The net water circulation in the Far Northern Great Barrier Reef

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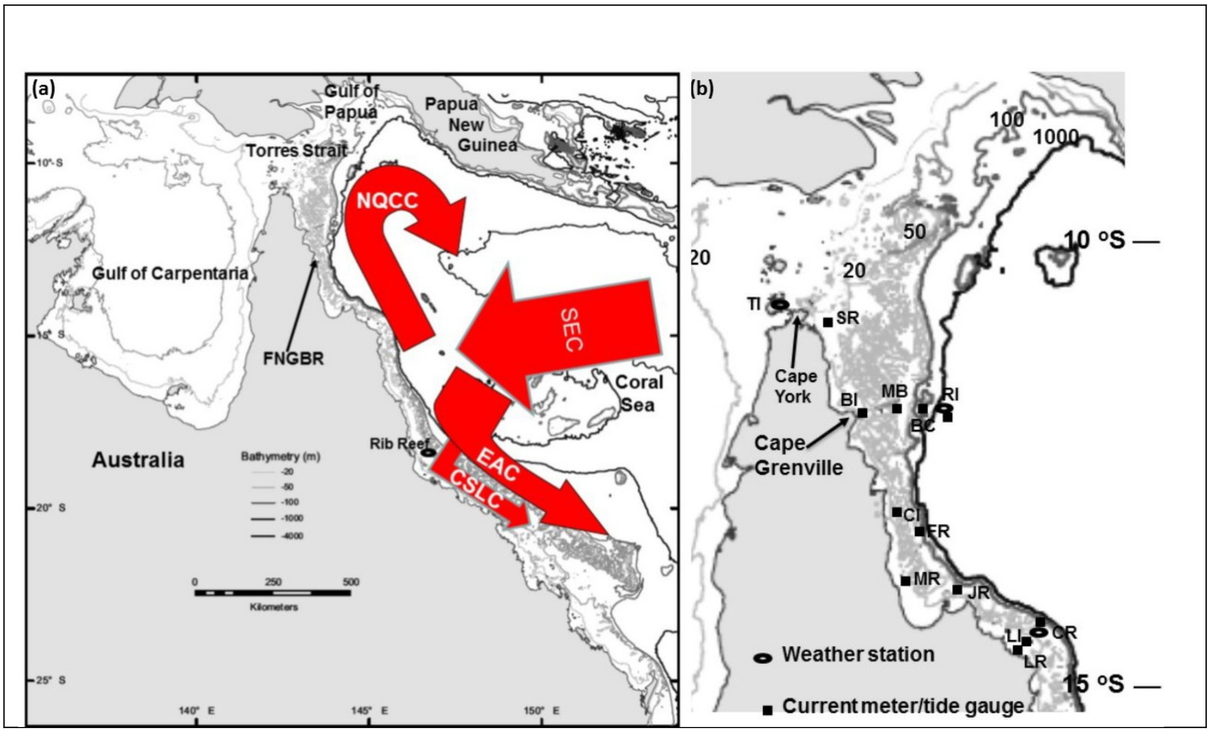
Abstract

The 500 km long Far Northern Great Barrier Reef (FNGBR) is a semi-enclosed sea with little connectivity with the rest of the GBR further South. Its mean circulation is controlled by the prevailing southeasterly (northwestward) wind that generates a wind-driven mean longshore flow that is enabled by an inflow of oceanic water in the South. From an examination of single-point, mid-depth current meter data at ten sites over one year, it appears that there is no net current during calm weather, which implies that the northward North Queensland Coastal Current in the adjoining Coral Sea does not intrude in the FNGBR. Only about 20-40% of the wind-driven longshore transport continues northward to exit the FNGBR through Torres Strait because of blockage by reefs, shoals and islands and by the tidal friction effect in shallow waters. The remaining 60-80% of the flow appears to be deflected seaward to the Coral Sea in the North, an observation that appears to be supported by oceanographic modelling. This situation differs from that in the central and southern Great Barrier Reef where the southward flowing East Australian Current intrudes on the shelf and generates a net current even during calm weather.

Keywords: currents; mean sea level; wind; waves; oceanic exchange.

1. Introduction

The 500 km long Far Northern Great Barrier (FNGBR; Figure 1) is located between 10 and 15 °S. It is the northeast continental shelf of Queensland, Australia; it is the northern section of the GBR lagoon. This northern lagoon is formed by ribbon of reefs stretching all along the continental shelf break for 90 % of its distance, the remaining 10% being reef passages (Pickard et al., 1977), making the FNGBR a semi-enclosed sea. Its effective width increases from about 7 km at Barrow Point (13.4 °S) to 152 km near Cape York (10.7 °S; at the southern latitude of Torres Strait). The lagoon is shallow and its depth does not exceed 40 m at the shelf edge. A linear assembly of reefs, the 'middle reefs', separates the inner channel from the outer channel, the latter also comprises, especially North of Cape Grenville, numerous non-emergent coral reefs and emergent sand banks readily visible in satellite images (Figure 1); the bathymetry data are available at https://data.gov.au/data/dataset/australian-bathymetry-and-topography-grid-june-2009. The middle reefs occupy up to ~ 30% of the shelf width. In the South the area is partially closed by the 7 km wide constriction, < 20 m deep, between Barrow Point and South Warden Reef.



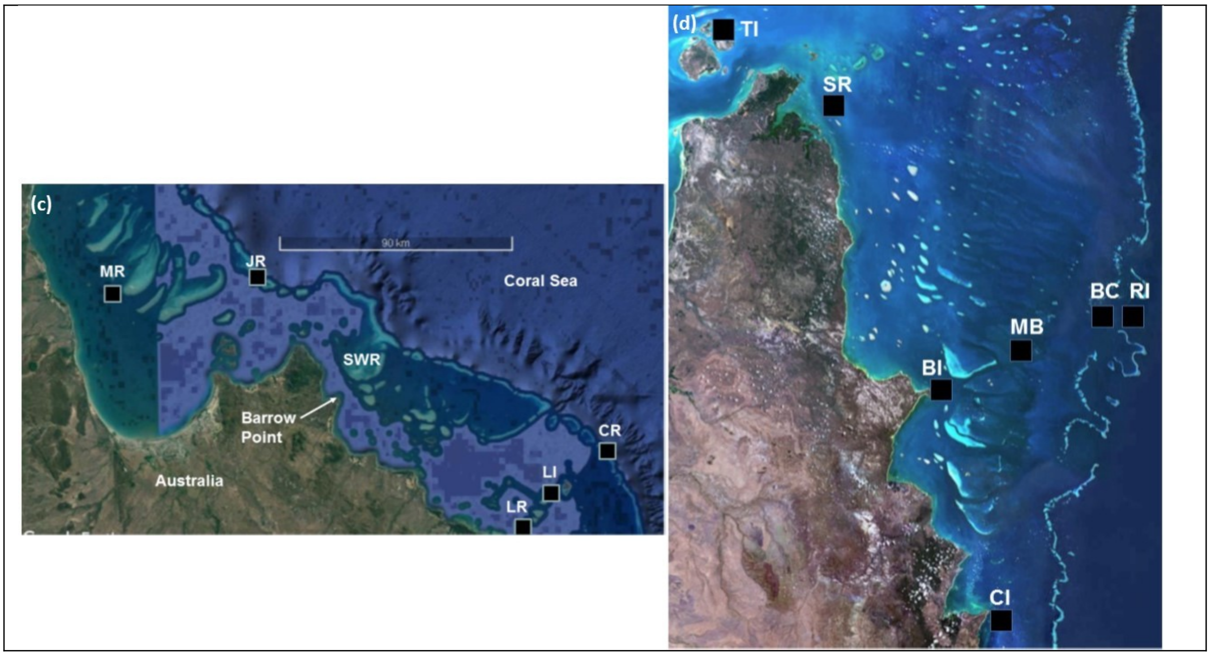


Figure 1. (a) A general location map and the bathymetry of the Far Northern Great Barrier Reef (FNGBR) and surrounding seas and gulfs. The location of the weather station at Rib Reef is also shown. (b) Location of the moorings in 1981-1982 at Thursday Island (TI), Shortland Reef (SR), Bird Island (BI), Middle Banks (MB), Blackwood Channel (BC), Raine Island (RI), Chapman Island (CI), Franklin Reef (FR), Magpie Reef (MR), Joan Reef (JR), Linnet Reef (LR), Lizard Island (LI) and Carter Reef (CR). (c) and (d) show the mooring locations in Google Earth satellite views clearly showing the inner and outer channels as well as the narrow (7 km wide) bottleneck between Barrow Point and South Warden Reef (SWR).

The water circulation in this region has been very little studied compared to that in Torres Strait further North and the central and southern sections of the GBR further South (Kingsford and Wolanski, 2019). Indeed there have been no physical oceanography field studies in that area since 1981-1982 when oceanographic moorings were maintained for a year. Aanderaa RCM4 and RCM5 current meters were deployed at mid-depth for a year, and serviced 6 months after the initial deployment, at the sites shown in Figure 1. Aanderaa tide gauges were bottom mounted at a number of sites also shown in Figure 1 and Aanderaa weather stations were deployed over Raine Island and Carter Reef (also shown in Figure 1). These provided current, sea level and wind data (Wolanski and Thomson, 1984; Cahill and Middleton, 1993). These publications demonstrated that the longshore currents in the lagoon are wind-driven but they did not establish a water budget nor did they document the water exchange rates between the Coral Sea and the FNGBR. In the Coral Sea the landward flowing South Equatorial Current (SEC) splits into two currents on reaching Australia, the northward flowing North Queensland Coastal Current offshore from the FNGBR, and to the southward flowing East Australian Current (EAC) that also generates the southward flowing Coral Sea Lagoonal Current (CSLC) in the central and southern GBR (Figure 1; Kingsford and Wolanski, 2019).

Based on the 1981-1982 oceanography data, this short paper answers three physical oceanography questions that may have important ecological implications about the connectivity patterns in the FNGBR, namely (1) does the North Queensland Coastal Current (NQCC) in the adjoining Coral Sea drive a net current in the lagoon?; (2) does the central GBR (i.e. the GBR south of Barrow Point) connect with the FNGBR?; (3) does all the northward flowing water in the FNGBR during the dominant southeasterly (SE) trade winds flow out through Torres Strait?

2. Methods

Oceanographic data

The data set is listed in Table1 according to general location and date. According to whether a current meter was deployed in a channel or a reef passage, either longshore currents or cross-shelf currents were recorded. The mooring locations are shown in Figure 1. The half-hourly sea level and currents data were low-passed filtered using the Godin tide-killer filter $A_{24}^2\ A_{25}/24^2\ 25$. The mean sea level data were not detrended. The hourly wind data were daily-averaged. The wind data from Thursday Island were the only available wind data for Torres Strait for that period but they were recently found to be unreliable due to orographic effects (Li et al., 2017) and thus they were not used in this study.

Table 1. Oceanographic and meteorologic data set

Wind	**Dates**	**Cross-shelf currents**	**Dates**
Thursday Island (TI)	Oct. 1981- Oct. 1982	Blackwood Channel (BC)	Oct. 1981 - Apr. 1982
Raine Island (RI)	Oct. 1981 - Oct. 1982	Joan Reef (JR)	Oct. 1981 - Apr. 1982
Carter Reef (CR)	Apr. 1982 - Oct. 1982		
Ribb Reef	Oct. 1981 - Apr.1982	**Sea level in the Coral Sea**	
		Raine Island (RI)	Oct. 1981 – Oct. 1982
Longshore currents		Carter Reef (CR)	Apr. 1982 – Oct. 1982
Shortland Reef (SR)	Oct. 1981 – Oct. 1982		
Middle Banks (MB)	Oct. 1981 - Oct. 1982	**Sea level in FNGBR**	
Chapman Island (CI)	Oct. 1981 - Oct. 1982	Shortland Reef (SR)	Oct. 1981 - Apr. 2982

Franklin Reef (FR)	Apr. 1982 - Oct. 1982	Bird Island (BI)	Oct. 1981 – Apr. 1982
Magpie Reef (MR)	Oct. 1981 – Oct. 1982	Middle Banks (MB)	Oct. 1981 – Apr. 1982
Linnet Reef (LR)	Oct. 1981 – Apr. 1982	Magpie Reef (MR)	Oct. 1981 – Apr. 1982

Modelling

The domain of the 2-D, non-structured SLIM model of Torres Strait of Wolanski et al. (2013) and Li et al. (2017) was extended southward to include the FNGBR (Figure 2a) and a fringing strip of the Coral Sea. The mesh was designed to fit the reef passages and the channels all over the shelf, as exemplified in Figure 2b. The bathymetry data were taken from https://data.gov.au/data/dataset/australian-bathymetry-and-topography-grid-june-2009. The open boundary conditions follow those of Li et al. (2017), namely the sea levels (tides plus mean sea level derived from satellite altimetry) for the open boundaries A-B, D-E-F, and the observed tidal currents plus the mean (wind-driven) currents along the transects B-C and G-H. The open boundary F-G was assumed closed. The model was also forced by the wind. The breaking of oceanic waves along the outer reef crest is important in driving a landward flow over the outer reef (Lentz et al., 2016). As the FNGBR has long reefs stretched along the shelf break and narrow reef passages separating them, wave breaking had to be included in the model. Indeed, wind-driven surface gravity waves are always present during the prevailing southeast trade winds (Wolanski, 1986). Wave breaking was parameterised in the model using the simple, engineering-like method of Wolanski et al. (1993), namely that a 1.5 m significant wave height swell breaking over the reef crest applies over the reef crest a landward stress equivalent to that of a wind of 15 m s^{-1} over the reef crest. Based on the wave data of Wolanski (1993), a 1.5 m significant wave height was assumed in the Coral Sea during strong southeasterly tradewinds. Friction was parameterised using a Manning roughness coefficient of 0.0335, characteristic of sand, and 0.1675 over coral reefs to represent their larger bottom roughness

(Nelson, 1996; Lowe et al., 2015; Lentz et al., 2016). The reefs map was obtained from https://eatlas.org.au/data/uuid/d2396b2c-68d4-4f4b-aab0-52f7bc4a81f5. There are no altimetry satellite data for 1981-1982; thus the model could not be accurately verified for the mean currents against these current meter data. The model however reproduced fairly reliably the tidal currents, as will be shown in a further paper. In the present simulation aimed at explaining the different net water circulation around reef passages in the North and in the South of the FNGBR, we assumed a mean sea level difference of 0.6 m across Torres Strait, an east-southeasterly wind of 13 m s^{-1}, and a constant mean sea level between points E and F, as such values are typical of the observations for recent years by Li et al. (2017).

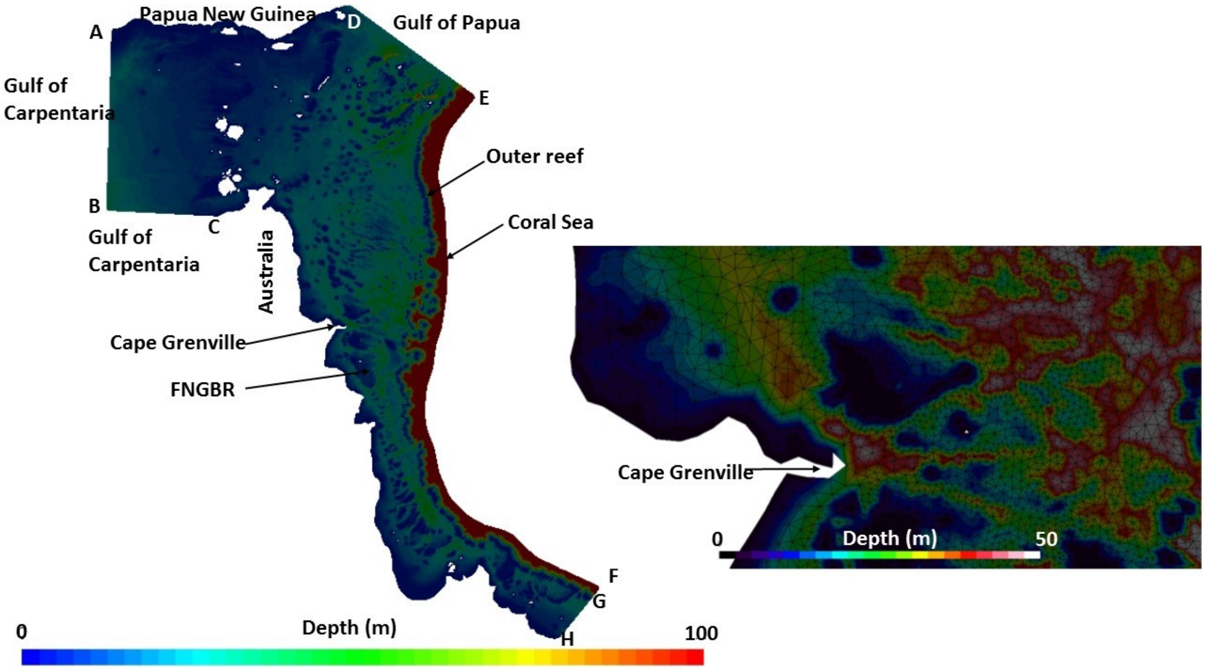


Figure 2. (Left) The SLIM oceanographic model domain and the bathymetry. Points A-H are discussed in the text. (Right) A close-up view of the bathymetry and the model mesh near Cape Grenville.

3. Results

The field data are summarised in the time-series plots of the low-frequency currents, wind and mean sea level in Figure 3 (Oct. 1981 – Apr. 1982) and Figure 4 (Apr. 1982 – Oct. 1982). From Oct. 1981 to April 1982 the longshore winds varied from northward to southward, with larger northward wind speeds in the South. From April to October 1982 the wind was spatially uniform. During that latter period the longshore currents were always northward. What is most evident during that period is that the longshore currents were proportional to the longshore wind. For instance at Chapman Island (Fig. 3d) the correlation coefficient between wind and current was 0.8 and the longshore current was zero during calm weather. That finding demonstrates that there was wind-driven mean longshore flow, however no longshore flow from the offshore NQCC.

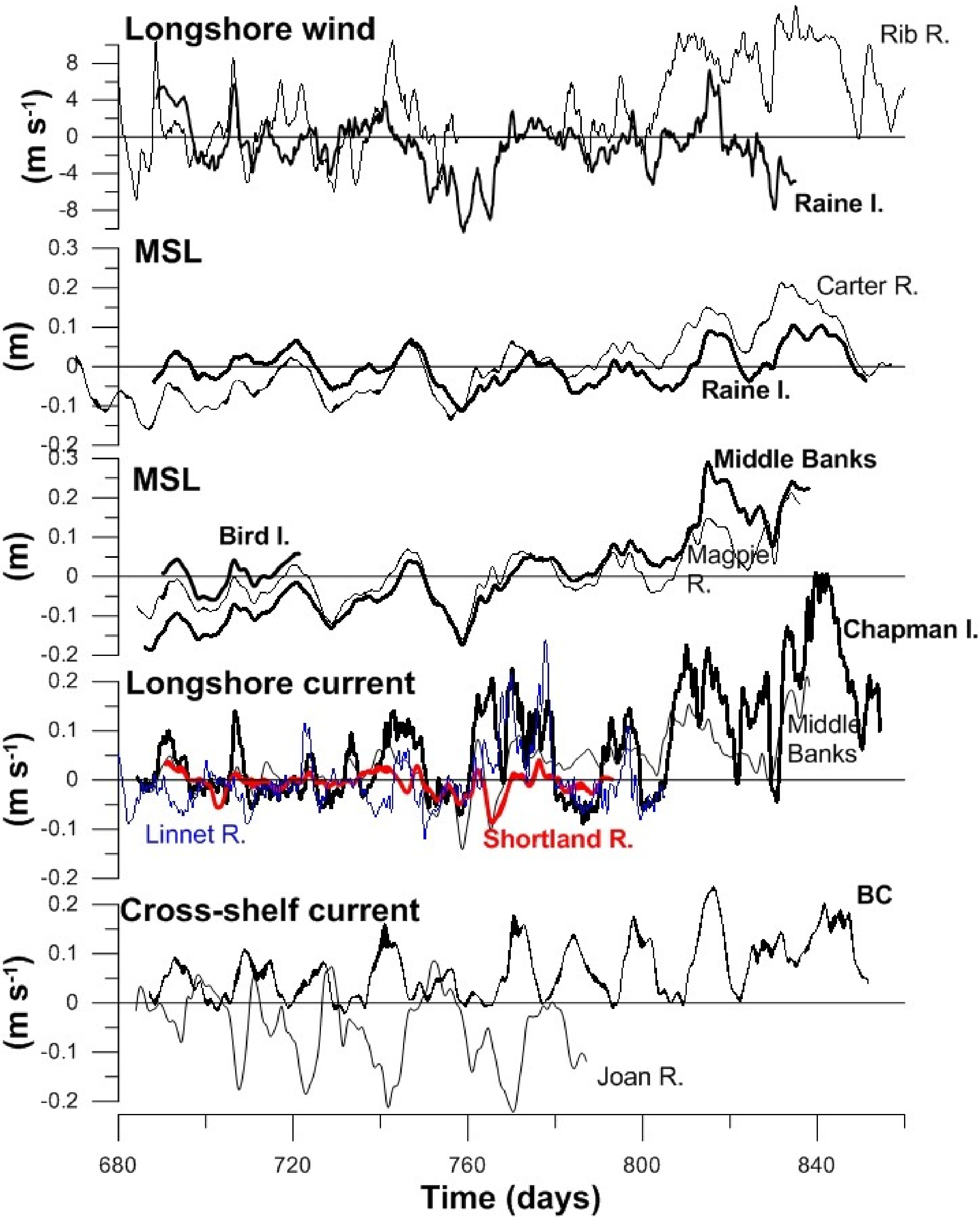


Figure 3. Time-series plot for October 1981 to April 1982 of the longshore wind (positive if northward) at Raine Island and Rib Reef, the mean sea level (MSL) in the Coral Sea at Raine Island and Carter Reef, the MSL in the FNGBR at Bird Island, Middle Banks and Magpie Reef, the longshore current (positive if northward) at Chapman Island, Middle Banks, Shortland Reef and Linnet Reef,

and the cross-shelf currents (positive if seaward) in the reef passages at Blackwood Channel (BC) and Joan Reef (JR). Time is in day number from January 1, 1980. The site locations are shown in Figure 1.

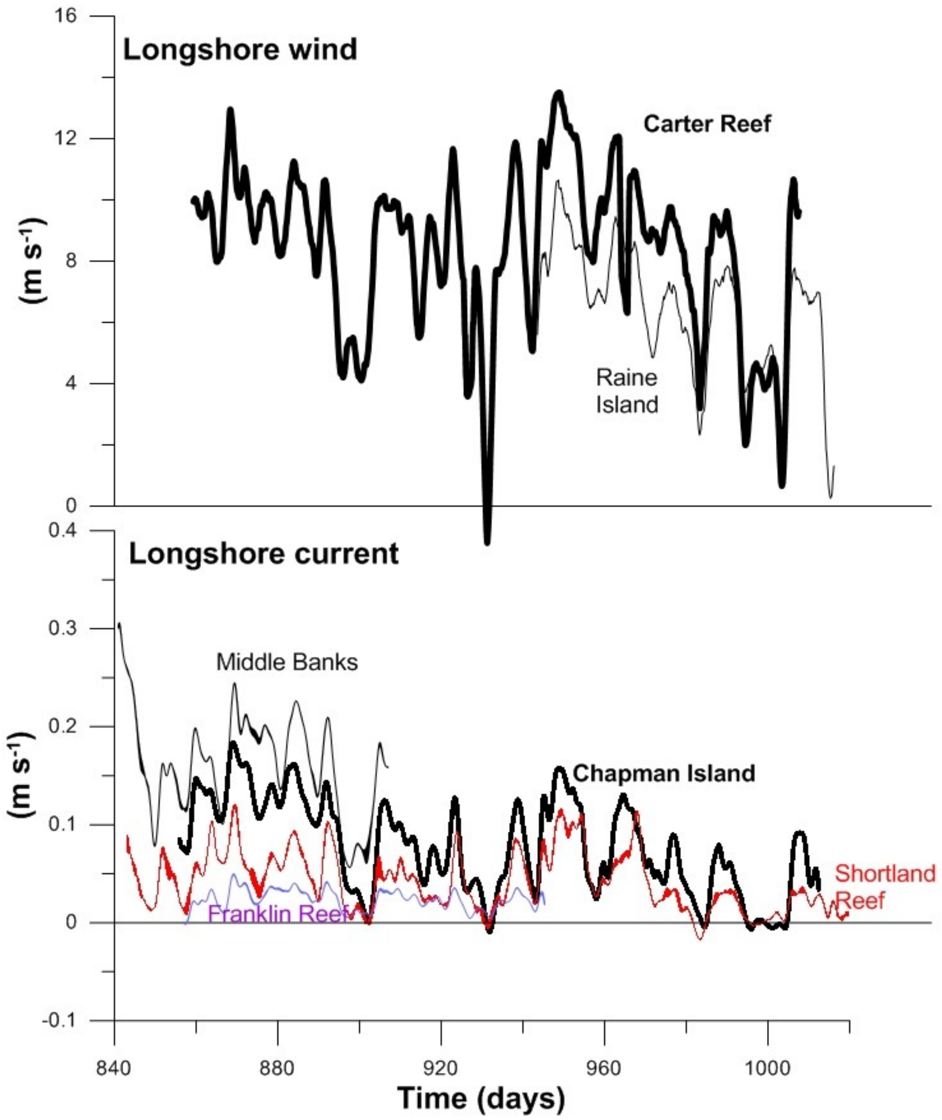


Figure 4. As in Figure 3, time-series plot for April 1982 to October 1982 of the longshore wind at Carter Reef and Raine Island, and the longshore current at Middle Banks, Chapman Island, Shortland Reef and Franklin Reef.   The site locations are shown in Figure 1.

The current at Linnet Reef (Fig. 1c), at the southern entrance of the bottleneck off Barrow Point, determines the water connectivity between the central GBR to the South and the FNGBR to the North. This current was always less than 0.05 m

s^{-1} (Figure 2), except during a short period of strong southward wind. At Lizard Island (Fig. 1c) the current was also typically less than 0.08 m s^1 and was southward during calm weather because this is in the intrusion zone of the SEC that generates the southward flowing EAC (Wolanski and Pickard, 1985; Choukroun et al., 2010; Hock et al., 2017; Kingsford and Wolanski, 2019). Thus the peak net longshore northward water flux through the bottleneck off Barrow Point (Figure 1c) is estimated to be the same as the flow around Linnett Reef estimated to be about 7800 $m^3 s^{-1}$, for a transect width off Linnett Reef of roughly 13 km with a mean depth of about 12 m.

The northward current during strong winds in the inner channel at Chapman Island (Fig. 1d) was about 0.15 m s^{-1}, corresponding to a peak northward water flux of about 46,500 $m^3 s^{-1}$ as the transect width is about 11 km and the mean depth of about 28 m The northward current during strong winds in the outer channel at Franklin Reef (Fig. 1d) was about 0.05 m s^{-1}, corresponding to a peak northward water flux of about 15,700 $m^3 s^{-1}$ as the transect width is about 15 km and the mean depth of about 21 m The peak northward water flux over the FNGBR at the latitude of Chapman Island-Franklin Reef was thus about 62,200 $m^3 s^{-1}$, which is about 8 times larger than the flux from the central GBR to the FNGBR. This extra water (54,400 m^3 s^{-1}) has to come from somewhere, and the only candidate is the Coral Sea. Indeed, the landward current in the reef passage at Joan Reef (Fig. 1c) was 0.2 m s^{-1} during strong winds and zero during calm weather (Figure 3), a finding also demonstrating that the current was not due to the SEC intrusion on the shelf because in that case the current through the reef passage would not vanish during calm weather. That particular reef passage was 2 km wide with a depth of 40 m, corresponding to a net water flux of about 16,000 m^3 s^{-1}. From an examination of the bathymetry data North of Joan Reef, the extra reef passages around Joan Reef needed to generate an inflow of 54,400

$m^3 s^{-1}$ occur within a distance of 58 km from Joan Reef, i.e. about half of the distance between Joan Reef and Franklin Reef. From the data it thus appears thus the water flux from the central GBR to the FNGBR accounts for only about 1/8 of the water flux in the southern region of the FNGBR and that 7/8 of the water flowing through the South of the FNGBR comes from the Coral Sea. Further North, the longshore currents in the inner channel at Shortland Reef (Fig. 1d) was < 0.1 m s^{-1}, somewhat smaller than at Chapman Island, though the inner channel is narrower than at Chapman Island, while it was larger (0.2 – 0.25 m s^{-1}) in the outer channel at Middle Banks (Figures 1d and 2). At that latitude the peak net northward water flux was about 192,000 $m^3 s^{-1}$ for a mean current of 0.15 m s^{-1} across a transect width of 61 km with a mean depth of 20 m, an estimate that takes into account the numerous non-emergent reefs scattered across the mid- to outer-shelf in that area.

At the shelf break the peak cross-shelf current at Blackwood Channel (Fig. 1d) was seaward at 0.15 m s^{-1} during strong winds, i.e. the water was flowing against the wind, and zero during calm weather (Fig. 3). This seaward current in the North of the FNGBR is presumably due to several effects, namely (1) the longshore currents in coastal waters are decreased by the tidal friction effect due to large tidal currents and small depths (Wolanski and Thomson, 1984); (2) the northward longshore water flux on the mid-shelf at the latitude of Middle Banks cannot go all through Torres Strait either because (a) there are numerous shoals, islands and reefs on the shelf to the North (Figure 1) , (b) it cannot flow to the Gulf of Papua because of a dense barrier of reefs and islands in the northeast Torres Strait (Wolanski and Thomson, 1984), (c) as controlled by tidal friction in shallow waters, only about 40,000 to 80,000 $m^3 s^{-1}$ can flow westward through Torres Strait for a mean sea level difference ΔMSL across Torres Strait of, respectively, 0.3 m (Wolanski et al., 2013) and 0.6 m (Li et al., 2017; 0.6 m was the maximum observed value of ΔMSL). Thus the excess water flux of 112,000 to 152,000 $m^3 s^{-1}$ in the north of the FNGBR has to flow seaward to the Coral Sea. Assuming that the cross-shelf flow data at Blackwood Channel are representative, this could be achieved by an outflow through all the reef passages within a distance of 152 to 207 km of Blackwood Channel. All these estimates of fluxes are only order-of-magnitude estimates as they are based on mid-depth single point mooring data.

4. Modelling to explain the observations near reef passages

The outflow through reef passages in the North is tentatively consistent with the time-series plot of mean sea level (MSL; Figure 2), showing that the MSL fluctuations were coherent everywhere and that they were larger inshore than in the Coral Sea; there thus existed a sea level slope pushing water seaward.

The SLIM model provides some insight in the different net water circulation near and through near reef passages in the North and in the South of the FNGBR. In the North, in Blackwood Channel near Raine Island (figure 1d), Figure 5a shows a predicted landward flow over the outer reefs, as driven by wave breaking, a complex circulation with eddies, and a prevailing seaward flow through the reef passage (labelled M in the figure); importantly, northward flowing outer shelf water (labelled N in the figure) also exits the FNGBR through the passage at M. For the same location, Figure 5b shows the water transport (depth X velocity), suggesting that a net seaward flow prevails through the passage, that the net circulation is made complex both by the bathymetry and the wave breaking over the outer reef, but that the transport by wave breaking over the outer reef is small compared to the net transport over the shelf and through the reef passage. In the South, in the two reef passages around Joan Reef (Figure 1c), Figures 5c and d show a predicted landward flow over the outer reef as a result of wave breaking and a prevailing strong landward flow through the reef passages; this inflow then merges with the northward longshore current and adds to it; also the contribution of wave breaking to the transport (velocity X depth) is small. The model thus appears to support the observation of an inflow from the Coral Sea in the South of the FNGBR and an outflow to the Coral Sea in the North of the FNGBR during the prevailing tradewinds.

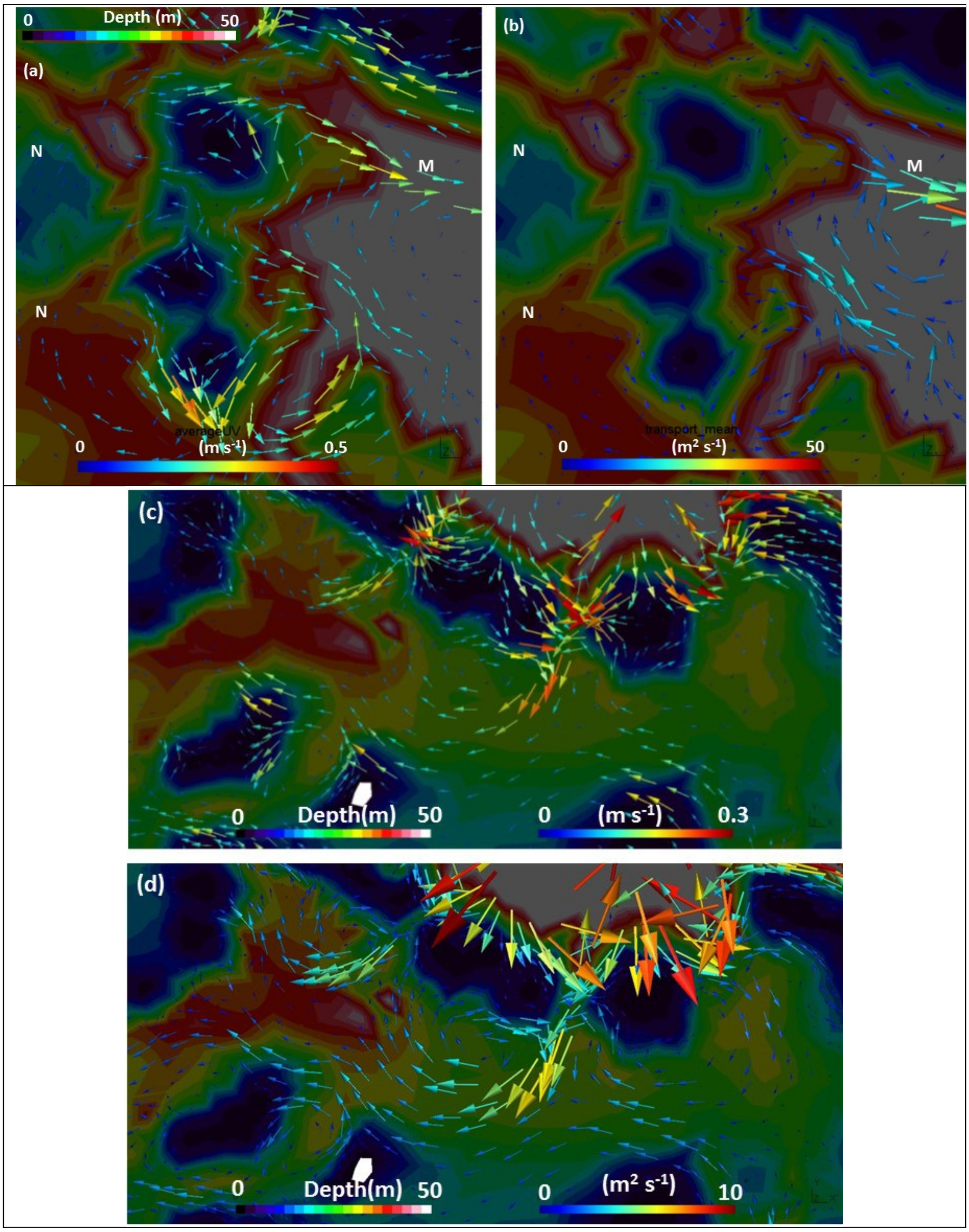


Figure 5. Predicted, tidal-averaged (a) velocity and (b) transport (velocity X depth) in Blackwood Channel (the reef passage near Raine Island (Figure 1d) in the North of the FNGBR. Predicted, tidal-averaged (c) velocity and (d) transport (velocity X depth) around Joan Reef and the two reef passages to the east and west (Figure 1c) in the South of the FNGBR.

5. Conclusions

As sketched in Figure 6, the 500 km long Far Northern Great Barrier Reef (FNGBR) is a semi-enclosed sea, with only a small connectivity with the rest of the GBR further South. The northward North Queensland Coastal Current in the adjoining Coral Sea does not intrude in the FNGBR, so that there is no net current during calm weather. This situation differs markedly with that in the central and southern Great Barrier Reef where the shouthward flowing East Australian Current, generated by the South Equatorial Current (SEC), intrudes on the shelf and generates a net current (the CSLC in Figure 1a) even during calm weather. The mean circulation in the FNGBR is controlled by the prevailing southeasterly (northwestward) tradewind that generates an oceanic inflow in the South. It appears that only about 20-40% of this northward current can exit the FNGBR through Torres Strait in the North because of blockage by reefs, shoals and islands and by the tidal friction effect in shallow waters. The remaining 60-80% of the flow appears to be deflected seaward to the Coral Sea in the North.

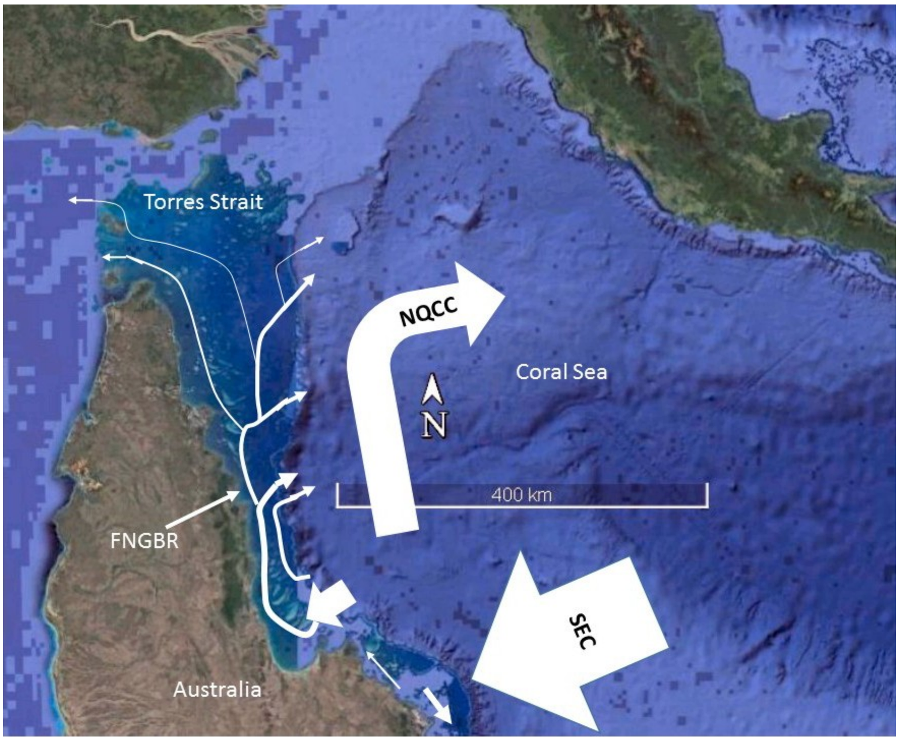


Figure 6. A sketch of the water circulation during the dominant southeasterly trade wind in the Far Northern Great Barrier Reef (FNGBR) and the Coral Sea. There is a negligible net circulation during calm weather as the NQCC does not intrude in the FNGBR.

The volume V of water in the FNGBR is about 1.125 X 10^{12} m^3 and during strong winds the peak net water flux Q is about 192,000 $m^3 s^{-1}$. Thus the residence time of water, that can be estimated to be equal to V/Q, is about 67 days during strong winds, and much larger the rest of the time, a finding which justifies the tag ‘semi-enclosed sea’ for the FNGBR. This is an order-of-magnitude estimate. It shows however that the residence time of the FNGBR is similar during strong winds, but much larger during calm weather, to that (also about 67 days) of the central GBR (Andutta et al., 2013), as the latter is a much more open system without ribbon reefs at the shelf edge and with the prevailing, southward flowing CSLC (Figure 1) helping to flush the system.

The connectivity between the FNGBR and the central GBR appears small but still it may have ecological implications that have been so far little explored by ecologists (Schiller et al., 2015; Hock et al., 2017; Jon Brodie, pers. com.).

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