of water that reduces its density. This warmer and lighter water remains at the surface of the water column creating a stratified layer. This effect can be diminished directly by surface heat fluxes or mixed due to turbulence. Winds are the major source of turbulence that can mix warm waters down into the water column. The depth to which they can mix is dependent on the winds strength (Steinberg, 2008).
2.4.4 Mixing
Wind-driven mixing can extend down to depths exceeding 100 meters in tropical oceans, well beyond the maximum depths of coral reefs. This depth usually defines the location of the main thermocline between warm surface layers and cooler deep water. Deep-mixing occurs through surface water convergence, entrainment driven by larger turbulent eddies or current shear instabilities (Kantha & Clayson, 2000).

2.4.5 Ecological significance of mixing
The oceanic surface mixed layer mediates the exchange of mass, momentum, energy, heat and dissolved gases between the atmosphere and the ocean (Kantha & Clayson, 2000). In tropical waters the surface layer is nutrient deprived, so deepening of the mixed layer can draw up nutrients to the photic zone, enabling an increase in primary productivity and cooling of surface waters. Thus deep chlorophyll maxima are widespread in the open ocean near the thermocline. (Huisman et al., 2006)

2.5 Great Barrier Reef Specific Oceanography

2.5.1 Mixing on the Great Barrier Reef
Church & Craig (1998) describe the GBR shelf to be well mixed during most of the year assisted by the strong southeast trades. In addition to this, energy required for vertical mixing from the sea floor up through the water column is sourced from currents that are dominated by the tides (Steinberg, 2008).

2.5.2 Tidal dominated mixing
A strong Spring/Neap tidal system exists on the GBR which provide an important source of energy for mixing. Tidal currents generate turbulence due to shear produced by friction along the sea floor. The tidal currents tend to have a significant cross-shelf component near the shelf edge and are important in regulating upwelling processes (Thompson & Golding, 1981). On the GBR a persistent cold bottom boundary exists on much of the outer shelf. In areas with strong currents and/or shallow water, mixing can extend to the surface. This occurrence is common in channels between reefs along the coast. In deeper water this mixing is diminished where there is negligible turbulence available. In this instance, surface wind mixing doesn’t extend to the tidal mixing at the sea floor (Steinberg, 2008).
2.5.3 Water Temperatures
In the Austral summer period between December and February, hotter waters are apparent on the reef tops of large mid-shelf reefs and in the shallow waters along the coast. In contrast, waters are 2°C cooler along the outer edge of the continental shelf where the dense reef matrix occupies around 90% of the shelf break. Skirving & Guinotte (2001) reported that intrusions into the reef matrix, causes the upwelling of cooler, deeper water onto the outer shelf. These mechanisms effectively provide a microclimate for the outer reef corals keeping them cooler and less susceptible to heat stress than their mid-shelf counterparts (Skirving & Guinotte, 2001). Sweet

2.5.4 Currents on the GBR

Figure 3 displays the complex pathways that divide the southern part of the South Equatorial Current (SEC) into jets. These jets are the North/South Vanuatu Jet (NVJ/SVJ) and the South/North Caledonian Jet (SCJ/NCJ). Both of these jets feed the western boundary current system, consisting of the EAC and the North Queensland Current (NQC).

The SEC is the primary driver of Coral Sea circulation. The surface waters of the SEC are warmed by several degrees as they traverse the equatorial Pacific and form a mixed surface layer up to 150 meters depth (Cane, 1983). Inside the reef matrix there is a complex circulation due to the interaction of currents from tide, wind, continental shelf waves, inflows from the SEC and the physical barrier of the reefs themselves.
2.5.5 Western Boundary Currents

As the NVJ/SVJ and SCJ/NCJ approach the continental shelf of Australia the jets are deviated North to the NQC (or Hiri current) and south via the EAC (Pickard et al., 1977). These currents are major drivers of along-shelf flows on the GBR (Wolanski, 1994). The NQC is guided by topography around the perimeter of the Gulf of Papua and the majority eventually flows around the Louisiade Archipelago to the Papua New Guinea northern coast in the Solomon Sea (Burrage, 1993). The EAC traverses the Shelf in the opposite direction drawing nutrients to lower latitudes of Australia and has a mean current speed of 0.4m/s (Pickard et al., 1977).

2.5.6 El Nino

The SEC and EAC strengthen during El Niño events of the El Niño/La Niña-Southern Oscillation (ENSO) cycle. This is due to the SEC being displaced south, which favours the EAC flow (Cane, 1983) displayed in Figure 4. Wolanski & Pickard (1985) noted that the strengthening of the EAC in the central GBR during the 1982-1983 El Niño may account for anomalous currents in their data.

![Figure 4 Schematic of the two phases of the El Niño Southern Oscillation during a La Niña (left) and El Niño (right) cycle (Steinberg, 2008)](image)

2.5.7 Wind generated currents

The south-west monsoon (variable from December-March) and south-east trade winds (dominant from April-November) both reinforce the NQC. These winds in turn oppose the EAC creating a seasonal minimum transport and can cause surface flow reversals of the EAC (Cahill & Middleton, 1993). Along the coast the south-east trade winds dominate the inner shelf, creating a well-mixed northward coastal current. Overall, southeast trade winds force surface waters on-shore which suppresses upwelling along the shelf edge. Episodic coastal upwelling can occur to replace the surface waters transported offshore by the wind (Garret, 1979).
2.5.8 River Plumes

The tropical northern region of the East Australian coast there is subjected to consistently high rainfall. This is due to the uplift of humid trade winds on coastal mountain ranges. This water feeds two major rivers that effects the GBR, the Burdekin River in the central GBR (19.3°S) and the Fitzroy River in the south (23.3°S), these provide significant seasonal flows to the GBR during the cyclone and monsoon season (December to April) (Burrage et al., 2002). In extreme flood events, flood waters can reach the outer reef, especially in the northern regions where the reef is closer to river outflow, cross-shelf river plumes are diminished around 19°S, by oceanic inflows through the Palm and Magnetic passages (King et al., 2001). A major flood event occurred in the South East Queensland in late November to the 12th of January 2011 when the Australian continent received some unprecedented rainfalls (Bureau of Meteorology, 2011). A subsequent sediment plume from this flood event is displayed in Figure 5.

![Figure 5: Flooding in the Burdekin River shown by the Aqua-MODIS instrument on January 4, 2011 (NASA, 2011)](image)

2.5.9 Upwelling

Similar to some other coral reefs the GBR extends all the way out to the edge of the shelf in a region of warm oligotrophic surface water with large tides. Thompson writes that the strong tidal currents draw up cool nutrient-rich water from depth to explain the vast
amounts of biomass on the GBR (Thompson & Golding, 1981). Upwelling on the GBR can also be enhanced by bottom generated Ekman layer currents, geostrophic pumping and favorable winds and currents (Garret, 1979) (Nof & Middleton, 1989).

Upwelling is important to the health of the GBR as it affects the depth of the thermocline and controls the relative amounts of cool nutrient rich and warm oligotrophic surface waters that reach the continental shelf from the Coral Sea (Andrews & Gentien, 1982). These intrusions from below the thermocline not only enhance primary productivity but help to alleviate heat stress experience on corals which remediates coral bleaching events (Baker et al., 2008). Andrews (1982) found water that had been upwelled can be 1-4.5°C cooler than surface lagoon waters.

2.5.10 Hydrodynamic Modelling on the Great Barrier Reef

The design of a water quality improvement plan (WQIP) for the GBR is recommended to include a modelling framework that links the management of agricultural activities in catchments that drain into the GBR to water quality and ecological responses in receiving waters (Webster et al., 2008). This would enable the link of land use and contaminant supply models to the transport of contaminants down rivers and through estuaries. Ultimately this would lead to the fate and transport of nutrient and contaminant material within the GBR region (Brinkman et al., 2011).

A robust and validated three dimensional (3D) hydrodynamic model provides a foundation for modelling the fate and transport of material delivered to the marine environment (Brinkman et al., 2011). Hydrodynamic models simulate the advection and mixing of water, making them a necessary precursor to the development of water quality and ecological response models that can be applied in the GBR region to support WQIP development and implementation, outlined in Figure 6 (Webster et al., 2008).
Figure 6 Primary components of a material transport and transformation models, showing internal linkages between sub models and linkage to ecological impacts models (Webster et al. 2008).
3  Approach

Output from a whole of GBR oceanographic model was used to determine the variance in cross- and along- shelf exchange as the basis for this project. The Sparse Hydrodynamic Ocean Code (SHOC) was used by the Australian Institute of Marine Science (AIMS) to model hydrodynamics of the continental shelf from Moreton Bay to the mainland of Papua New Guinea, extending eastwards into the Coral Sea Territories, a sufficient distance to avoid the topographical complexities of the Queensland and Marion plateaus. The model was run for a period of 26 days in January (3rd – 28th) 2011. The model output was processed, visualised and analysed using MATLAB.

![Figure 7 Regional SHOC model domain and bathymetry (Brinkman et al 2011)](image)

3.1  The SHOC Model

The Sparse Hydrodynamic Ocean Code (SHOC) is a finite difference hydrodynamic model developed by the Environmental Modelling group at the Commonwealth Scientific and Industrial Research Organisation’s (CSIRO) Division of Marine Research.
The model is intended to be a general-purpose model based on the paper of Blumberg and Herring (1987), applicable to scales ranging from estuaries to regional ocean domains (applied in this project). Outputs from the model include three-dimensional distributions of velocity, temperature, salinity, density, passive tracers, mixing coefficients and sea level. Inputs required by the model include forcing due to wind, atmospheric pressure gradients, surface heat and water fluxes and tides and other open-boundary conditions such as low frequency currents represented in Figure 8 (Brinkman et al., 2011).

The SHOC model is based on the three dimensional equations of momentum, continuity and conservation of heat and salt, employing the hydrostatic and Boussinesq assumptions (Herzfeld et al., 2009). The equations of motion are discretised on a finite difference stencil corresponding to the Arakawa C grid, similar to those described in Blumberg and Herring (1987) (Brinkman et al., 2011).

The model uses a curvilinear orthogonal grid in the horizontal and a choice of fixed ‘z’ coordinates or terrain-following σ coordinates in the vertical. The ‘z’ vertical system allows for wetting and drying of surface cells, useful for modelling regions such as tidal flats where large areas are periodically dry (Brinkman et al., 2011). SHOC has a free surface and uses mode splitting to separate the two dimensional (2D) mode from the three dimensional (3D) mode dependant on user specification, this allows for better user discrepancy between computational cost and accuracy of results (Herzfeld, 2006).

Figure 8 Schematic representation of major forcing inputs for the SHOC model (Brinkman et al. 2011)
This project utilized the 3D component and was restricted to smaller areas of analysis due to model size.

3.1.1 Grid mesh and Resolution

The SHOC model grid resolution ranges from 3km to 7km, with a large portion of the model domain having resolution of approximately 4 km displayed in Figure 9. This provides reasonably well resolved dynamics for the regional scale of the GBR. The model interpolates between axis points conforming to the governing equations of momentum, continuity and conservation (Herzfeld et al., 2009). The grid size of the regional SHOC model is 220 x 500 horizontally with 45 vertical layers. The grid has a minimum depth of 1 m, and maximum depth of 4000 m (Brinkman et al., 2011).

Time steps for the regional model are 90 s and 5 s respectively for the 3D and 2D modes, giving a runtime ratio of approximately 31:1.

The Bathymetry data for the grid was derived primarily from the Geoscience Australia - Australian bathymetry and topography grid (Geoscience Austalia, 2009) which had a spatial resolution of approximately 250m. The vertical datum for this data was set at mean sea level (MSL). The coastline was determined by using MSL and the bathymetry data set to delineate the boundary between wet and dry cells (Brinkman et al., 2011).
3.1.2 Model Forcings
Oceanic forcing for the SHOC model was provided by the global ocean operational model OceanMAPS, operated by the Bureau of Meteorology (BOM). Tidal forcing is included via the OTIS tidal model superimposed on the low frequency sea level oscillation provided by OceanMAPS on the regional grid open boundary and introduced via a local flux adjustment (Hertzfeld, 2009).

Atmospheric forcing products (wind, pressure, heat flux, precipitation and evaporation) are supplied by the ACCESS atmospheric model at 1/8 degree resolution. ACCESS provides wind, mean sea level pressure, cloud amount, air temperature and dew point temperatures. From these variables, bulk schemes are used to compute sensible and latent heat fluxes, and black body radiation may be used to compute long wave radiation (Kondo, 1975) (Zillman, 1972). The sum of these and computed short wave input provides a net heat budget (Brinkman et al., 2011).

3.1.3 Model Run
The SHOC model output analysed in this project was for the period from January 3rd to January 28th. This time period gave sufficient data to differentiate between spring and neap tides which literature suggests influences exchange on the GBR (Wolanski, 1994) (Pickard et al., 1977).

3.1.4 Visualisation
Interpreting scripts written in MATLAB were created by DR Nicole Jones from The University of Western Australia, to simplify the SHOC model output. These scripts were heavily relied on in. The model output files were visualised using Computer modelling software MATLAB.

3.2 Study Sites
The area of interest is across the entirety of the GBR on the Australian Shelf from the Torres Straight down to just North of Fraser Island (25°S). Originally two reef segments of interest were identified by Richard Brinkman see Figure 10. These regions were later expanded to reach the shoreline to better understand inshore exchanges. The overall analysis area was also extended to include broader northern, southern and a central region of study at 15°S, 22°S and 19°S respectively.
Figure 10 Original Proposed Study Areas

Figure 11 Arial View of study areas in MATLAB
3.2.1 Australian Continental Shelf

The project investigated cross- and along-shelf processes, hence the outer limit of the study area was the edge of the Australian Continental shelf. The shelf length varies along the coast though remains within 300km offshore. The focus for the model output was therefore focussed within this 300km limit of the coast. The outer limit of the shelf was determined as the point where the shelf met the continental slope, evident by a relatively significant depth increase over a short distance.

3.2.2 Reef Density

This project studies the variance in cross-shore exchange between dense and sparse reef assemblages. Spagnol et al (2001) write that dense reef assemblages are more frequent throughout the northern expanses of the GBR and that sparse reef assemblages are more prevalent in the southern GBR. Using the aid of Google Earth (2011) Imaging software, appropriate study regions of sparse and dense reef area were selected. This imagery (see Figure 10) showed reef location which provided necessary information for transect selection.

3.2.3 Transects

Transects were selected in both the cross- and along-shore directions at the Northern and Southern locations on the GBR to analyse the variability in exchange. Transects were selected by latitude according to reef density variability outlined in literature (Pickard et al., 1977). Once selected, the transects were incrementally moved in all directions to obtain a broader understanding of the individual research areas, this was achieved by cross-shore transects being moved in 0.1° increments North and South and along-shore transects being shifted in 0.01° increments East and West. The selected areas were required to be on the continental shelf (as defined in 3.2.1) and within the extent of the GBR.

3.2.4 Vector Rotation

The GBR generally follows the curvature of the East Australian coastline (Wolanski & Pickard, 1985). As the coastline varies with latitude, cross- and along-shelf currents are defined by the angle of the main land. The angle of deviation was calculated by calculating the angle of the coastline using two points from the GPS image of Google Earth. The angle was applied to cross- and along-shelf currents that were originally calculated from due north and due south directions in the SHOC model (Herzfeld et al., 2009).
3.3 Data Analysis

Data was analysed using MATLAB code written for this project and heavily supported by code supplied by Nicole Jones at The University of Western Australia. Data was visualised predominantly by use of QuickTime video created in MATLAB. These videos were created to display the variation in density, along-shore velocity and cross-shore velocity over the study period. Data was analysed by use of using 2D cross- and along-shore velocity profiles, time series vectors and calculated flux time series. Visualisations allowed for baseline interpretation that was quantitatively verified by the flux time series calculations.

3.3.1 Along-Shore transects

Along-shore transects were taken at numerous locations on the GBR. Three areas of interest have been presented below in the results section to display the regional variation on the GBR. These regions were from the Northern, Central and Southern GBR. Each transect was taken parallel to the coast and limited by the length of straight coastline and the extent that the continental shelf follows the coast. These lengths varied from 100-160km. This length was important to determine the effects of narrow channels in dense reef assemblages that transport oceanic and tidal flows (Wolanski & Van Sended, 1983). The magnitude of 100km also provided a regional flux relationship, averaging out local variability in exchange. The depth of the along-shore transects was limited to within 60m to specify as I am interested in determining the effects of the reefs (Wolanski, 1994). Transects varied in average depths due to their position on the continental shelf, the northern region in particular is relatively shallow (10-20m) on the continental shelf until it suddenly drops to >90m outside of the study zone (Wolanski & Bennet, 1982).

3.3.2 Cross-shore flux

Cross-shore velocities were analysed for the lengths and depths of the along-shore transects. Flux in the Cross-shore direction was calculated by integrating the cross-shore velocities over the area of each transect as outlined in Equation 1 Cross Shore Volume Flux.

\[
\text{Equation 1 Cross Shore Volume Flux}
\]

\[
\text{Cross Shore Volume Flux} = \int_{\text{Transect Depth}}^{\text{Transect Depth}} \int_{\text{Transect Length}}^{\text{Transect Length}} \text{Cross Shore Velocity} \, dx \, dz \text{ (m}^3/\text{s)}
\]
Time series plots were created to display the variation in cross-shore flux as a function of time. These plots were for the duration of the model run (January 3rd-28th). For further comparative purposes between sites, these flux calculations were divided by the transect distance to provide an average area flux.

**Equation 2 Cross Shore Area Flux**

\[
\text{Cross Shore Area Flux} = \frac{\text{Cross Shore Flux}}{\text{Transect Distance}} \quad (m^2/s)
\]

### 3.3.3 Cross-Shore transects

Cross-shore transects were taken from the same locations of the GBR as the along-shore transects, intersecting at the origin of the cross-shore transects. Due to some small islands in the southern region of my analysis, the comparative cross-shore transect was relocated so as to not include breaching islands in the analysis. Each transect was taken perpendicular to the coast and was limited by the length of the continental shelf present in the region. Cross-shore transect lengths varied from 26-221 km, these lengths were determined primarily by depth and were limited to within 60 m. An exception to this was made in the northern region where the shelf length was relatively narrow, to enable an accurate calculation of exchange a small portion of the transect was analysed up to 90 m depth.

### 3.3.4 Along-shore flux

The along-shore velocities were analysed for the lengths and depths of the cross-shore transects. Flux in the along-shore direction was calculated by integrating the along-shore velocities over the area of each transect as outlined in **Equation 1 Cross Shore Volume Flux**.

**Equation 3 Along Shore Volume Flux**

\[
\text{Along Shore Volume Flux} = \int_{\text{Transect Depth}}^{\text{Transact Length}} \int_{\text{y}}^{\text{z}} \text{Along Shore Velocity} \ dy \ dz \quad (m^3/s)
\]

Time series plots were created to display the variation in along-shore flux as a function of time. These plots were for the duration of the model run (January 3rd-28th). For further comparative purposes between sites, these flux calculations were divided by the transect distance to provide an average area flux.
3.3.5 Envelope of Tidal Elevations

The envelope of the tidal elevations was determined by using tide predictions from stations where tide constituents had previously been determined. These stations were individually selected by their close proximity to the areas of this study. These locations were from Low Wooded Isle in the northern region, Cape Bowling Green in the central region and Penrith Island in the south region. The envelope of the tidal elevations captures the amplitude of the spring-neap variation in the tidal signal. Tidal elevation was visualised as a time series plot to compare to a time series plot of cross- and along-shore flux.

3.3.6 Salinity and Density Plots

Salinity and density plots were created for cross-shore transects using the variables available from the SHOC model. This was to investigate the influence of salinity and density on exchange processes. These plots provided the ability to observe the offshore extent of freshwater plumes by the presence of low salinity surface flowing waters.
4 Results

To examine flow across reefs, the study area was required to be located within an area that contained reefs. Transects were located in 20-60m water depth which encompassed the extent of depths that coral reefs grow.

The northern along-shore transect was difficult to locate due to the narrow section of shallow shelf water in the region. Beyond this shelf depth the region quickly drops off to 90m. The proportion of cross-shore volume flux attributed to the 90m depth quickly outweighs the effects shown on the shelf.

The central and southern along-shore transects were required to be relatively far offshore at 60 and 110 km respectively from the coastline, this was due to the location of the GBR being further offshore at this location. The southern region also has two deep channels that run along shore and the selection of transects avoided these regions.

Selected regions encompassed the variation in dense and sparse reef assemblages. By observing reef locations with Google Earth and following the literature of Pickard (1977), dense and sparse locations were selected in the north and south regions respectively. The central transect was chosen primarily due to its proximity to the Burdekin River at 19.3°S. To compare the transect exchange of regions without a river it was supported by a reference of a region that had a consistent river out flow.
4.1 North Along-Shore Transect

Latitude and Longitude: (15.0°S, 145.56°E)
Transect Length: 1.0°
Angle: 39.29° Clockwise from due West

Figure 12 Along-Shore transect location within the Northern GBR

Figure 13 Transect Distance Along-Shore from origin, showing Cross-Shore velocity (m/s) in the Northern GBR (+ve Offshore)
Figure 14 (Above) Cross-Shore Volume flux over time of Northern Along-Shore transect (+ve Offshore)

Figure 15 (Below) Envelope of Tidal elevation from Low Wooded Isle

4.1.1 Location Characteristics
The northern transect was located at 15.0°S, 145.56°E and extends for 109km in a north east direction. The water depth is between 15-30m on average but drops down to 90m at both northern and southern ends of the transect.

The cross-shore velocities displayed in Figure 13 vary in strength and direction over time, initially having a strong onshore component then reversing to have a strong offshore component. The cross-shore velocity ranges up to 0.5m/s in both onshore and offshore directions.

4.1.2 Cross-Shore Flux’s
Cross-shore flux had a moderate cyclic pattern showing a more prevalent onshore pattern. Flux reversal occurs on the 20th of January where flux changes from peak offshore values to peak onshore values. The summated cross shore flux per meter transect is 34.6m²/s onshore.
4.1.3 Tidal Comparison

For the first tidal cycle there isn’t a strong relationship between cross-shore volume flux and tidal elevation at Low Wooded Isle (Figure 15). Spring tide at Low Wooded Isle forms a peak at the same time as cross-shore volume flux. The subsequent flux reversal also occurs at similar time to the tidal elevation reversal at the 22nd of January.

4.2 Central Along-Shore Transect

Figure 16 Along-Shore transect location within the Central GBR

Latitude and Longitude: (19.1°S, 148°E)
Transect Length: 1.3°
Angle: 39.39° Clockwise from due West
Figure 17 Transect Distance Along-Shore from origin, showing Cross-Shore velocity (m/s) in the Central GBR (+ve Offshore)
4.2.1 Location Characteristics

The central transect was located at 19.1°S, 148.0°E and extends for 144km in a north east direction Figure 17. The water depth is consistently around 50m. This transect is located just north of the Burdekin River outflow.

The cross-shore velocities are initially onshore with low velocity, before reversing to a strong offshore velocity on January 22\textsuperscript{nd}. The cross-shore velocity range is 0.4m/s onshore (only for brief periods) and up to 0.5m/s offshore.

4.2.2 Cross-Shore Flux’s

Cross-shore flux in the central region shows a strong offshore flux component. Notably the flux originally has a positive onshore component, though over the time period become stronger in the offshore direction. The volume flux deviates frequently in direction. This occurs three times during the period of this study at 10\textsuperscript{th} 16\textsuperscript{th} and 20\textsuperscript{th} of January. The summated cross-shore flux per meter transect is 65.8m\textsuperscript{2}/s offshore.

4.2.3 Tidal Comparison

Despite the general progression to offshore volume flux there is still a prevalent relationship between the cross-shore volume flux and the tidal elevation at Cape Bowling Green (Figure 19). Deviations of flux magnitude overlap with spring and neap tides.
4.3 South Along-Shore Transect

Figure 20 Along-Shore transect location within the Southern GBR

Figure 21 Transect Distance Along-Shore from origin, showing Cross-Shore velocity (m/s) in the Southern GBR (+ve Offshore)

Latitude and Longitude: (21°S, 151.0°E)
Transect Length: 1.5°
Angle: 45.11° Clockwise from due West
4.3.1 Location Characteristics

The southern transect was located at 21°S, 151.0°E and extends for 159km in a northeast direction Figure 20. The water depth ranges from 30 to 60m, the transect has a deep channel that is located between 75 and 105 km where the depth changes from 30m either side to 60m in the center of the channel.

The cross-shore velocities are consistently low in velocity and gradually vary between on and offshore direction. There is a relatively low maximum velocity of 0.3m/s in both directions.

4.3.2 Cross-Shore Flux’s

Cross-shore flux in the southern region had two distinctly similar peaks in offshore flux that followed similar patterns over time The two peaks and opposing troughs appear to be centralised around 0 volume flux. The subsequent total cross shore flux per meter transect is 0.5m²/s offshore.

4.3.3 Tidal Comparison

The southern cross-shore transect aligns with the sinusoidal pattern in the tidal envelope at Penrith Island (Figure 23). The two distinct peaks mentioned, coincide with neap tides and the troughs with spring tides.
4.4 North Cross-Shore Transect

Latitude and Longitude: (14.9°S, 145.25°E)
Transect Length: 0.3°
Angle: 39.29° Clockwise from due North

Figure 24 Cross-Shore transect on the North GBR
Figure 25 Transect Distance from shore (km), showing Along-Shore velocity (m/s) in the Northern GBR (+ve Northward)

![Along-Shore Flux Graph]

Figure 26 (Above) Along-Shore Volume flux over time of Northern Cross-Shore transect (+ve Northward)

Figure 27 (Below) Northern Transect Closest Tidal Variation

![Tides at Low Wooded Isle Graph]

Figure 28 (Above) Northern Density Profiles at 19th and 28th January (kg/m^3)  
(Below) Northern Salinity Profiles at 19th and 28th January (ppt)
4.4.1 Location Characteristics
The cross-shore transect was located at 14.9°S, 145.25°E and extends for 26km in a north west direction (Figure 24). The water depth is between 20-25m on average but drops down to 90m only 12km offshore.

The along shore velocities show a consistent strong southern component, although the flow weakens around the 22nd of January. The along-shore velocity ranges between 0.5m/s in a southern direction to 0.4m/s in a northern direction, though notably the southern maximum is far more prevalent throughout the study period.

4.4.2 Along-Shore Flux and Tidal Comparison
Along-shore flux has a prevalent strong southern flow direction. The flux is consistently in a southern direction. A large reduction in southern flux strength occurs on the 22nd of January when the southern along-shore volume flux changes from 10^7 m^3/s to 0 m^3/s over a two day time period. The integrated along-shore flux per meter transect is 534.2m^3/s south, by far the largest exchange examined in this project.

The northern along-shore volume flux shows deviation from the Low Wooded Isle envelope of tidal elevation. This is apparent until the reduction in southern flux strength coincides with a spring tide on the 20th January.

4.4.3 Density and Salinity
The density and salinity profiles in Figure 28 were selected at dates that showed maximum onshore and offshore velocities. The profiles show that less dense, lower salinity water was present across the reef transect during periods with northern flow. The opposite was shown for periods of high southern velocity, which had relatively higher density and salinity.
4.5 Central Cross-Shore Transect

Figure 29 Cross-Shore transect on the Central GBR

Figure 30 Transect Distance from shore (km), showing Along-Shore velocity (m/s) in the Central GBR (+ve Northward)

Latitude and Longitude:
(19.745°S, 147.6°E)

Transect Length: 1.1°

Angle: 35.25° Clockwise from due North
Figure 31 (Above) Along-Shore Volume flux over time of Central Cross-Shore transect (+ve Northward)

Figure 32 (Below) Tidal elevation at Cape Bowling Green

Figure 33 (Top) Central Density Profiles at 17th and 22nd January (kg/m^3)

(Bottom) Central Salinity Profiles at 17th and 22nd January (ppt)
4.5.1 Location Characteristics

The northern transect was located at 19.745°S, 145.25°E and extends for 113km in a northwest direction Figure 29. The water depth is between 20-50m. This transect was located south of the Burdekin River outflow.

The along-shore velocities displayed in Figure 30 show flow reversal occurs as different times of analysis. There is a strong southern flowing current at the furthest extent of the transect on the outer shelf region 100km from shore. The profile displays shows preferential pathways of strong northern flow arise on the shelf at various stages 14th, 22nd and 20th of January. The along-shore velocity ranges up to 0.5m/s in both north and southern direction.

4.5.2 Along-Shore Flux and Tidal Comparison

Along-shore flux is originally in a southerly direction though changes to a northerly direction towards the end of the study period. There is an oscillating tendency in the flux pattern with three flux reversals on the 13th, 16th and the 20th of January. The summated along-shore flux per meter transect is 11.3m²/s south.

The oscillations in along-shore flux coincide with the sinusoidal pattern in tidal elevation at Cape Bowling Green (Figure 32). Despite the northern progressing trend, there exists a relationship between flux and the envelope of tidal elevation at Cape Bowling Green. The flux changes direction in this study region and occurs between spring and neap tides.

4.5.3 Density and Salinity

The density and salinity profiles of the central transects showed that there is consistently low salinity and low density in the area over this time period. There is also exists a large low salinity low, density intrusion displayed Figure 33 on the 17th January.
4.6 South Cross-Shore Transect

Latitude and Longitude: (22.149°S, 149.6°E)
Transect Length: 2.0°
Angle: 45.11° Clockwise from due North

Figure 34 Cross-Shore transect on the South GBR

Figure 35 Transect Distance from shore (km), showing Along-Shore velocity (m/s) in the Southern GBR (+ve Northwards)
Figure 36 (Above) Along-Shore Volume flux over time of Southern Cross-Shore transect (+ve Northward)

Figure 37 (Below) Tidal elevation at Penrith Island

Figure 38 (Top) Southern Density Profiles at 11\textsuperscript{th} and 22\textsuperscript{nd} January (kg/m\textsuperscript{3})

(Bottom) Southern Salinity Profiles at 17\textsuperscript{th} and 22\textsuperscript{nd} January (ppt)
4.6.1 Location Characteristics
The southern cross-shore transect was located at 22.149°S, 149.6°E and extends for 221km in a northwest direction (Figure 34). The water depth is variable along this transect having two distinct deep channels that occur from 70-110km and 130-160km. These channels are 60m deep whereas the remainder of the transect is relatively shallow being around 10-20m. There is a large ridge from 160-100km where water depth changes from 60m to 15m just before the edge of the continental shelf at 220km.

The cross-shore velocities displayed in Figure 35 show isolated channel flow is predominant in this reef section. Cross-shore velocities reach 0.5m/s in both directions often occurring simultaneously at different distances along the transect. This pattern persistently occurred along the barrier at the 50km ridge, flows off the ridge often opposed flows on the ridge.

4.6.2 Cross-Shore Flux and Tidal Comparison
Cross-shore volume flux has a strong cyclic pattern despite initial variance between the 8th and 13th of January where the flux deviates from this pattern. The summated average cross shore flux per meter transect is 37.7m$^2$/s north.

The sinusoidal pattern in tidal elevation at Penrith Island (Figure 37) has a strong relationship with the cyclic pattern in cross-shore volume flux, sharing a period of oscillation of around 14 days. There is a lag time between the two sinusoids as troughs and peaks don’t align.

4.6.3 Density and Salinity
The two comparative salinity and density profiles were taken coinciding with both a neap (11th January) and spring (22nd January) tide. The results show low salinity water is present in the near shore region of the transect. This low salinity water forms a vertical front that oscillates back and forth within the 25-95km range of the transect during study period. These oscillations are seen to coincide with the variation between spring and neap tides.
4.7 Volume Flux Comparisons

Table 1 Flux Summary’s for Investigated Transects, All Flux values are for the entire study period

<table>
<thead>
<tr>
<th>Location in GBR</th>
<th>Along-Shore Transect Distance (km)</th>
<th>Cross-Shore Transect Distance (km)</th>
<th>Cross-Shore Volume Flux x10^4(m³)</th>
<th>Along-Shore Volume Flux x10^6(m³)</th>
<th>Cross-Shore Volume Flux per m Transect</th>
<th>Along-Shore Volume Flux per m Transect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northern</td>
<td>109</td>
<td>26</td>
<td>-377.0</td>
<td>-13.89</td>
<td>-34.6</td>
<td>-534.2</td>
</tr>
<tr>
<td>Central</td>
<td>144</td>
<td>113</td>
<td>947.4</td>
<td>-1.28</td>
<td>65.8</td>
<td>-11.3</td>
</tr>
<tr>
<td>Southern</td>
<td>159</td>
<td>221</td>
<td>-8.7</td>
<td>8.34</td>
<td>-0.5</td>
<td>37.7</td>
</tr>
</tbody>
</table>

Table 1 shows comparatively the flux values at each transect location. Apparent from this table is the significant southern along-shore flux which is an order of magnitude higher than any other flux. The Southern transect was also the only transect to show an average northern flux.
5 Discussion

5.1 Along-shore Transects

The selection of along-shore transects was primarily to investigate the cross-shore exchange. The results show strong tidal influences on cross-shore exchange on the GBR. The results also support the works of Spagnol (2001) suggesting that reef density has a noticeable influence on exchange processes.

5.1.1 Location and depth

During the time period of the model output, there was an extreme flooding event that strongly influenced the offshore component of the central transect.

In the northern GBR region there are known dense reef assemblages that can block flow along large portions of the shelf. Existing within these dense reef areas are narrow channels that transport oceanic tidal flows. These tidal flows impact along shore transects taken in the area. The transect length was subsequently in excess of 100km to minimise the significance of individual tidal inflows interfering with the regional area. This effect was prominent in early analyses of the northern region when looking at shorter transects.

5.1.2 Cross-Shore velocity

Cross shore velocity varied in strength and direction at all locations of the study, the northern transects showed predominantly onshore flow where the central transect showed predominantly offshore flow, this relationship is clarified numerically by their flux components. The southern transect had the lowest peak and average cross shore velocities.

A major flood event occurred from Late November to the 12th Of January in Queensland which particularly influenced the central transect. Figure 5 shows a river outflow laden with sediment as of January 4th 2011, Figure 33 also displays an outflow of low salinity water along the surface. This explains the uncharacteristically high offshore velocities observed in Figure 21 at this location, a region where river plumes are normally diminished below 19°S by oceanic inflows through the Palm and Magnetic passages (King et al., 2001).

The velocity profiles of the northern transect show a consistent low velocity zone in a shallow region of 15-20m depth at 30-60km of the transect. Figure 13 shows the cross-shore velocity profiles on the 6th the 19th and the 22nd of January 2011 form preferential
pathways around the shallow reef area. This supports the ideas of Spagnol (2001) and suggests that reefs present in the area divert flow. Both onshore and offshore flow is diverted around this shallow reef area.

5.1.3 Cross-Shore Volume Flux

The cross-shore fluxes calculated for each along-shore transect show distinct pattern similarities despite the geographical separation. All fluxes from the 3rd-9th of January are in an onshore direction. Gradually all of these fluxes show some oscillatory movement around the 16th of January.

The northern transect has the most persistently onshore flow which is reinforced by the northern transect cross-shore volume flux per m transect being significantly higher than all other transects. The north transect has the most irregular flux pattern. This suggests that dense reefs present in the area are interrupting the flow which supports the observations of (Spagnol et al., 2001)

The central transect shows a strong offshore component that becomes apparent after the 16th of January, this is due to the increasing flow of river output from the large flooding event via the Burdekin River (Wolanski & Van Sended, 1983). The progressive temporal trend from onshore to offshore flow in the southern transect supports the idea that the flood waters are making their way offshore.

The southern transect has two distinct peaks in flux. This suggests that there isn’t a barrier diverting the path of offshore flow supporting the known sparse reef density of the area (Pickard et al., 1977)

5.1.4 Tidal Comparison

There is a strong tidal influence prevalent on each transect. Onshore fluxes generally coincide with high tidal elevations and converse for offshore fluxes which coincide generally with low tidal elevation.

The southern transect shows the strongest relationship to the envelope of tidal elevation data. This further supports that there is low deviation from tidal influences. Given the sparse reef in the area it is apparent that the fluxes in the area are significantly modified by tidal forcing.

The northern region shares a vague relationship to tidal elevation, particularly coinciding peak flux with peak tidal elevation on the 19th of January. This transect shows
the largest deviations away from tidal elevation and supports the view that physical barriers prevent flow in a cross-shore direction.

The central region has a strong relationship to tidal elevation despite the general offshore deviation. The region of the central transect is known to receive tidal inflows and onshore conditions were expected for this transect, the offshore deviation present in this study period is likely linked to the flooding that occurred in Queensland at this time. As the flood waters reach the study area the known onshore flow direction (King et al., 2001) is changed to an offshore flow direction.

5.2 Cross-Shore Transects
Cross-shore transects provided the ideal technique to examine along-shore exchange. By visualising a two dimensional cross section (along-shore), flow pathways around reef segments were easily identified. The EAC had a strong influence on the along-shore flow with strong currents from deep water being observed to influence exchange on the shelf. This was particularly prevalent in the northern and central transects.

5.2.1 Location and depth
There was more variability in the cross-shore transects due to the bathymetry of the regions varying significantly. Compared to the along shore transects that were chosen at comparative depths, the cross shore transects were required to be taken from shore.

Due to the narrow shelf length in the northern area of study the cross-shore transects was only able to obtain 3 data points on the shelf. The steep continental shelf was present at 25km from shore. This leads to errors related to contouring sparse data.

The southern transect was particularly different from the northern and central transects as it was over 200km long and had two deep channels and as well as many ridges.

5.2.2 Along-Shore Velocity
Along-shore velocity was primarily impacted upon by the prevalence of the EAC in each region. Especially in the northern transect, strong persistent currents in excess of 0.4m/s were present and at various stages the influence of this current was seen to traverse onto the shelf.

In the southern transect there are constantly opposing velocities across the top of a ridge 50km offshore displayed in Figure 35. The presence of these opposing velocities suggests there is a large eddy that forms on top of this ridge. The suggested eddy is also shown to reverse direction throughout the study period.
The along-shore velocities of the central transect show that the southward flowing EAC is prevalent at the shelf edge, though there are frequent inner shelf flows that transport water North through the center of the transect displayed in Figure 30.

5.2.3 Tidal Comparison to Along Shore Volume flux

A reversal of opposing velocities in the southern transect occurs on top of a ridge 50km from shore. This occurs at the same time as the envelope of tidal elevation changes from spring to neap tide. This suggests that the relationship of water flow over the ridge is influenced by the spring neap tidal cycle.

The southern region, along-shore volume flux shares a distinct relationship with the envelope of tidal elevation. Spring tides coincide with northern flow and neap tide with southern flow.

The northern region displays a constant southern flow, consistent with the influence of the EAC suggested over the region by Pickard et al. (1977). This strong southern flow is diminished however during a spring tide on the 20th of January, suggesting that in the Northern region, spring tides can oppose the flow of the EAC.

5.2.4 Salinity and Density

Salinity and density were observed to have strong relationships with along- and off-shore flow.

In the southern region, analysis of salinity and density showed that between the 50km ridge and the shore, there is a predominant low salinity and low density region. This region shows the influence of fresh water onto the GBR as flooding events bring large volumes of fresh water offshore.

The northern region showed less dense, lower salinity water was present across the reef transect during periods with northern flow. This suggests that northern flowing waters in the area carry relatively fresh water from the southern GBR regions.

The central region notably showed a large low salinity low density intrusion across the water surface extending up to 50km offshore. This represents the river outflow from the Burdekin River during a large flooding event, and shows the outer reaches of influence before the fresh water becomes well mixed beyond 50km.

5.2.5 Ecological and Contaminant Ramifications

The results of this project have indicated that location and presence of spring or neap tide will have significant ecological and contaminant ramifications. As fish larvae and
coral polyps are subjected to ocean currents, regions of high cross- and along- shelf exchange would broadcast these further, particularly in the northern regions with high along shore flow. This would provide a greater distribution of individual species, though somewhat counter acted by the increased predation.

5.3 Limitations and Extensions

5.3.1 Computational limitation
This thesis involved the analysis of the SHOC model output which came in a netCDF format. There were two output files available for this project; a shelf specific 2D model and a regional 3D model that was utilised in this report to quantify water velocities along and across coral reefs.

Due to the high resolution of the SHOC model, analysis using the student version of MATLAB was limited by the allowable computer memory. This is the underlying reason behind the use of transect analysis of this report. Increased model memory capacity would enable the analysis of whole regions of the GBR, providing more detailed analysis opportunities.

Agreeing with works of Brinkman et al. (2011) the SHOC model used throughout this project helps to form a foundation upon which to build other components of future receiving water quality models for the GBR, capable of simulating the transport and transformation of sediments, nutrients and pesticides through the GBR. A future modelling capability such as this could play a critical role in underpinning the development of a WQIP for the GBR.

5.3.2 Control Volume and Residence Times
To calculate residence times in specific areas of the GBR, the analysis of water flows along and across control volumes is required. This project was unable to calculate accurate control volumes for sections of the GBR due to the limitation of analysis to individual transect. When calculating control volumes this project was unable to account for varying bathymetry within defined boundaries. The analysis of the entire SHOC model output for this region would enable this calculation.
6 Conclusions and Recommendations

This project has contributed to the knowledge of cross- and along-shelf exchange processes on the GBR. The project supports current literature by highlighting the influence of a large spring and neap tide system on the exchange processes on the GBR.

This study agrees with the works of Spagnol et al (2001) and supports that exchange processes on the GBR are influenced by reef density. In particular that dense reef systems direct shelf water flow away from the reef areas.

This study's results serve as a reference for future advancements in oceanography of the GBR. By quantifying the shelf exchange processes at various locations of the GBR this project has contributed to the better understanding of physical processes that occur on within the GBR region.

The results of this study were compiled within one month of January 2011. A continuation of this project would help clarify the relationships shown in exchange. As the SHOC model has data from March 2010 until present, comparison to both past and future times would help certify the relationships established in this report. Specifically in relation to the large flood event that occurred in Queensland during study period, the same areas of study would be ideal to investigate during a La Niña cycle to note the variability between ENSO events.

The complexity of the 3D SHOC model was the main limitation of analysis of this study. Advancing this project by analysing the entire GBR, would enable the clarification of reef exchange processes supported by this research. By use of control volumes, residence times could be calculated and would provide key information essential for the development of a GBR WQIP and future commercial development initiatives.
Bibliography


Webster, I.T. et al., 2008. Review and Gap Analysis of Receiving-Water Water Quality Modelling in the Great Barrier Reef. CSIRO.


Appendices 1

Figure 39 Satellite image of Northern Study Region (Google Earth, 2011)
Figure 40 Satellite image of Central Study Region (Google Earth, 2011)
Appendices 3

Figure 41 Satellite image of Southern Study Region (Google Earth, 2011)