CORAL SEA - CORAL REEF HEALTH PROJECT

In situ measurements of water temperature and current flow

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On the cover – A Marriot HS (high sampling rate) drag and tilt current meter deployed at approximately 10m on a reef in the southern Coral Sea Marine Park. This current meter was deployed in February 2019 and the photo taken immediately prior to retrieval in February 2020. Image credit: Martin Russell

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There were a very large number of persons involved in the deployment and retrieval of Marriot HS (high sampling rate) drag and tilt current meters used in this project, especially Daniella Ceccarrelli, Deborah Burn, Vanessa Mesmer, and Andreas Dietzel.

We acknowledge the Traditional Owners of the sea country in which this research and monitoring was conducted, and pay our respects to their elders, past, present and emerging.

ii Executive Summary

The Coral Sea Marine Park is potentially well-connected to adjacent biogeographical provinces owing to westward flowing jets of the Southern Equatorial Current, more specifically, the north Vanuatu jet and the New Caledonia jet. However, patterns of connectivity for the Coral Sea are poorly understood due to i) the lack of long-term measurements of water circulation and oceanographic conditions and ii) the inherent constraints in existing hydrodynamic models. Critically, the development and improvement of both biophysical and underlying hydrodynamic models is fundamentally reliant on observational data, requiring *in situ* measurements of environmental conditions over extended periods at a wide range of locations.

A total of 84 Marotte HS (high sampling rate) drag and tilt current meters were deployed during the course of this study, mostly within the Coral Sea Marine Park (CSMP), providing time series measurements for flow velocity and direction, as well as temperature. Importantly, separate field trips were undertaken to ensure timely deployment of current meters at select reefs (mainly, Osprey and Bougainville Reefs) to record environmental conditions throughout the critical summer period (December – February).

The key findings of this research were as follows:

1. Environmental conditions

- 84 Marotte HS current and temperature loggers deployed in November and December 2019 captured the summer increase in water temperature associated with the 2020 bleaching event (Hoey et al. 2020), with maximum temperatures exceeding 31ºC.

- Summer water maxima were punctuated by periods of cooling that coincided with increased current velocity, indicative of storm activity and/or upwellings. Conversely, periodic intrusions of cool and warm water were likely generated by fine scale water movement generated by tidal flows. Together, these fluctuations in water temperature may have played a role in modulating the severity and spatial heterogeneity of coral bleaching (Hoey et al. 2020).

- *In situ* measurement of water temperature, velocity and direction showed consistent departure from measures estimated from existing hydrodynamic models (GBR4). The GBR4 model consistently over-estimates current velocity and fluctuation in the directionality of current flow. Meanwhile, the GBR4 consistently under-estimates the in-water temperature by 1-1.5ºC and failed to predict periodic intrusions of cool and warm water.

2. Connectivity

- Despite inherent limitation of the GBR4 to represent fine scale oceanographic conditions in the CSMP, it is the only operational hydrodynamic model to force the biophysical model (CONNIE2) available for the CSMP. This model provides significant insights into broad-scale connectivity patterns, albeit at a coarse resolution (4km).

- Yearly estimates of connectivity patterns were generated from CONNIE2 (CSIRO) between 2010 and 2017 to assess general patterns of connectivity between coral reef habitats in the CSMP. Connectivity between reefs was highly variable between years though distinct clusters of highly connected reefs were apparent for Queensland plateau, in the Central CSMP.

- The model predicted connections from CSMP reefs towards the GBR which is consistent is the dominant westerly current flow in the Coral Sea. Connectivity from northern CSMP reefs (Osprey and Bougainville) to the northern GBR was among the strongest connections observed in the model. No particles were released from the Great Barrier Reef to determine asymmetric patterns of connectivity.

- A detached Marrotte HS, deployed at Wreck Reef and recovered at the Keppel Island, further demonstrated connectivity from the southern CSMP to the inshore GBR.

3. Coral bleaching

- 36 temperature loggers were deployed to investigate the effect of temperature and current flow on the severity of bleaching at Osprey and

Bougainville Reefs in the northern CSMP and in the vicinity of Lizard Island in the northern GBR. Most notably, cold water intrusions recorded by *in situ* instruments indicate cold water intrusions likely mediated the ecological impacts of 2020 bleaching. Cold water intrusions on the GBR were attributable to storms, but recurrent intrusions on the steep sided outer slopes of reefs in the CSMP likely represent periodic upwelling events.

Further advances in understanding of hydrodynamics and connectivity for CSMP reefs will be best achieved by using an unstructured hydrodynamic model that allows for contrasting levels of resolution to capture both broad scale features of open ocean environments and local geomorphologic features and fine-scale processes that operate near reefs and in other shallow marine habitats. Such a model is in development to explore Coastal Ocean Marine Prediction Across Scales (COMPAS) across Australia. The *in situ* environmental data obtained during this study will be invaluable for testing the validity of the COMPAS models for the CSMP, though the data is currently concentrated in the *northeast transition* bioregion (Osprey and Bougainville Reefs). Further deployment of current meters across the broader extent of CSMP, wherever feasible, will provide a much greater information base for calibrating and validating hydrodynamic models, thereby contributing to improved understanding of large-scale connectivity across the CSMp and with adjacent biogeographical provinces.

Recommendations for future work are as follows:

i) Significant downscaling in hydrodynamic modelling is necessary to effectively represent environmental conditions in the CSMP, especially in areas adjacent to coral reefs and other shallow habitats. However, given the relatively few shallow habitats and their sparse distribution, downscaling to much higher resolution (e.g., 1 km resolution GBR1) hydrodynamic model for the entire region is not recommended.

ii) Improved understanding of hydrodynamics and connectivity for CSMP reefs will be best achieved by developing an entirely new hydrodynamic model that allows for variable resolution or unstructured meshes (e.g., Legrand et al. 2006) providing coarse resolution in oceanic environments but highly detailed resolution in near-reef environments.

iii) Continued deployment of oceanographic instruments, in particular long term instrument capable of measuring water temperature and current flow are necessary to facilitate the development of new hydrodynamic models for the CSMP and/ or improve on existing models designed for the GBR.

iv) *In situ* measurements of temperature and current flow are integral to our understanding of coral bleaching in the CSMP particularly given that frequent fluctuations in temperature are apparent in these offshore oceanographic environments. As such we recommend continued deployment of Marotte HS current meters at monitoring sites throughout the CSMP.

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1. Background

The Coral Sea is an environmentally significant ecosystem that connects Australia's Great Barrier Reef (GBR) with other western Pacific provinces (Ceccarelli et al. 2013). The major oceanographic features influencing the CSMP are westward flowing jets of the Southern Equatorial Current (SEC), that flow north of Vanuatu and north of New Caledonia, respectively (Gordeau et al. 2008; Figure 1.1). The SEC is strongest during the summer months and generates strong westerly flow from the Coral Sea to the GBR, where it bifurcates to form the south-flowing East Australian Current (EAC) and the Hiri Gyre in the Gulf of Papua to the north (Brinkman et al. 2002; Ridgway et al. 2018, Rousselet et al. 2016).

The Coral Sea supports a very rich fauna of coral reef species (Ceccarelli et al. 2013; Stuart-Smith et al. 2013; Hoey et al. 2020), representing a unique mix of species with affinities to both the GBR and other adjacent biogeographical provinces. There are also a range of species that distinguish the Coral Sea from other biogeographic provinces (Ayling and Ayling 1985, Oxley et al. 2004, Veron et al. 2011), potentially reflecting the unique oceanic environments that characterise reefs throughout the Coral Sea. Coral reef biodiversity (e.g., species richness of reef-associated fishes) is generally highest in the northern Coral Sea and declines with increasing latitude (Stuart-Smith et al. 2013; Hoey et al. 2020), in accordance with general latitudinal gradients and the proximity of the Coral Triangle biodiversity hotspot (Allen 2008).

Based on models of oceanographic circulation, larval transport is expected to occur westward from the Coral Sea to the GBR (Stuart-Smith et al. 2013). However, the westward flowing SEC is also expected to generate an effective barrier to connectivity between the northern and southern Coral Sea. Moreover, the large distances separating reefs will likely constrain connectivity both among reefs within the CSMP and to reefs in other regions. Resolving patterns of connectivity is important for the effective management of the CSMP, but also for establishing the importance of the Coral Sea within the broader biogeographical context.

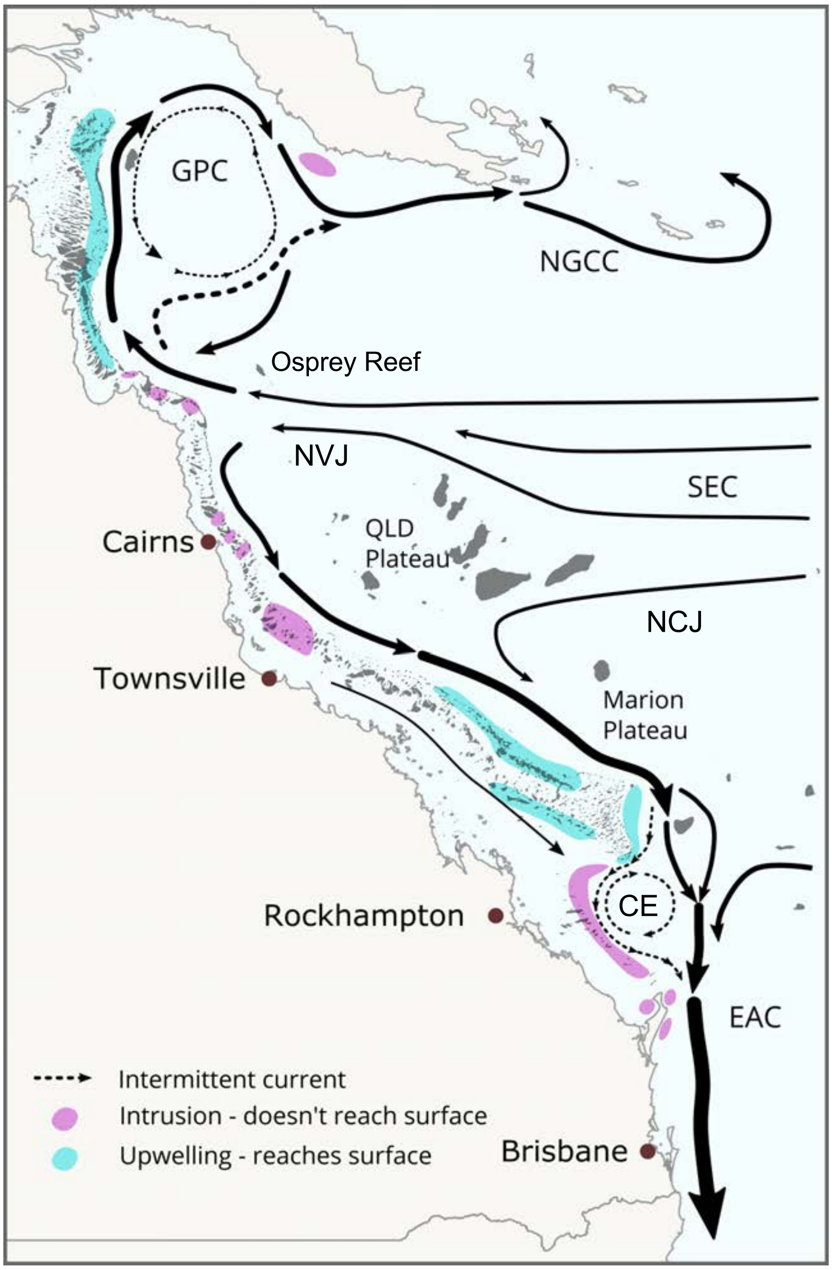

Figure 1.1. Prevailing surface currents in the Coral Sea and adjacent biogeographical provinces. GPC – Gulf of Papua current, NGCC – New Guinea Coastal Current, NVJ – North Vanuatu Jet, NCJ – New Caledonia Jet, SEC – South Equatorial Current, CE – Capricorn Eddy, EAC – East Australian Current. Source: Craig Stienberg and Eric Lawrey (2018) eatlas.org.au

1.2 Connectivity

There are two predominant approaches to investigate connectivity across marine seascapes; i) coupled biological-oceanographic models (e.g., Condie et al. 2005), and ii) extensive sampling of specific species over large areas to explore genetic structure (e.g., Williamson et al. 2016). Coupled biological-oceanographic models (biophysical models), such as CONNIE (http://www.csiro.au/connie), describe connectivity patterns by simulating the movement of passive particles based on major hydrodynamic features or hydrodynamic models. These have become increasingly sophisticated, with detailed spatial resolution of oceanographic processes (Bode et al., 2019), as well as incorporating knowledge of larval biology and behaviour. However, the accuracy and relevance of biophysical models, as well as underlying hydrodynamic models, requires significant validation and testing (e.g., Swearer et al. 2019).

Genetic tests of population connectivity (e.g., Williamson et al. 2016) rely on estimates of genetic diversity within and among populations to estimate the degree of gene flow. Genetic connectivity is thus, the degree to which gene flow affects ecological and evolutionary processes (Lowe and Allendorf 2010). However, measuring genetic connectivity requires the comprehensive sampling of populations, and is very sensitive to the nature and type of genetic marker being used (DiBattista et al. 2017). To improve resolution and accuracy, genetic connectivity is increasingly being assessed using next-generation sequencing technologies (e.g., ddRAD, DArTseq) to test for differences across large regions of a species' genome and also explore selective changes among populations (DiBattista et al. 2017). Ultimately, it is the combination of both biophysical models and analyses of genetic structure that best advance understanding of connectivity (e.g., DiBattista et al. 2017; Bode et al., 2019).

1.3 *In situ* measurements

The development and improvement of both biophysical and underlying hydrodynamic models is fundamentally reliant on observational data, requiring *in situ* measurements of environmental conditions over extended periods at a wide range of different locations. Critically, time series of relevant environmental variables (e.g., temperature, salinity or current flow) are necessary to calibrate and/or validate regional-scale models. Without calibration and validation, regional-scale models of hydrodynamics often fail to capture important and unique processes specific to each location (Bode et al. 2019).

At present, CONNIE (http://www.csiro.au/connie) is the best available model for simulating the dispersal of larvae from reefs in the CSMP, as well as for assessing connectivity between the CSMP and GBR (Hoey et al. 2020). Using this model, it appears there is widespread, but relatively weak connectivity patterns in the CSMP, and between the CSMP and the GBRMP (Figure 1.2). However, there are several potential issues with this model. Most notably, the Great Barrier Reef 4 km (GBR4) resolution model (https://research.csiro.au/ereefs/models/model-outputs/gbr4), which forces CONNIE, does not encompass the entire geographical extent of the Coral Sea. There are available options to extend the model domain by using alternative hydrodynamic models with even coarser resolution (10 km) such as Hycom (hycom.com) or BRAN2016 (e.g. Bluelink ReANalysis – BRAN; Oke et al. 2008). However, like GBR4, these models have not been calibrated nor validated in the CSMP.

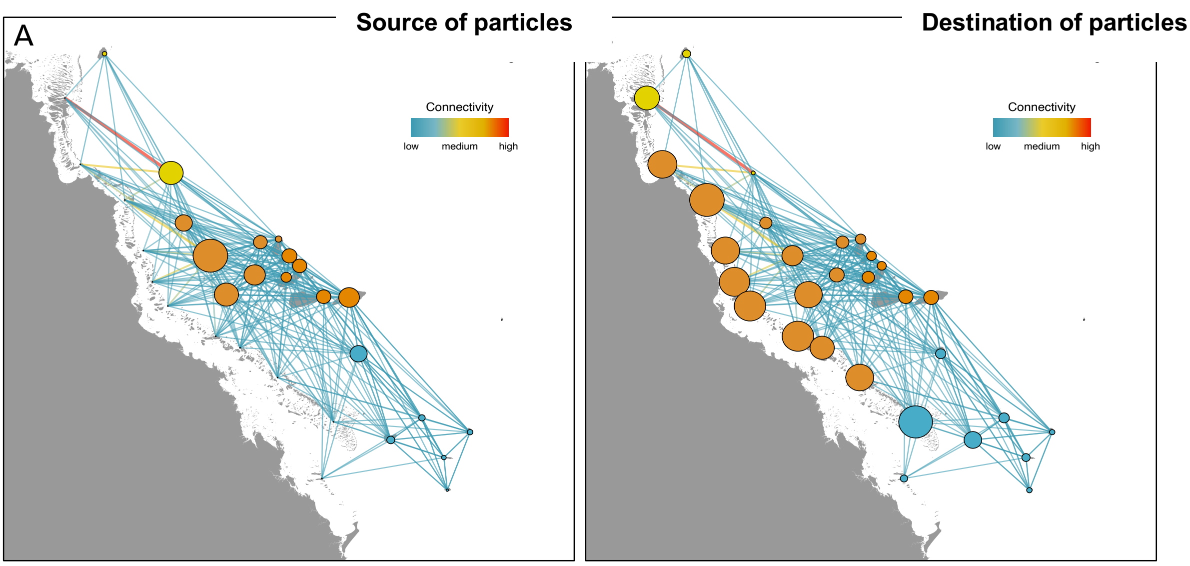

Figure 1.2 Predicted connectivity patterns based on biophysical modelling of larval dispersal (using CONNIE) for 20 source reefs in the Coral Sea Marine Park between 2010 and 2017. The degree of connectivity among individual reefs is represented by lines, with coloured nodes indicating important source (a) and sink (B) reefs.

While unequivocally focussed on understanding the hydrodynamics of the GBR, GBR4 encompasses much of the western Coral Sea and in particular, the Queensland Plateau (Steven et al. 2019). This increased geographical scope was intended to improve downscaling of global circulation models and better capture medium-scale processes that influence the hydrodynamics along the outer edge of the GBR (Steven et al. 2019). Even so, it is acknowledged that there is very sparse observational data to constrain the GBR4 model, especially in the Coral Sea. Relevant observational data for GBR4 is largely concentrated in near shore environments and at select reefs along the GBR (e.g., IMOS observation locations), with most observational data coming from very shallow (<2 m deep) environments (Herzfeld et al. 2016).

1.4 Objectives and scope

While there are oceanographic and water circulation models available for the Coral Sea (most notably, GBR4), the resolution of these models is generally too coarse to resolve reef-scale processes. More importantly, these hydrodynamic models are not calibrated for the CSMP, largely due to lack of *in situ* measurements. To address this gap, we deployed >50 Marotte HS (high sampling rate) drag and tilt current meters at key locations throughout the CSMP and at comparable locations on the Great Barrier Reef. These current meters not only provide important data to calibrate and validate existing hydrodynamic models, but also help to resolve fine-scale differences (and deviations) in environmental conditions. Such fine-scale variation is particularly relevant for understanding the potential transport and connectivity between reefs and the retention of water masses in the vicinity of reefs. This information is also critically important for reconciling fine-scale patterns in temperature, which may influence the incidence and severity of coral bleaching during marine heatwaves (e.g., McClanahan et al. 2007).

2. Methods

A total of 84 Marotte HS (http://www.marinegeophysics.com.au/current-meter) drag and tilt current meters (recording flow velocity and direction, and temperature) were deployed during the course of this study, which was conducted in parallel with the *Coral Reef Health in the Coral Sea Marine Park* research project (Hoey et al. 2020). The multi-year research and monitoring project (2018-2020) was fundamental in providing the opportunity to re-visit reefs and sites every 1-2 years to facilitate deployment and retrieval of instruments. However, the Marotte current meters can only record flow and temperature for 3 months (due to limited battery life and also inevitable fouling that changes the performance of the instrument). As such, current meters deployed during standard monitoring expeditions in February-March would fail to record local conditions during peak temperatures in the subsequent summer period, thereby limiting the utility of these data in reconciling fine-scale variation in the incidence and severity of coral bleaching. To redress this issue, we undertook additional deployment trips at the start of summer (November-December) in both 2019 and 2020, deploying current meters at Osprey and Bougainville, and at other nearby locations on the GBR (Table 2.1). These trips were largely opportunistic, and partly facilitated by tourism operators, thereby restricting the range of reefs and sites where current meters could be deployed.

In all, current meters were deployed at 14 reef across the CSMP (Figure 2.1) during 8 separate field trips (Table 2.1); December 2018 (Cato, Wreck, Saumarez, and Kenn Reefs), February 2019 (Saumarez, Frederick, and Flinders Reefs), March 2019 (Holmes and Bougainville Reefs), October 2019 (GBRMP: No Name and Yonge Reefs) and December 2019 (Bougainville and Osprey Reefs), February 2020 (Saumarez, Cato, Wreck and Frederick, Flinders), March 2020 (Moore and Holmes), and November 2020 (Bougainville, Osprey, North Direction, Eagle Island, Lizard Island). Current meters were deployed at select sites that best captured the latitudinal extremes (e.g., northernmost and southernmost tip) of each reef, though site selection was often constrained by prevailing weather. Additional loggers were also deployed in the entrance to lagoons and in reef passes, to measure water flow and temperature in areas where local features are likely to cause anomalous environmental conditions. We also prioritised the deployment of current meters at recurrent monitoring sites to maximise the opportunity to retrieve the instruments. At each site, current meters were generally deployed at two depths; shallow (3-8m) and deep (8-15m).

Table 2.1. Location and timing for the deployment of 84 Marotte HS drag and tilt current meters, which measure flow velocity and direction, as well as temperature. Current meters were deployed at multiple reefs within the Coral Sea Marine Park (CSMP) and at select locations within the Great Barrier Reef Marine Park (GBRMP). Current meters were retrieved up to 2 years after they were deployed, but only data from the first 3-months immediately after deployment was used. Where date of retrieval is blank, these current meters were lost (often broken off at the basal tip of the logger) or yet to be retrieved.

Logger	Marine Park	Reef	Latitude	Longitude	Depth (m)	Date Deployed	Date Retrieved
1430	CSMP	Cato	-23.24763	155.53525	10.0	5/12/18	19/2/20
1366	CSMP	Cato	-23.24763	155.53525	5.0	5/12/18	19/2/20
1437	CSMP	Cato	-23.24406	155.54829	10.0	5/12/18	19/2/20
1423	CSMP	Wreck	-22.17814	155.17674	7.5	6/12/18	20/2/20
1434	CSMP	Wreck	-22.17814	155.17674	2.0	6/12/18	
1427	CSMP	Saumarez	-21.87617	153.65356	15.0	7/12/18	17/2/19
1452	CSMP	Saumarez	-21.87617	153.65356	3.0	7/12/18	17/2/19
1426	CSMP	Kenn	-21.20459	155.77238	3.0	11/12/18	21/2/20
1428	CSMP	Kenn	-21.20459	155.77238	8.0	11/12/18	21/2/20
1623	CSMP	Frederick	-21.01130	154.35043	11.5	17/2/19	22/2/20
1626	CSMP	Frederick	-21.01130	154.35043	2.5	17/2/19	22/2/20
1429	CSMP	Saumarez	-21.87617	153.65356	15.0	17/2/19	18/2/20
1451	CSMP	Saumarez	-21.87617	153.65356	3.0	17/2/19	
1439	CSMP	Flinders	-17.53675	148.55112	9.3	27/2/19	28/2/20
1447	CSMP	Flinders	-17.53675	148.55112	3.4	27/2/19	
1159	CSMP	Holmes East	-16.41015	148.01141	11.0	14/3/19	9/3/20
1364	CSMP	Holmes East	-16.41015	148.01141	4.5	14/3/19	9/3/20
1452	CSMP	Bougainville	-15.49273	147.08638	4.0	15/3/19	6/12/19
1424	CSMP	Bougainville	-15.49273	147.08638	14.0	15/3/19	6/12/19
1432	CSMP	Bougainville	-15.48139	147.10422	8.0	15/3/19	10/3/20
1431	CSMP	Osprey	-13.80140	146.54640	5.0	16/3/19	
1440	CSMP	Osprey	-13.80140	146.54640	14.0	16/3/19	8/12/19
1436	CSMP	Osprey	-13.88078	146.55881	17.0	17/3/19	7/12/19
1555	GBRMP	Lizard Island	-14.64499	145.45356	7.5	24/10/19	16/3/20

1562	GBRMP	Lizard Island	-14.64499	145.45356	5.5	24/10/19	16/3/20
1543	GBRMP	North Direction	-14.74078	145.50628	6.9	25/10/19	Feb-20
1553	GBRMP	North Direction	-14.74078	145.50628	3.0	25/10/19	Feb-20
1422	GBRMP	No Name North	-14.64499	145.45356	12.3	27/10/19	Feb-20
1442	GBRMP	No Name North	-14.64499	145.45356	4.8	27/10/19	Feb-20
1325	GBRMP	No Name South	-14.65974	145.64759	10.1	27/10/19	Feb-20
1453	GBRMP	No Name South	-14.65974	145.64759	3.9	27/10/19	Feb-20
1421	GBRMP	Yonge North	-14.57038	145.61683	3.6	27/10/19	Feb-20
1425	GBRMP	Yonge North	-14.57038	145.61683	9.0	27/10/19	Feb-20
1544	CSMP	Bougainville	-15.51182	147.13219	11.8	6/12/19	10/3/20
1546	CSMP	Bougainville	-15.51182	147.13219	7.8	6/12/19	10/3/20
1558	CSMP	Bougainville	-15.51895	147.12624	6.9	6/12/19	10/3/20
1559	CSMP	Bougainville	-15.49273	147.08638	14.0	6/12/19	10/3/20
1563	CSMP	Bougainville	-15.51922	147.12646	15.2	6/12/19	10/3/20
1519	CSMP	Osprey	-13.89183	146.55296	6.2	7/12/19	
1551	CSMP	Osprey	-13.88078	146.55881	17.0	7/12/19	11/3/20
1552	CSMP	Osprey	-13.88700	146.55690	6.1	7/12/19	11/3/20
1554	CSMP	Osprey	-13.89183	146.55296	15.6	7/12/19	11/3/20
1557	CSMP	Osprey	-13.88700	146.55690	13.4	7/12/19	11/3/20
1528	CSMP	Osprey	-13.80093	146.54893	13.1	7/12/19	11/3/20
1549	CSMP	Osprey	-13.80140	146.54640	5.0	8/12/19	11/3/20
1556	CSMP	Osprey	-13.80140	146.54640	14.0	8/12/19	11/3/20
1560	CSMP	Osprey	-13.80093	146.54893	5.4	8/12/19	11/3/20
1561	CSMP	Osprey	-13.80140	146.54640	10.5	8/12/19	11/3/20
1622	CSMP	Saumarez	-21.87617	153.65356	3.0	18/2/20	
1625	CSMP	Saumarez	-21.87617	153.65356	15.0	18/2/20	6/2/21
1624	CSMP	Cato	-23.24763	155.53525	10.0	19/2/20	
1627	CSMP	Cato	-23.24763	155.53525	5.0	19/2/20	
1620	CSMP	Wreck	-22.17814	155.17674	2.0	20/2/20	
1621	CSMP	Wreck	-22.17814	155.17674	7.5	20/2/20	7/2/21
1427	CSMP	Frederick	-21.01130	154.35043	2.5	22/2/20	
1433	CSMP	Frederick	-21.01130	154.35043	11.5	22/2/20	9/2/21
1636	CSMP	Flinders	-17.53675	148.55112	3.4	28/2/20	
1640	CSMP	Flinders	-17.53675	148.55112	9.3	28/2/20	16/2/21

1632	CSMP	Moore	-15.88657	149.15158	3.0	7/3/20	
1642	CSMP	Moore	-15.88657	149.15158	9.0	7/3/20	
1634	CSMP	Holmes	-16.52613	147.80701	2.9	9/3/20	
1639	CSMP	Holmes	-16.52613	147.80701	8.7	9/3/20	
1422	CSMP	Bougainville	-15.48066	147.10858	6.9	24/11/20	22/2/21
1442	CSMP	Bougainville	-15.51922	147.12646	16.0	24/11/20	22/2/21
1552	CSMP	Bougainville	-15.49282	147.08649	5.6	24/11/20	22/2/21
1556	CSMP	Bougainville	-15.49282	147.08649	15.0	24/11/20	22/2/21
1558	CSMP	Bougainville	-15.51895	147.12624	7.4	24/11/20	22/2/21
1638	CSMP	Bougainville	-15.48066	147.10858	17.2	24/11/20	22/2/21
1425	CSMP	Osprey	-13.80093	146.54893	13.9	25/11/20	24/2/21
1515	CSMP	Osprey	-13.88700	146.55690	15.1	25/11/20	24/2/21
1528	CSMP	Osprey	-13.80140	146.54640	16.1	25/11/20	24/2/21
1549	CSMP	Osprey	-13.89183	146.55296	16.9	25/11/20	24/2/21
1551	CSMP	Osprey	-13.80140	146.54640	7.6	25/11/20	24/2/21
1557	CSMP	Osprey	-13.89183	146.55296	6.9	25/11/20	23/2/21
1559	CSMP	Osprey	-13.80093	146.54893	8.1	25/11/20	23/2/21
1560	CSMP	Osprey	-13.88700	146.55690	6.0	25/11/20	
1453	GBRMP	Nth Direction	-14.74188	145.50558	6.5	26/11/20	26/2/21
1546	GBRMP	Nth Direction	-14.74960	145.5138	12.2	26/11/20	26/2/21
1554	GBRMP	Nth Direction	-14.74960	145.5138	5.3	26/11/20	26/2/21
1562	GBRMP	Nth Direction	-14.74188	145.50558	4.1	26/11/20	26/2/21
1544	GBRMP	Eagle	-14.73390	145.37893	12.5	27/11/20	26/2/21
1555	GBRMP	Eagle	-14.73390	145.37893	7.2	27/11/20	26/2/21
1553	GBRMP	Lizard Island	-14.74487	145.45445	12.4	29/11/20	26/2/21
1563	GBRMP	Lizard Island	-14.74487	145.45445	7.4	29/11/20	26/2/21

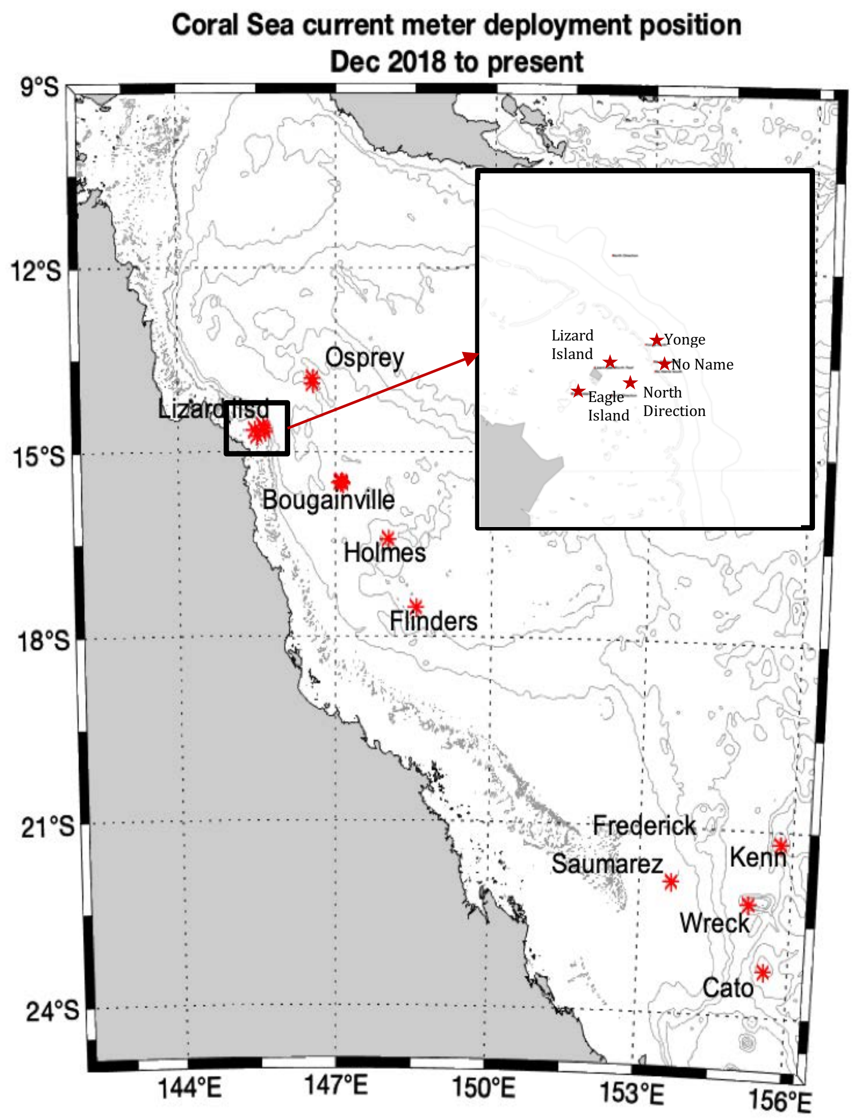

Figure 2.1. Map showing the locations of the 14 reefs where the current meters were deployed between December 2018 and March 2021.

To compare *in situ* data obtained from the extensive and recurrent deployments of Marotte HS current meters, with GBR4 model predictions of current velocities and directionality, we extracted relevant modelled data for each of the major deployment periods (e.g., summer 2019/2020). Importantly, the areal extent of reefs where current meters were deployed is entirely encompassed within the geographical extent of the GBR4 hydrodynamic model (Figure 2.2). Regional conditions also varied between years that current meters were deployed. There were weaker than normal wind fields (especially in the northern Coral Sea) and relatively weak surface currents in 2019-2020 and 2020-2021 (Figure 2.2).

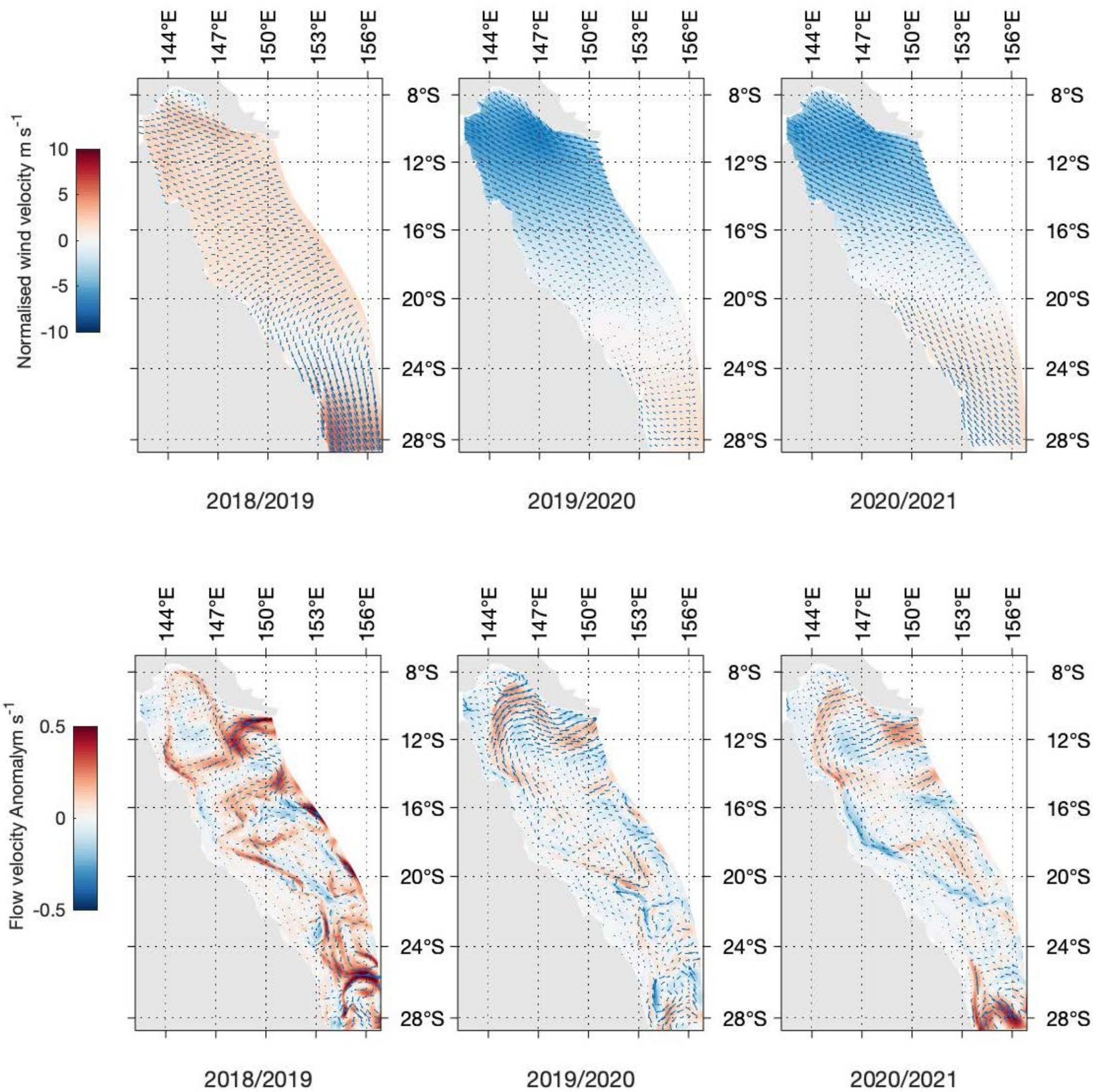

Figure 2.2. Coral Sea wind (top) and surface circulation (bottom) anomalies for summer (November to March) if 2018-2019, 2019-2020 and 2020-2021. Typical conditions for wind and surface circulation were computed based on the 10 year average using eReefs GBR4 (https://research.csiro.au/ereefs/models/model-outputs/gbr4). Conditions for relevant summer periods are then presented as differences (anomalies) relative to the 10-year climatology.

2.1 Deployment of current meters

Marotte HS current meters were deployed by hammering a 600 mm long (12 mm diameter) stainless steel stake into the reef matrix. The current meters were then attached to a triangular loop on the upper end of the stake using a heavy duty (7.6 mm wide) cable tie, allowing the current meter to tilt freely on the pre-attached quick chain link. A 30 mm long nylon safety tether (securing the current meter directly to the shaft of the spike) was also fitted, mainly to retain current meters during deployment (Figure 2.2). Of the 84 instruments deployed during this study, 8 went missing. These current meters mostly broke at the basal tip of the plastic housing, such that the tip was still attached to the stake. Mostly, it was the current meters that were deployed in shallow environments that were broken and therefore, lost, whereas devices deployed at the same sites, but in deeper water were found intact and successfully retrieved. This likely reflects the higher exposure to extreme weather conditions and wave action in shallow reef environments in the Coral Sea. It is currently unknown what level of wave forcing is required to break these current meters.

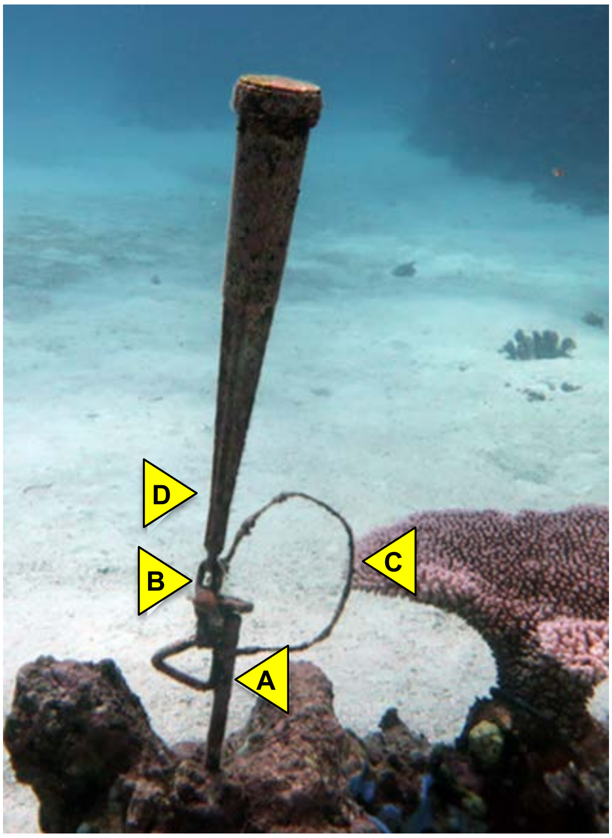

Figure 2.2 Marotte HS drag and tilt current meter deployed on the reef, showing A) stainless steel stake that is hammered into the reef matrix, and triangular loop welded to the shaft of the stake, B) quick chain link, which allows the current meter to tilt, C) nylon tether, and D) plastic housing and predominant location where lost current meters had broken away from the point of attachment. Photo: Martin Russell

Of the current meters that went missing, one was later found in the Keppel Islands (off Curtis Island) by researchers from JCU. This current meter was originally deployed at Wreck Island. The transit of this current meter from the Coral Sea to the inner GBR, provides a unique demonstration of the potential connectivity between these systems. While it is unknown when the current meter became detached, it was deployed at Wreck Island on the 20th of February 2020 and found in the Keppel Islands in early April 2021.

2.2 Data analysis and storage

Marotte HS current meters record current speed based on the extent to which the current meter is tilted from the basal point of attachment, whereby the angle of tilt has been carefully calibrated to reflect the velocity of water movement. The current meter also records the orientation of tilt, and thereby water movement, using an in-built compass. Current meters were set to record current speed and direction at 1-3 second intervals.

Following retrieval of current meters, the batteries were immediately removed and individual SD cards were stored separately. All data was then extracted using the Marotte HS software (https://www.marinegeophysics.com.au/software). This data was subsequently averaged across 10 minute intervals to smooth out high frequency fluctuations in velocity and focus on longer term trends in current flow. The data for each instrument was then saved as a CSV table and imported into Matlab for further analyses. Maps of velocity were created using the m_map package in Matlab. All CSV files are also stored, and publicly accessible, via the Tropical Data Hub hosted by James Cook University (https://research.jcu.edu.au/data/default/rdmp/home). Data pertaining to each current meter is labelled using the logger number, reef name, site details and date of deployment, as per Table 2.1.

Data from Marotte HS current meters were directly compared to data generated from the GBR4 hydrodynamic model. No formal statistical comparisons were conducted. Rather comparable time series data from both the current meters and the GBR4 model were plotted and compared visually.

3. Findings

Data extracted and analysed from the deployment of Marotte HS current meters reveals considerable fine-scale variation in velocity and direction of water currents, as well as for water temperature. Most current meters were intentionally deployed late in the year (November-December) to record environmental conditions during the subsequent 3-months of increasing temperature. Accordingly, most of the time series do reveal sustained increases in temperature over the subsequent summer months (Appendix 1). The maximum temperatures recorded often exceeded 31°C, especially in 2019-2020 (Table 3.1). However, the inexorable rise in summer-time temperatures (e.g., Figure 3.1) was punctuated with periods of cooling (often coinciding with increasing current velocity, indicative of local storms activity) and conspicuous short-term (e.g., diurnal) temperature excursions. At Bougainville Reef, for example, there were periodic intrusions of both cool water and warm water that occurred at all sites (Figure 3.2), but were asynchronous. Similar patterns were also observed at Osprey Reef, and may be broadly reflective of the variable conditions that occur along the steep outer slopes of CSMP reefs, though we are yet deploy current meters on the outer slope of most other reefs.

Intrusions of cooler water (up to 2.5 °C cooler) were especially pronounced in deeper water (> 10m depth). Given these cool water intrusions were most pronounced at depth, they are likely driven by upwellings, and although relatively short-lived would decrease any heat stress and potential mediate coral bleaching on corals in these areas. Conversely, intrusions of warmer water (up to 2.7 °C warmer) are most apparent in shallow reef environments, and mainly on north-west corner Bougainville Reef (Site 1). These warm-water intrusions are likely generated by shallow reef flat or lagoonal water flowing over the reef crest, and may conflate heat stress during marine heatwaves. However, exposure to fluctuating temperatures might also pre-condition corals to elevated temperatures, and thereby moderate bleaching responses during severe heatwaves (*sensu* Safaie et al. 2018).

Table 3.1. Summary of environmental data, including predominant current velocity (cm/s) and direction (heading, degrees), and temperature (average, minimum and maximum; °C) recorded by deploying Marotte HS current meters in the CSMP and on the GBR (see Figure 2.1 for location of reefs). Instances where the maximum recorded temperatures exceeded 31 °C are shown in red. Data is organised by timing of deployment, whereby current meters deployed over the summer periods (indicated by the start and end dates in successive years) were generally deployed in November of December, and other current meters with start and end dates in the same year were deployed during February-March.

				Current		Temperature		
Year	Reef	Site	Depth	Velocity	Direction	Avg	Min	Max
2018-2019	Cato	Site 1 (SE)	5	9.8	43	26.7	25.2	28.4
2018-2019	Cato	Site 1 (SE)	10	10.2	257	26.5	22.4	28.6
2018-2019	Cato	Site 3 (Entrance)	10	13.9	353	26.7	25.2	28.2
2018-2019	Kenn	Site 4	3	13.6	19	26.9	25.7	28.4
2018-2019	Kenn	Site 4	8	10.5	233	27.2	25.5	29.3
2018-2019	Saumarez	Site 2 (East)	15	19.4	242	27.5	22.7	31.9
2018-2019	Saumarez	Site 2 (East)	15	12	357	28.0	26.3	29.9
2018-2019	Wreck	West Islet	7.5	13.9	236	26.9	25.9	28.1
2019	Bougainville	Site 6 (NE)	8	12.5	235	27.7	25.6	29.7
2019	Flinders	Site 7 (NW)	9.3	16.8	27.5	28.3	27.3	29.3
2019	Frederick	Site 1 (N)	2.5	11.8	267	27.7	26.0	30.0
2019	Frederick	Site 1 (N)	12	7.4	282	27.7	26.3	29.1
2019	Holmes	East	11	16.1	29	28.9	28.2	29.4
2019-2020	Bougainville	Site 1 (North)	4	19.4	5	28.4	27.1	32.6
2019-2020	Bougainville	Site 1 (North)	14	12.3	2	29.4	26.8	31.5
2019-2020	Bougainville	SE	7.8	29.3	29	29.6	27.2	31.5
2019-2020	Bougainville	SE	11.8	26.8	356	29.4	26.7	31.4
2019-2020	Bougainville	Southern point	6.9	28.3	238	29.5	27.1	31.5
2019-2020	Bougainville	Southern point	15.2	28.9	313	29.3	26.2	31.3
2019-2020	Lizard Is.	North Reef	5.5	25	44	28.5	25.2	31.5
2019-2020	Lizard Is.	North Reef	7.5	21.8	38	28.5	25.3	31.3
2019-2020	Lizard Is.	North Reef	12	13.6	103	29.4	27.6	30.8
2019-2020	No Name	North	4.8	40.9	246	26.7	25.3	29.3
2019-2020	No Name	North	12.3	35.5	254	26.9	25.1	29.5
2019-2020	No Name	South	3.9	32.4	233	27.0	25.4	29.1
2019-2020	No Name	South	10.1	35.5	254	27.1	25.6	28.9
2019-2020	Nth Direct	Site 1	3	17.1	257	28.6	25.4	32.2
2019-2020	Nth Direct	Site 1	5.5	13.9	292			
2019-2020	Osprey	Site 1 (NH)	14	22	273	28.3	26.8	30.0
2019-2020	Osprey	Site 6	17	22.3	294	28.3	26.8	29.8
2019-2020	Osprey	Site 1 (NH)	5	25.1	264	29.5	27.7	31.5
2019-2020	Osprey	Site 1 (NH)	14	19.6	44	29.3	27.2	31.0
2019-2020	Osprey	Site 6	17	22.5	279	29.3	26.5	30.9
2019-2020	Osprey	Ad Anchor	6.1	27.2	246	29.4	26.8	31.5
2019-2020	Osprey	Ad Anchor	15.6	20.3	36	29.3	26.7	31.1
2019-2020	Osprey	NE	5.4	18.4	258	29.4	27.6	31.7
2019-2020	Osprey	NE	13.1	21.7	258	29.4	27.5	31.5
2019-2020	Osprey	North Horn	10.5	14.5	350	29.4	27.8	31.0

2019-2020	Osprey	Round the bend	15.6	13	354	29.2	26.8	31.1
2019-2020	Yonge	North	9	27.9	233	26.7	24.6	29.2
2019-2020	Yonge	North	3.6	36.4	236	28.1	25.6	30.7
2020-2021	Bougainville	Site 1 (North)	6	12.7	39	29.2	26.9	30.8
2020-2021	Bougainville	Site 1 (North)	15	9.7	257	29.1	26.5	30.6
2020-2021	Bougainville	3 (Entrance)	7	11.3	250	27.8	27.0	28.4
2020-2021	Bougainville	3 (Entrance)	17	15.7	245	28.1	27.2	29.1
2020-2021	Bougainville	SE	16	27.7	286	27.6	27.0	28.1
2020-2021	Eagle Island	SE	7	11.8	263	29.5	27.6	31.0
2020-2021	Eagle Island	SE	12	13.6	328	29.4	27.6	30.8
2020-2021	Flinders	Site 7 (NW)	9	13.6	328	29.4	27.6	30.8
2020-2021	Nth Direct	North	4.1	18	280	29.4	27.4	31.1
2020-2021	Nth Direct	North	6.5	11.9	260	28.0	27.6	28.5
2020-2021	Nth Direct	South	5.3	10.7	259	29.2	27.3	30.8
2020-2021	Nth Direct	South	12.2	13.3	313	29.3	27.5	30.7
2020-2021	Osprey	Site 1 (NH)	7	21.9	41	29.6	27.7	31.5
2020-2021	Osprey	Site 1 (NH)	16.1	16.9	328	29.3	27.4	30.9
2020-2021	Osprey	Ad Anchor		22.8	256	29.3	26.7	30.6
2020-2021	Osprey	NE	8	29.2	253	29.9	27.7	32.0
2020-2021	Osprey	NE	14	29.2	253	29.3	27.4	32.0
2020-2021	Osprey	Round the bend	7	24.8	3	29.5	27.7	31.1
2020-2021	Osprey	Round the bend	17	13.8	0	29.1	26.6	30.7

Bougainville Reef is located in the northern Coral Sea in the path of the northern arm of the SEC, the North Vanuatu Jet. The current velocity and directionality of water flow recorded using current meters deployed during summer 2019-2020 at Bougainville Reef, are consistent with the predominance of strong flow originating from the east, as predicted by the summer-time strengthening of the SEC (Brinkman et al. 2002). Most notably, the highest current velocity (30-40 cm/s) was recorded at the south east corner of Bougainville Reef, which is likely to be much more exposed to the prevailing westward flowing currents (Figure 3.1), compared to current meters deployed at sites on the north-west and south-west corners, which are partly sheltered by the reef. Current flows recorded from shallower habitats were generally stronger than those recorded at greater (> 10m) depth, possibly due to contribution of wind forcing and wave energy.

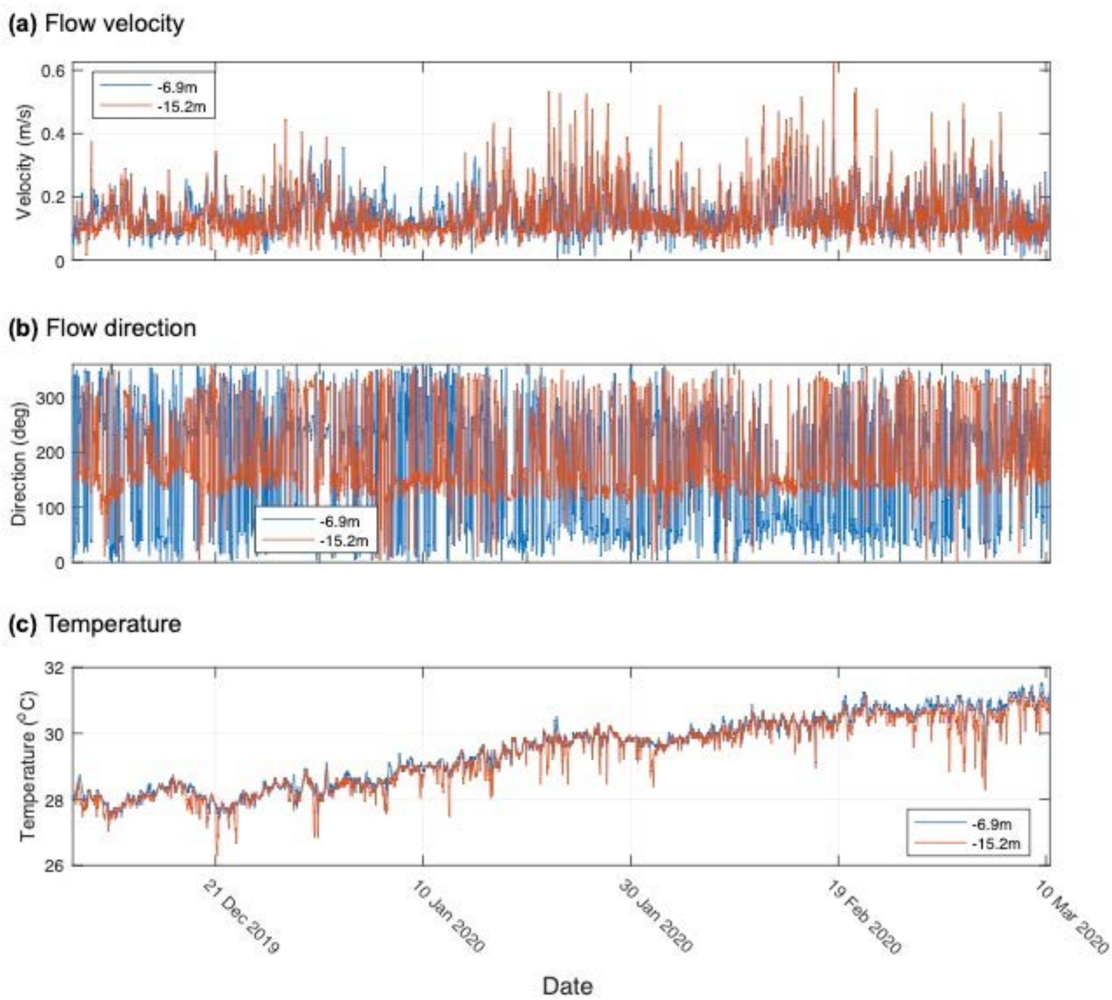

Figure 3.1 Time series data for (a) flow velocity, (b) flow direction, and (c) water temperature between depths (6.9m and 15.2m) on the south-east side of Bougainville Reef over a 3-month period (Dec 2019-Mar 2020). *Comparable figures for all sites are shown in Appendix 1*.

Currents recorded on the southernmost point of Bougainville Reef (originally labelled SE corner, though this is not the same as the SE site) were very different from those recorded at other sites, possibly reflecting refraction of current flow down the western edge of Bougainville Reef; the shallow current meter revealed a relatively weak and multi-directional flow, while the current flow recorded in the deeper (15.2 m depth) habitat was much stronger, and predominantly oriented to the north-west.

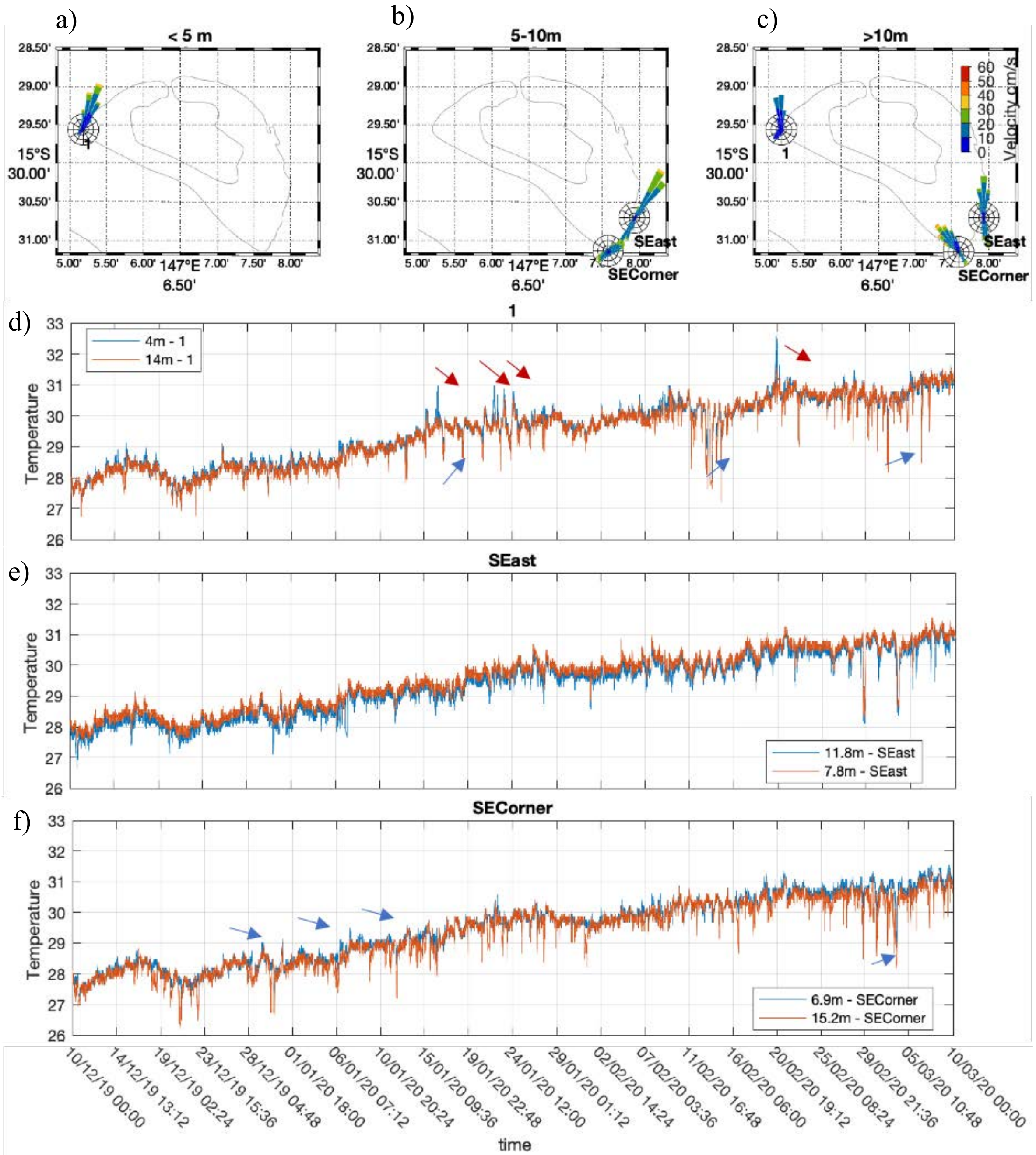

Figure 3.2. Environmental conditions (current flow and direction, and temperature) recorded using Marrote HS current meters at Bougainville Reef (December 2019 to March 2020). Velocity roses show the direction and velocity of current observed at three distinct sites around Bougainville during the December 2019 to March 2020 deployment and specific sampling locations that were a) <5m depth, b) 5-10m depth or c) >10m depth. Time series show the temperature observed at d) the NW corner, e) SE, and f) southernmost point. The blue arrows indicate cooler water intrusions, the red arrows indicate warmer water intrusions.

3.1 Comparisons of observed versus modelled conditions

A key contribution of this study is the increased availability of *in situ* data that may be used to calibrate (where necessary) and validate predictions of environmental conditions from existing hydrodynamic models that encompass large areas of the CSMP. Environmental data recorded using *in situ* current meters (temperature, velocity and direction) is therefore, directly compared against modelled data from eReefs GBR4 (https://research.csiro.au/ereefs/models/model-outputs/gbr4/) for specific locations and specific time periods.

For the 2019-2020 summer period, at the most exposed site (north-east) at Osprey Reef, there is generally strong alignment between observational data and modelled data for temperature (Figure 3.3). In particular, the GBR4 model effectively captures the general warming that occurred at this site over the period from December 2019 to March 2020. This is to be expected given that the GBR4 model assimilates satellite-derived measurements of sea surface temperature. However, there was a consistent negative bias in the modelled temperature data, whereby observed temperatures were 1 to 1.5 °C warmer than predicted (Figure 3.3.), especially in shallow water habitats. Modelled temperatures also failed to predict periodic intrusions of both cool and warm water, caused by specific physical features of the reef structure, which will be very hard to predict. For this location (which would be expected to be particularly exposed to the prevailing oceanic flow), the model over estimates current velocities by an average of 120 cm/s and fails to capture observed variability in current velocities and directionality (Figure 3.3).

Discrepancies between observational versus modelled environmental data are apparent across all sites at Osprey Reef (Figure 3.4) for the period December 2019 to March 2020. Most importantly, the GBR4 model consistently overestimates current velocities across all sites, failing to account for localised processes that not only moderate current flow, but lead to much higher than expected variability in the directionality of current flows. Similarly, time series data from the GBR4 model periodically deviates from the recorded conditions and poorly represents observed differences between depths within each location (Figure 3.5). These findings suggest that it will not be simple or straightforward to constrain existing model predictions to better reflect the observed stochasticity in currents (especially in terms of directionality). Rather, significant downscaling in hydrodynamic modelling will be required to explicitly account for the particular geomorphologic features and fine-scale processes affecting current flow at the interface of oceanic currents and coral reefs across the CSMP.

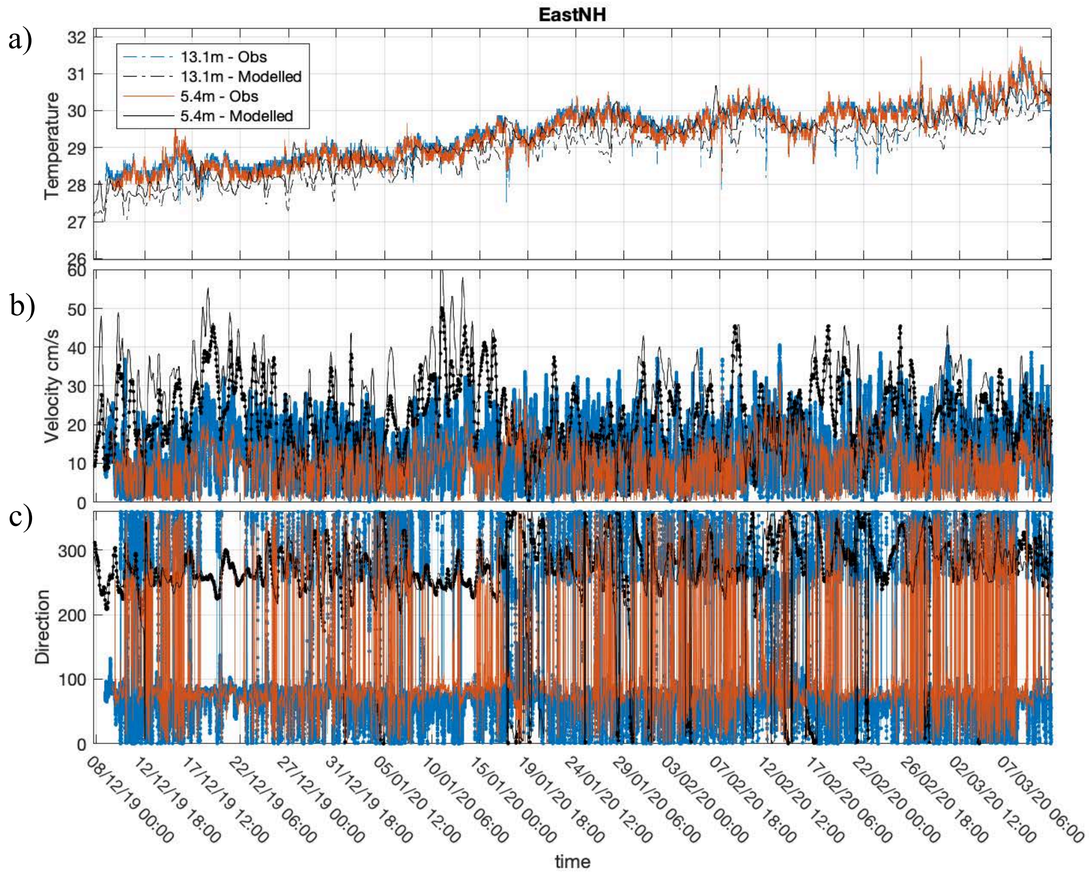

Figure 3.3. Comparison of the GBR4 model data to one site on the north-east side of Osprey Reef. Modelled data is represented in black. Data shown for a) temperature, b) velocity and c) direction are compared for two depths, at 13.1m and 5.4m.

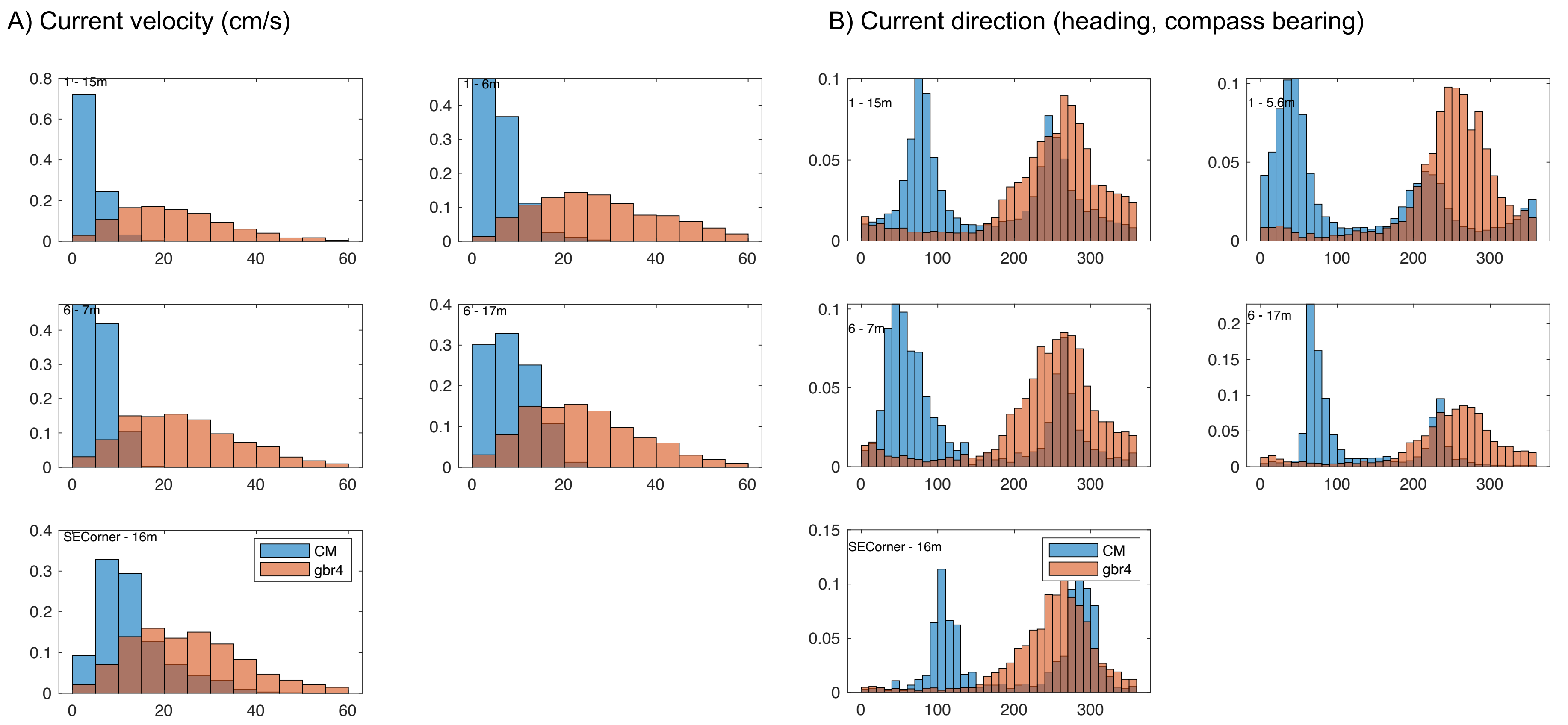

Figure 3.4. Comparisons of normalized velocity (A) and direction (B) for *in situ* data from current meters (in blue) and model predictions from GBR4 (jn red) for 5 sites around Osprey Reef. These comparisons highlight the marked discrepancies between observed versus modelled data, where by the current flows in near reef environments are much lower and direction of flow much more variable than predicted by the medium-scale (4 km) hydrodynamic model.

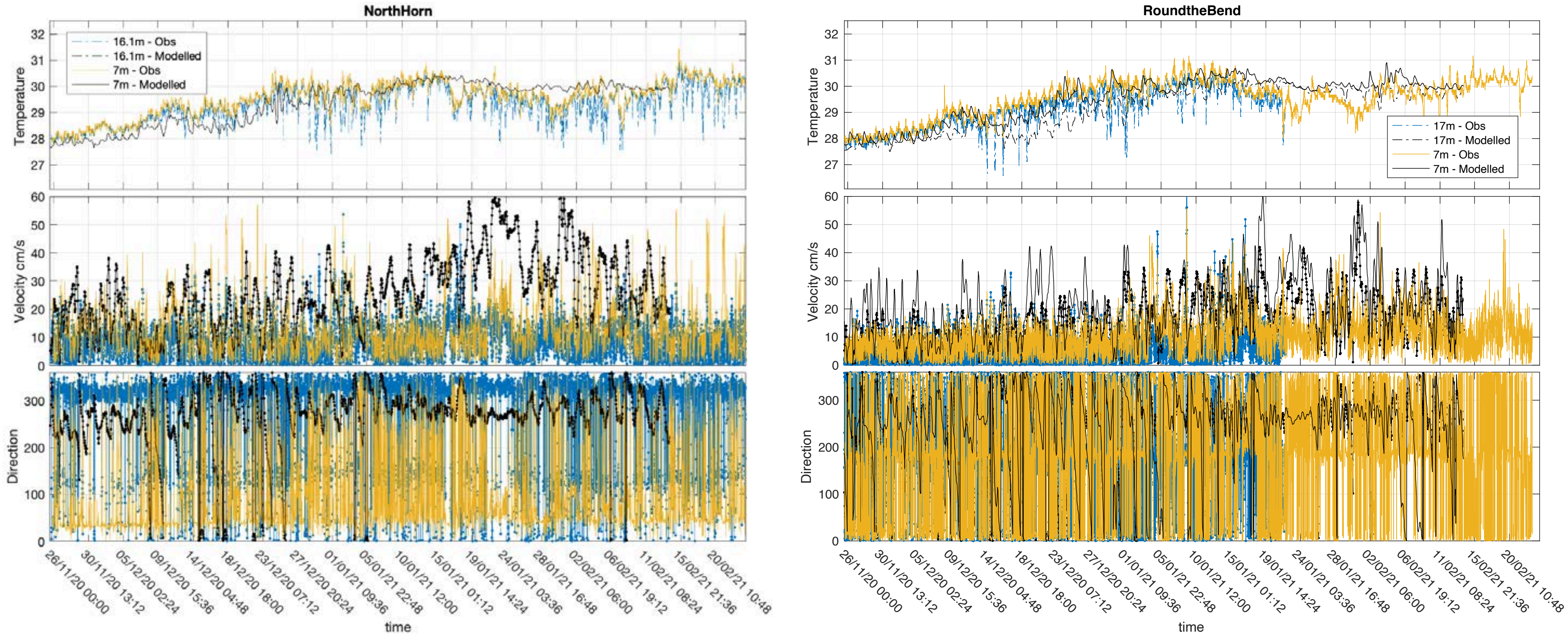

Figure 3.5. Time series of temperature, current velocity and direction for North Horn and Round the Bend at Osprey Reef, for *in situ* data form current meters (colored) and model predictions from GBR4 (jn black).

The presumed transit of the current meter that was originally deployed at Wreck Island, but became detached and was later retrieved at the Keppel Islands on the inshore GBR, provides a further opportunity to validate model predictions of connectivity (via biophysical models) between the CSMP and GBRMP. To account for uncertainties in the specific timing and duration of this transit, we explored the predicted destination for passive drifting particles released from Frederick and Wreck Reef, after a period of 50 days, averaged over multiple years (2010-2017). The overall extent of potential destinations for passively drifting particles released from reefs in the southern Coral Sea demonstrates that there is support for connections to the reefs in the southern GBR (Figure 3.6). In particular, there is potential intrusion of particles to nearshore reefs (such as the Keppel Islands), though these particles likely transit around the southernmost extent of the Swains Reefs (rather than through) and are then advected north by the Capricorn Eddy through the Capricorn Channel (Kleypas and Burrage 1994; Weeks et al. 2010). While there is a very low likelihood of particles released from the southern CSMP ending up on the inshore GBR (the most likely scenario is that particles are entrained and remain within the vicinity of these reefs), the likelihood might be enhanced in certain years and periods owing to the increased strength of the Capricorn eddy.

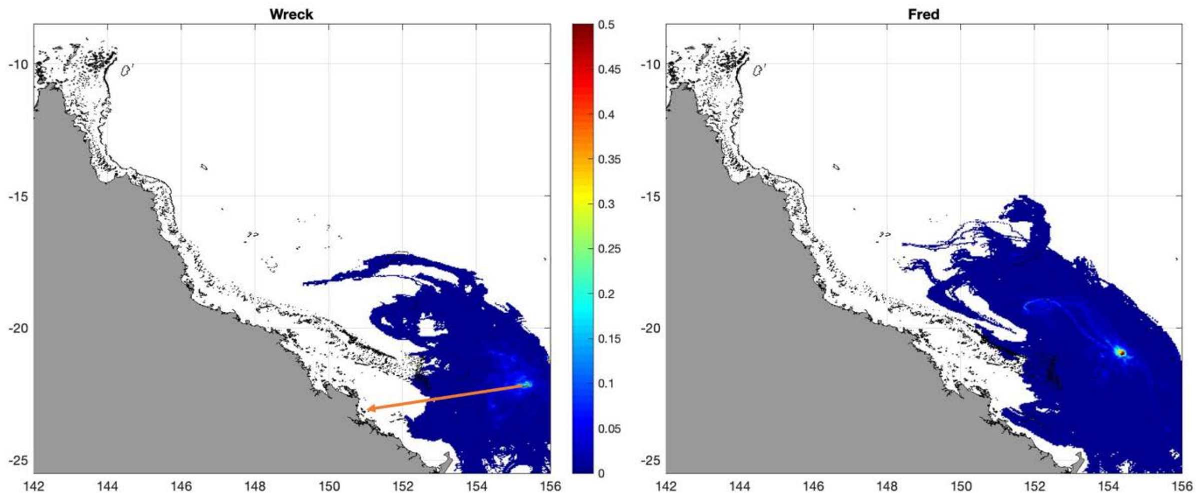

Figure 3.6. Heatmap showing the potential dispersal from reefs in the southern Coral Sea (specifically Wreck and Frederick Reefs) averaged over a 7-year period. Particles were released at new moon between October 2010 and September 2017 and followed for 50 days using CONNIE2, which is forced by GBR4. Arrow shows the minimum displacement distance for one of the current meters that become dislodged at Wreck Reef and was later discovered on the inner GBR.

3.2 Predicted connectivity

Despite inherent limitations of the GBR4 model, owing to the coarse resolution (4 km) which constrains the effective representation of geomorphologic features and fine-scale processes that are fundamental in understanding environmental conditions in shallow reef environments, this is the only operational model to force biophysical models (e.g, CONNIE2) for the CSMP. Also, the large-scale and necessarily coarser hydrodynamic models may provide significant insights into broad-scale patterns of inter-reef connectivity. We therefore, used archived data (2010-2017) to assess overarching patterns of connectivity among the individual reefs in the Coral Sea, as well as assessing connectivity to relevant sections of the GBR. Yearly connectivity matrixes (Figure 3.8) were constructed using the Leiden algorithm using Python 3 , following Tragg et al. (2019). The Leiden algorithm was used to define modularity (Figure 3.8) and resulting communities represent reefs that are well connected to each other and can be seen as self-contained ecological sub-regions.

Although there was apparent interannual variation in modelled patterns of connectivity, attributable to changes in current strength (see Figure 2.2), the essential structure of connectivity networks was essentially the same (Figure 3.8), reflecting the geographic proximity of reefs and predominant current flows among reefs and regions. For example, connections were often apparent among reefs (Cato, Frederick, Kenn, Saumarez, and Wreck) in the southern CSMP (Figure 3.7), which in turn sometimes exhibited connections with Marion Reef to the north, and the Capricorn Bunker group of reefs on the GBR, to the south (Figure 3.8). These reefs collectively formed a fairly distinct cluster (Figure 3.8). Reefs in the central CSMP were mostly connected with other reefs in the central CSMP, though levels of connection varied between years, and distinct clusters were sometimes apparent within this region (Figure 3.8).

Reefs in the northern CSMP exhibit the lowest levels of inter-reef connectivity. Most notably, no connectivity was reported between Osprey and Bougainville, (Figures 3.8 and 3.9), though there was reported connectivity between Osprey and

Ashmore. Osprey and Bougainville were also predicted to have moderate to strong connectivity with reefs in the northern GBR.

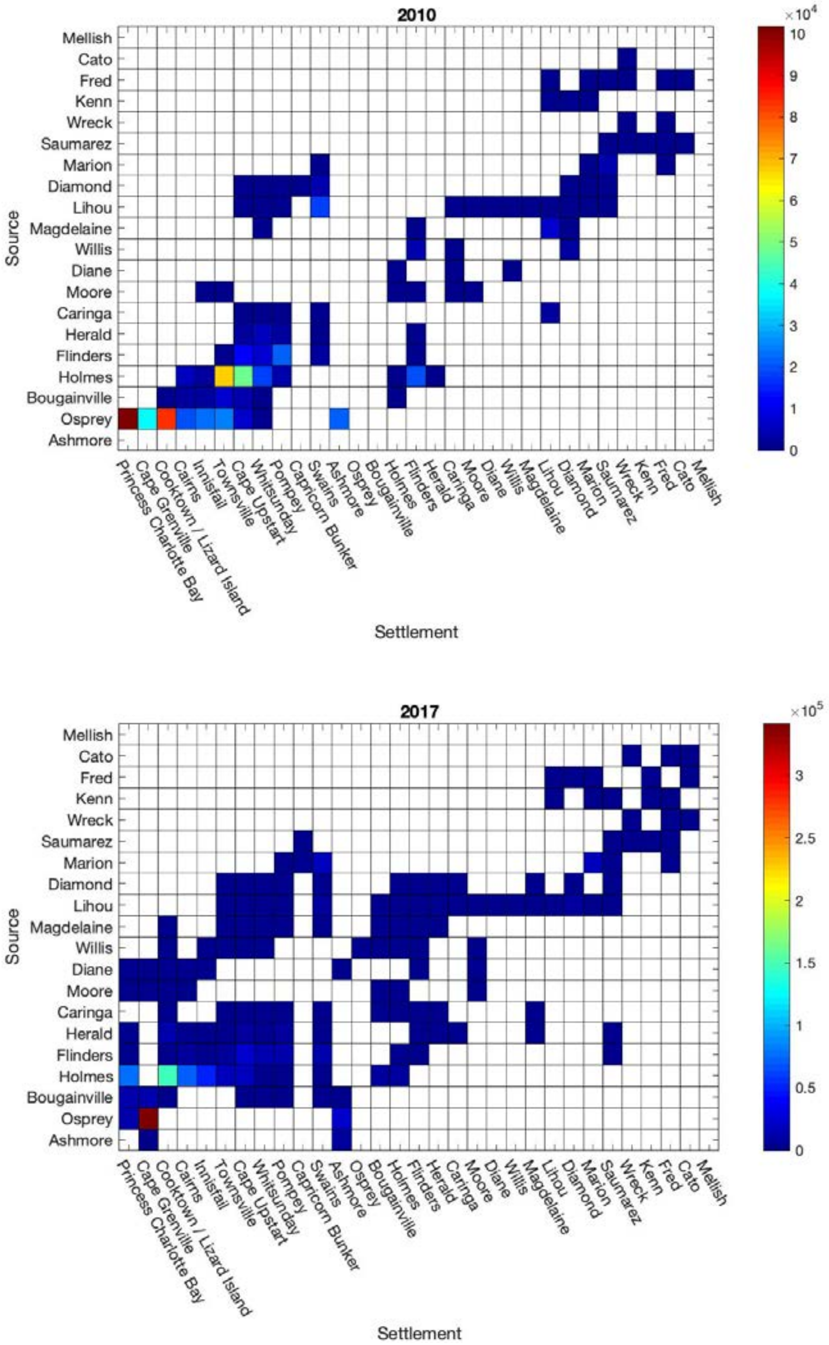

Figure 3.7. Connectivity matrices for Coral Sea reefs based on archived hydrodynamic data for 2010 versus 2017. Connectivity was assessed based on redistribution of passive particles over 50 days, using CONNIE2, which is forced by GBR4. Data for all years (2010 through 2017) is presented in Appendix II. Colours indicate the approximate number of particles (out of 2.5 x 10^6) released from each source reef that are likely to reach (and thereby potentially settle) at other reefs throughout the CSMP and on the GBR.

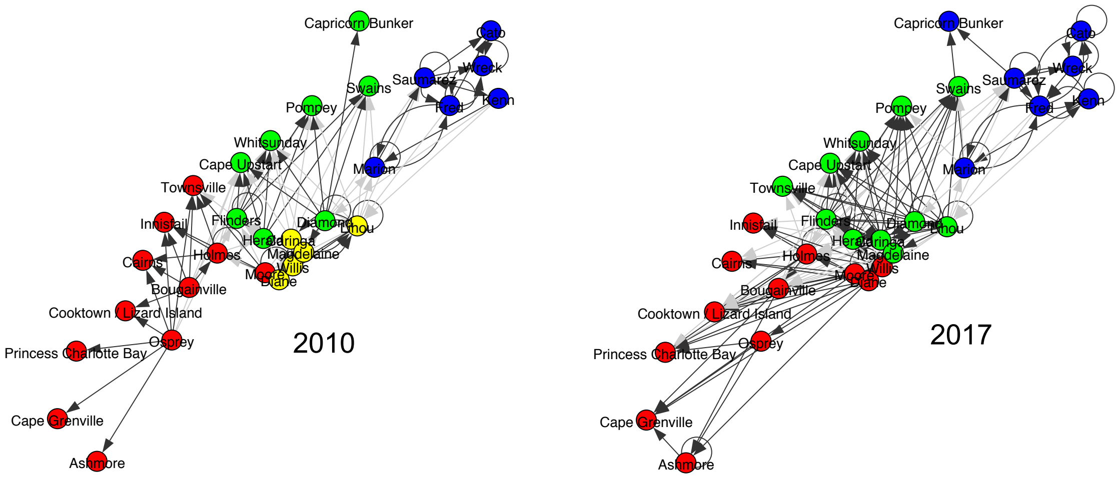

Figure 3.8. Comparative connectivity among Coral Sea reefs and comparable regions (e.g., Whitsundays versus Swains) on the GBR in 2010 versus 2017. Connectivity was assessed based on redistribution of passive particles over 50 days, using CONNIE2, which is forced by GBR4. Modularity was assessed using the Leiden algorithm which separates reefs into relatively well connected groups, which may be considered as self-contained ecological sub-regions. Colours indicate distinct clusters of reefs, based on relative connectivity.

3.2 Fine-scale temperature fluctuations and coral bleaching

The most conspicuous feature of the multi-year *Coral Reef Health in the Coral Sea Marine Park* research and monitoring project (Hoey et al. 2020), was the widespread incidence of mass coral bleaching in 2020 (Hoey et al. 2020). Mass coral bleaching had been recorded in the CSMP prior these surveys (in 2016 and 2017), and was one of the factors that motivated recurrent sampling throughout 2018-2020. However, coral bleaching recorded in 2016 and 2017 was relatively moderate (Harrison et al. 2018, 2019), especially compared to mass-bleaching recorded in 2020 (Hoey et al. 2020), reflecting differential levels of heat stress (Figure 3.9), measured as Degree Heating Weeks (DHW). Virtually the entire geographical extent of the Coral Sea was exposed to > 8 DHW in 2020, with the highest levels of heat stress occurring in the southern and central Coral Sea, where 12 to 14 DHW were recorded. By comparison, heat stress in 2016 and 2017 was mostly concentrated in the northern and central Coral Sea, and most reefs experienced < 8 DHW.

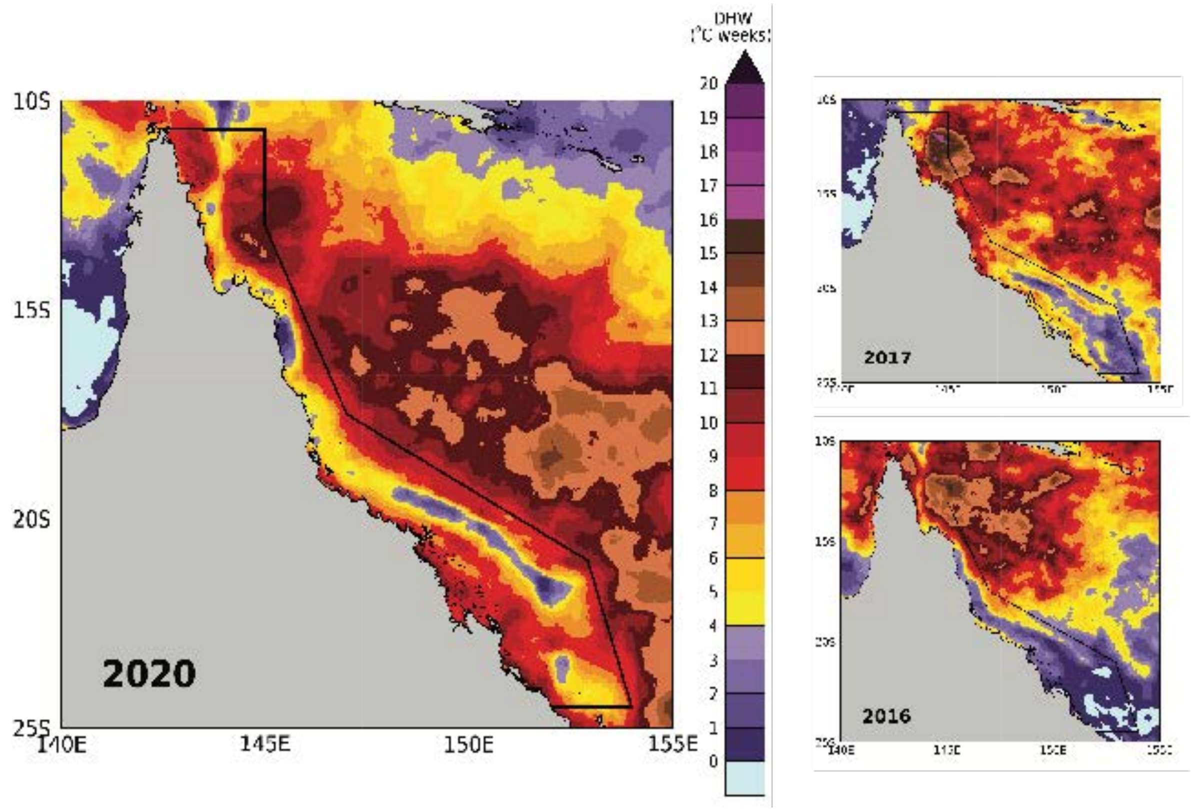

Figure 3.9. Annual maximum thermal stress (Degree Heating Week, DHW) for the three most recent major bleaching events in the Coral Sea: 2016, 2017 and 2020. SST data from NOAA Coral Reef Watch (https://coralreefwatch.noaa.gov).

The extent of coral bleaching recorded in 2020 across reefs in the CSMP and GBR does not clearly relate to recorded levels of heat stress at these locations. Most notably, bleaching appeared to be much worse in the central CSMP (Figure 3.10), even though southern reefs were exposed to equally high, if not higher levels of overall heat stress. This pattern might be partly explained by the particular sequence of surveys, whereby reefs in the southern GBR were surveyed first and potentially before the full extent of bleaching was apparent. The extent of bleaching recorded at each reef and site, may also be influenced by taxonomic composition of the coral assemblage, where highest levels of bleaching simply reflect increased abundance of bleaching-susceptible taxa (e.g., *Acropora*) at those reefs (Hoey et al. 2020). Importantly, further sampling was conducted in 2021 to assess the full extent and ecological consequences of the 2020 mass-bleaching, based on estimates of coral loss at each site (Hoey et al., In prep), which will resolve some of the potential discrepancies in the reported incidence of coral bleaching. However, inter-reef differences and especially intra-reef differences (i.e., among sites and depths) in the extent of bleaching and coral loss, might also be explained based on the specific history of, and recent exposure to, temperature anomalies at individual sites, which can only be assessed with *in situ* monitoring of environmental conditions.

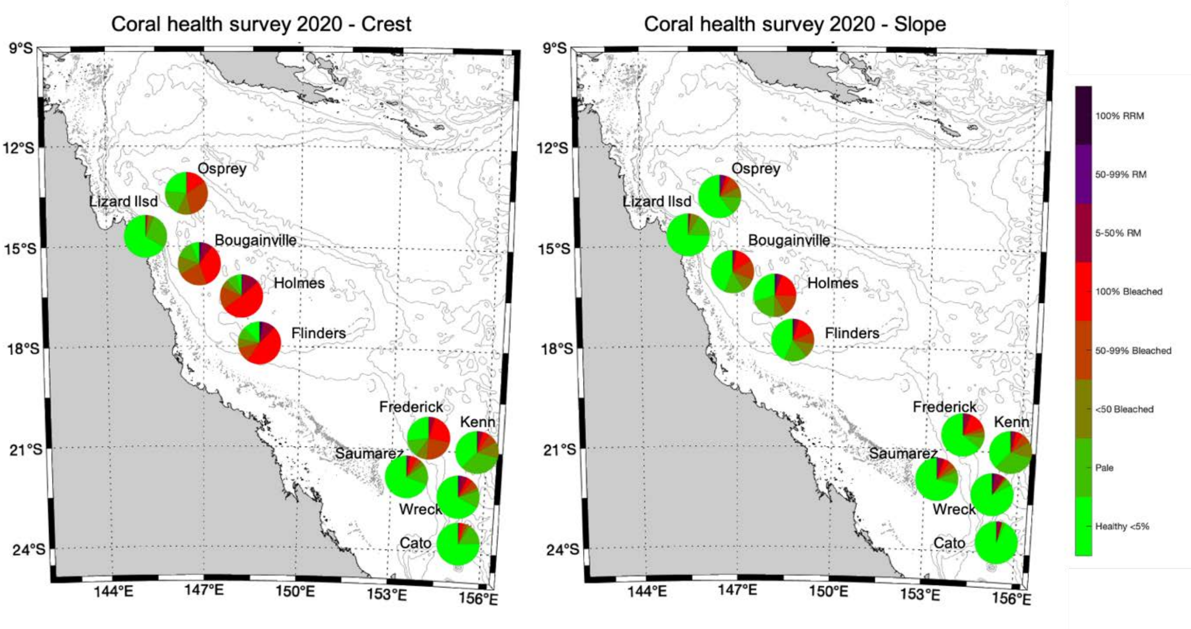

Figure 3.10. Coral bleaching survey undertaken in the Coral Sea showing the extent of bleaching in the Coral Sea reef following the 2020 heatwave.

During the summer 2019-2020, 36 current meters were deployed at 2 reefs in the northern CSMP (Osprey and Bougainville Reefs) and 4 reefs in the northern GBR (No Name, Lizard Island, North Direction and Yonge). These instruments collected invaluable data on temperature and velocity during this latest marine heatwave (Figure 3.11), which may help to reconcile spatial differences in bleaching severity among these reefs (see Figure 3.10). Most notably, the level of bleaching recorded on reefs in the northern GBR (e.g., Lizard Island) was much more moderate than recorded at CSMP reefs of equivalent latitude (Osprey and Bougainville).

Low levels of post-bleaching mortality recorded in the northern GBR may be partly attributable to severe storm activity in early 2020, which culminated in the formation of Tropical Cyclone Trevor (category 3), which traversed the GBR just north of Lizard Island on March 17-19. There was a corresponding suppression of water temperature, with current meters at Lizard Island (North Reef) recording >30 °C at both 4.5 m and 7.5 m depth on March 9^{th}, which declined to 28.3 °C on March 17^{th}, at both depths, coinciding with a period of very high current speeds recorded at this location. There was a similar decline in water temperature recorded from March 7^{th} at Osprey Island in the Coral Sea. Perhaps even more importantly, the environmental data from *in situ* current meters reveals the presence of frequent cold water intrusions, which are likely tidally induced and enhanced by the complex bathymetry of the reefs. At Lizard Island, for example, the temperature recorded at 7.5m varied 1-2 °C on diurnal cycles in early January 2020 (Figure 3.11). Infrequent, but recurrent cold water intrusions were also recorded in the Coral Sea (Figure 3.11; see also Figure 3.2). Critically, these intrusions may greatly moderate the temperature stress imposed on corals during major heatwaves, and are not revealed using satellite SST as they rarely reach the surface layer and are also very localised.

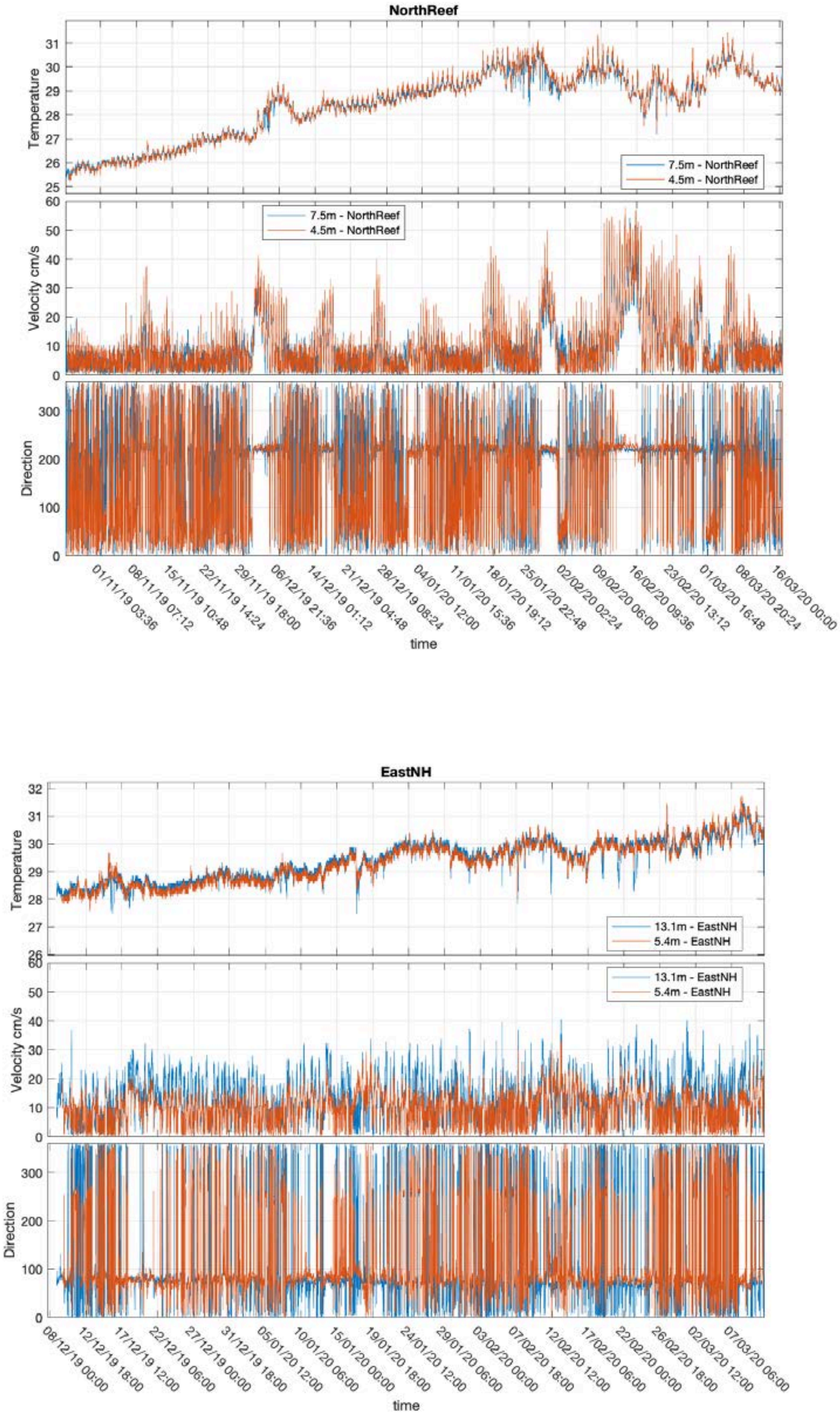

Figure 3.11. Time series data for (a) Temperature (°C) (b) velocity (cm/ s) and flow direction (heading, compass bearing) for Lizard Island (North Reef) and Osprey Reef (NE) over a 3-month period in summer 2019-2020.

4. Conclusions

The coral reefs in the CSMP are some of Australia's most isolated coral reef environment. Their isolation and inaccessibility have limited opportunities for detailed research and monitoring of this region and the deployment of long-term instrumentation to record oceanographic conditions, which are necessary for calibrating and validating hydrodynamics models in the regions. We deployed Marotte HS current and temperature loggers to record temperature, current velocity and current direction during 3-month periods throughout coral reef environments of the CSMP in order to assess the accuracy of a medium-scale (4 km) hydrodynamic model (GBR4), which was explicitly developed to link global ocean circulation models to fine-scale oceanographic processes in the GBR (e.g. GBR1).

Overall, 84 Marotte HS current and temperature loggers were deployed throughout the CSMP recording temperature, current velocity and current direction providing detailed data to assess the accuracy of GBR4 in the CSMP. Although overall trends were consistent across in situ measures and predicted measures, the GBR4 model consistently over-estimates current velocity and fluctuation in the directionality of current flow, and under-estimates the in-water temperatures. These findings indicate GBR4 is largely incapable of resolving reef scale processes, and poorly represents environmental conditions on shallow reef environments across the CSMP. The results may partly due to the difficulty of capturing near-reef environmental conditions and the complexity of current flow in these areas. Given that GBR4 was developed explicitly to capture global ocean circulation, it may be better suited to represent oceanic environments in the CSMP.

Although, GBR4 was unable to precisely replicate near-reef conditions, it is likely to capture large-scale ocean currents and reflective broad connectivity patterns in the CSMP. Monthly estimates of connectivity patterns generated from CONNIE2 (2010-2017) indicated large fluctuations in the strength and direction of connectivity between individual reefs in the CSMP. Nevertheless, regional clusters of highly connected reefs were apparent in the central and southern regions of the CSMP, indicated reefs within each of the regions are more likely to be regularly connected compare to reefs outside these regions. The models also predicted connections from CSMP reefs towards the GBR which is consistent is the dominant westerly current flow in the Coral Sea. In particular, connectivity from northern CSMP reefs (Osprey and Bougainville) to the northern GBR was among the strongest connections observed in the model. The northern CSMP is therefore likely to be a critical region that connects the CSMP with the GBR.

The deployment of Marotte HS current meters at Osprey Reef, Bougainville Reef and Lizard Island provided detailed data of the environmental condition leading up to the 2020 coral bleaching event that affected 63% of all corals in the CSMP (Hoey et al. 2020, 2021). Insofar, our understanding of the environmental conditions that moderate the severity of bleaching in coral communities have relied almost entirely on the retrospective assessments of bleaching events and satellite derived sea surface temperature data (Glynn 1984; Hughes *et al.* 2017b; Harrison *et al.* 2019). The *in situ* data obtained during the course of this study identified periodic cold and warm water intrusions that may be involved in moderating corals response to temperature stress during major heatwaves, as experience in 2016, 2017 and 2020 (Harrison et al. 2019, Hoey et al. 2020). Critically, the early deployment and detailed assessment of coral communities prior to (Hoey et al. 2020) and following from (Hoey et al. In prep) the 2020 bleaching event provide a unique opportunity to develop predictive models to assess the effect of environmental variables on the severity of bleaching, which currently explain only 9-50% of the spatial variation in bleaching response (McClanahan *et al.* 2019), highlighting that the mechanisms that moderate the severity of bleaching events remain only partly resolved.

5. Recommendations

In situ data from Marotte HS current meters deployed during the current study shows that the GBR4 model consistently overestimates current velocities, and underestimates temperature, even during years when oceanic flows are relatively weak. These findings highlight the limited capacity of this medium-scale (4 km resolution) hydrodynamic model to account for localised processes that not only moderate current flow, but lead to pronounced variability in the directionality of current flows. However, it will not be simple or straightforward to constrain model predictions to better reflect the observed stochasticity in currents (especially in terms of directionality). Rather, significant downscaling in hydrodynamic modelling will be required to explicitly account for the particular geomorphologic features and fine-scale processes affecting current flow adjacent to coral reefs. The issue is however, that there are relatively few shallow reefs and other habitats that are widely dispersed across the large geographical extent of the CSMP, making it difficult to justify the development of a much higher resolution (e.g., 1 km resolution) hydrodynamic model for the entire region.

Improved understanding of hydrodynamics and connectivity for CSMP reefs will be best achieved by developing an entirely new hydrodynamic model that allows for variable resolution or unstructured meshes (e.g., Legrand et al. 2006). These unstructured models can provide much higher resolution wherever needed, and especially in areas with coral reefs or other shallow marine habitats, to better represents key features and fine-scale processes. An unstructured hydrodynamic model has been developed as part of the environmental modelling suite by CSIRO, to explore Coastal Ocean Marine Prediction Across Scales (COMPAS; https://research.csiro.au/cem/software/ems/hydro/unstructured-compas). This model is expected to accelerate the delivery of a national hydrodynamic model, which will encompass the CSMP, and provide highly resolved information for shallow and coastal environments (Griffin et al. 2021). However, the model is still being developed and tested and needs in situ data on currents to demonstrate its predictive value in different regions (Griffin et al. 2021). It is important, therefore, to continue to collect in situ information on environmental conditions in the CSMP, wherever feasible.

Environmental data presented this study comes mostly from Osprey and Bougainville Reefs, which are both in the *northeast transition* bioregion (Director of National Parks 2018). There is comparatively little information from other CSMP bioregions, and especially the *northeast province*, which is the largest bioregion. Sampling was concentrated at Osprey and Bougainville Reefs simply due to accessibility and opportunity, which was particularly important to allow for timely deployment of current meters at the start of summer, and outside of the annual monitoring voyages. Given inherent constraints to research and monitoring in the CSMP (as discussed above) it is important to capitalise on opportunities to advance research, but it is also necessary to conduct comparable research in areas that are relatively inaccessible, to maximise representation across all distinct bioregions. It may be necessary therefore, to conduct bi-annual voyages to advance research and monitoring across the CSMP, with separate trips in early (October-November) and late (February-March) summer. The initial trips would not only allow for the deployment of current meters (and any other sampling devices, e.g., coral settlement tiles), but would also facilitate research on coral reproduction (Baird et al. 2002) and other seasonal processes. The current meters and other sampling equipment could then be retrieved 4-months later (in February-March), while undertaking bleaching assessments and yearly monitoring of reef health.

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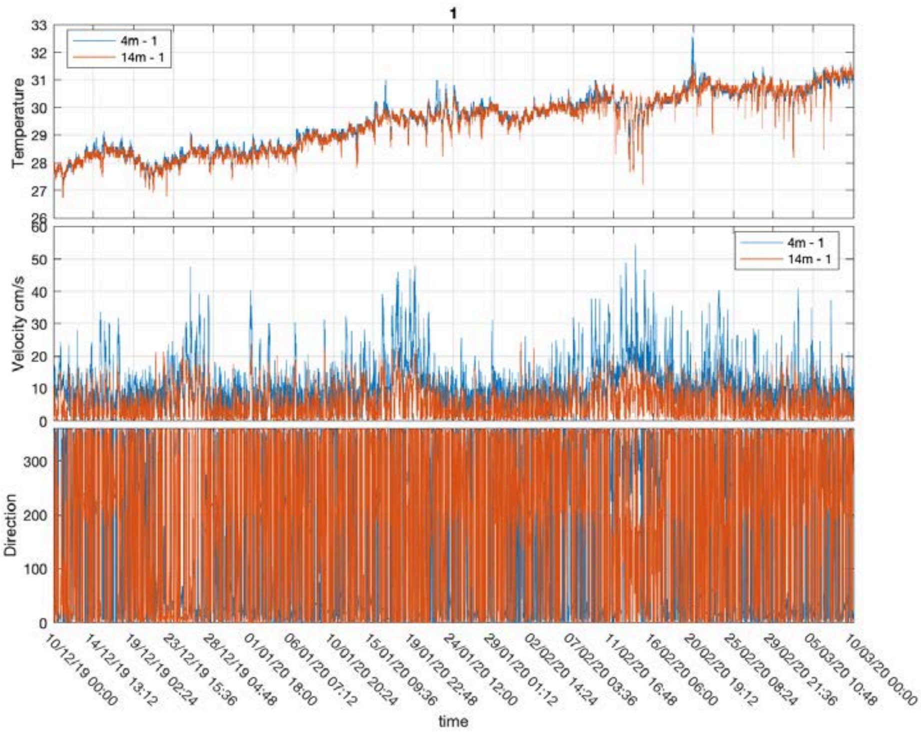
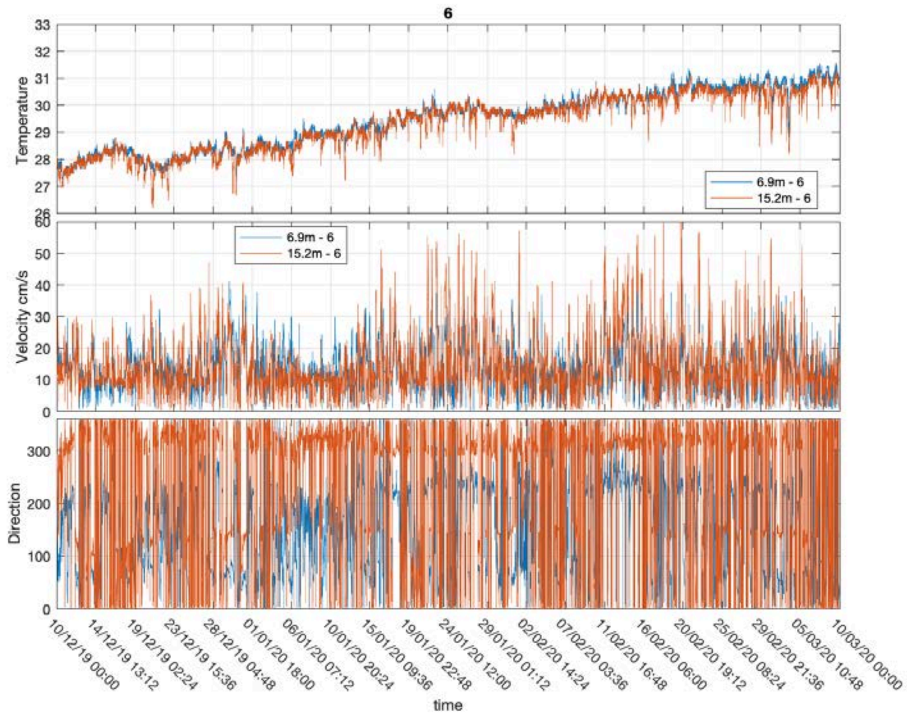
6. Appendices

Appendix 1. Time series for (upper panel) water temperature (°C), (middle panel) flow velocity (cm/s), (lower panel) flow direction (heading – compass bearing), for different depths (where available) at all sites for Coral Sea (in alphabetical order). Data were extracted and averaged over 10-minute intervals for up to 3-months, or as long as the current meter was recording.

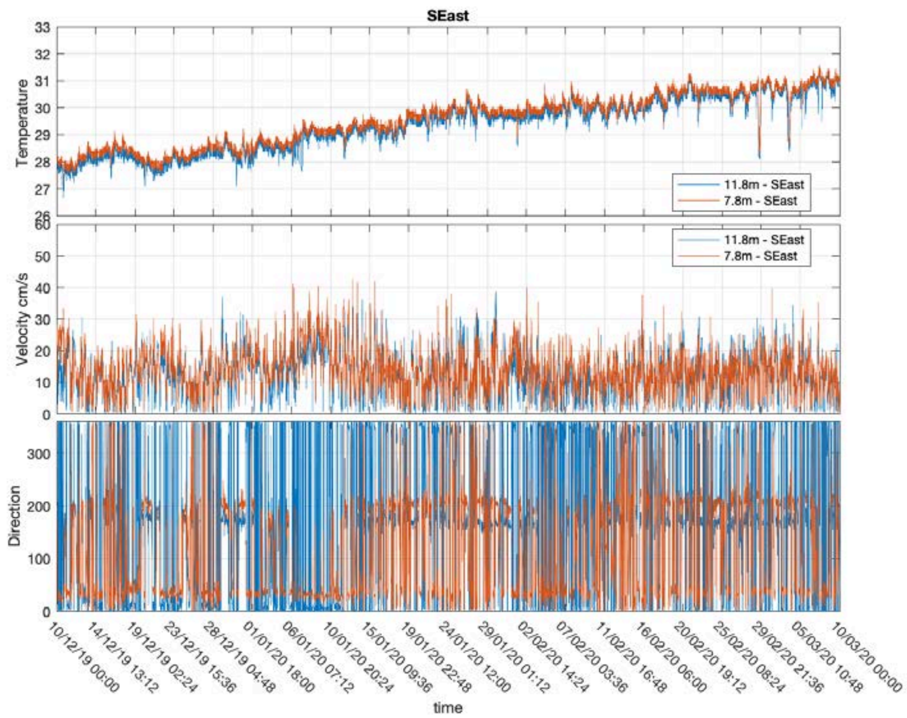
Bougainville #1 (December 2019)



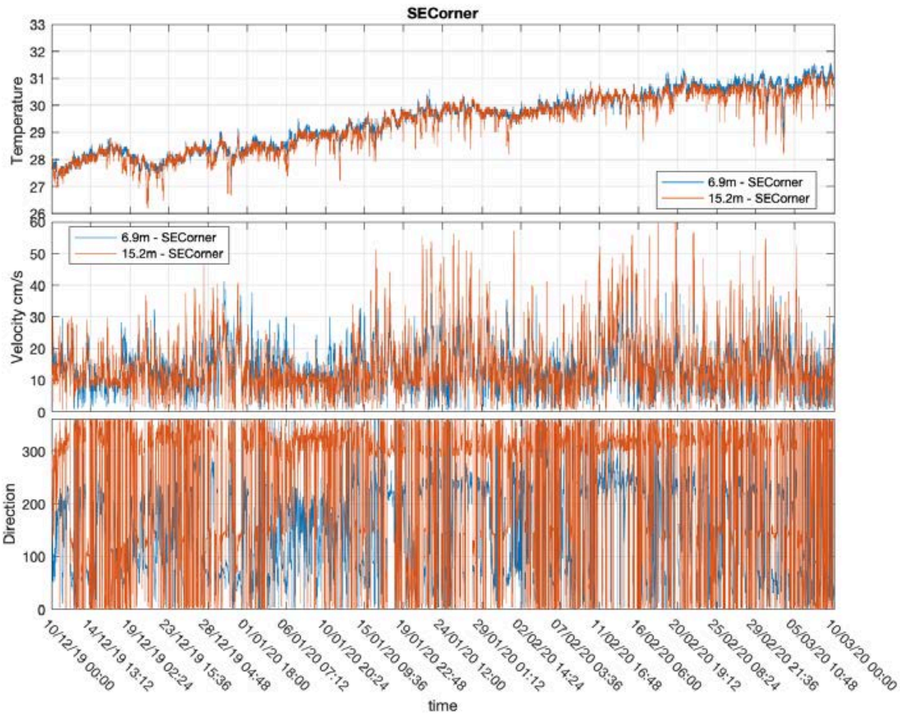
Bougainville #6 (December 2019)



Bougainville SE (December 2019)



Bougainville Southernmost Tip (December 2019)



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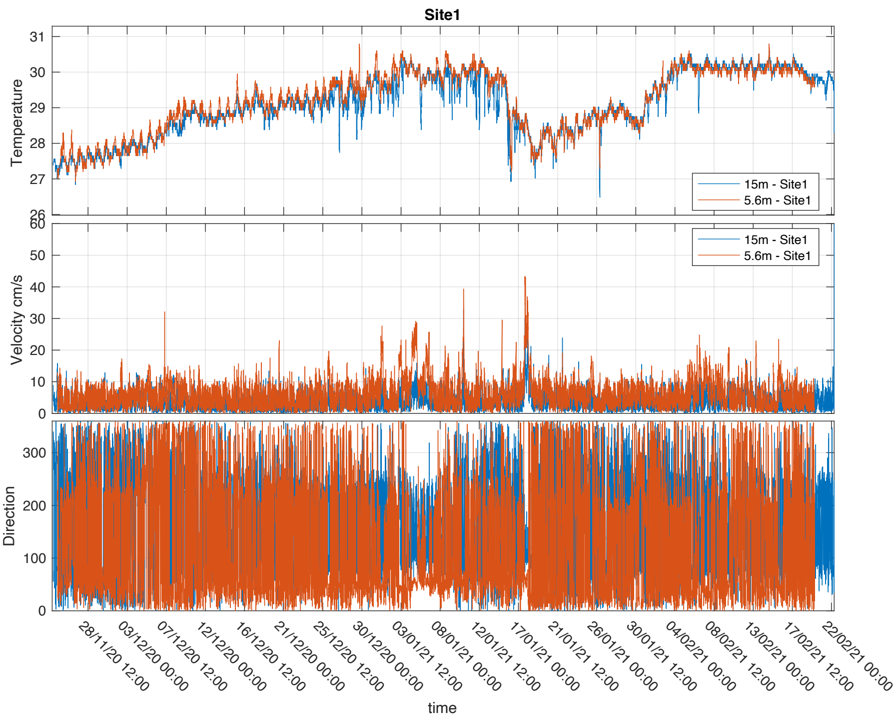
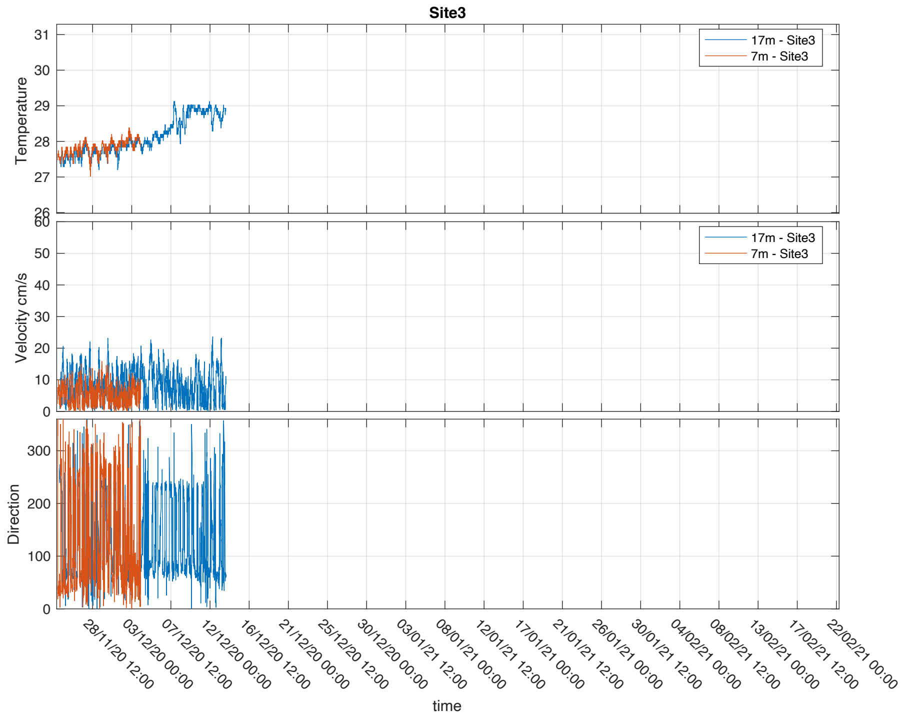


Bougainville #3 (November 2020)



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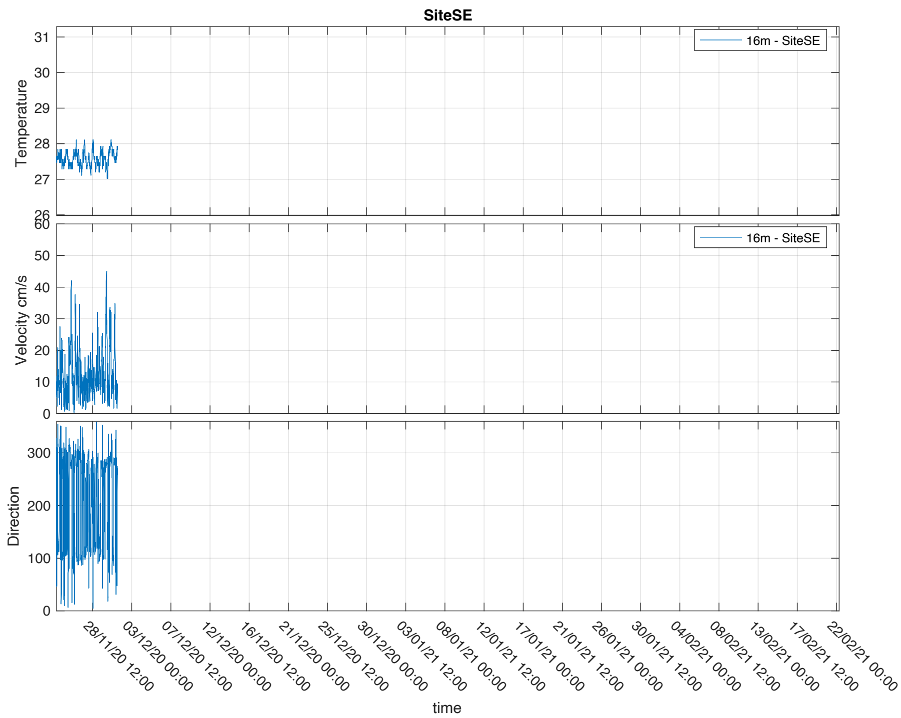

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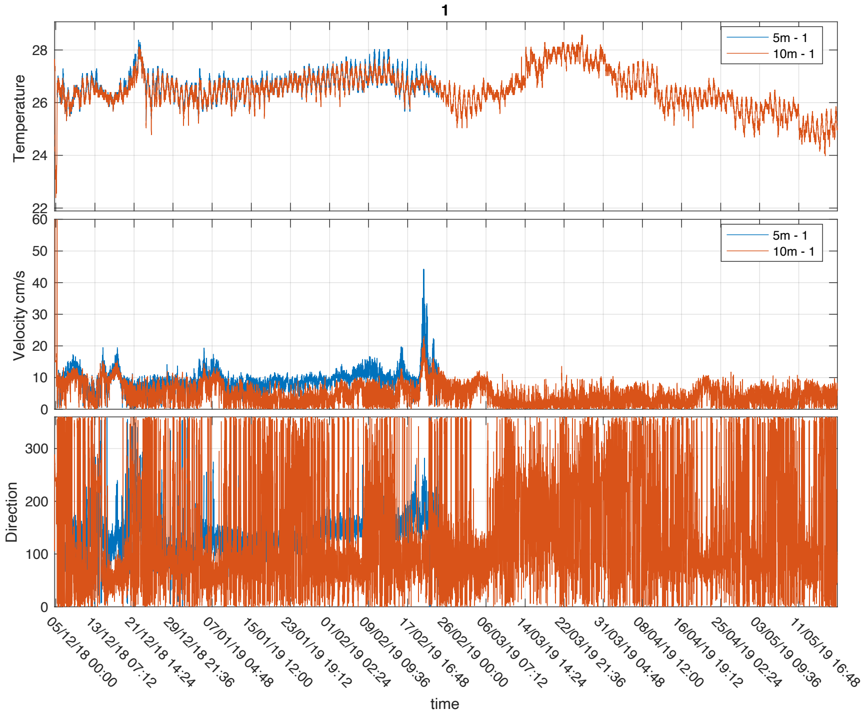

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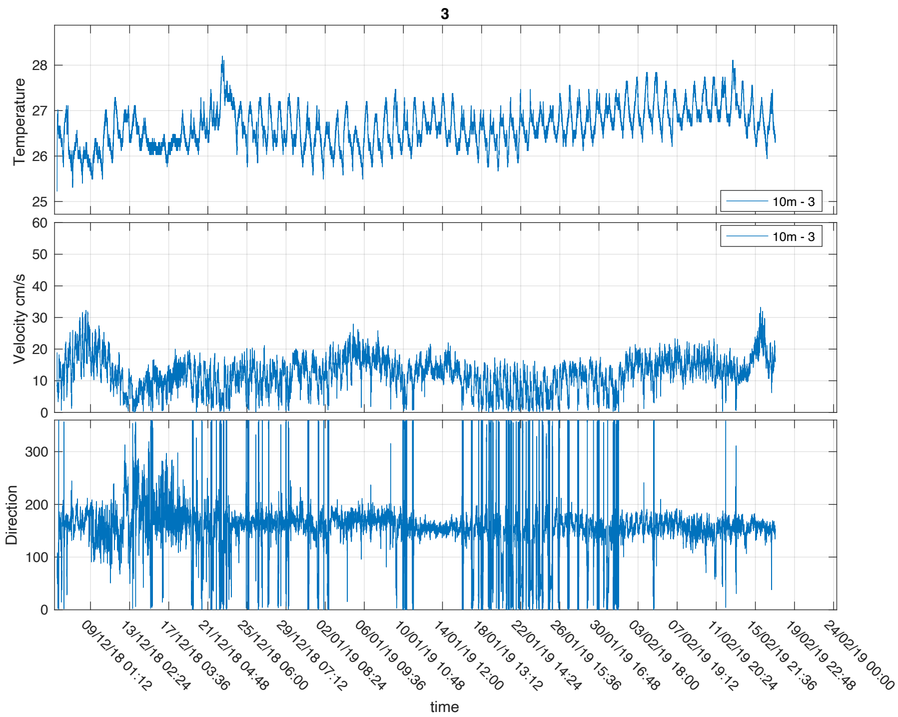
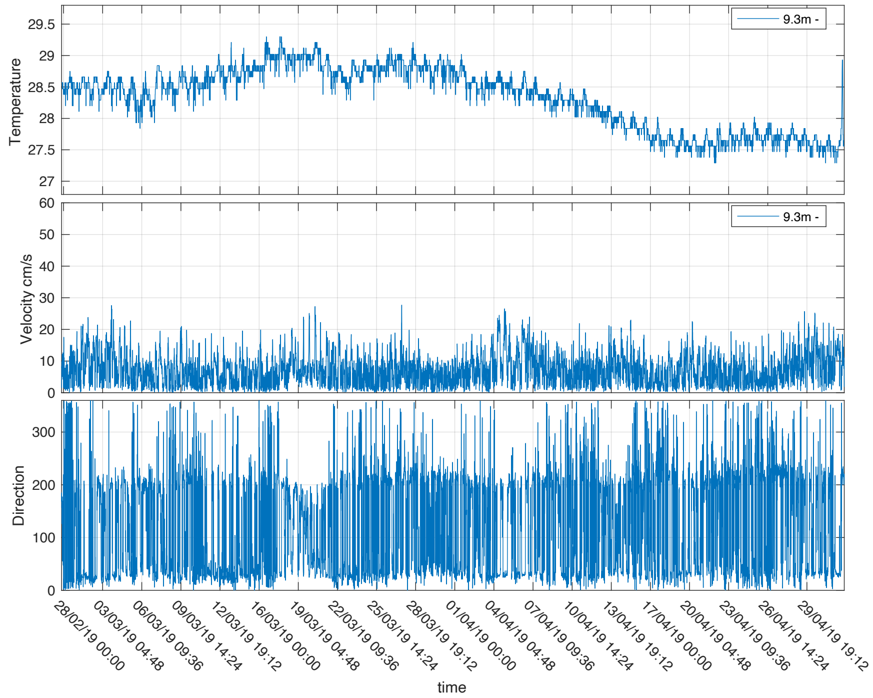
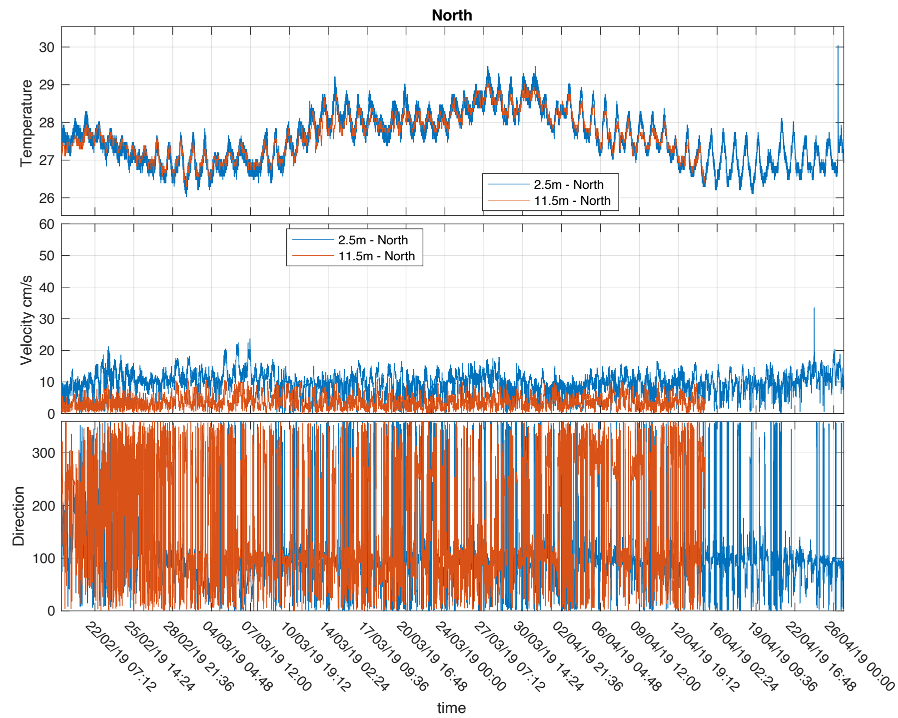


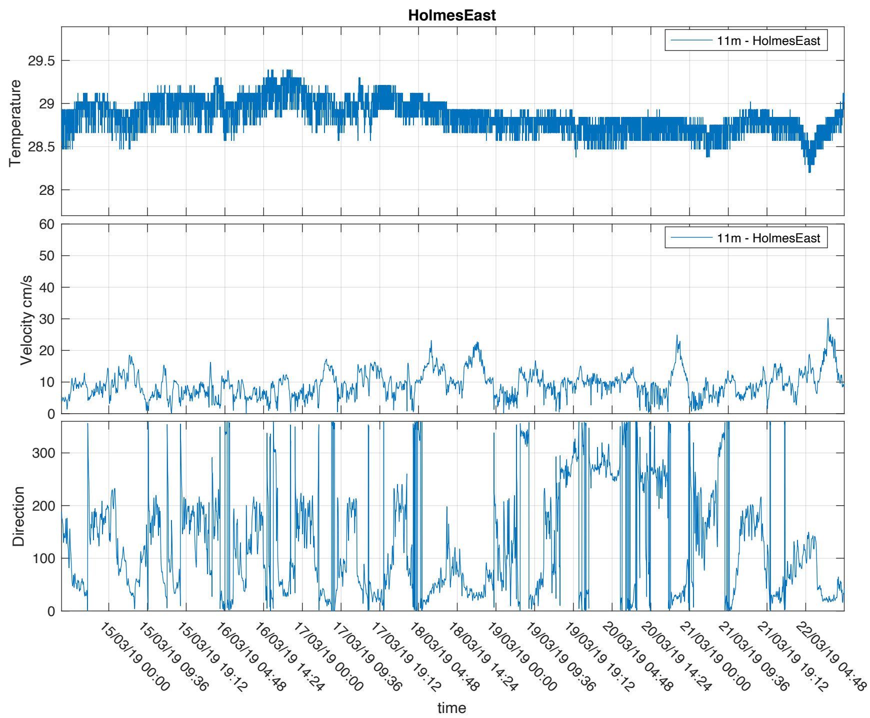
Flinders (February 2019)



Frederick (February 2019)

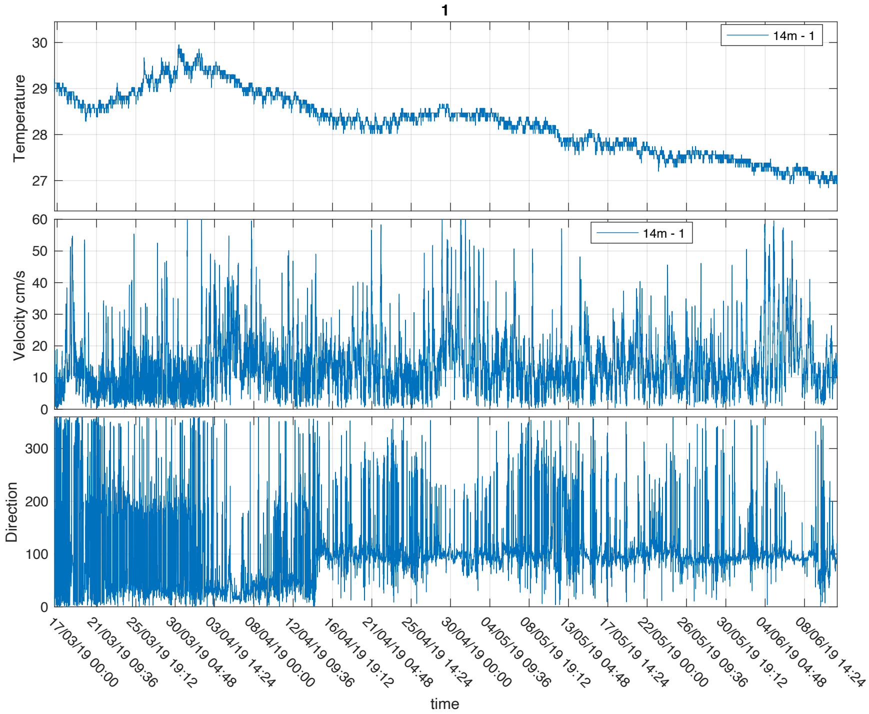


Holmes (March 2019)



Kenn (December 2018)

Osprey #1 (March 2019)



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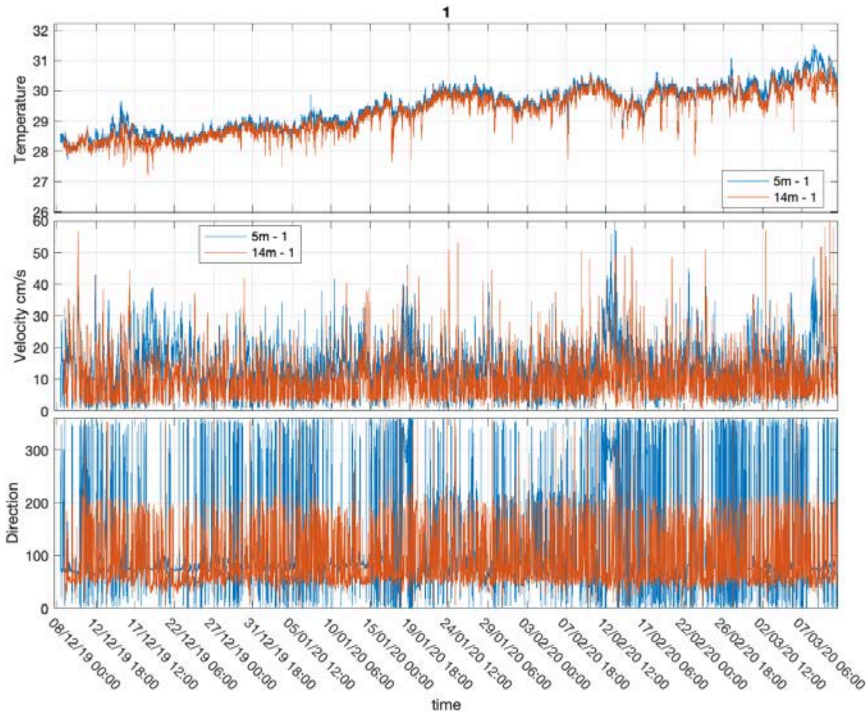
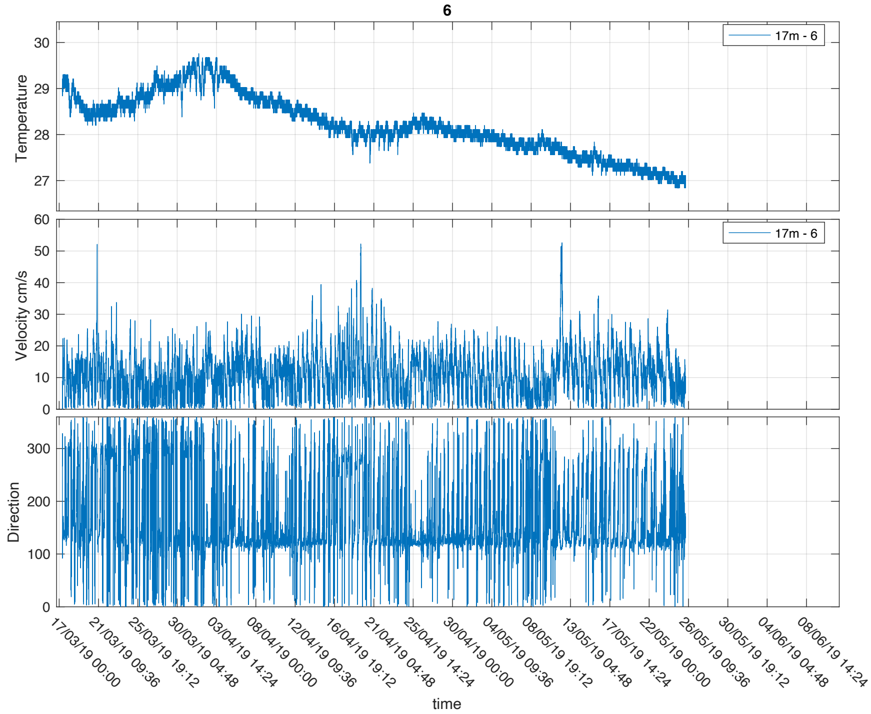


Osprey #6 (March 2019)



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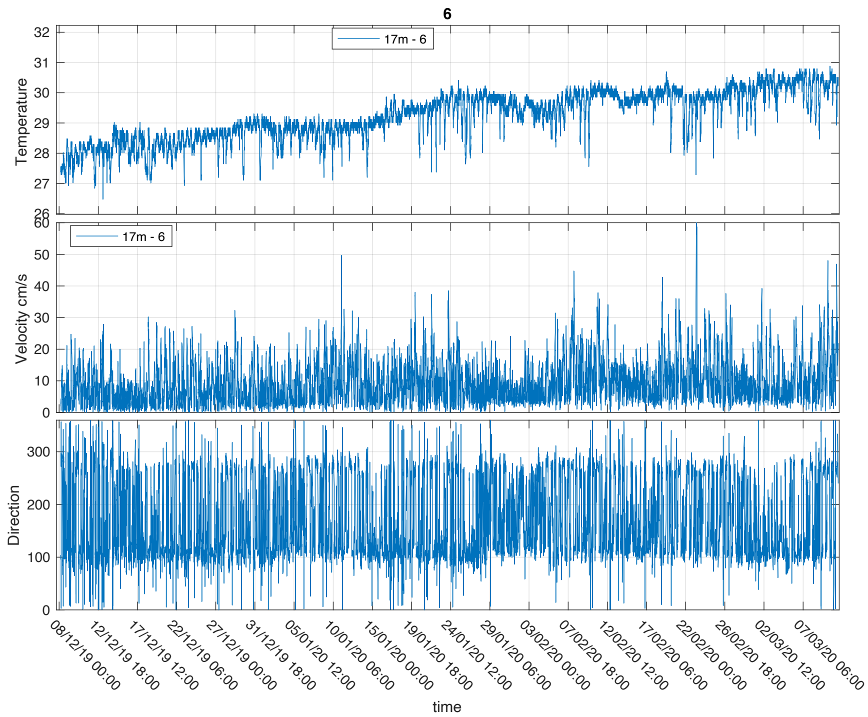
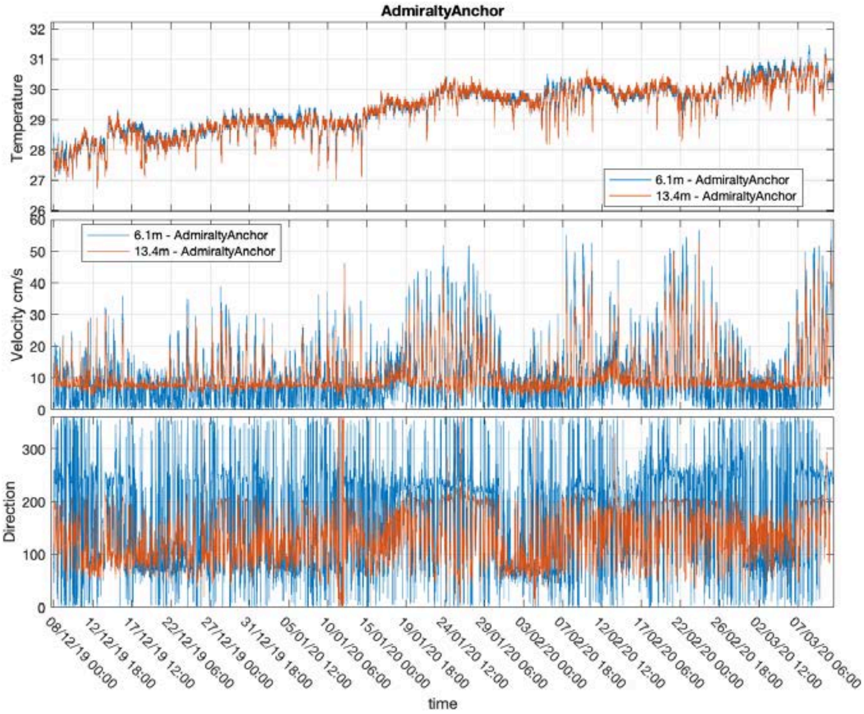
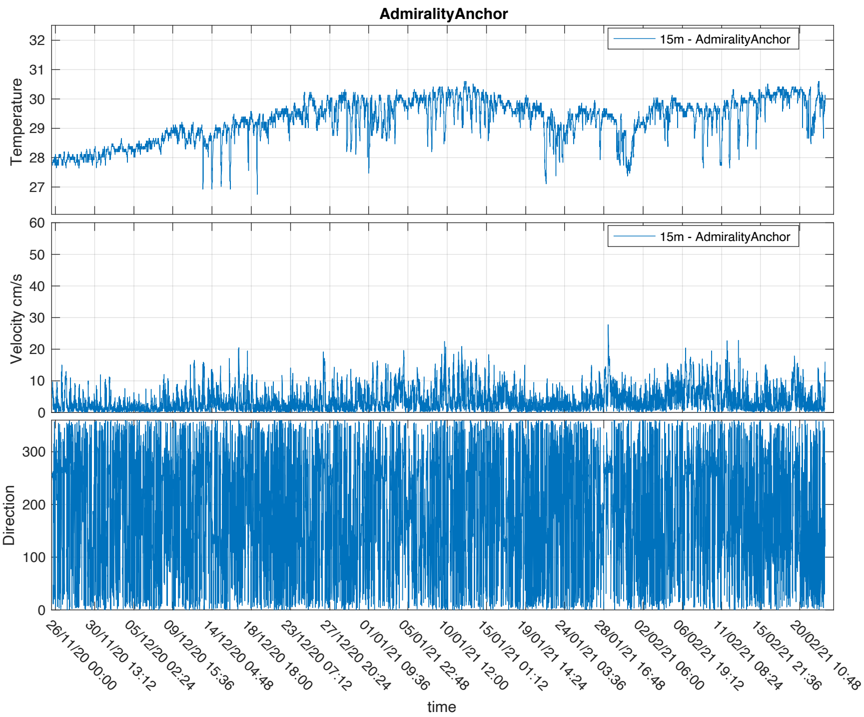


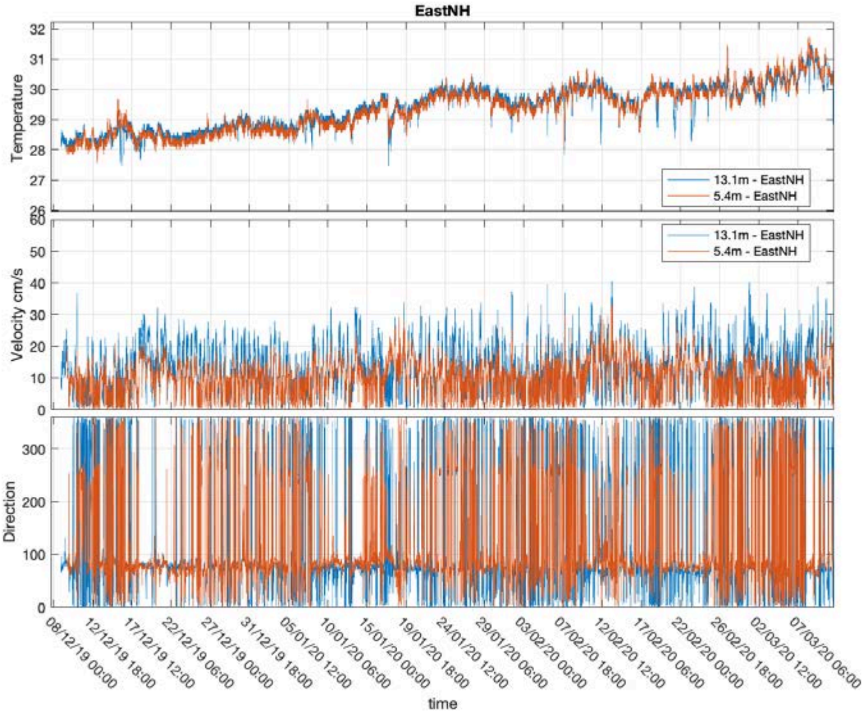
Osprey Admiralty Anchor (December 2019)



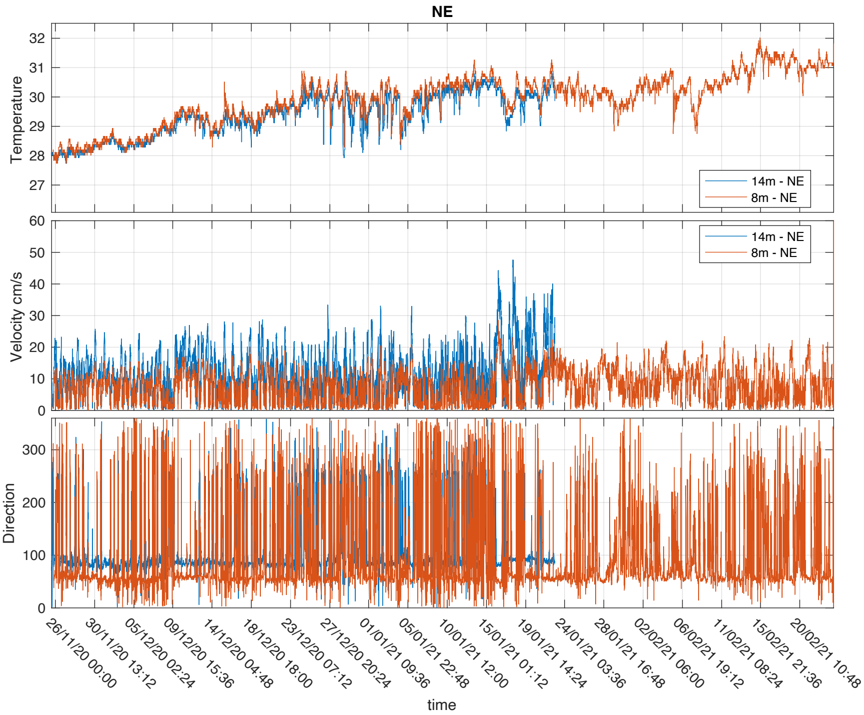
Osprey Admiralty Anchor (November 2020)



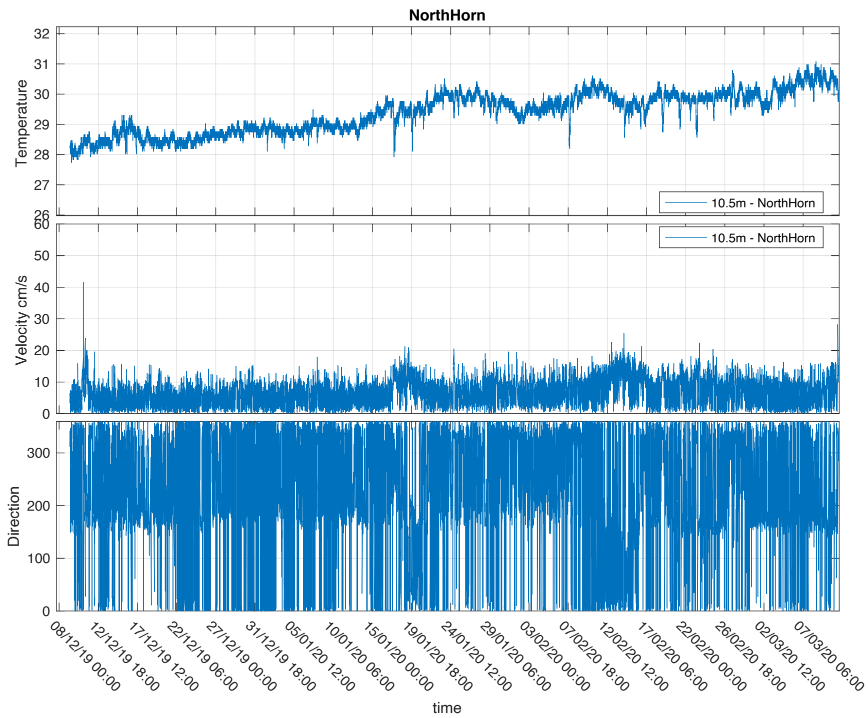
Osprey NE (December 2019)



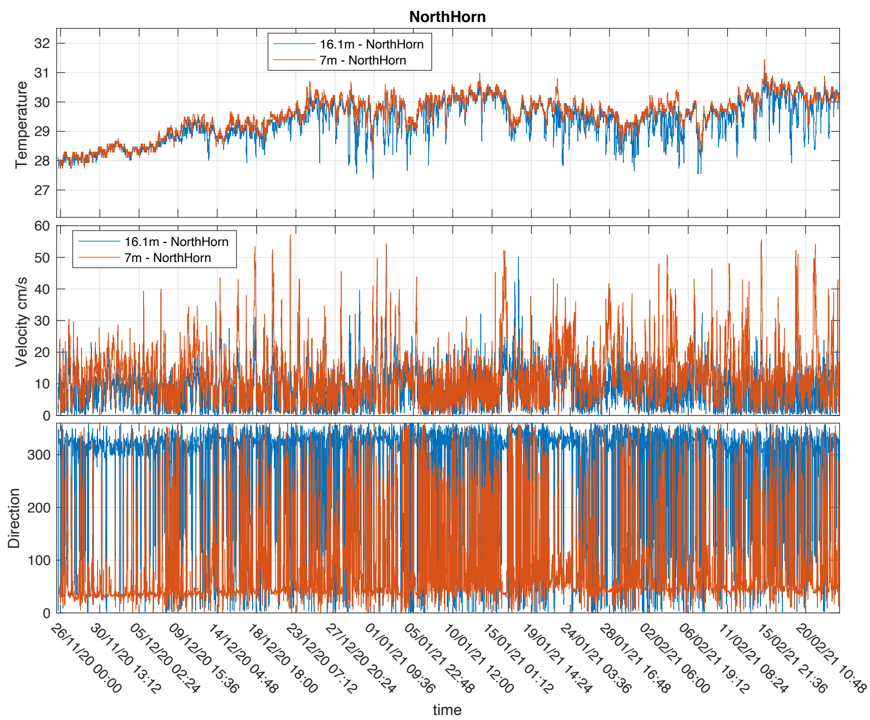
Osprey NE (November 2020)



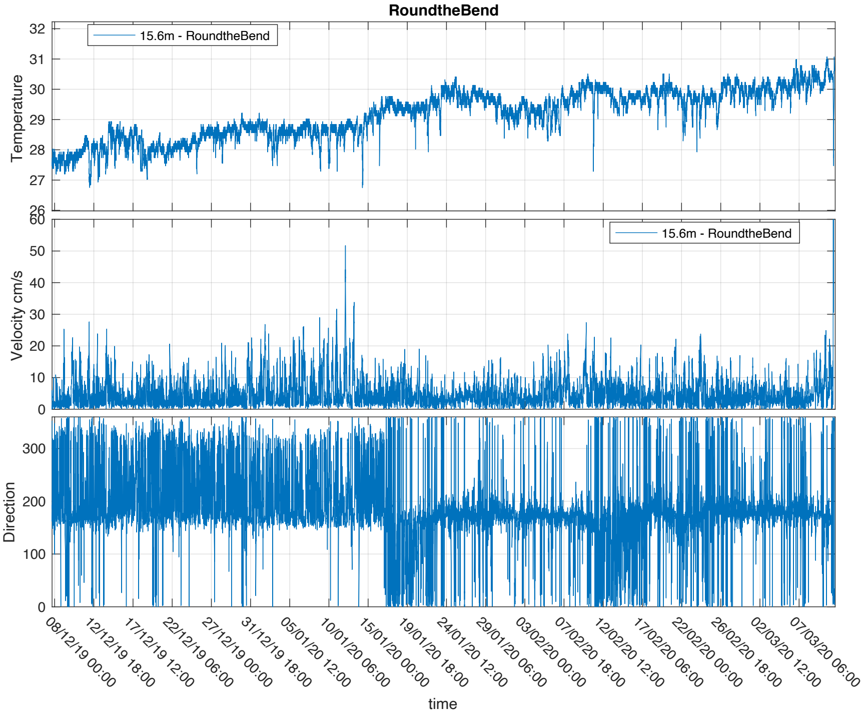
Osprey North Horn (December 2019)



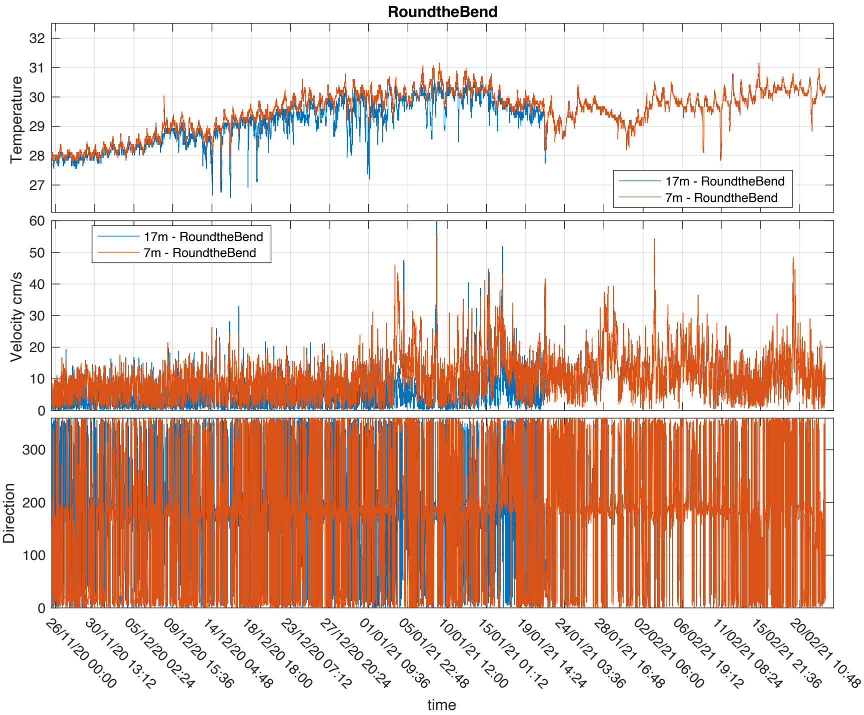
Osprey North Horn (November 2020)



Osprey Round the Bend (December 2019)

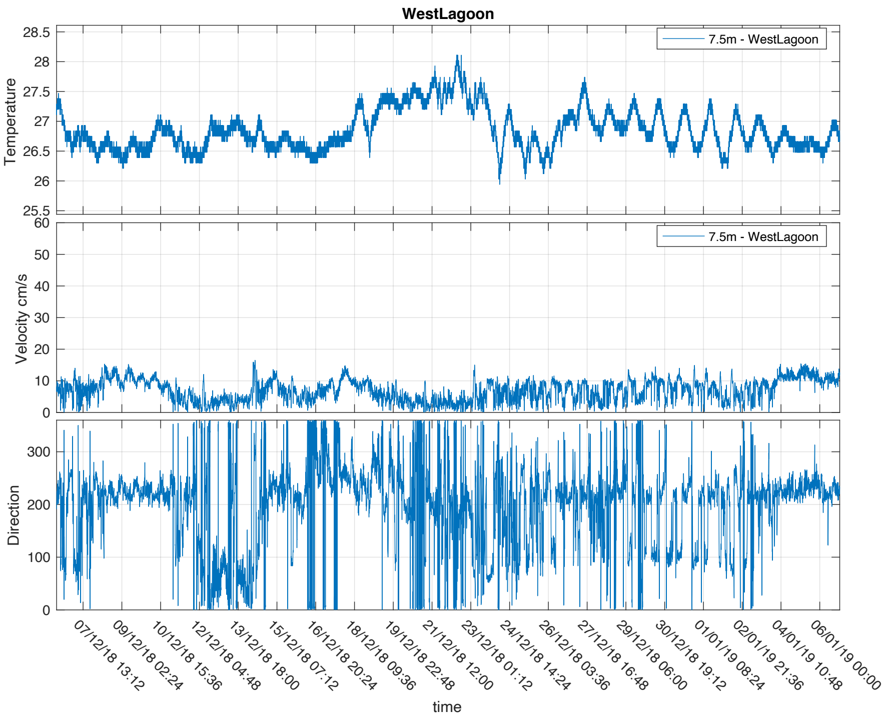


Osprey Round the Bend (November 2020)

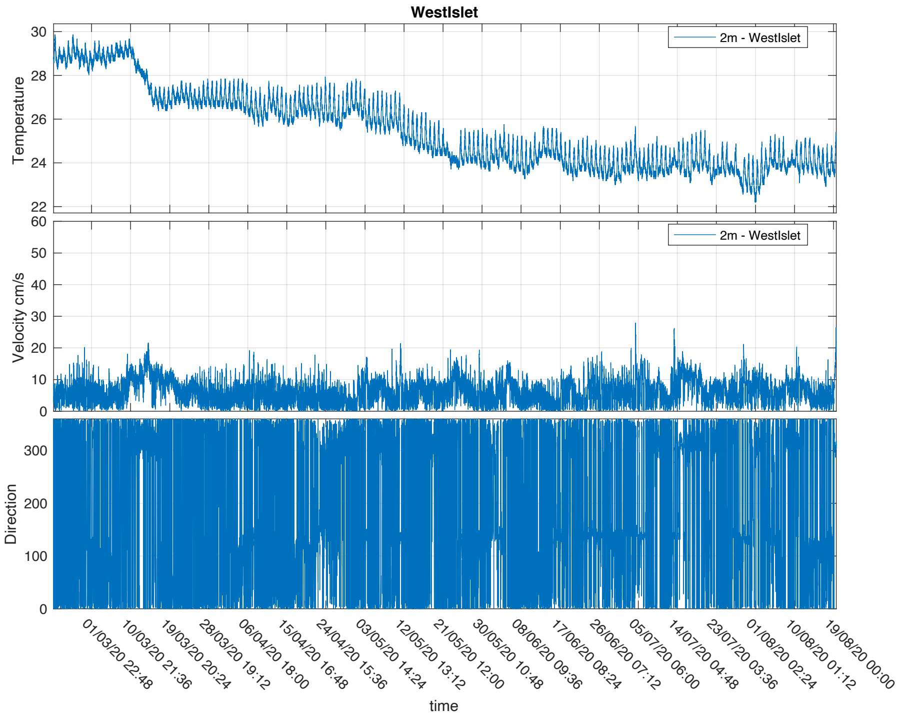


Saumarez (December 2018 and February 2019)

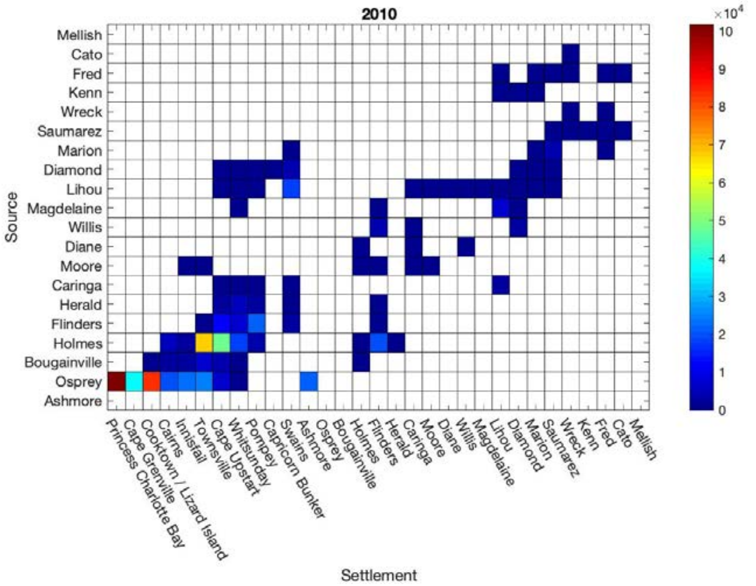
Wreck (December 2018)

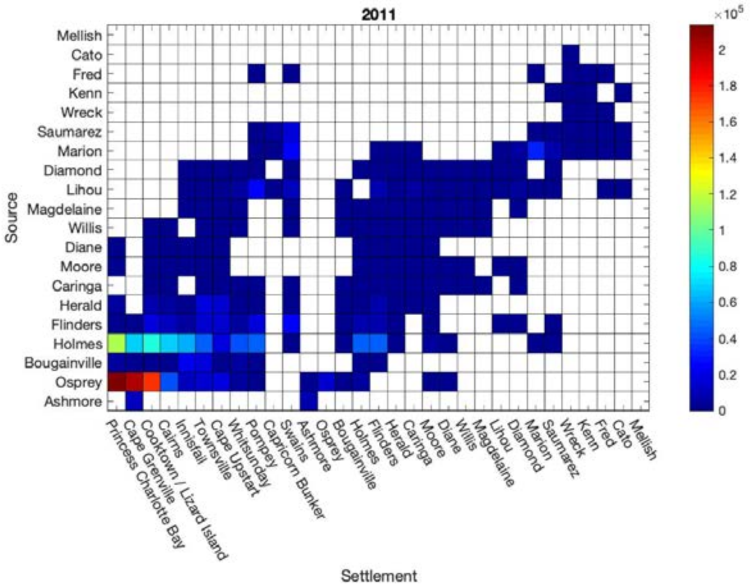


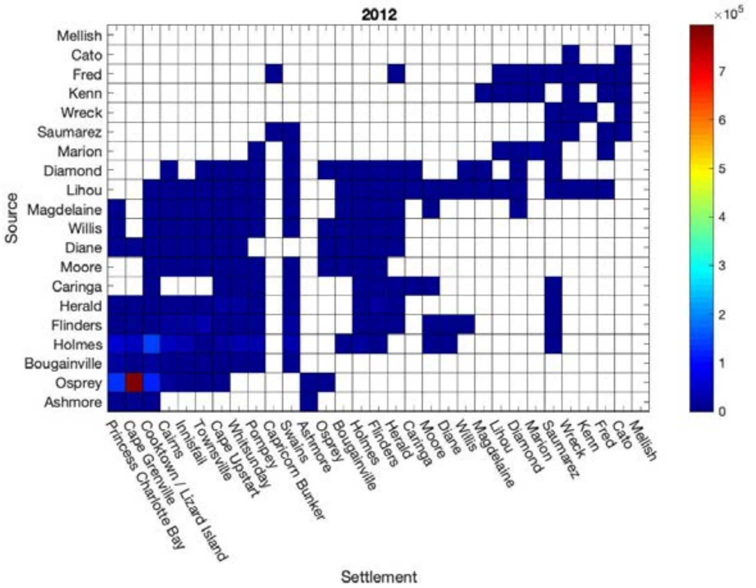
Wreck (March 2020)

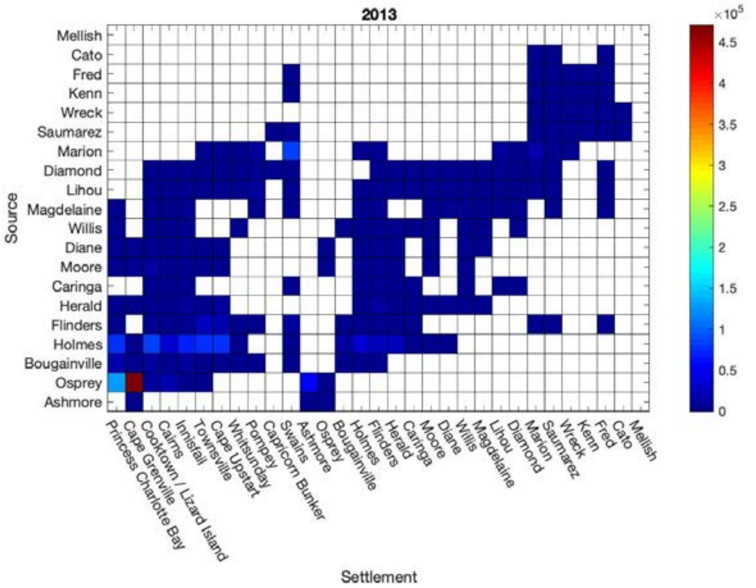


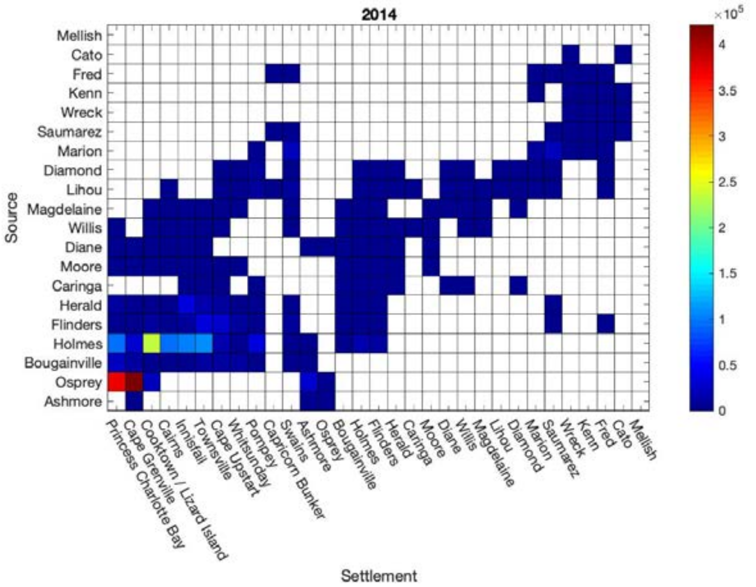
Appendix II. Connectivity matrices for Coral Sea reefs based on archived hydrodynamic data from 2010-2017. Connectivity was assessed based on redistribution of passive particles over 50 days, using CONNIE2, which is forced by GBR4. Data for 2010 and 2017 are presented in Figure 3.7, but repeated here to allow for comparisons among years.

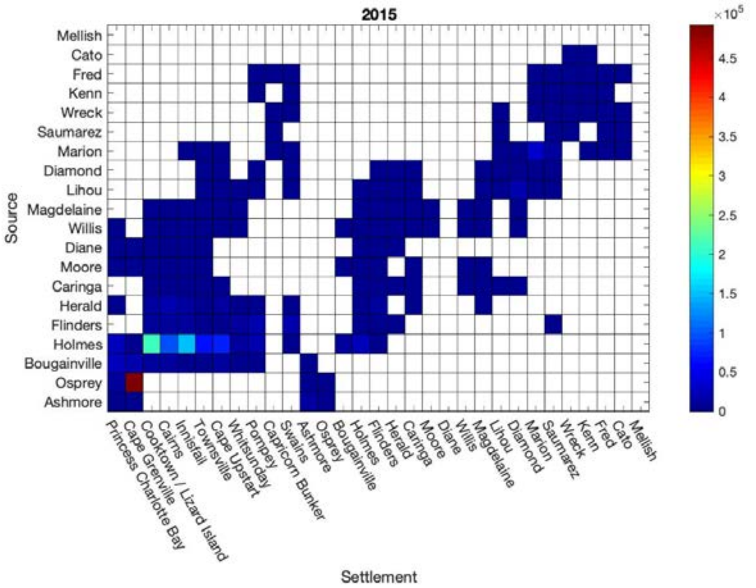


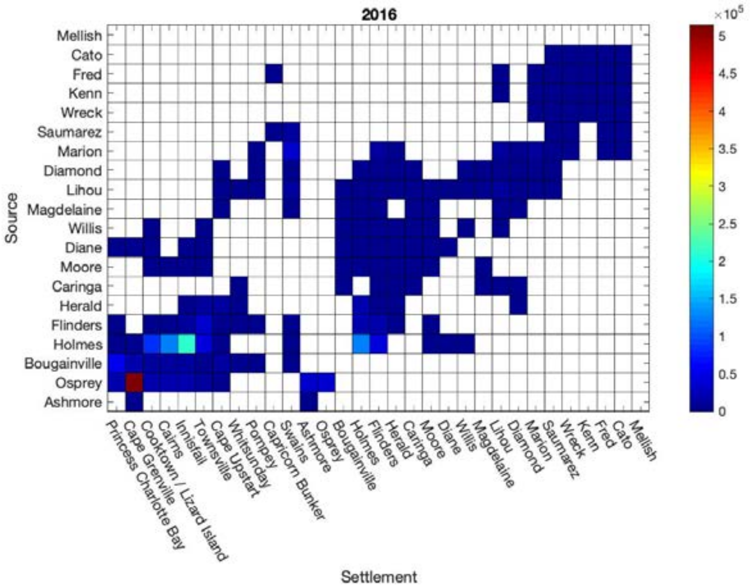



2012
Source
Settlement
×10^5


2013
Source
Settlement
×10^5


2014
Source
Settlement
×10^5


2015
Source
Settlement
Mellish
Cato
Fred
Kenn
Wreck
Saumarez
Marion
Diamond
Lihou
Magdelaine
Willis
Diane
Moore
Caringa
Herald
Flinders
Holmes
Bougainville
Osprey
Ashmore
Princess Charlotte Bay
Cape Grenville
Cooktown / Lizard Island
Cairns
Innisfail
Townsville
Cape Upstart
Whitsunday
Pompey
Capricorn Bunker
Swains
×10^5


2016
Source
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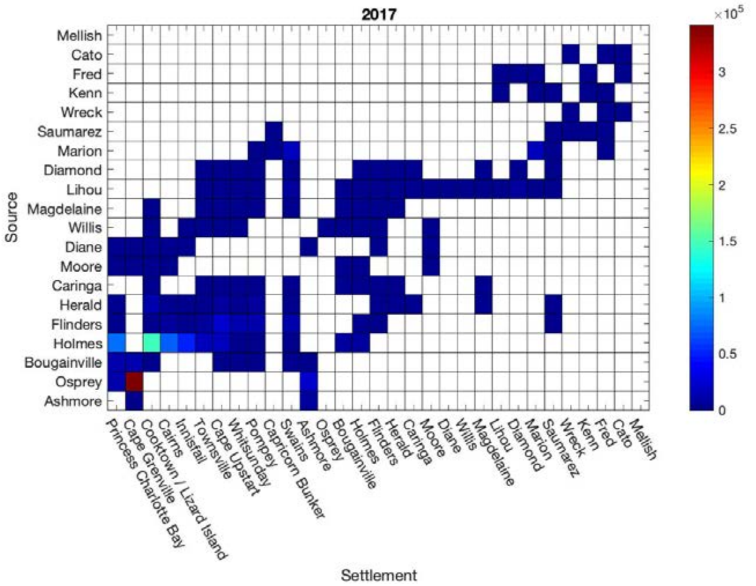
×10^5


2017
Source
Settlement
×10^5