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Oceanographic drivers of bleaching in the GBR: from observations to prediction

Volume 1: Summary of oceanographic conditions during the 2015-17 bleaching years

Craig R. Steinberg, Jessica A. Benthuysen, Eduardo Klein-Salas, Neal E. Cantin, Hemerson Tonin, Simon Spagnol and Claire M. Spillman



Australian Government

Australian Institute of Marine Science

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ACRONYMS

3D ..... three-dimensional
ACCESS ..... Australian Community Climate and Earth-System Simulator
AIMS ..... Australian Institute of Marine Science
ANFOG ..... Australian National Facility for Ocean Gliders
AODN ..... Australian Ocean Data Network
AOML ..... Atlantic Oceanographic and Meteorological Laboratory
ARC ..... Australian Research Centre
AVHRR ..... Advanced Very-High Resolution Radiometer
BoM ..... Bureau of Meteorology
CoE ..... Centre of Excellence
CRW ..... Coral Reef Watch
CSIRO ..... Commonwealth Scientific Industrial Research Organisation
DHW ..... Degree Heating Week
DHWmax ..... Maximum summer value of the degree-heating week
EAC ..... East Australian Current
ENSO ..... El Nino Southern Oscillation
GBR ..... Great Barrier Reef
GBR1 ..... eReefs model at 1km resolution
GBR4 ..... eReefs model at 4km resolution
GBRF ..... Great Barrier Reef Foundation
GBRMPA ..... Great Barrier Reef Marine Park Authority
IMOS ..... Integrated Marine Observing System
IOD ..... Indian Ocean Diploe
IPO ..... Interdecadal Pacific Oscillation
JCU ..... James Cook University
LTMP ..... Long Term Monitoring Program
MHW ..... Marine Heatwave
MJO ..... Madden-Julian Oscillation
MMM ..... Maximum Monthly Mean
MMP ..... Marine Monitoring Program
MODIS ..... NASA's Moderate Resolution Imaging Spectroradiometer
NASA ..... National Aeronautics and Space Administration
NCRIS ..... National Collaborative Research Infrastructure Strategy
NESP ..... National Environmental Science Program
NOAA ..... United States National Oceanic and Atmospheric Administration
PAR ..... Photosynthetically Active Radiation
RRRC ..... Reef and Rainforest Research Centre Limited
SIEF ..... Science Industry Endowment Fund
SST ..... Sea Surface Temperature
SSTAARS ..... Sea Surface Temperature Atlas of Australian Regional Seas
TC ..... Tropical Cyclone
THREDDS ..... Thematic Realtime Environmental Distributed Data Services
TWQ ..... Tropical Water Quality
WMO GTS ..... World Meteorological Organisation Global Telecommunications System

ABBREVIATIONS

˚C ..... degrees Celsius
˚S ..... degrees of latitude South
˚E ..... degrees of longitude East
E ..... east
km..... kilometre
m..... metre
N ..... number of samples or North
S ..... south
W ..... west
%..... percent

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In situ temperature data was provided by the AIMS weather station and temperature logger programs. Observations were obtained from a number of facilities of Australia's Integrated Marine Observing System (IMOS): the Queensland and Northern Australian Mooring sub-facility of the Australian National Mooring Network, Ships of Opportunity, Glider, Satellite Remote Sensing and Argo facilities. The Sea Surface Temperature Atlas of the Australian Regional Seas was accessed through IMOS OceanCurrent. IMOS is enabled by the National Collaborative Research Infrastructure Strategy (NCRIS). It is operated by a consortium of institutions as an unincorporated joint venture, with the University of Tasmania as Lead Agent. Wave buoy temperature data was accessed from the Queensland Government's Department of Environment and Science Coastal Impacts Unit.

The eReefs model simulations were produced as part of the eReefs project (eReefs.info), a collaboration between the Science Industry Endowment Fund (SIEF), the Commonwealth Scientific Industrial Research Organisation (CSIRO), the Australian Institute of Marine Science (AIMS), the Bureau of Meteorology (BOM), and the Great Barrier Reef Foundation (GBRF), with support from BHP Billiton Mitsubishi Alliance, the Australian and Queensland governments.

All of NOAA Coral Reef Watch's products were accessed through a web portal at http://coralreefwatch.noaa.gov. NOAA Coral Reef Watch work is supported primarily by the NOAA Coral Reef Conservation Program and the NOAA National Environmental Satellite, Data, and Information Service's Center for Satellite Applications and Research. ReefTemp products were obtained from the Bureau of Meteorology. (http://www.bom.gov.au/environment/activities/reeftemp/reeftemp.shtml).

The authors wish to acknowledge all the individual research teams, divers and tourist operators who have contributed time and effort in the field to collect and document the GBR Bleaching response in 2016 and 2017.

PREFACE

For the first time, back-to-back mass coral bleaching occurred on the Great Barrier Reef (GBR) and Torres Strait in 2016 and 2017 as part of a continuous global bleaching event that started in late 2014 (Eakin et al, 2018). The combined effect has meant that the majority of the reef has been severely affected; however, there remain significant areas that have survived along the length of the GBR. This project seeks to understand how reef scale, regional and global oceanographic and meteorological processes influence the severity and spatial variability of thermally driven coral bleaching for the Great Barrier Reef and Torres Strait.

The project gathers available observations and uses them to assess and validate a range of model types from nowcasting and short-term forecasting eReefs models; sub-seasonal to seasonal predictive ACCESS models and the identification of regions and oceanographic mechanisms associated with them that produce persistent resistance to warming and coral bleaching through the development of a hazard map and an analysis of the eReefs model over mass coral bleaching events.

The report is structured in four main components with each written as separate volumes:

Volume 1 - Summary of oceanographic conditions during the 2015-17 bleaching years.

All available, relevant environmental observations of the recent bleaching events will be gathered to be more easily discoverable to researchers and managers via a gateway/summary webpage. These include hundreds of temperature loggers deployed along the GBR by AIMS, weather stations and the use of IMOS remote sensing, moorings and glider deployments. This publicly available and quality controlled data set will allow the most comprehensive understanding yet of how individual coral reefs faired in these events.

Volume 2 - 3D-Bleaching in the GBR: Development and analysis of a 3D climatology and heat accumulation bleaching products using eReefs.

The new eReefs 3D modelled heat accumulative bleaching products developed here provide a deeper understanding of bleaching refugia in the GBR. The algorithm is adapted from NOAA's widely used and globally recognised Degree Heat Week (DHW) satellite derived product. A common characteristic of proposed refugia is a reduction in temperature variability and a certain insensibility to extreme conditions. We show that the understanding of regional oceanographic processes is key to understand the effectiveness of cool water persistence that can counteract warming processes and the heat stress that leads to coral bleaching. New heat accumulative bleaching products were developed, blending a climatology of high-resolution SST observations (The 2-km Sea Surface Temperature Atlas of the Australian Regional Seas; SSTAARS) with a high-resolution 3D hydrodynamic model, the 1km eReefs model (GBR1).

Volume 3 – Development of a hazard map for the Great Barrier Reef to predict regions with a lower risk of persistent warming and coral bleaching.

A hazard map is a framework for risk assessment consisting of a series of geographical layers or maps that defines:

a) The location of static conditions that may induce or reduce the incidence of bleaching in coral communities. These layers include the detailed bathymetry and derived characteristics, like the steepness of the reefs front and the presence of inter-reef channels;
b) The climatology of some oceanographic and meteorological variables that are known to be a factor that could induce or protect the corals from bleaching, like accumulated heat, recurrent upwelling areas, tidal mixing areas, photosynthetically active radiation (PAR) and the probability of mixing of the water column; and
c) The anomaly maps for each of the analysed variables for 2016 and 2017 related to its climatology. This report presents the climatology and the corresponding anomalies of oceanographic and meteorological variables that may promote or protect coral reef from bleaching. The potential of a predictive capability using this technique is also explored.

Volume 4 – Observations and predictions of marine heatwaves in the GBR

Development of skilful marine heatwave prediction tools are critical for marine management of ecosystem resources and services. This project aims to synthesise our knowledge of marine heatwaves (MHW) over the GBR Marine Park (GBRMP) and adjacent Coral Sea and investigate ways to apply state-of-the-art ocean prediction systems for MHW predictions. First, we applied a recently developed marine heatwave framework to consistently quantify marine heatwave metrics over the GBR and Coral Sea using a sea surface temperature product. We found that mass coral bleaching events in the GBR coincided with some of the longest, most spatially extensive, and severe MHWs during summer months in the satellite record. We then used these results to explore ways in which sub-seasonal to seasonal prediction systems can be used for MHW prediction. We provide recommendations on further areas of research and how users can interpret predictions from short-term (10 days) to seasonal (months) time scales in the context of MHWs. This study is timely given the extensive 2020 MHW and mass coral bleaching along the GBRMP and Coral Sea.

EXECUTIVE SUMMARY

For the first time back-to-back mass coral bleaching occurred on the GBR and Torres Strait in 2016 and 2017 as part of a continuous global bleaching event that started in late 2014 (Eakin et al, 2019). The combined effect has meant that the majority of the reef has been severely affected. However, there remain significant areas that have survived along the length of the GBR. This project seeks to understand how reef scale, regional and global oceanographic and meteorological processes influence the severity and spatial variability of thermally driven coral bleaching for the Great Barrier Reef (GBR) and Torres Strait.

All available environmental temperature observations of the recent bleaching events are gathered to be more easily discoverable to researchers and managers via a summary webpage. These include hundreds of temperature loggers deployed along the GBR by AIMS, weather stations and the use of IMOS remote sensing, moorings, Argo profilers, gliders and NOAA surface drifters deployments. These publicly available and quality-controlled data sets will allow the most comprehensive understanding yet of how individual coral reefs faired in these events. A summary and explanation of climate, meteorology and physical oceanographic conditions is provided for the 2015-16 and 2016-17 mass coral bleaching events

The data are used to assess how well the eReefs models are predicting the recent warming during bleaching events and then analyse the reasons behind variations of the bleaching response. The data validations provide confidence in using various satellite products and the eReefs model being used to produce 3D coral bleaching products.

This study has provided evidence of a number of meteorological and oceanographic processes that can help explain the spatial coral bleaching responses along the GBR including:

- Mass coral bleaching is occurring more frequently due to rising ocean temperatures globally and the persistence of doldrum like weather due to a suppressed monsoon, lower cloud cover and winds.
- Weather events such as wind and swell generated from close or distant tropical cyclones that can mix and cool the reef waters.
- Episodic physical oceanographic processes can work in concert with complex reef topography and tides to produce significant large scale refugia for corals that are persistently cooler.

1.0 INTRODUCTION

Coral bleaching is a stress response when coral polyps expel their symbiotic algae, called zooxanthellae, primarily in response to elevated sea temperatures (Hughes et al., 2017). This breaks down the symbiotic relationship corals rely on for their nutrition. The white coral skeletons can be seen through the transparent coral tissue after the colourful zooxanthellae are lost, hence the term “bleaching”. Corals tend to live within narrow thermal limits that often characterise the world’s tropical oceans, so a persistent temperature rise of as little as 1 degree above normal summertime levels can trigger bleaching. It can also be exacerbated by other environmental factors or stressors (e.g., high light levels, low temperatures, freshwater and a deterioration of water quality). If the stress is removed in time, the zooxanthellae can re-establish and the coral can recover; otherwise, mortality will occur.

All available, relevant environmental temperature observations of the recent bleaching events are gathered in this report and on the eAtlas (https://eatlas.org.au/gbr/nesp-twq-4-2-temperature-data-2015-17) to be more easily discoverable to researchers and managers via a gateway/summary webpage. These observations include hundreds of temperature loggers deployed along the GBR by AIMS, weather stations and the use of IMOS remote sensing, moorings and glider deployments. These publicly available and quality-controlled data sets allow the most comprehensive understanding yet of how individual coral reefs faired in these events, through knowledge of their measured thermal histories.

The following sections identify and compile the sources of temperature and associated oceanographic data. The AIMS temperature logger data set was calibrated and quality controlled, and together with the IMOS moorings data, validated against the eReefs 1km hydrodynamic model. Local climatologies were developed for the in situ loggers with visualisation dashboards that integrate the data with heating indicators. These can be used to see how each reef faired over the bleaching summers by knowing how much warmer they were above the local climatology.

1.1. Compilation of temperature and oceanographic data

Over the last fifteen years a number of major efforts have significantly expanded the sustained monitoring of the Great Barrier Reef (GBR). The Australian Institute of Marine Science's (AIMS) on-reef weather stations were initiated in the 1980’s, however the Great Barrier Reef Marine Park Authority’s (GBRMPA) Marine and AIMS’ Long-Term Monitoring Programs (LTMP) have added loggers to their sites under the AIMS Sea Water Temperature Observing System over the last two and three decades respectively. The Integrated Marine Observing System (IMOS) commenced in 2007 and has introduced a host of new platforms and technologies providing data that are all publicly available. With the growth in observations from multiple organisations there is not a clear summary of what is available.

To provide an entry point to the major publicly available temperature observations from physical oceanographic data collected on the Great Barrier Reef during the recent 2016 and 2017 mass coral bleaching events an eAtlas website (https://eatlas.org.au/gbr/nesp-twq-4-2-temperature-data-2015-17) was created.

The primary data set for this collection is temperature from over 100 long term temperature logger locations within the reef from the AIMS temperature logger program. Other observing platforms include both mobile gliders and drifting buoys to permanent fixed weather stations and moorings. Collectively, these comprehensively quality-controlled data sets are provided to ease uptake by research and users to better characterise and understand the development of thermal stress events on the GBR.

Summary plots of the data can be interrogated and daily climatologies are provided so users can quickly determine the thermal history and anomalies at each site. Other relevant data sets are provided from multiple observing platforms with a summary plot. Some data sets have well developed websites with data visualisations and so a link to those sites and data sources are also provided as the recommended location from which to access the data.

Beyond observations some key climatologies are presented - from SSTAARS a satellite SST derived climatology (Wijffels et al., 2018) and calculated from the in situ temperature loggers, when there is a long enough record to do so.

This collection accessed through the dashboard includes data from the AIMS temperature logger program, AIMS weather stations, Queensland Government wave buoys and the IMOS Moorings (Figure 1). Each data type and primary source is described in the following sections with accompanying resource links to the primary data providers.

1.1.1. AIMS temperature logger program dashboards.

AIMS temperature loggers are deployed by the AIMS Reef Plan Marine Monitoring Program (MMP), the AIMS Long-term Monitoring Program (LTMP), and other staff either at AIMS or neighbouring institutions including James Cook University (JCU). During the back-to-back coral bleaching summers in 2016 and 2017, the primary temperature instruments deployed were the Vemco Minilog-II-T (https://www.bodc.ac.uk/data/documents/nodb/pdf/minilog2t.pdf) and ReefNet Sensus Ultra (https://reefnet.ca/products/sensus/). Though a significant upgrade is currently underway to upgrade the loggers deployed under this program. Figure 1 shows an interactive map of the loggers along the GBR.

The data for this period has been processed and quality controlled by this NESP 4.2 project. Temperature climatologies have been developed for a select number of sites with sufficiently long records. In addition, the SSTAARS climatology has been used at all locations to provide context to the shorter in situ temperature records. The data are available through the AIMS Data Catalogue (https://www.aims.gov.au/docs/data/data.html) and the Australian Ocean Data Network (AODN) Portal (https://portal.aodn.org.au/).

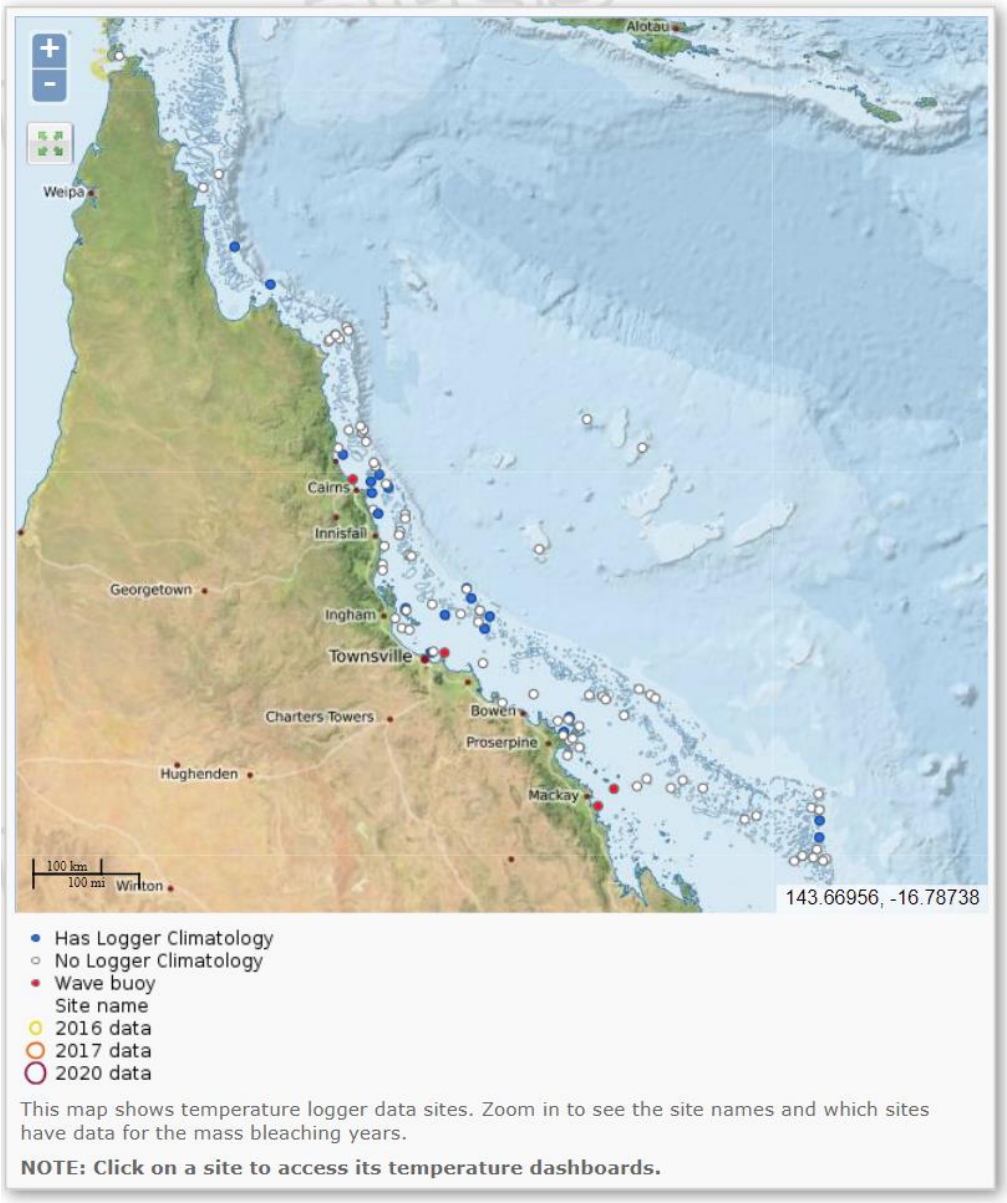


Figure 1: Map of the distribution of temperature loggers along the Great Barrier Reef.

Resource Link:

- https://eatlas.org.au/gbr/nesp-twq-4-2-temperature-data-2015-17

Data from the individual reefs can be accessed by zooming in on the map and clicking on the circles from the eAtlas article link: https://eatlas.org.au/gbr/nesp-twq-4-2-temperature-data-2015-17 (Figure 1). Figure 2: Example dashboard for Cattle Bay temperature loggers 2014-15 (red),2015-16 (orange) and 2016-17 (blue) showing the timeseries plotted over the logger (dark blue) and SSTAARS (light blue) climatologies. Grey shaded areas show the 1st and 2nd standard deviations of temperature shows the initial interactive dashboard for Cattle Bay, Orpheus Island with plots of the temperature observations from the reef flat and also the reef slope if the tab on the top left of the plot is clicked. A metadata summary, map and description of each of the reef locations is also provided.

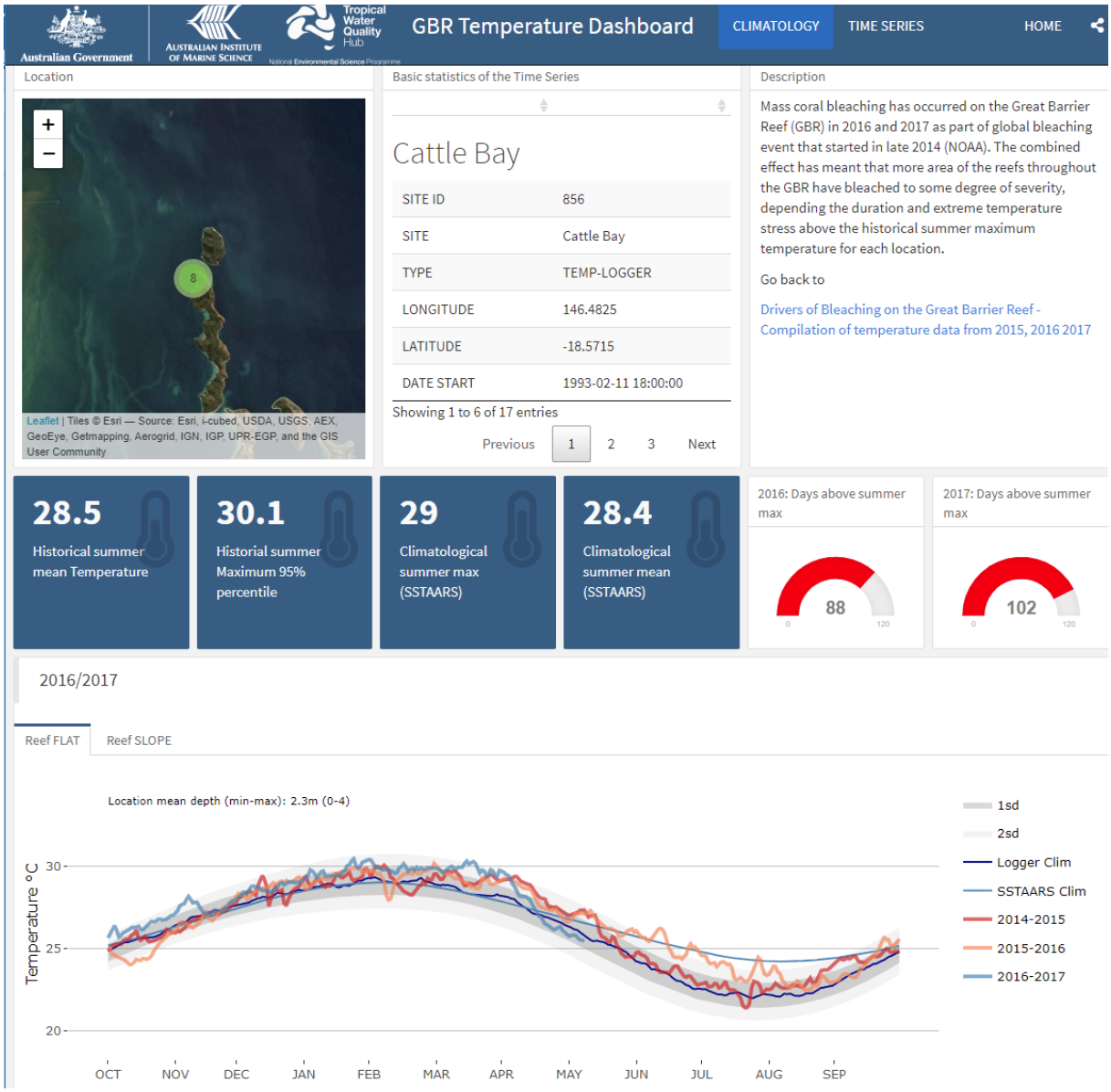


Figure 2: Example dashboard for Cattle Bay temperature loggers 2014-15 (red),2015-16 (orange) and 2016-17 (blue) showing the timeseries plotted over the logger (dark blue) and SSTAARS (light blue) climatologies. Grey shaded areas show the 1st and 2nd standard deviations of temperature

Climatologies are plotted calculated from the temperature logger observations if the record is long enough (see section 2.2 from more information) and also from the SSTAARS climatology (see section 2.3). The 1 and 2 standard deviations give an indication of the expected variability on each day.

Clicking “TIME SERIES” on the banner at the top reveals the time series plots of both of the reef flat and slope sites (Figure 3: Example dashboard for Cattle Bay temperature loggers showing the time series of each location: Reef FLAT for the period October 2015-September 2016 (top) and Reef SLOPE for 2002-2020 (bottom).). A slide bar at the bottom of each plot allows the full historical record to be viewed. In this case 1996 – 2017 can be seen. The window view can also be adjusted to see a subset of the record.

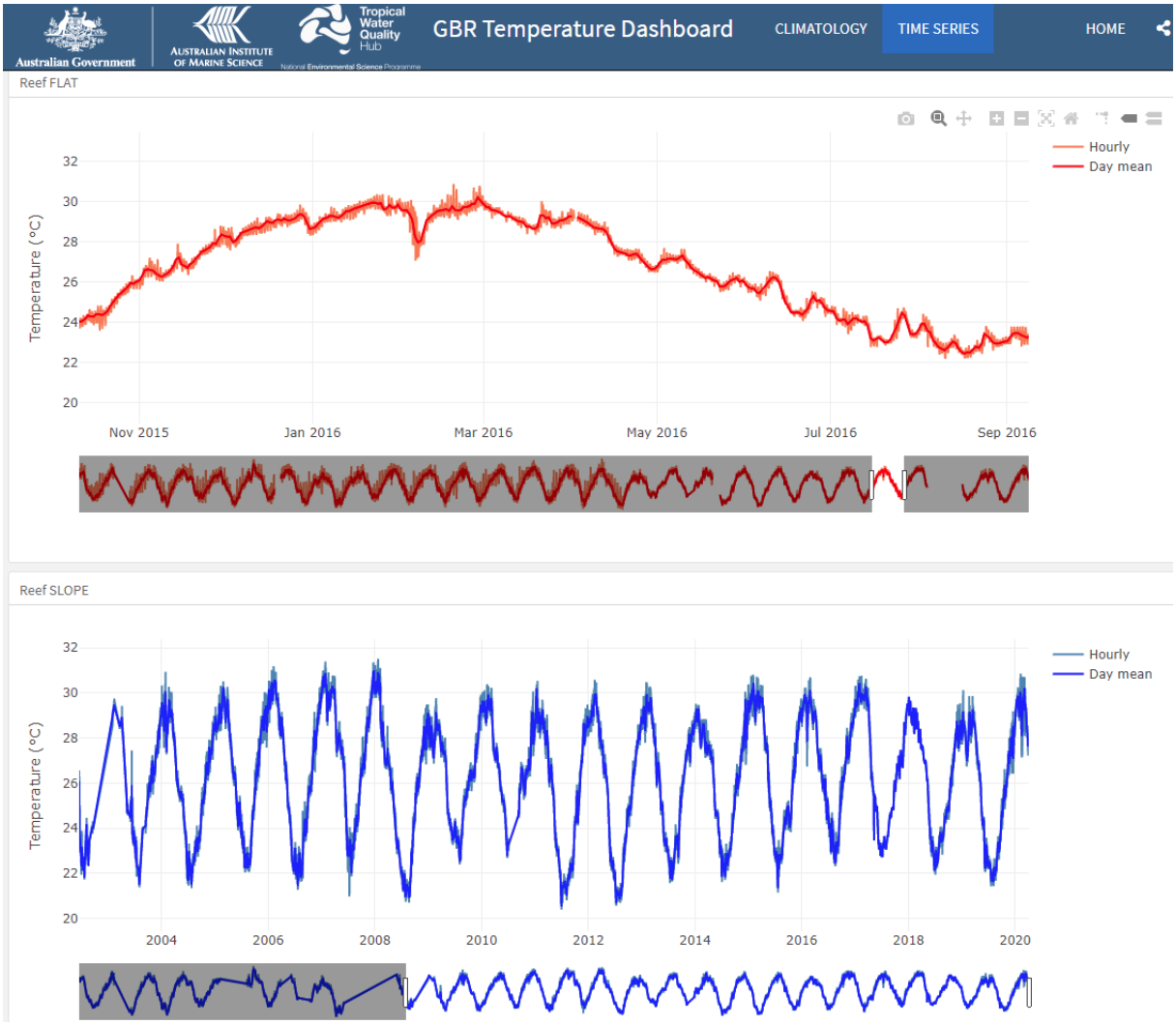


Figure 3: Example dashboard for Cattle Bay temperature loggers showing the time series of each location: Reef FLAT for the period October 2015-September 2016 (top) and Reef SLOPE for 2002-2020 (bottom).

1.1.2. AIMS Weather Stations

AIMS has a network of 18 weather stations located mainly on coral reef locations across northern Australia that provide essential, real-time data every 10 minutes on above-water meteorological conditions and in-water temperatures. The data represents the best long-term, on-reef record of climate and climate events in the region. Data can be downloaded from each station via the link below. The advanced charts allow historical data to be plotted and downloaded. Figure 4 shows the range of atmospheric observations from the weather stations beyond in the water temperatures that are focussed on here.

Resource Link:

- Real time data: https://weather.aims.gov.au/#/overview

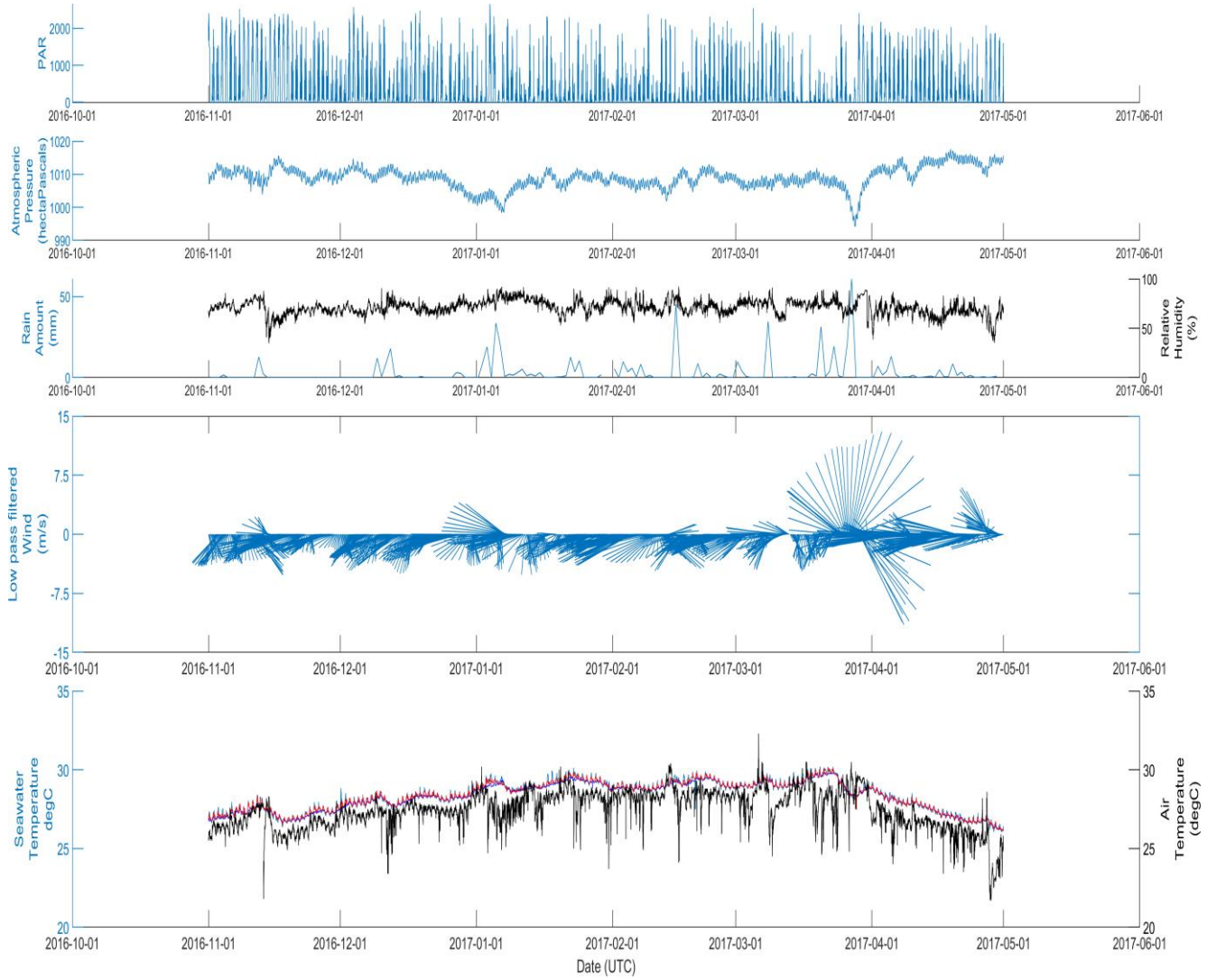


Figure 4: An example plot for Davies Reef temperature loggers weather station 2016-17: Descending from the top is PAR, atmospheric pressure, rain and relative humidity (in black), low passed wind as a stick plot, water (red and light blue) and air (in black) temperatures.

1.1.3. IMOS OceanCurrent

The IMOS OceanCurrent website (http://oceancurrent.imos.org.au/) provides daily satellite sea surface temperature and Ocean Colour (chlorophyll-a) maps around Australia. The website overlays data from other Integrated Marine Observing System (IMOS) platforms: Argo profilers; gliders; HF Radars; surface drifting buoys; underway ship temperatures and moorings. This provides an excellent resource for an overall picture of the state of Australia's seas. Figure 5 shows an example of both the SST map and the corresponding ocean colour map.

From the maps, a user can click on the various platforms to quickly get a visualisation of that specific data platform. Geostrophic currents derived from satellite altimeters are also plotted to help discern the ocean currents. There are also a number of anomaly products and percentiles calculated from the SSTAARS climatology described in Section 2.3.
Links to resources:

- Daily SST products
- Anomaly products based on SSTAARS climatology.

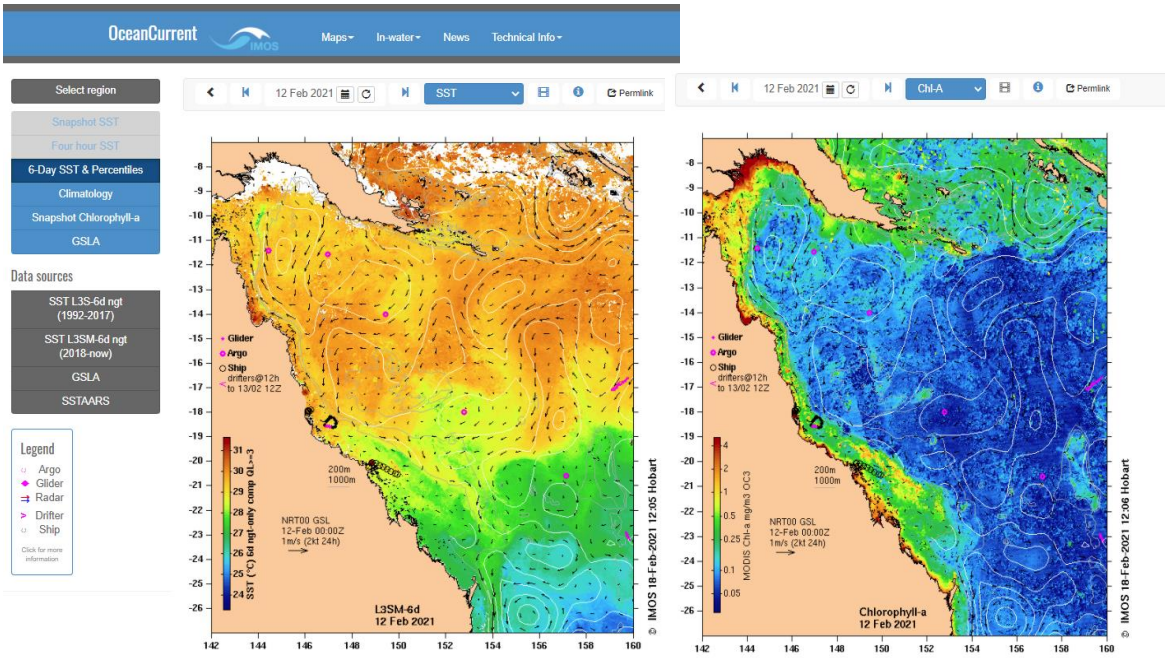


Figure 5: Screenshots of IMOS OceanCurrent from 12 February, 2020 of the six-day average SST map (left panel) and an IMOS Ocean Colour map 12 February, 2021 (right panel). Black arrows indicate geostrophic currents from satellite altimetry. Cloud or low quality data is white. Other observing platforms are described in the legend (bottom left) including Argo, gliders, radar, surface drifting buoys and ships.

1.1.4. IMOS Great Barrier Reef Moorings

Queensland IMOS Moorings as shown in Figure 6, collect key oceanographic data from shelf arrays located in the northern tropics along the Great Barrier Reef. The mooring arrays provide near real time and delayed mode observations comprising physical (temperature, salinity, sea level and currents) and water quality measurements (turbidity, chlorophyll fluorescence and PAR). They are one of the few ways sustained measurements of vertical water column structure is made and are useful in determining the thermal stratification caused by spring-summertime warming and also of identifying cold water intrusions. Most of the moorings are on the outer continental shelf and slope away from the coral reefs to provide an understanding of the structure of the open ocean. Of note is the sparse array which means there is only data at a handful of key locations. Note the moorings off Lizard Island were not operating during the period of this study and so through water column observations are only available in the central and southern GBR.

Resource Links:
Queensland IMOS Moorings:

- https://imos.org.au/facilities/nationalmooringnetwork/qldnorthernausmoorings/
- Deployment Summaries: https://www.aims.gov.au/imosmoorings

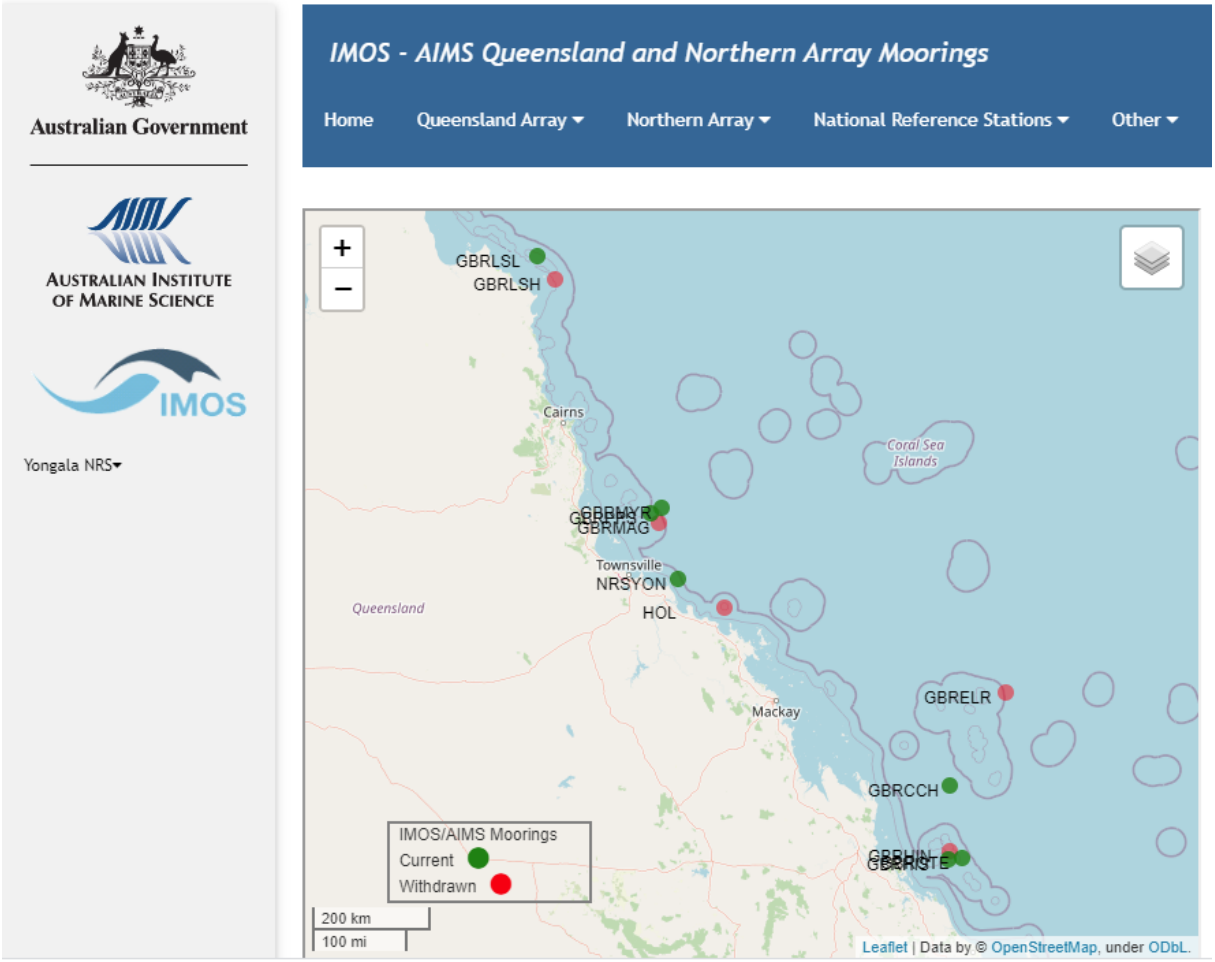


Figure 6: Map of the Q-IMOS GBR moorings array.

The deployment summary webpage (Figure 6) allows the reader to access a description of each mooring deployment by clicking on the circles to see what instruments were deployed and how they were configured for sampling. Links to the data on the AODN can also be found from this page.

Gridded Long Time Series Plots from the moorings are also being made available from the AODN to promote the uptake of useable data by non-specialist end-users. Figure 7 shows an example plot of the data from Capricorn Channel over the two summers of interest. The warming of the water column from spring to summer and eventual cooling in April can be tracked.

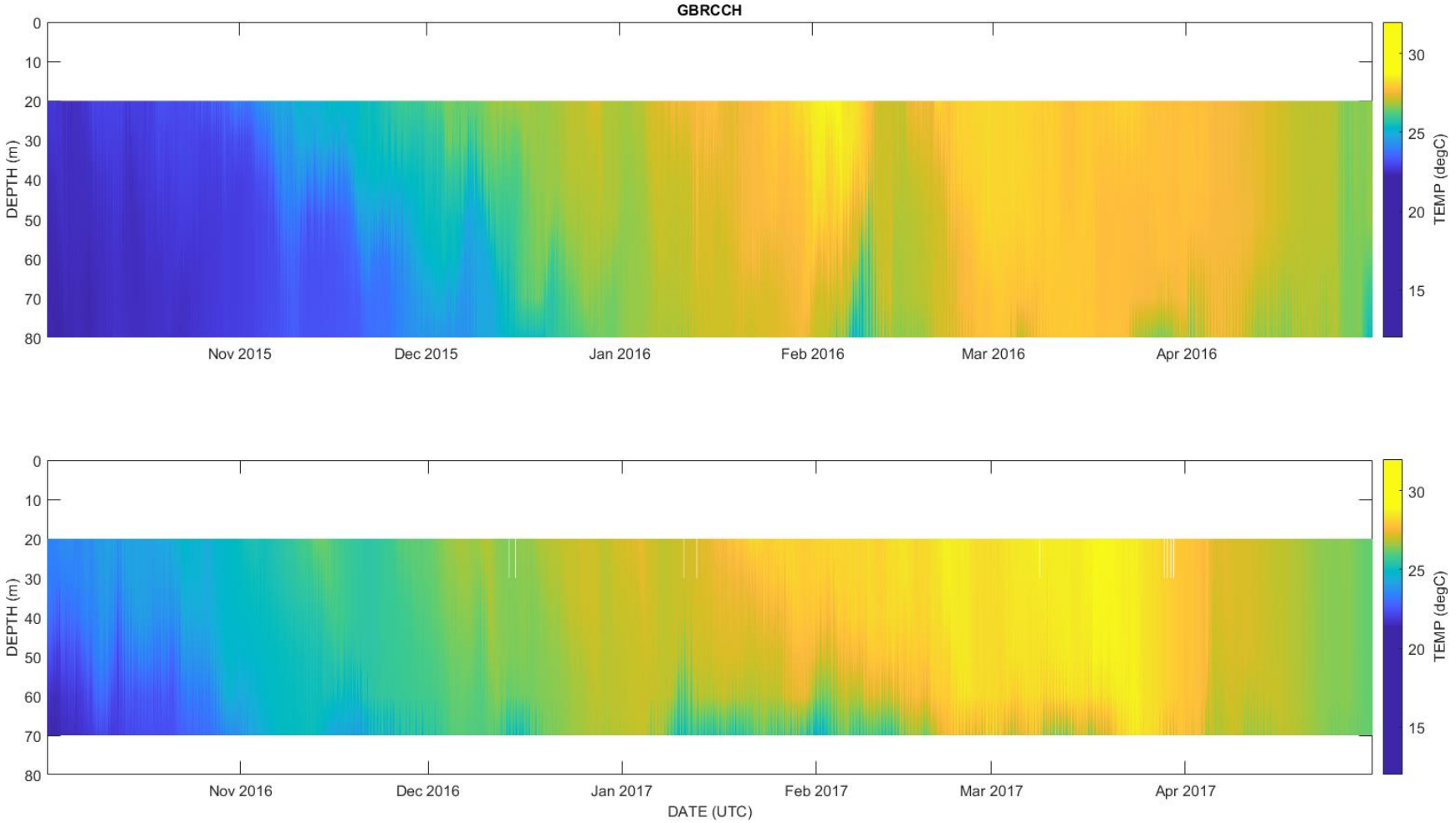


Figure 7: Plot of temperature interpolated through the water column for Q-IMOS GBR mooring in Capricorn Channel for Oct 2015- Apr 2016 (top) and Oct 2015- Apr 2016 (bottom).

1.1.5. IMOS Gliders

IMOS ocean gliders are operated by the University of Western Australia and tasked by the Queensland node scientists on regular missions of which the GBR is allocated 4 missions per year. These have been supplemented in recent years in an initiative to monitor extreme events such as the marine heatwaves associated with the coral bleaching events.

The first ever Slocum glider deployments in the Central GBR occurred in October 2015 with CSIRO, followed by deployments by the Ocean Glider Facility in November 2015. From 1 October 2015 – 30 April 2016, there were 9 glider deployments. From 1 May 2016 – 30 August 2016, there were 3 glider deployments. There were no glider deployments from September – December 2016.

The tracks of the gliders over the 2015-16 and 2016-17 summers are shown in Figure 8. From 1 Jan 2017 – 30 April 2017, there was one Slocum glider deployment (continental shelf, <200m) and two Seaglider deployments (deep water, <2000 m) near Lizard Island. In total, there were 15 glider deployments from 1 October 2015 – 30 June 2017. Figure 9 shows two glider tracks for March – April 2016 with temperature profiles during the peak of the marine heatwave. The link to the glider summary plots via OceanCurrent provide a comprehensive history of IMOS and CSIRO glider deployments around Australia.

Resource Links:

- Glider summary plots: http://oceancurrent.imos.org.au/gliders/index.php
- IMOS visualisation tool: https://imos.org.au/gliderscope/

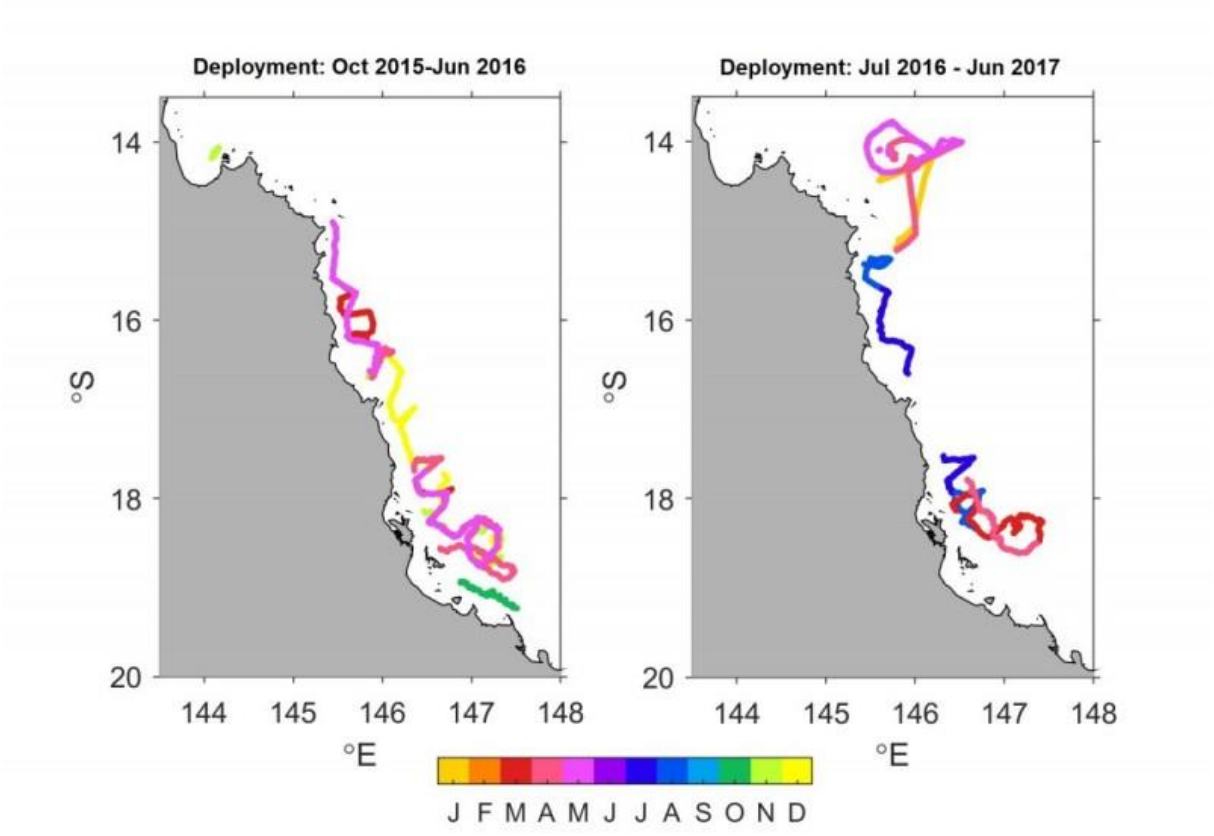


Figure 8: Footprint of the 15 glider deployments from (left panel) 1 October 2015 – 30 June 2016 and (right panel) 1 July 2016 – 30 June 2017. The trajectories indicate the months (colours) that the waters were sampled.

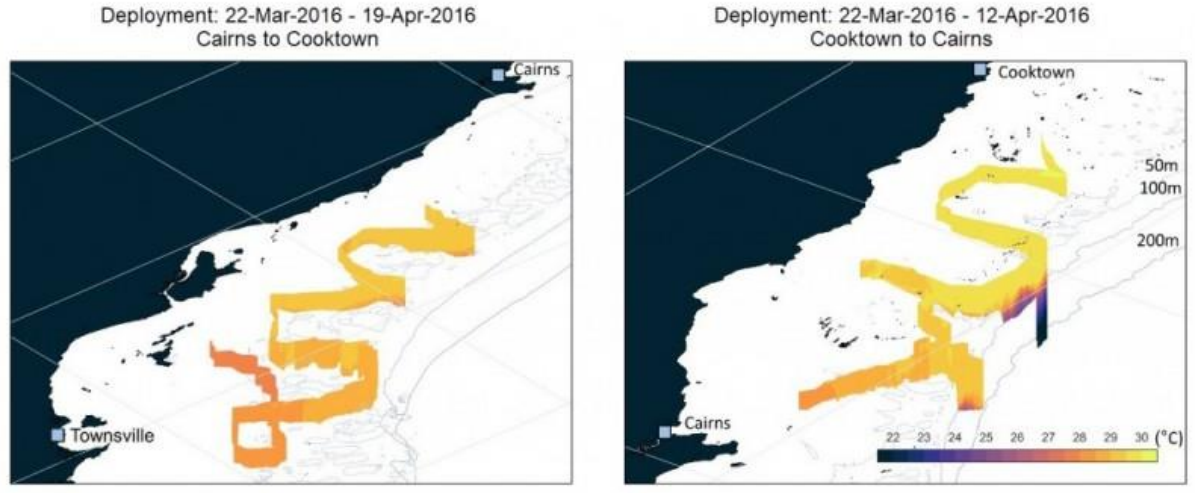


Figure 9: Slocum glider temperatures through the water column (3D) during the 2016 marine heatwave in the Great Barrier Reef. The deployments occurred from (left panel) 24 March 2016 – 19 April 2016, Cairns to Cooktown and (right panel) 22 March 2016 – 12 April 2016, Cooktown to Cairns. The same colour scale is applied. Adapted from Benthuysen et al. (2018).

1.1.6. IMOS Ships of Opportunity Underway Thermosalinograph

Through the IMOS Ships of Opportunity – Sensors on Tropical Research Vessels sub-facility, the AIMS RV Cape Ferguson collects temperature data (and other water properties) with water sampling intake at 1.9 m depth. Water temperature is sampled every 10 sec and data are sent hourly (near real time) to the AIMS Data Centre, Bureau of Meteorology for processing and submission to the World Meteorological Organisation (WMO) Global Telecommunication System (GTS), and IMOS to be made available on the AODN Portal. The data can be used to validate the satellite SSTs and be used in operational weather and marine forecasting. These measurements are particularly useful during periods of cloud covers where the satellites cannot sense SSTs.

From 1 Oct 2015 – 30 Apr 2016, data are available from 16 voyages, primarily in the central and southern GBR. From 1 Oct 2016 – 30 Apr 2017, data are available from 17 voyages. The AIMS ship temperature data set is available from the AIMS Data Catalogue and the AODN Portal.

Over these time periods, there were only two voyages for the RTM Wakmatha, which collected temperature data and other water properties, during late March 2016 and early April 2016 (not shown; data available from the AODN Portal).

Resource Links:

- RV Cape Ferguson via AIMS Data Centre via the AODN portal
- Metadata record for RTM Wakmatha Data via the AODN portal

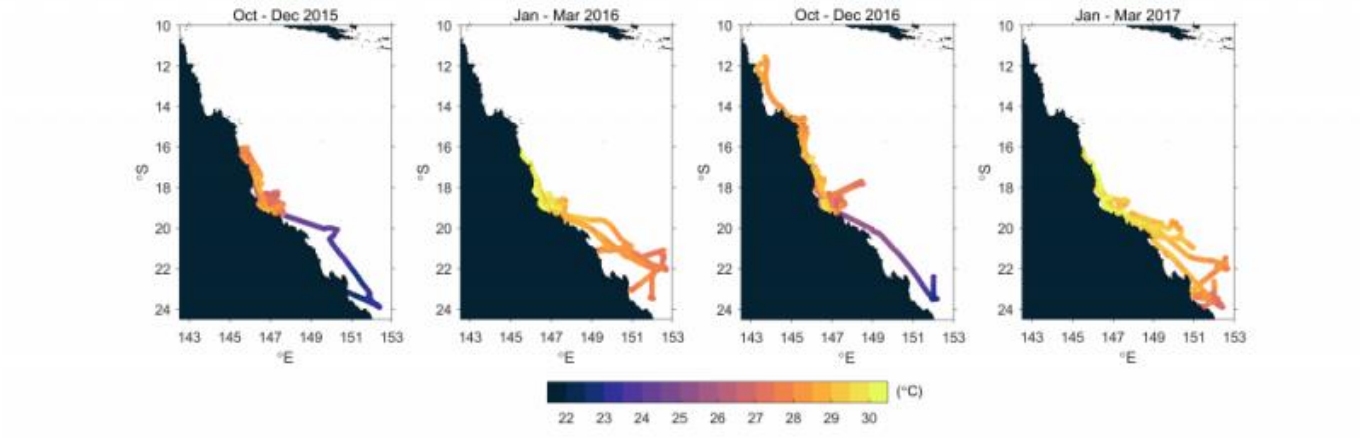


Figure 10: AIMS R/V Cape Ferguson voyage tracks and hourly-averaged temperature data from three-month periods from 2015-2017.

1.1.7. Queensland Government Temperatures from the Wave Buoy Network

The Queensland wave buoys are arrayed along the Queensland coast providing long term monitoring of waves and temperature (Figure 11). The data is useful for coastal validation of satellite imagery and knowing the sea state during weather events. These provide coastal observations away from the shore and coral reefs and provide a useful source of data for the validation of models and satellite SST.

Resource Links:

- Wave buoy locations and real time data
- Wave buoy data archive

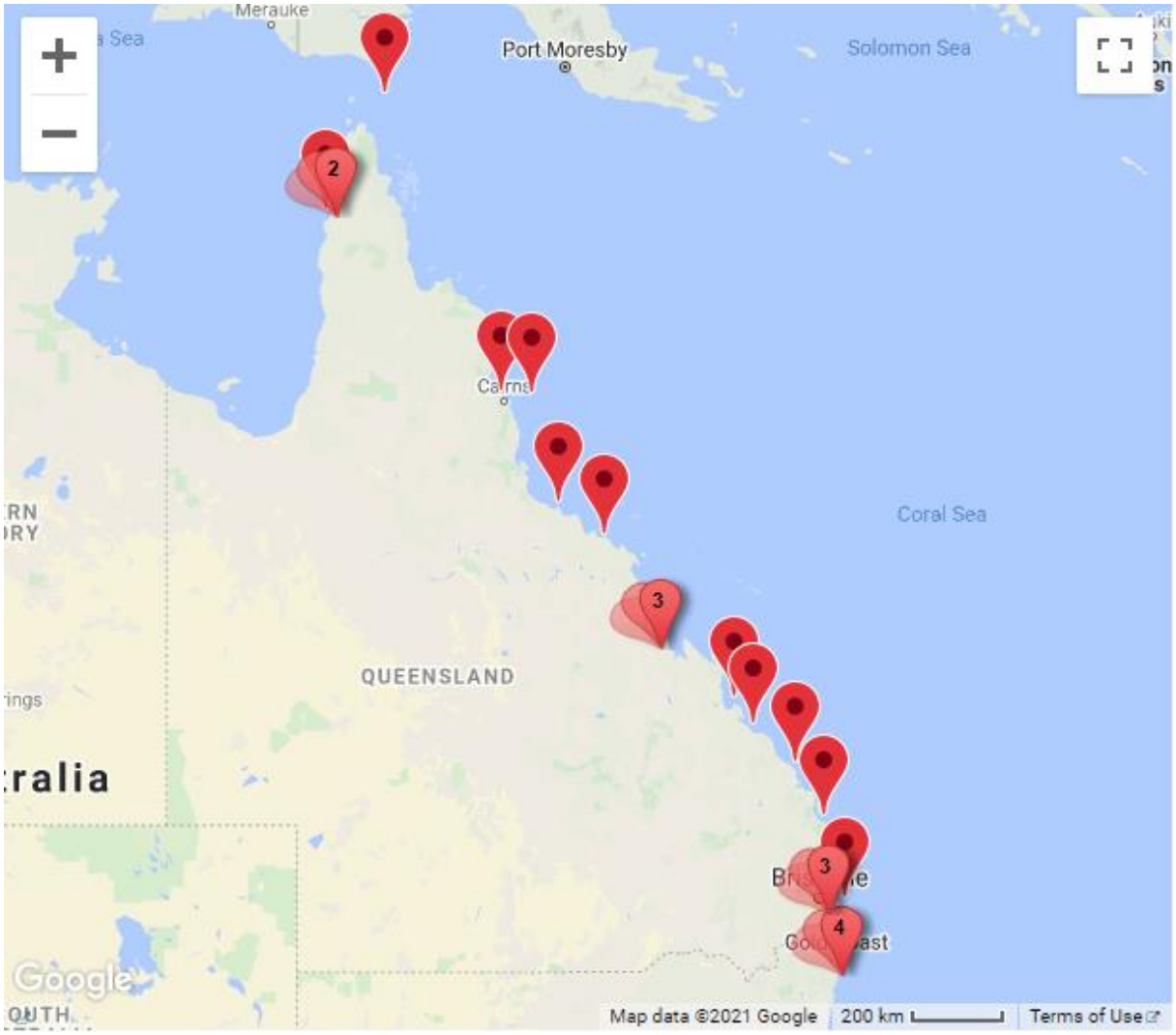


Figure 11: The Queensland Government's Wave Buoy Network.

1.1.8. AOML surface drifting buoys

Surface drifting buoys from NOAA's Global Drifter Program measure temperature at 20-30 cm depth. This temperature data is used by satellite algorithm developers to calibrate and validate remotely sensed sea surface temperatures. From 1 July 2015 – 1 July 2017, there were 28 total drifters that entered the GBR Marine Park (Figure 12). Between the two years, 7 drifters from 1 July 2015 – 1 July 2016 and 22 drifters from 1 July 2016 – 1 July 2017 (within the overlapping period) were present in the Coral Sea-GBR region.

Resource Link:

- AOML surface drifting buoys

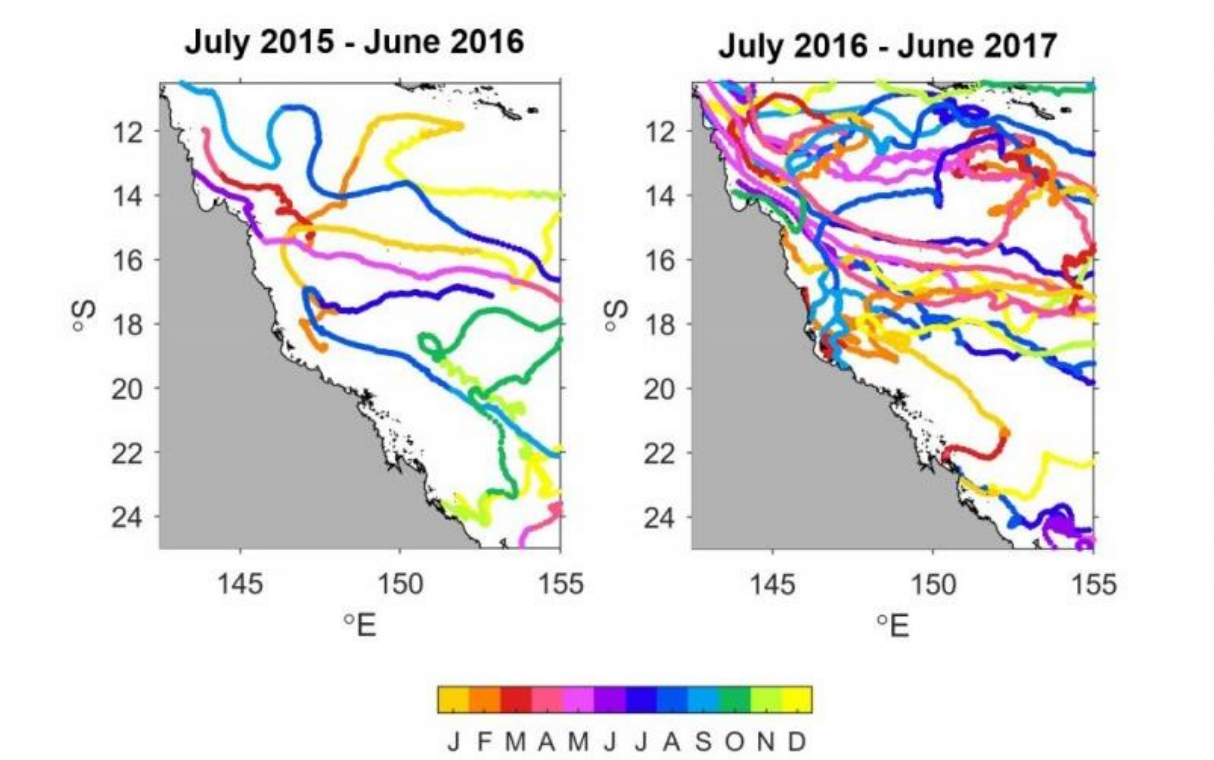


Figure 12: Surface drifting buoys trajectories from the AOML database from (left panel) 1 July 2015 – 30 June 2016 and (right panel) 1 July 2016 – 30 June 2017. At a particular location, the colour represents the month over which that drifter traversed that position.

1.1.9. AIMS Temperature Logger Program Climatologies

GBR temperature loggers have been used to provide daily climatologies at over 69 reef flat or slope locations where the record's length and data quality is deemed to be sufficient and is based on the hourly registers from loggers with 10 or more years of data. To exclude the more recent rapid warming from the climatologies, only data up to 2012 has been used (Lough et al., 2018). They are being used to calculate anomaly products and coral bleaching metrics and to compare with other satellite derived products such as the NOAA DHW and ReefTemp products.

The resource link below provides a link to download all of the data with scripts that generated the climatology. The data is then plotted as per Figure 13.

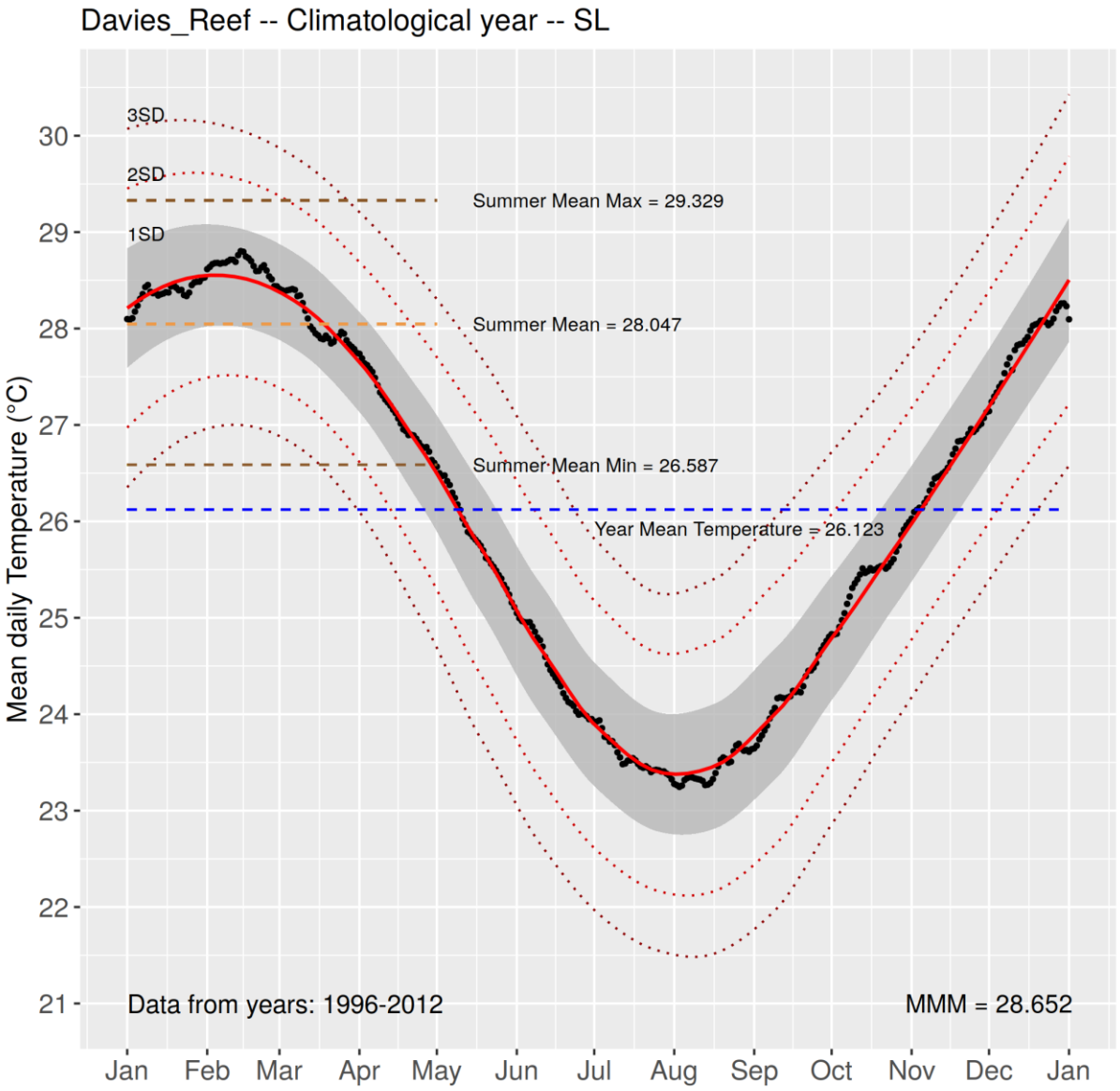


Figure 13: Climatology of the Davies Reef Slope temperature logger. The black points represent the climatological temperature value for each day of the year. The red curve is a smooth fit to the points with 95% confidence interval (grey band). Dotted lines are the 1, 2 and 3 standard deviations of the fitted line. MMM is the maximum monthly mean temperature of the time series.

Resource Link:

- Temperature Loggers Climatology for the GBR region

2.0 METHODOLOGY

The main data set created specifically under this project is the *in situ* temperature logger data. To use it for the period of interest we also needed to produce climatologies to better validate and compare with other climatology and anomaly products such as the NOAA Degree Heating Week and ReefTemp Degree Heating Days. This meant the entire history of temperature observations were reprocessed with some re-calibrated as errors were detected in the original dataset. Section 2.3 introduces the Sea Surface Temperature Atlas of Regional Seas (SSTAARS) which is used to compare with the logger observations and climatology on the dashboard described in Section 1.1.1.

All other datasets have had various types of quality control applied from the institutions they are sourced from and so are considered ready for use.

2.1 In situ Temperature Data Processing and Quality Control

AIMS Data Centre maintains a database with all the data and metadata related to the temperature logger program. To evaluate the quality of the data, a full database download was obtained (Figure 14). The data contains temperature records from 1022 instruments at 123 sites and 284 locations. Normally, the loggers were deployed in two or more locations (reef flat FL, reef slope SL, channel CH). The temperature logger sites are classified according to common coral reef topography location. Reef flat is the shallow area atop the reef itself that usually has a shallow lagoon. This area can often pond at low tide and so will have the most extreme range of temperatures. The reef slope loggers are often 5-7m deep on the side of the reef – usually coinciding with AIMS Long Term Monitoring Program sites – as they are deeper they will fluctuate less than the reef flat locations. A further distinction for the reef slope type of deployment is whether it is in a narrow channel between reefs. This area will be associated with stronger currents and is more likely to be well mixed. A full catalogue of the data availability was produced including temporal coverage at each of the sites/locations.

Central Sector

Code

lat	lng	Location	ts.start	ts.end	ts.len	ndeployments	ts.duration	ngaps	gap.max	gap.min	gap.total	completeness	timeline	tempCover	coverIndexPlot
-19.2	146.9	Geoffrey Bay	1991-11-20	2018-06-01	9690	130	26.5	5	227	7	636	93.4		91.8	
-18.6	146.5	Cattle Bay	1993-02-11	2018-06-01	9241	110	25.3	3	156	2	226	97.6		91.4	
-18.3	147.4	Myrmidon Reef	1995-04-13	2018-06-01	8450	61	23.1	2	314	12	326	96.1		82.4	
-18.8	147.6	Davies Reef	1996-05-02	2018-06-01	8065	84	22.1	2	161	8	169	97.9		80.1	
-16.7	146.1	Arlington Reef	1996-03-27	2018-06-01	8101	38	22.2	2	256	151	407	95.0		78.0	
-18.7	147.7	Chicken Reef	1996-04-27	2018-06-01	8070	48	22.1	3	182	122	453	94.4		77.2	
-18.4	147.0	Kelso Reef	1995-07-04	2018-06-01	8368	60	22.9	3	967	2	973	88.4		75.0	
-16.4	145.6	Low Isles	1996-03-30	2018-06-01	8098	33	22.2	2	887	16	903	88.8		73.0	
-18.4	147.5	Dip Reef	1996-04-25	2018-06-01	8072	30	22.1	2	1463	149	1612	80.0		65.5	
-18.5	146.5	Pelorus Island	1993-08-07	2018-06-01	9064	80	24.8	2	3026	102	3128	65.5		60.2	
-19.1	146.9	Florence Bay	1995-09-04	2012-11-02	6269	39	17.2	1	392	392	392	93.7		59.6	
-16.8	146.0	Green Island, Qld	1996-03-26	2018-06-01	8102	22	22.2	5	1000	141	2347	71.0		58.4	
-18.6	147.1	John Brewer	1996-04-23	2018-06-01	8074	41	22.1	4	1850	2	2329	71.2		58.3	

Figure 14: Sample of the loggers' data availability catalogue from the AIMS Data Centre.

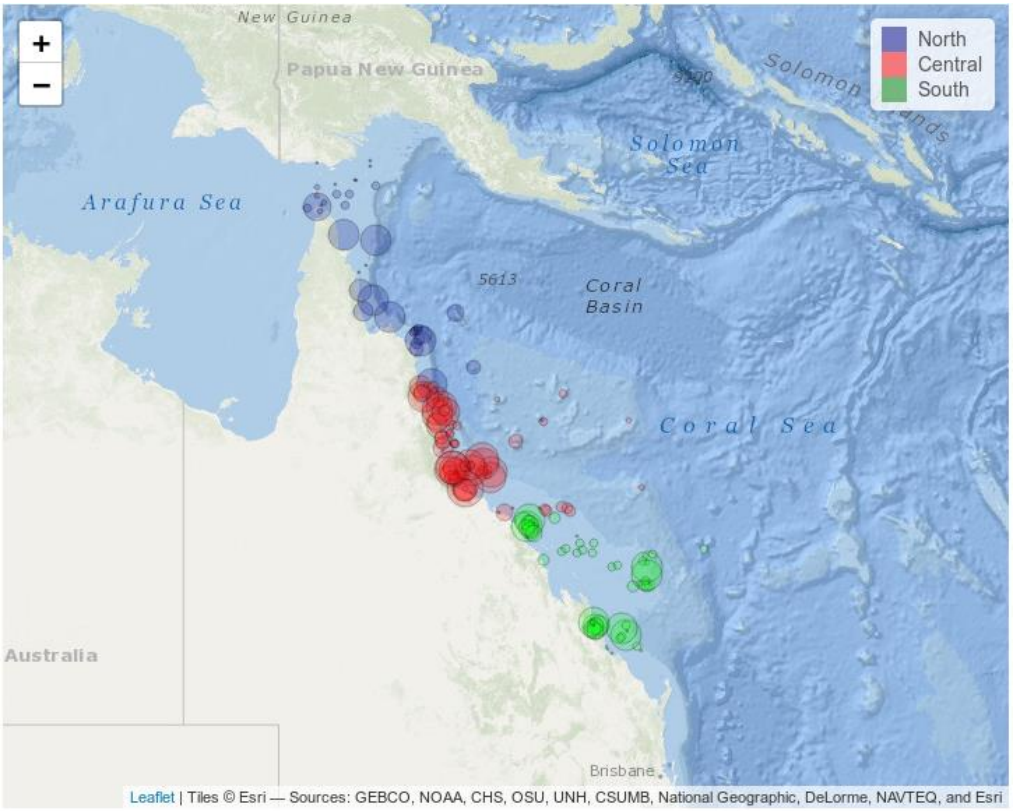


Figure 15: Location of the temperature loggers' sites on the GBR. The size of the circle represents the number of years of data.

The temperature program makes use of a wide range of people to deploy and recover the instruments. Whilst the majority are long term observations where other studies provide the opportunity to visit the sites, others can be deployed for much shorter studies. Figure 15 reveals the distribution of temperature loggers along the GBR and a visualisation of the length of records of each site.

Due to the nature of the AIMS temperature logger program, the quality control procedures are applied at different stages of the operation. In general, two main procedures of QC are applied:

1. Calibration of the instruments
2. Quality control of the calibrated data

The calibration files for all the loggers were reviewed and after some errors detected in the calibration algorithm, all data was re-calibrated with correct coefficients and formulae.

The quality control protocol for the calibrated data consisted in several standard QC tests. Every test was indicated with a flag as passed (0) or failed (1). Tests were adapted from Morello et al (2014) and Toma (2016) were implemented as per Table 1 and Table 2 below.

Table 1: Quality control flag definitions

Flag #	Description	Notes
1	Value greater that possible maximum value	Temp max = 33
2	Value lower that possible minimum value	Temp min = 19
3	Start before deployment datetime	
4	End after recovery datetime	
5	Spike test	
6	Excessive gradient test	
7	Flat line test	T = 4h

Then one single QC flag as set, according to IMOS standards as shown in Table 2:

Table 2: IMOS overall quality control flag definitions

IMOS QC flag	Description
0	No QC performed
1	Good data
2	Probably good data
3	Bad data, potentially correctable
4	Bad data
5	Value changed
6-8	Not used
9	Missing value

The resulting flags from the QC procedures were added to each of the records as individual columns. Figure 16: Example of the QC tests performed on a temperature loggers times series. The top panel is the original series. The middle panels show individual points that fail the spikes and the excessive gradient test. The bottom panel are the QC flags for each point for the spike and gradient tests.is an example of the QC procedures applied to a temperature logger in the register. A subset of the temperature time series is shown at the top and the any failed tests, in this example spikes or too high a gradient are plotted in the middle plots. The bottom plot identifies which particular test or tests that observation point failed for each point.

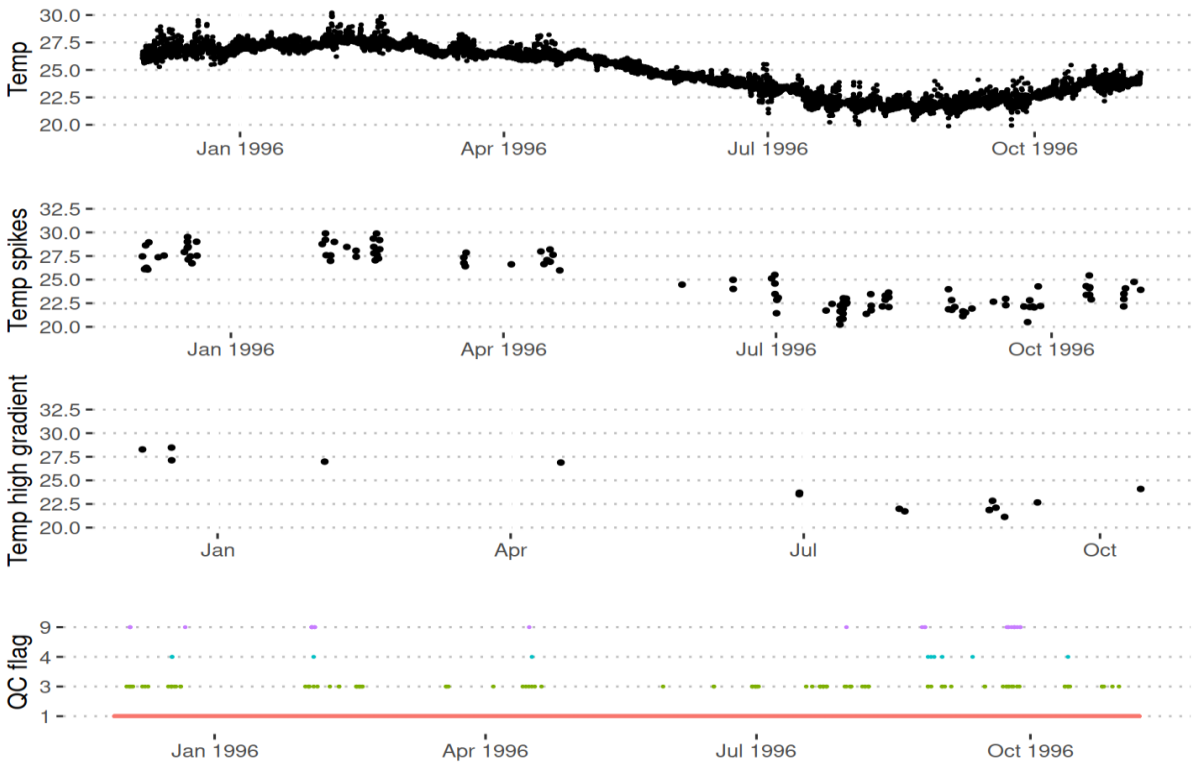


Figure 16: Example of the QC tests performed on a temperature loggers times series. The top panel is the original series. The middle panels show individual points that fail the spikes and the excessive gradient test. The bottom panel are the QC flags for each point for the spike and gradient tests.

2.2 In situ Temperature Climatologies

Considering the large network of temperature loggers over the GBR daily climatological values were determined for the temperature record for the sites with more than 10 years of observations prior to 2012. Climatologies for over 70 sites we generated from records extending up to 30 years. Ten years was considered a minimum length for this study as it would include a number of ENSO cycles however a longer period would be preferable to include an Inter-decadal Pacific Oscillation (IPO). The climatologies are a useful tool to describe the average behaviour of the temperature and can then be used to estimate anomalies in future records. Climatological summaries and plots were produced initially for the sites at reef flat and reef slope locations (Figure 17).

The quality-controlled time series from different deployments at the same reef location were blended and the daily statistics calculated. For each location slope or reef flat (denoted SL or FL respectively), the original temperature values, normally at 10 minutes interval, were averaged to the hour and the timestamp set to the beginning of the hour. Only good data is used (IMOS QC flag 1 in Table 2) for the calculations. The hourly records were summarised into daily values according to the day of the year for each year and the average temperature for each of the days was calculated. Additional statistical descriptors were also calculated for each day (daily median, minimum, maximum, standard deviation, median absolute deviation and the 0.03, 0.01, 0.1, 0.32, 0.50, 0.68, 0.90, 0.99, and 0.997 percentiles).

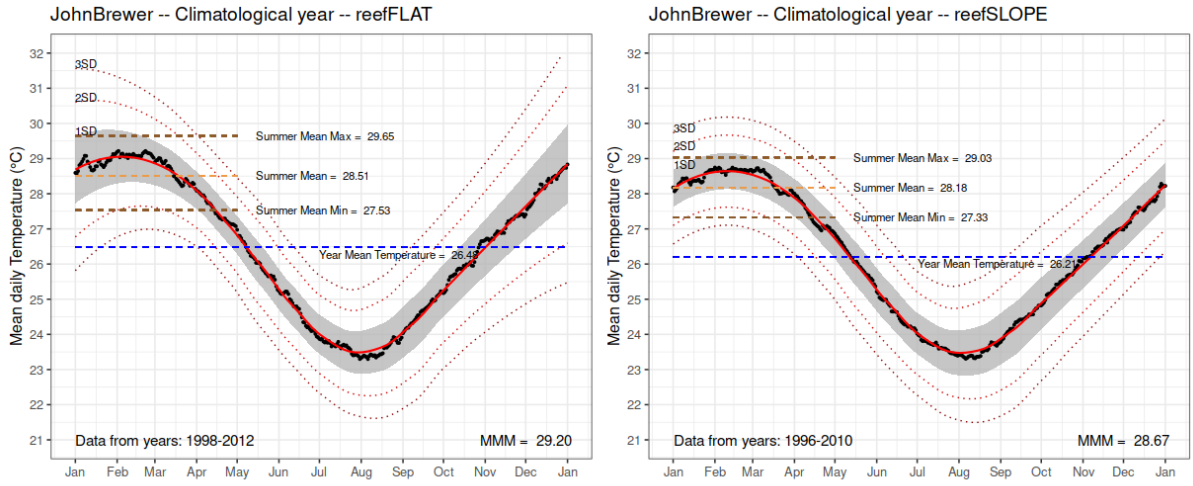


Figure 17: An example plot for reef location specific temperature loggers (reef FLAT left, reef SLOPE right) climatological year for John Brewer reef.

Figure 18 shows the entire record of temperature observations from John Brewer Reef. Long breaks in the record can be due to many reasons such as instrument failure, or loss due to an extreme weather event or theft. This illustrates the need to always look at the source data that contributes to the climatology to get an understanding of each location's observing gaps and limitations.

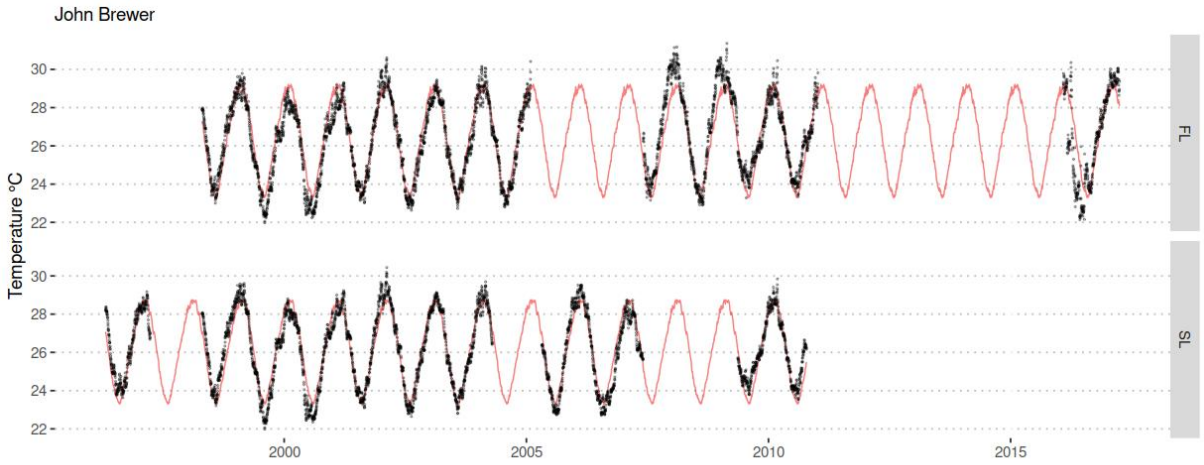


Figure 18: Data availability for John Brewer site at reef flat and slope locations. The data is plotted as points (black) over the reference climatological values (red line). FL: reef flat, SL: reef slope

2.3 Sea Surface Temperature Atlas of Australian Regional Seas (SSTAARS)

The Australian Sea Surface Temperature Atlas of Regional Seas (SSTAARS) is a daily SST climatology product that is used to calculate anomalies and percentiles around Australia. The daily SST product at 2km resolution is produced from 25 years of de-biased and georeferenced sea surface temperature data from NOAA Polar Orbiting Environmental Satellites received from six Australian and two Antarctic reception stations following international GHRSST

principles (Wijffels et al., 2018). The atlas reveals unprecedented detail of SST structure attributed to regional oceanographic phenomena such as tidally driven entrainment cooling over shelves and reef flats, wind-driven upwelling, shelf winter water fronts, cold river plumes, the footprint of the seasonal boundary current flows and standing mesoscale features in the major offshore currents. Figure 19 shows the February monthly climatology from OceanCurrent.

Links to resources:

- SSTAARS visualised on Ocean Current
- SSTAARS data access (AODN)

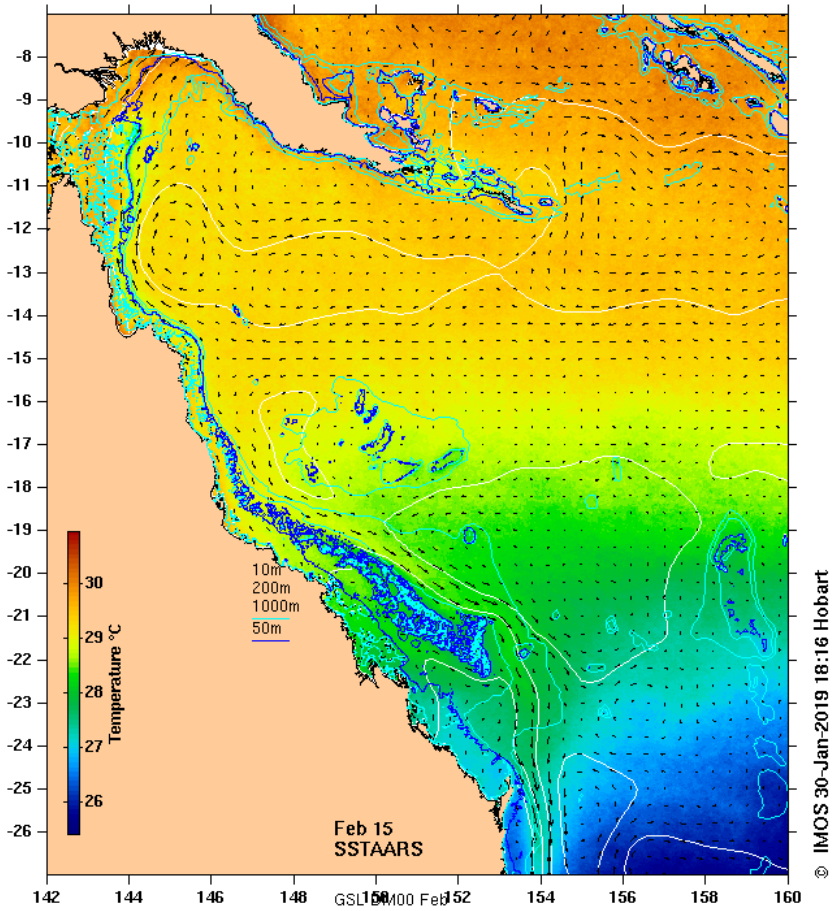


Figure 19: SSTAARS Climatology for February (centred in the middle of the month) for the GBR and Coral Sea region.

3.0 RESULTS AND DISCUSSION

This section provides an analysis of the thermal histories of the 1km eReefs model and observed temperatures from in situ loggers and IMOS moorings in the following two sections. The eReefs validation is also discussed in more detail in section 3.1 of Volume 2 (Langlais et al., 2021). The full comparison and statistics for all sites and mooring locations is available from the eAtlas project page (https://eatlas.org.au/nesp-twq-4/drivers-of-bleaching-4-2) and summarised in section 3.1 and 3.2.

Section 3.3 and 3.4 discusses the climate, weather and oceanographic conditions experienced over the 2015-17 period when the back-to-back bleaching occurred. Some references are made to the 2019-20 bleaching event and the intervening years given they reflect the significant inter-annual variability that has been monitored throughout the life of this project. The 2019-20 event happened late in the process so the majority of in situ field observations were not yet available for inclusion in this report. Readers can refer to the 2019-20 coral bleaching event in Volume 4 (Benthuysen et al., 2021).

3.1 Validation of the eReefs 1km Model with In Situ Temperature Observations

To validate the eReefs output, hourly temperature time series were extracted from the eReefs GBR 1km model for 326 reef locations, including reef flat, reef slope and reef channel for the period 2015-2017. The model was then compared with the in situ register and several goodness-of-fit statistics were calculated (see Appendix 1, Volume 2 of Langlais et al., 2021). In general, the variability of the differences at reef flat locations was higher than at the reef slope locations. Plots of the time series were made from model and observations for each site and reef location (Figure 19 – Figure 20). Figure 21 shows the extent of the differences between the model and observations (Figure 21). In this case the sites for Cattle Bay on Orpheus Island is shown.

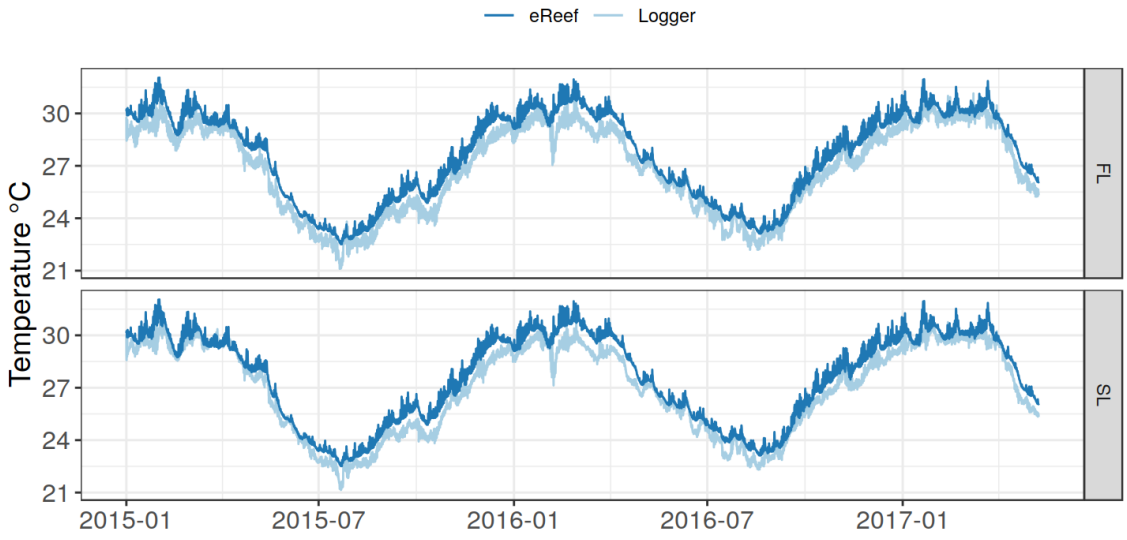


Figure 20: Temperature time series from the eReefs model (dark blue) and in situ logger (light blue) for Cattle Bay (Orpheus Island) site. Flat (FL) and slope (SL) locations.

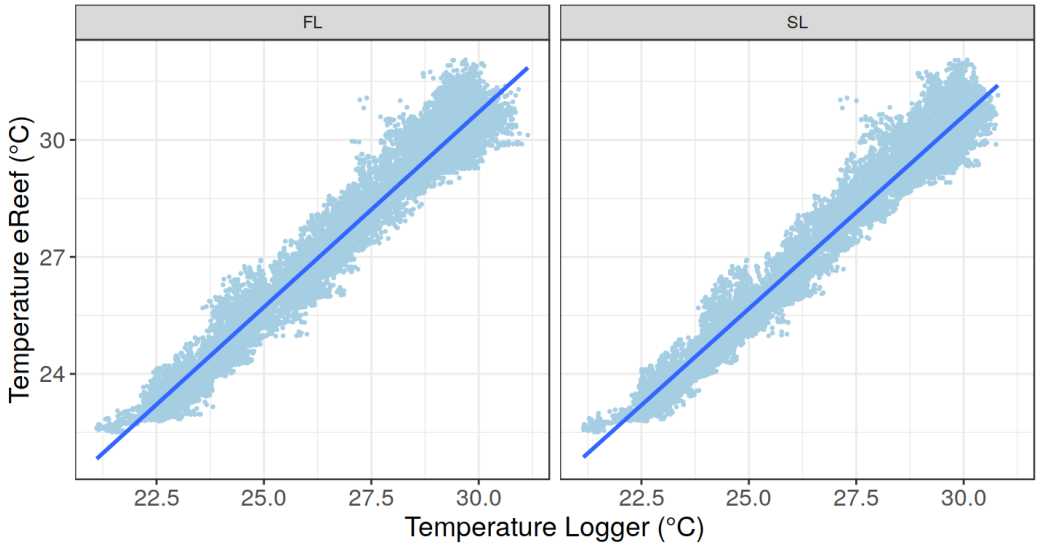


Figure 21: Temperature scatter plots from the eReefs model (dark blue) and in situ logger (light blue) for Cattle Bay (Orpheus Island) site. Flat (FL) and slope (SL) locations.

Figure 22 shows the distribution of the temperature differences for all sites at Cattle Bay. Overall, the variability of the differences at reef flat locations was higher than at the reef slope locations. Figure 24 shows the spread of the differences broken down into reef flat and slope locations and Figure 24 the mean offset between the eReefs model temperature and observations. The mean difference for all sites was 0.36 °C at reef flats and 0.25 °C at reef slopes, with the GBR1 model output values higher on average than loggers at the flat and slope locations.

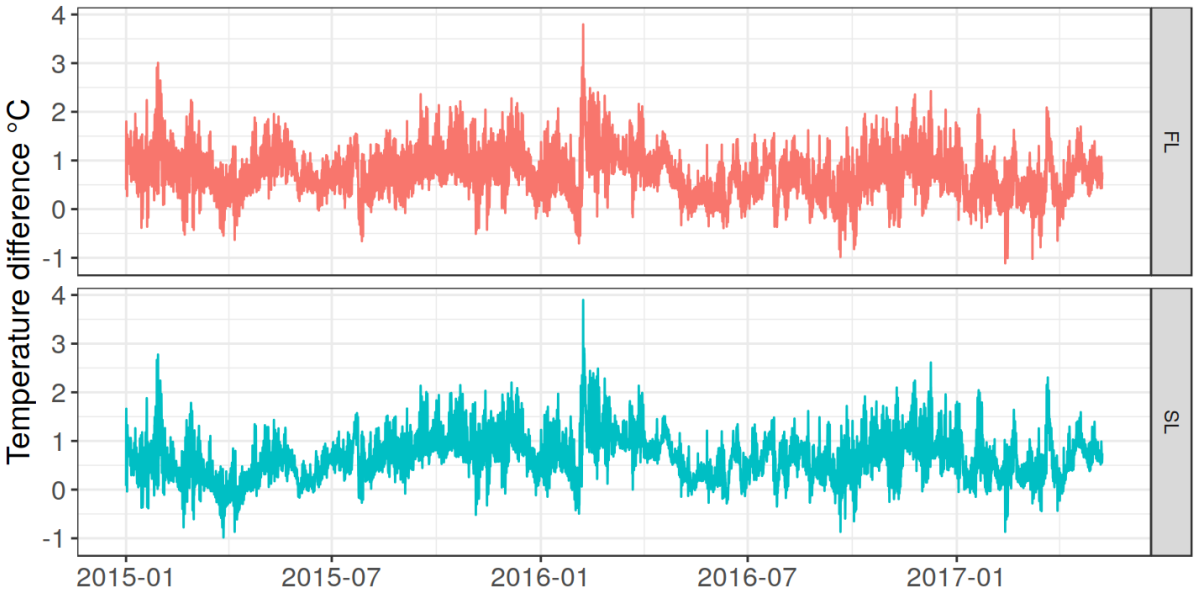


Figure 22: Absolute difference of the temperature register from the eReefs model and the in situ loggers. Cattle Bay, Orpheus Island, at reef flat (FL) and reef slope (SL) locations.

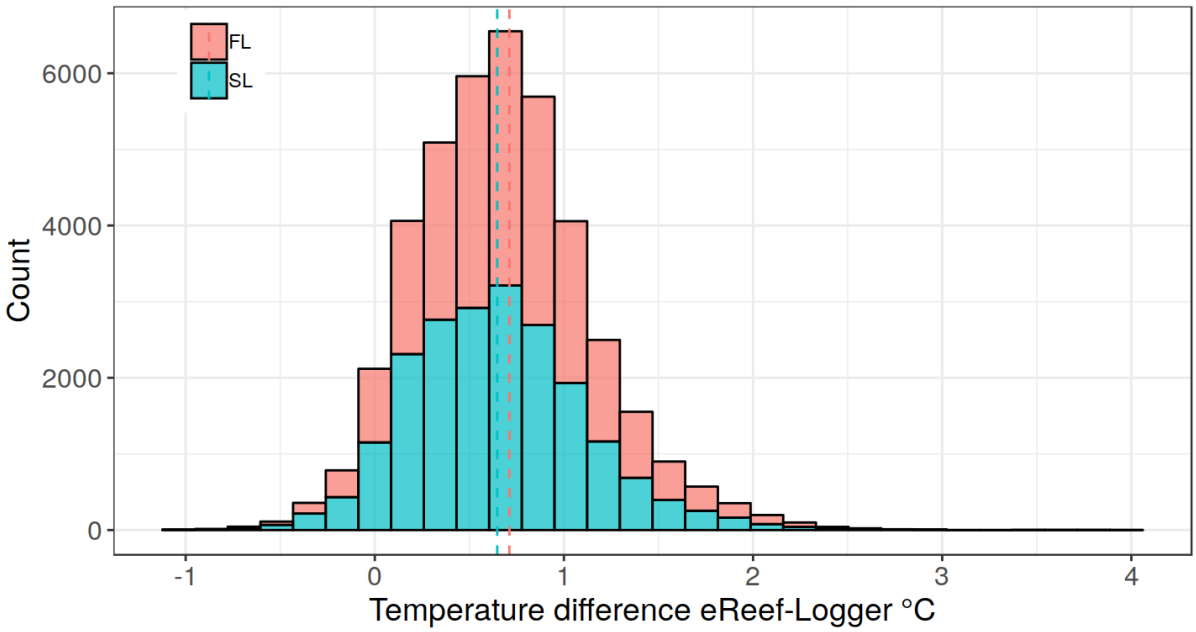


Figure 23: Distribution of the difference between eReefs temperature and in situ temperature. The vertical dashed lines represent the mean difference value. Cattle Bay, Orpheus Island, at reef flat (FL) and reef slope (SL) locations.

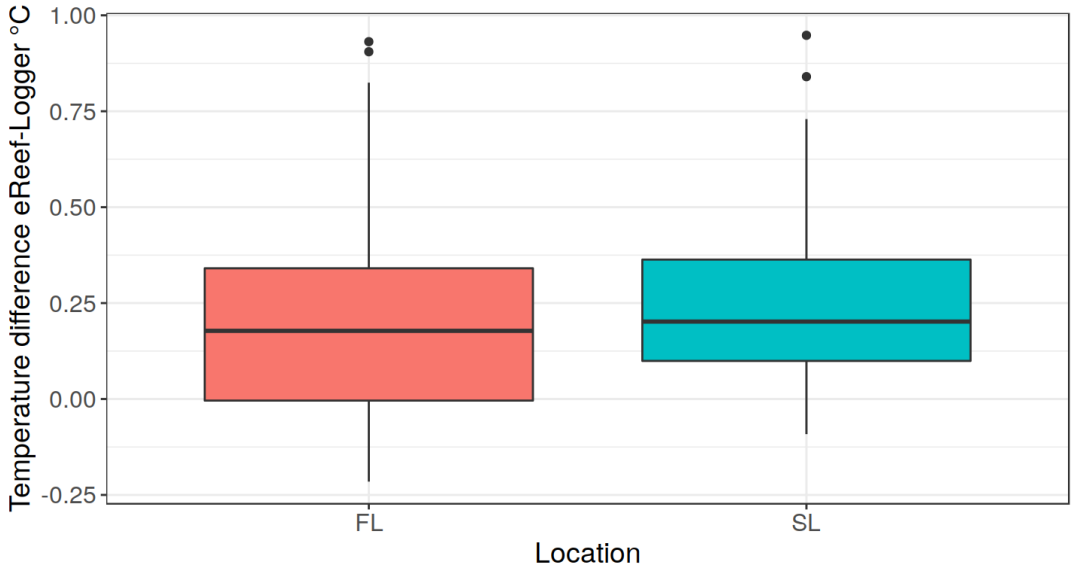


Figure 24: Mean difference between the eReefs model temperature and in situ temperature records at the reef flat (FL) and Slope (SL – including channel) locations. The plot summarises the comparison results at 99 sites over the GBR.

3.2 Validation of the eReefs 1km model with Mooring Temperature Observations

In this section the eReefs 1km model temperature predictions are compared against the in situ temperature loggers distributed throughout the water column on the IMOS moorings as described in Section 1.1.4. Temperature observations made throughout the water column are important as they provide an understanding of both how deep the surface warm layers penetrate and the identification of upwelled waters. Figure 25 shows the distribution of instrumentation with temperature sensors on the mooring from the seafloor to 11m below the surface. More information is available from the moorings webpage: (https://www.aims.gov.au/imosmoorings)

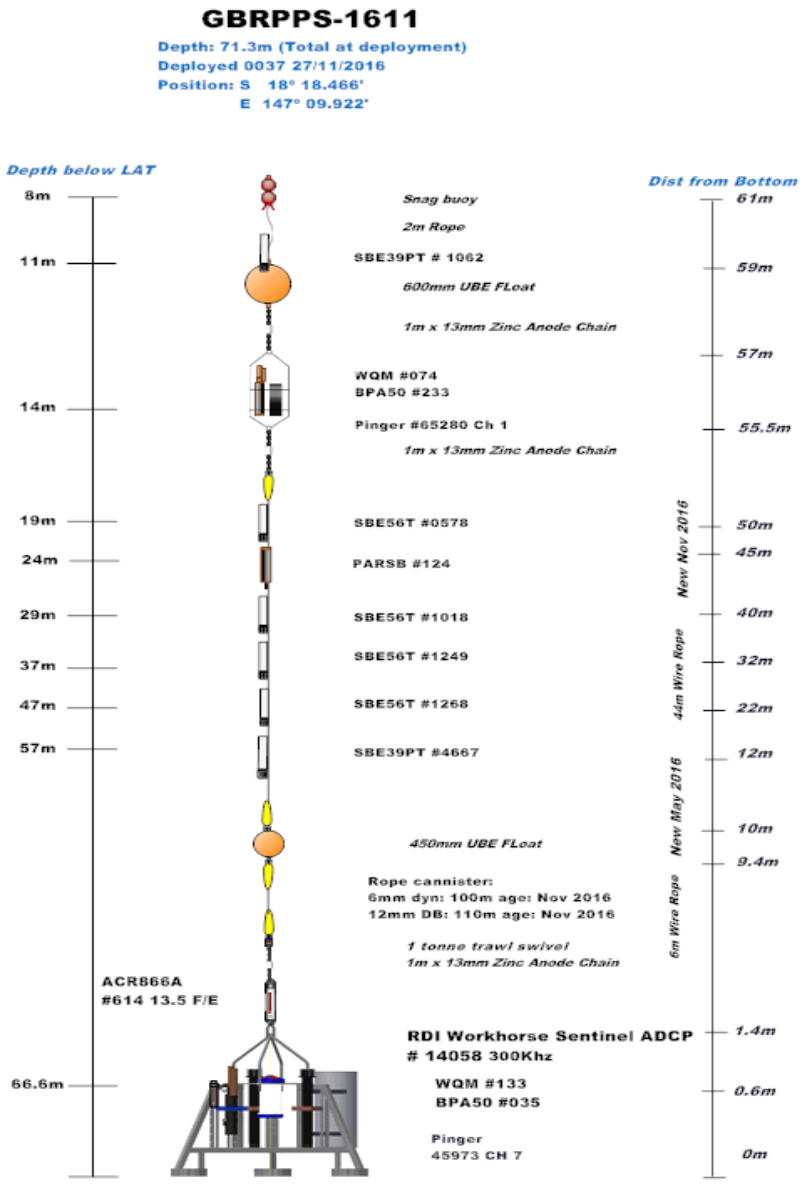


Figure 25: Mooring diagram of the IMOS Palm Passage Mooring as deployed on the 27th of November 2016. The mooring diagram shows the different components that make up a mooring. Instrument makes and serial numbers are important to identify for quality assurance and so that sensor specifications, history of deployment and calibrations can be tracked. From top to bottom the instruments with temperature sensors are: Seabird temperature loggers (SBE39PT & SBE39T); Wetlabs Water Quality Monitors (WQM). Left axis shows depth below the surface, Right axis height above bottom.

Figure 26 and Figure 27, reveal that the moorings observations show greater variability with depth than the model, indicating that the eReefs model may not be reproducing some of the finer scale oceanographic processes that determine thermocline depth accurately. This can lead to a significant difference in temperature between eReefs and the observations. This difference is partly due to the mismatch in model grid resolution of 1km being compared to a point measurement and some physical processes are not included in the model. These include small scale eddies and turbulent anisotropic internal waves that are likely to be present at the mooring locations and can be a major factor in thermocline movement up or down. A specialised internal wave model and greater vertical resolution to improve the simulations would be necessary to improve the eReefs model performance in such situations. Some ocean processes can also be chaotic. The model may well produce fine-scale structure such as small eddies however the timing and location can be slightly offset resulting in mismatches with the temperature observations.

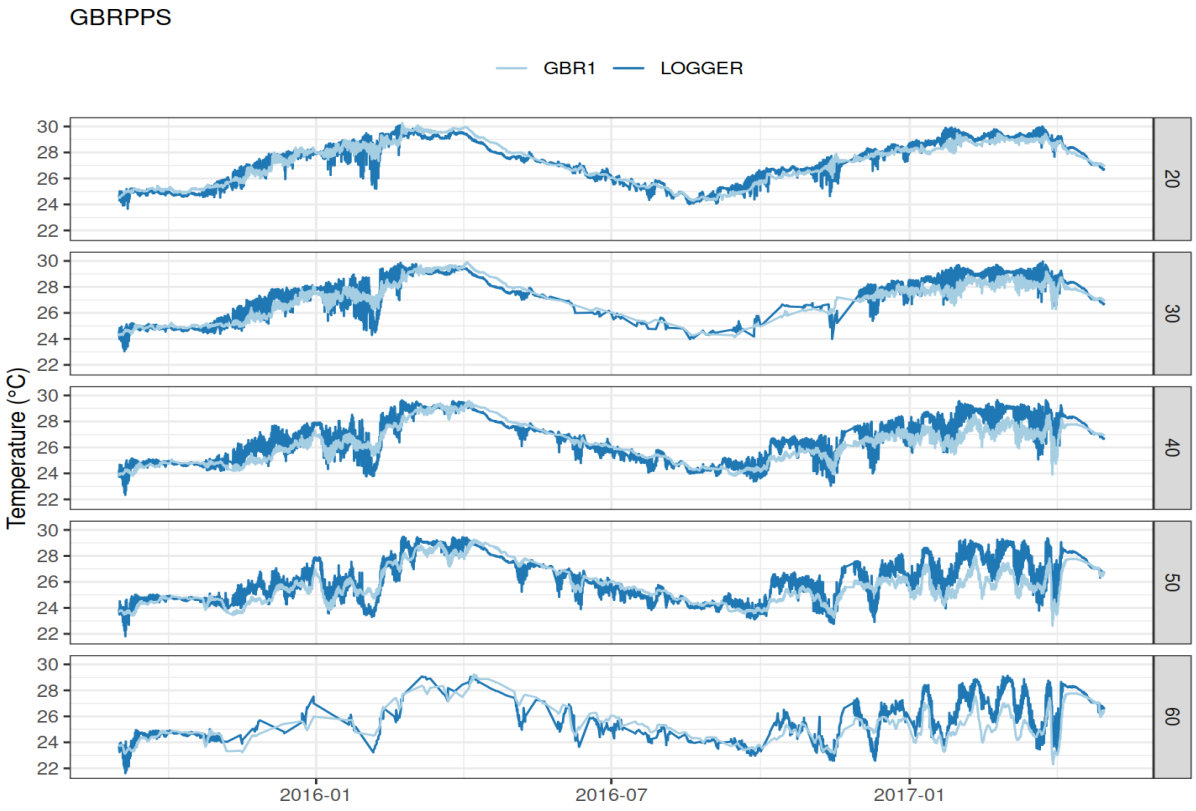


Figure 26: Temperature time series of the eReefs model GBR1and observations through the water column at the Palm Passage mooring (GBRPPS).

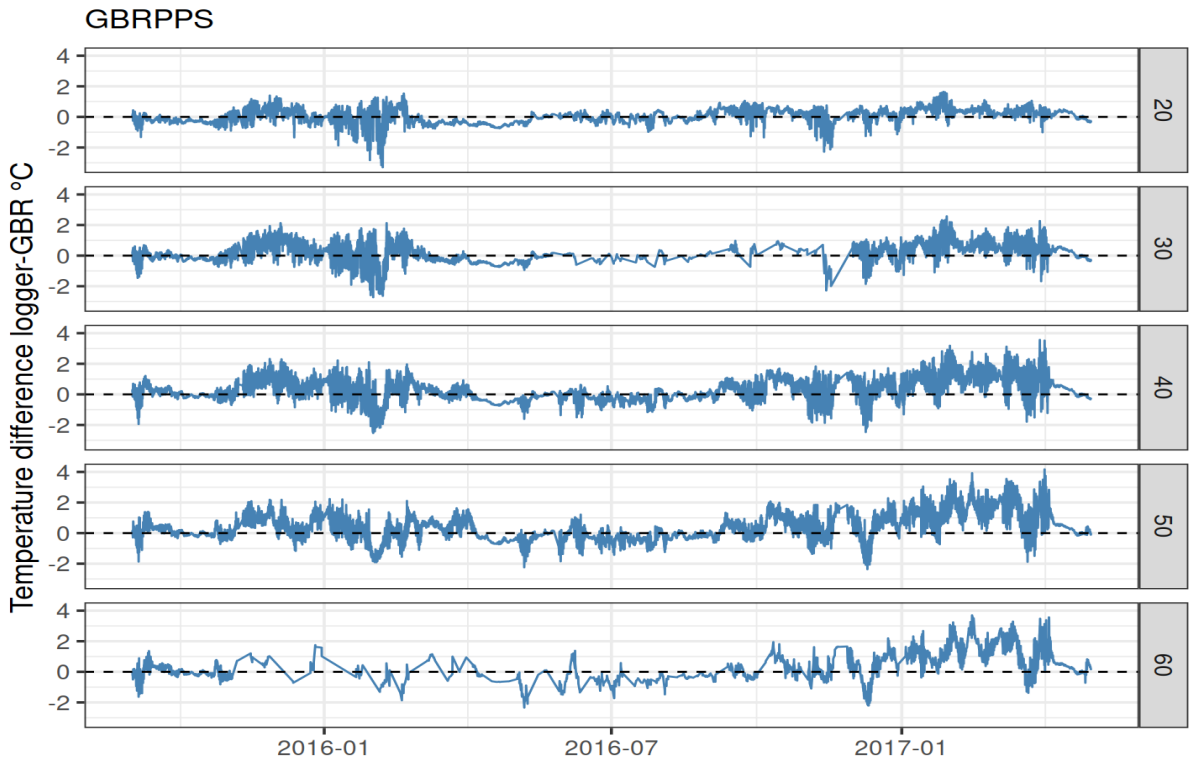


Figure 27: Temperature difference between eReefs model GBR1 and observations through the water column at the Palm Passage mooring (GBRPPS).

Table 3 summarises the comparison of both reef and mooring loggers. This table can also be found in Section 3.1.2 of Volume 2 (Langlais et al., 2021) where the results are explained in more detail. Here the mooring observations are on average warmer than the eReefs model, the reverse of the comparison with the reef loggers. The reasons for this are not completely clear however it is known that eReefs is warmer in the shallows mainly from the way it was tuned to absorb the insolation when it was being set up.

Table 3: Summary of GBR1 vs. temperature logger validation at mooring and reef sites for 2016-2017

Source	Number of logger locations	Number of match ups in time and depth	Depth Range	Mean temperature difference (°C) loggers minus GBR1	Standard deviation (°C)	5th-95th quantiles mean temperature difference
Mooring	47	539,108	10 - 190	0.32	0.52	-0.34 - 1.21
Reef Slope and Flat	236	676,671	1 - 10	-0.32	0.35	-0.91 - 0.25

3.3 Climate and Weather

"Climate is what on average we may expect, weather is what we actually get."
Andrew John Herbertson, Outlines of Physiography, 1901.

In October 2015 NOAA Coral Reef Watch declared the possibility of a mass coral bleaching event for the GBR — given that the Northern Hemisphere had already experienced widespread bleaching in the boreal summer. In early 2016 the GBR bleached partly due to the strong El Nino however it happened again in 2017 and 2020 when El Nino was neutral.

Large interannual variations in ocean conditions are driven from a range of large-scale climate drivers such as El Nino Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD) in addition to a clear overall warming trend associated with global climate change (Lough et al., 2018). Weather systems typically have a scale of hundreds to thousands of kilometres, and can affect large areas of the reef. This can be seen during the 2015-16 and 2016-17 bleaching events where heat stress was moderated in the southern GBR due to winds associated with tropical lows and cyclones (Bainbridge, 2017).

Table 4 summarises the key drivers of climate variability that were active for the summers of 2015-16, 2016-17, 2017-18, 2018-19 and 2019-20, during which three of the most severe bleaching events recorded occurred on the GBR. Only the summer of 2015-16 had a strong El Nino signal. Given the long-term global warming trend the phase of ENSO will increasingly be less of a determinant of a bleaching year (lough et al., 2018).

The prevailing winds along the GBR vary from moderate to strong southeast (SE) Trades from April to November and weaker northwest (NW) monsoon winds from December to March. However, the monsoon winds are subject to the Madden Julian Oscillation (MJO) being active over northern Australia when a low pressure trough descends southwards on a 30 to 60 day cycle (http://www.bom.gov.au/climate/mjo/). This trough is often confined to the northern GBR and rarely reaches the latitude of Townsville (19^{o}S).

Table 4: Summary of climate drivers in the Great Barrier Reef (GBR) for the period 2015-2020. IOD: Indian Ocean Dipole; MJO: Madden Julian Oscillation; TC: Tropical Cyclone.

	2015-2016	2016-2017	2017-2018	2018-2019	2019-2020
Pacific Ocean State	El Niño	Neutral	Neutral	Neutral	Neutral
Indian Ocean Dipole	Positive IOD	Negative IOD	Neutral	Neutral	Strong positive IOD
Cloudiness	Less cloudy than normal	Normal	Less cloudy than normal	Normal	Less cloudy than normal
SST	Feb, Mar and Apr hottest since 1900	Jan: third hottest since 1900	Average	Cooler	February hottest since 1900
Tropical cyclones	Distant TCs Tatiana and Winston in Coral Sea	Severe TC Debbie late March	TC Linda and Iris in March	TC's Owen, Penny, Oma, Trevor, Ann	Weak TC Gretel in mid-March
MJO	Weak	Average	Average	Active Monsoon trough	Weak
Bleaching response	Mass bleaching in Torres Strait and northern GBR	Mass bleaching in northern & central GBR	Minor	Minor	Mass bleaching in full length of GBR

A plot of low passed supra diurnal filtered winds from Lizard Island (~14.7ºS) shows that even at this low latitude south-easterly winds dominate the 2015-2016 monsoon season with short-lived bursts of monsoonal wind from late December 2015 to late March 2016 (Figure 28). The monsoon winds however play a significant episodic role in that they enable upwelling to bring cooler waters from depth to the surface. They can also allow the East Australian Current to accelerate in the absence of the stronger opposing south-east trade winds, lifting the thermocline along the continental shelf-break to allow intrusions of cold water onto the shelf and coral reef matrix.

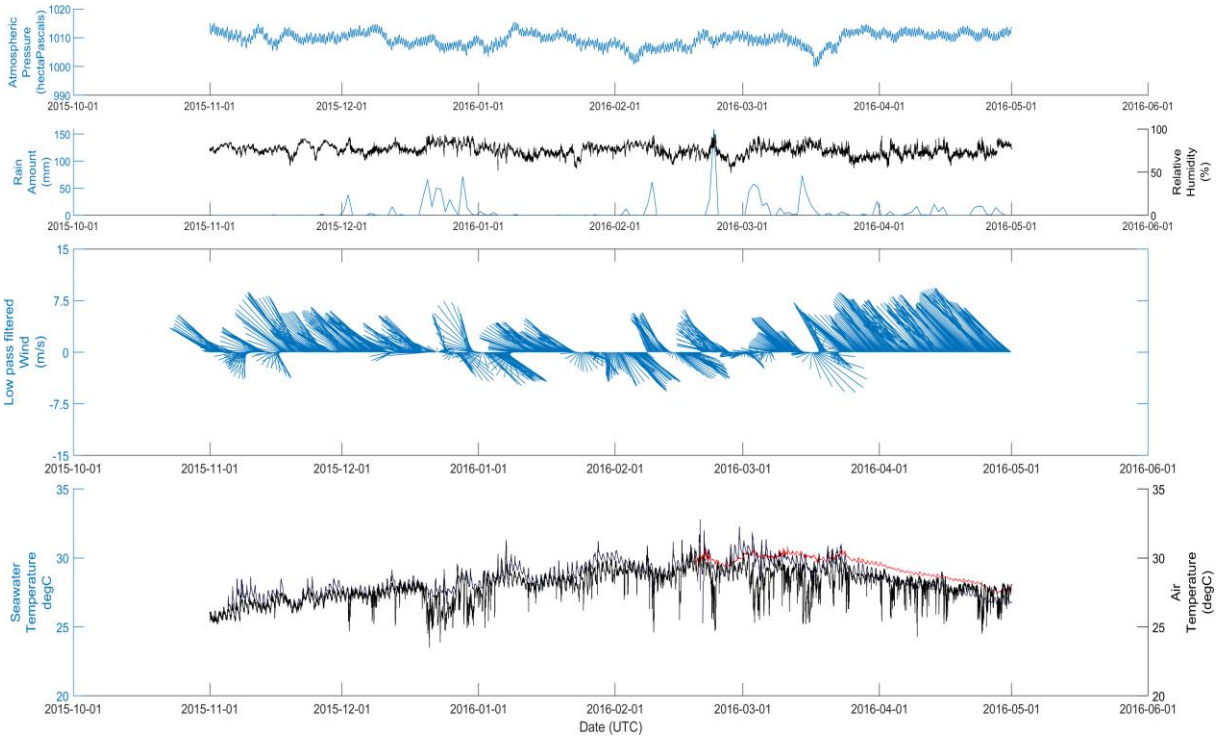


Figure 28: Time series plot of weather station data from Lizard Island for the period 1 November, 2015 to 30 April, 2016. Descending from the top: Atmospheric pressure, rain and relative humidity; Low pass (> 24 hours) filtered wind vectors; air (black) and water temperatures (red).

3.3.1 The 2015-16 Coral Bleaching Event

El Niño events typically result in warmer than normal sea surface temperatures across large parts of the tropical oceans where coral reefs occur. Seasonal outlook models by NOAA and BoM predicted the 2015–16 El Niño to extend to the Southern Hemisphere through 2016's austral summer. The most severe mass coral bleaching on record for the GBR and northern Australia subsequently occurred, peaking in March 2016. The primary drivers of these record-breaking ocean temperatures, in addition to global warming, was the strongest El Niño event on record combined with changes in local weather patterns. Figure 29 shows the intense heat accumulation in the northern Coral Sea extending to off Townsville (19^{o}S) with the EAC.

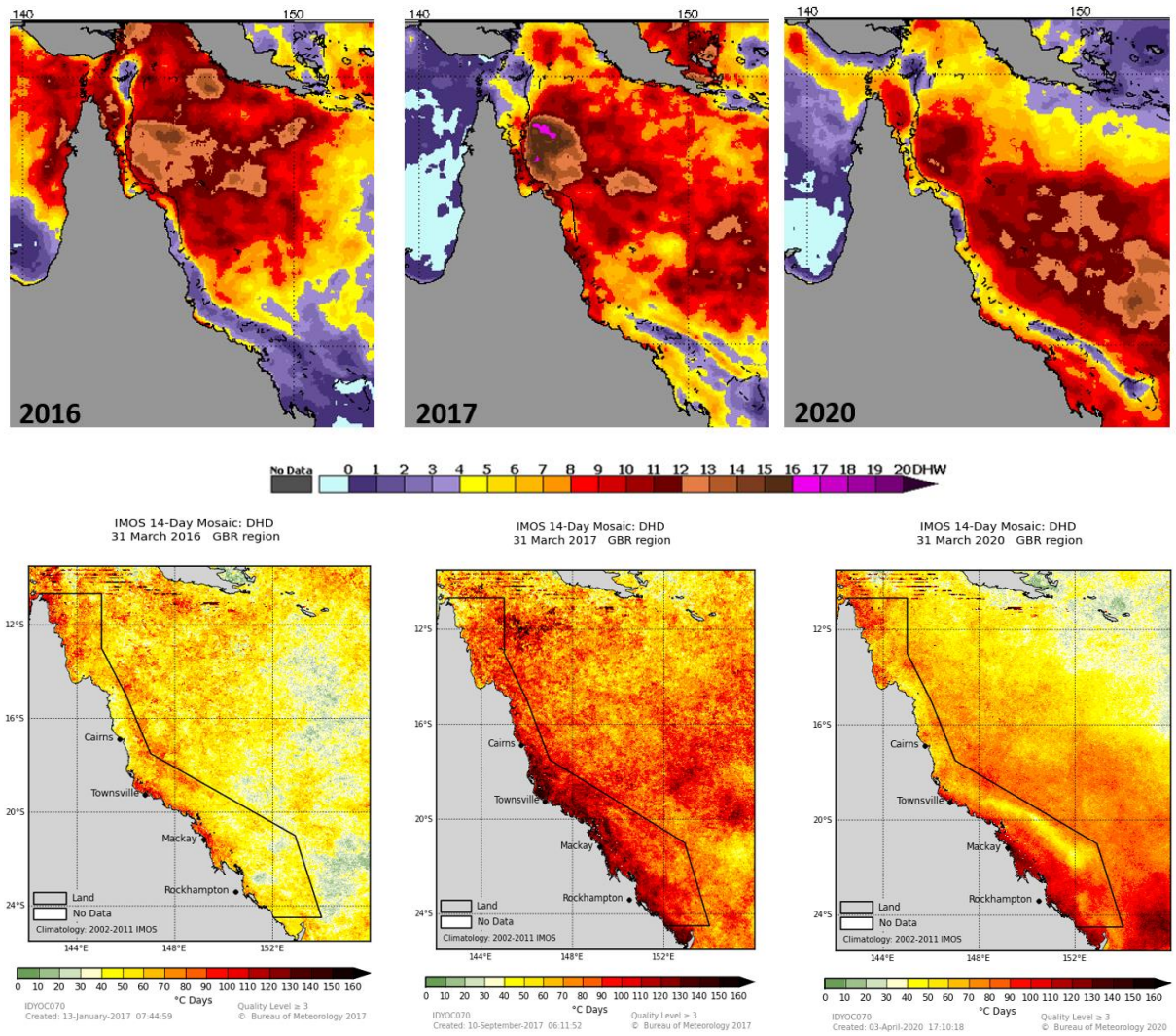


Figure 29: Top: Satellite derived end of summer heat accumulation by NOAA's Degree Heating Week 5km product (www.coralreefwatch.noaa.gov/satellite/bleaching5km/index.php) observed for the Coral Sea as at March 30 for 2016 (left), 2017 (centre) and 2020 (right). Bottom: Degree Heating Days, a complementary product by BoM ReefTemp Next Generation using higher resolution 1km satellite SST data (Garde et al, 2014), accumulated over 1 December-31 March for 2016 (left), 2017 (centre) and 2020 (right).

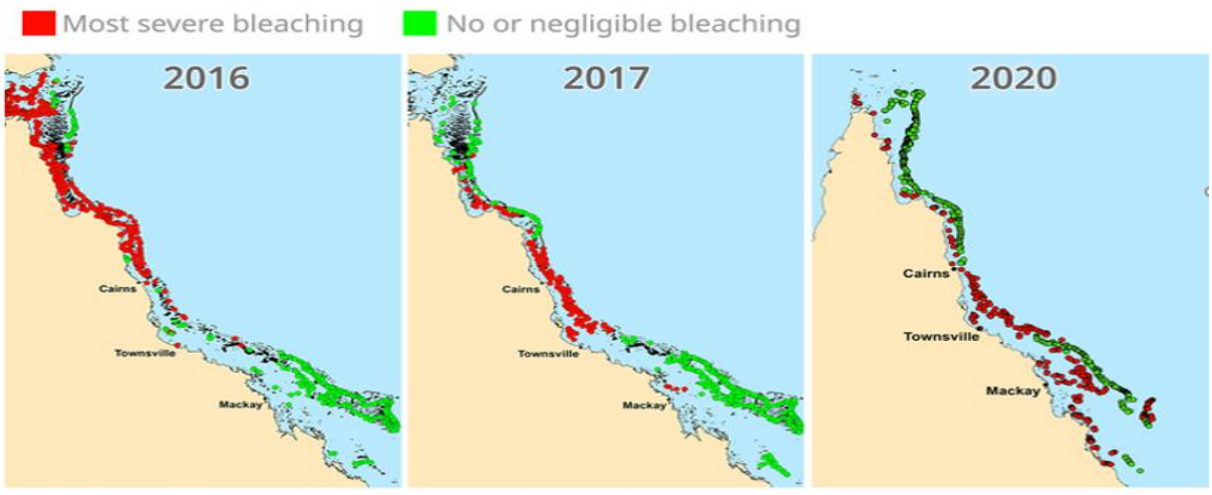


Figure 30: ARC CoE aerial surveys of bleaching for the years 2016, 2017 and 2020.

The NOAA CRW DHW product has a different heat accumulation algorithm and climatology to the BoM ReefTemp as well as resolution (5km vs 1km respectively) so there can be differences in patterns along and across the reef. ReefTemp does show more intense heat along the coast and this is partly due to the resolution of the product being higher and therefore able to resolve shallower coastal and reef top areas better.

Aerial surveys conducted by the Australian Research Council (ARC) Coral Reef Studies Centre of Excellence (CoE) (Figure 30) and in-water surveys by GBRMPA, JCU and AIMS found that bleaching in the 2015-2016 event had affected the majority of the GBR. Bleaching and subsequent mortality were most severe at lower latitudes north of Cairns with up to 50% mortality north of Lizard Island, reducing to 16% southwards from Lizard Island to off Tully.

The southern GBR was relatively unaffected by the bleaching largely due to weather systems associated with tropical cyclones (Table 4) and their remnants (Carrigan and Puotinen, 2013). The prevailing winds throughout the year are the south-east trade winds. These are forced by the mid-latitude belt of high-pressure systems at 30-35^{o}S moving air toward the equatorial low-pressure belt. However, during the tropical cyclone season, the intense low pressure systems and monsoon troughs act in a similar way forcing strong south-easterly winds along the GBR.

Figure 31 shows streamlines of the wind flow associated with ex TC Tatiana and Severe TC Winston in mid-February, highlighting the strong south-easterly winds that formed to the south and south-west of these systems. These winds cooled the sea-surface through both evaporation of water absorbing ambient heat and vertical mixing of the water column via the generation of significant waves through friction with the wind and the generation of turbulence in the water column. The combination of the two systems meant that there were significant cooling mechanisms persisting for over a month during the peak of summer. Whilst TC Winston devastated Fiji, by the time it approached the GBR it was a weak tropical low that eventually crossed the coast north of Cairns.

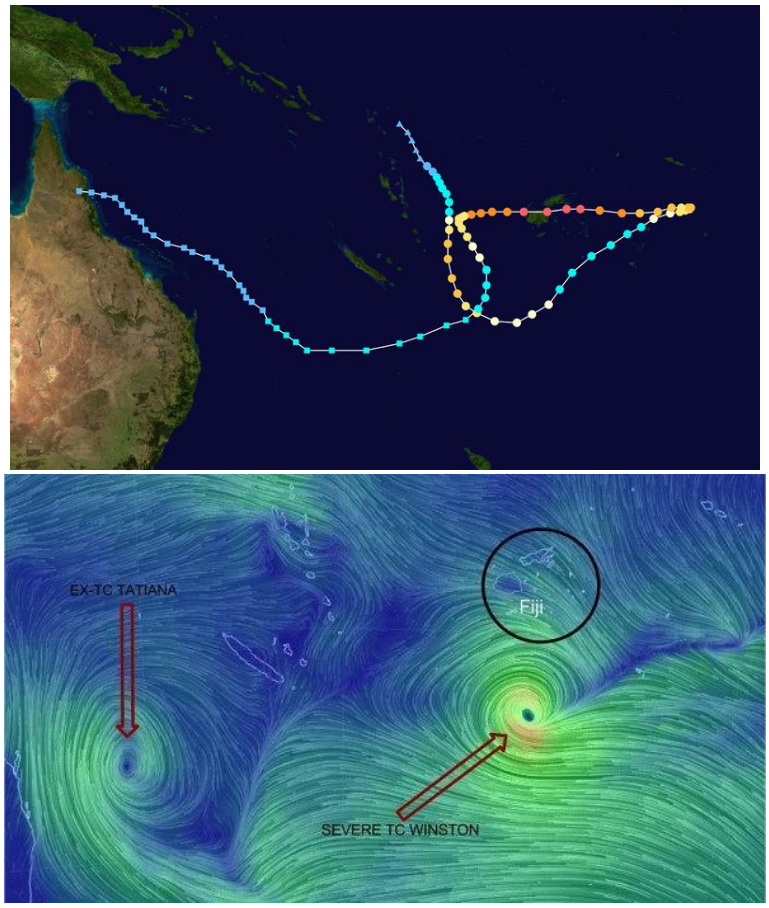


Figure 31: Track of TC Winston 7 February – 3 March, 2016 (Top) and wind fields associated with ex TC Tatiana and Severe TC Winston – 15 February, 2016 (Bottom).

3.3.2 The 2016-17 Coral Bleaching Event

In contrast to 2015-16, the 2016-17 coral bleaching event occurred in a neutral ENSO year and the summer forecasts indicated there was a low risk of coral bleaching. However, there was concern regarding warmer ocean temperatures over winter as they may have pre-conditioned the GBR for extreme warming through the spring and summer.

Sea surface temperatures were again considerably warmer than average for the 2016-17 summer on the GBR. Summer (December-January-February) 2017 was the third hottest since 1900 and SST observations across the reef show that January 2017 was warmer than January 2016. In particular, March 2017 was the second hottest March on record to date after 2016. These anomalously warm conditions led to a second consecutive year of mass coral bleaching on the GBR. During this summer, global warming and local weather patterns were the primary factors driving anomalously warm ocean conditions.

Whilst El Niño has often been associated with mass bleaching, events have occurred on the reef during neutral years e.g. 2002 (Berkelmans et al., 2004). As background temperatures rise due to global warming, it is projected that the link between ENSO and bleaching will weaken. A negative IOD developed in July 2016 and ended in November 2017 as the monsoon trough transitioned to the southern hemisphere. This event helped drive Australia's wettest May–September period in 117 years of record (http://www.bom.gov.au/climate/enso/wrap-up/archive/20160705.archive.shtml) however the impact on the GBR was minimal.

Bleaching was most prevalent in the northern and central GBR during the 2016-17 summer extending further south than in the previous summer (Figure 30). Whilst the far northern shelf experienced less heat accumulation than in 2015-16 (Figure 29) most of the more susceptible corals in that region had previously died leaving more thermally tolerant corals to experience the second mass coral bleaching event a year later. Of note is how deep the heat reached down into the water column on the shelf during this event. Palm Passage is near the continental shelf-edge off Townsville (in 70 m of water). Summertime warming occurred throughout the water column (Figure 32), though in the 2016-17 summer there was more evidence of cooler bottom water intrusions that could mix upwards with the tidal currents as they interacted with coral reefs compared to the summer 2015-16.

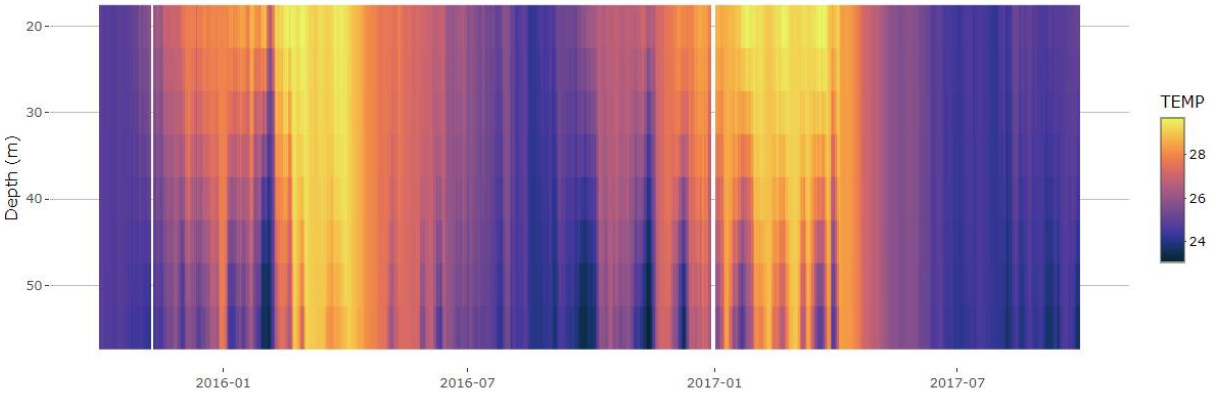


Figure 32: Temperature (ºC) profile plot from the IMOS Palm Passage mooring (GBRPPS) from November 2015 to September 2017.

The glider mission in March-April shown in (Figure 33) reveals that the warming in Palm Passage in summer 2016-17 extended as deep as 100m at the shelf break. There is also a clear indication of internal wave activity which can bring cooler water up to 60m on the shelf. The initial stages of the mission show some cooler water on the shelf however that disappears as the mission progresses and the water column continues to warm.

Severe category 4 TC Debbie led to cooling of surface waters over the mid and southern GBR in late March 2017. This is reflected in cooler mean observed SSTs in April as a result of winds colling the waters, reducing the southern extent of bleaching. The destructive force of the cyclone around the Whitsundays meant any bleaching, if it did occur, was not able to be surveyed due to large sections of coral reef being reduced to rubble. The cooling here was more intense given the proximity of the cyclone whereas the stronger but distant TC Winston and closer but weaker ex-TC Tatiana in resulted in far less damage to the GBR with an overall positive impact through reducing heat stress.

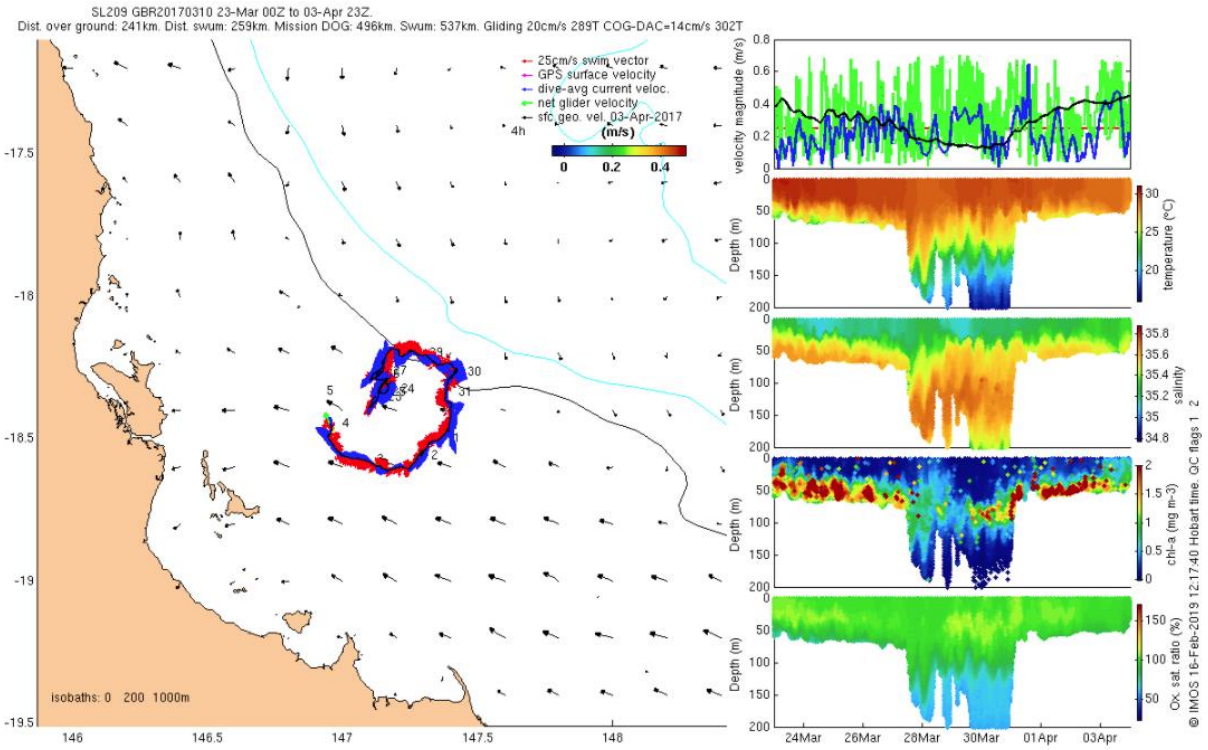


Figure 33: IMOS glider anti-clockwise track and profiles (from top: currents; temperature, salinity, Chlorophyll-a fluorescence, Oxygen saturation ratio) from a mission in Palm Passage 23 March - 3 April, 2017.

3.3.3 The 2017-19 years

The 2017-18 summer was considered an average summer, in terms of SSTs over the GBR. The 2018-19 summer was cooler than expected however due to a series of five tropical cyclones occurring in the region and an active monsoon trough. The monsoon trough in February was considered an exceptional rainfall event by the Bureau of Meteorology (Australian BoM Special Climate Statement 69), and consisted of strong convergence along a trough with a series of embedded lows across northern Australia and into the Coral Sea (Figure 34). This created a lot of cloud and rainfall that kept the region relatively cooler than average and free of bleaching through the remainder of the summer.

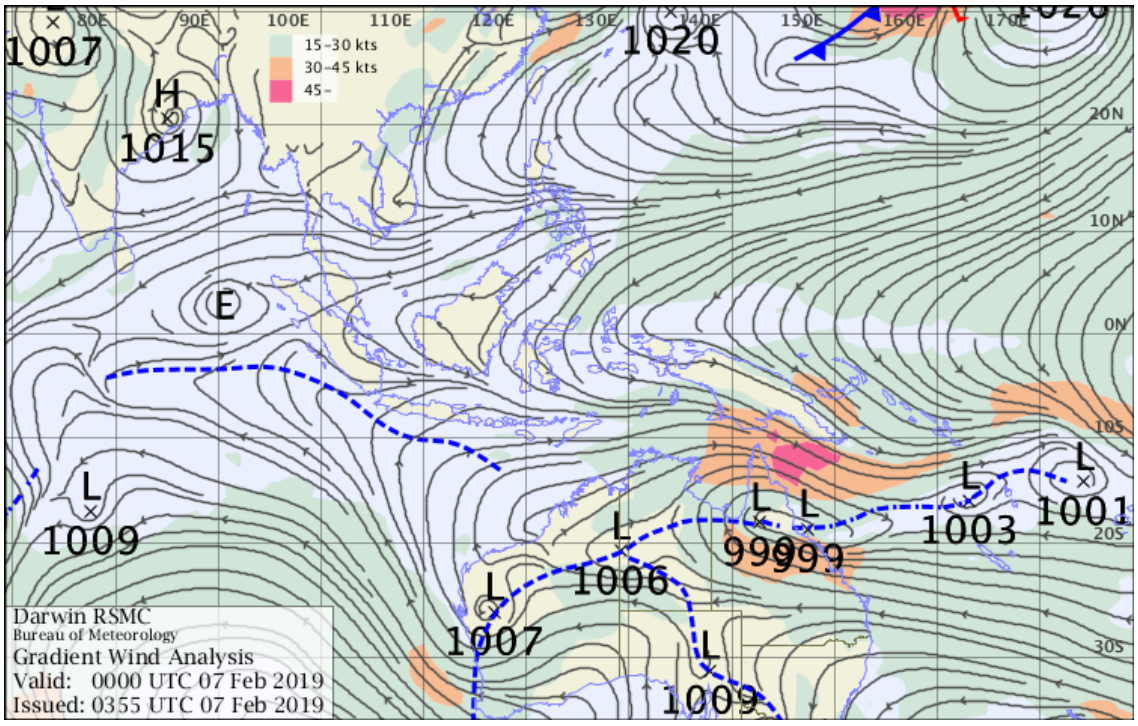


Figure 34: BoM tropical gradient wind analysis for the monsoon trough on February 7, 2019. Troughs are denoted by the broken blue line. Streamlines are denoted by the dark grey lines with arrows showing the direction of wind flow. Winds 15-30 kts (Green), 20-45 kts (Orange) and >45 kts (red).

3.3.4 The 2019-20 Coral Bleaching Event

During the summer of 2019-20, ARC CoE aerial surveys revealed that bleaching occurred over the length of the GBR from central Torres Strait to Gladstone. Coastal to mid-shelf waters were the worst affected, including the reefs offshore from Mackay. The outer shelf reefs covering the area south of Cairns to east of Townsville were also severely affected. Outer shelf reefs north of Cairns and offshore from Mackay were least affected (Figure 30).

Figure 35 shows that unlike in 2016 and 2017, the 2020 warming was confined to the top 20-25m in the central GBR limiting the depth to which bleaching could occur. Some moderate cooling of approximately 1^{o}C was due to the increased south-easterly winds associated with TC Gretel which formed in the northern Coral Sea from a monsoonal trough on March 10 and then tracked away to the south-east. Whilst the warming didn't penetrate as deeply into the water column, it affected the southern GBR that had previously escaped bleaching in the earlier two events. TC Gretel was not strong nor present long enough to significantly cool the region but did provide some respite.

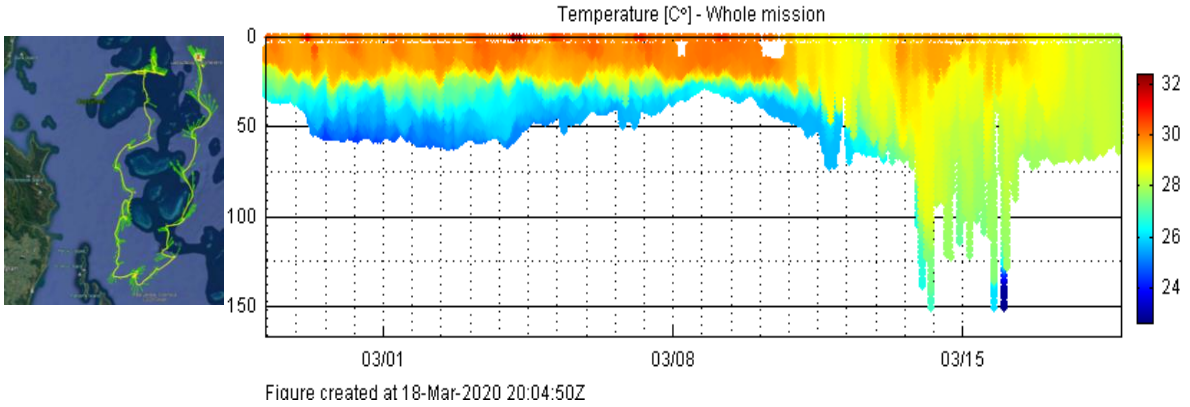


Figure 35: IMOS glider track (left panel) and temperature profiles along the track (right) in the central GBR off Dunk and Palm Islands (27 February to 20 March 2020).

3.4 Physical Oceanography

Throughout all the documented GBR bleachings since 1998 (Berkelmans et al., 2004, Hughes et al. (2018), Cantin et al. (2020)), a pattern emerges where there are persistently cooler regions which resist the accumulation of heat and have thus been spared from bleaching (Figure 29). These areas are also evident in the summer-time climatology (Figure 36) where the vagaries of weather in any one summer are averaged out. The two large regions along the GBR are:

1. Outer shelf edge reefs extending from off the Whitsundays, the Pompeys to the Swains reef complexes (Figure 36)
2. Eastern Torres Strait and the shelf edge ribbon reefs off Cape York

The finer scale detail in the bleaching response (from hundreds of metres to hundreds of kilometres) can be attributed to oceanographic processes and understanding those processes are the key to explaining the reasons for these potential refugia from bleaching (Steinberg, 2007, Bridge et al., 2013, Green et al., 2019).

Whilst atmospheric forcing dominates each summer's ocean warming (and cooling) the ocean currents redistribute that heat. The GBR receives water from the westward Southern Equatorial Current which then bifurcates when it reaches the continental shelf at 14 to 16°S to form the poleward flowing East Australian Current (EAC) and the equatorial flowing Gulf of Papua Current (Figure 36). The interactions of these western boundary current systems with the continental slope and reef structures are the key to their upwelling responses. As they are in remote locations direct observations are lacking and so satellite observations and models are used to investigate these processes.

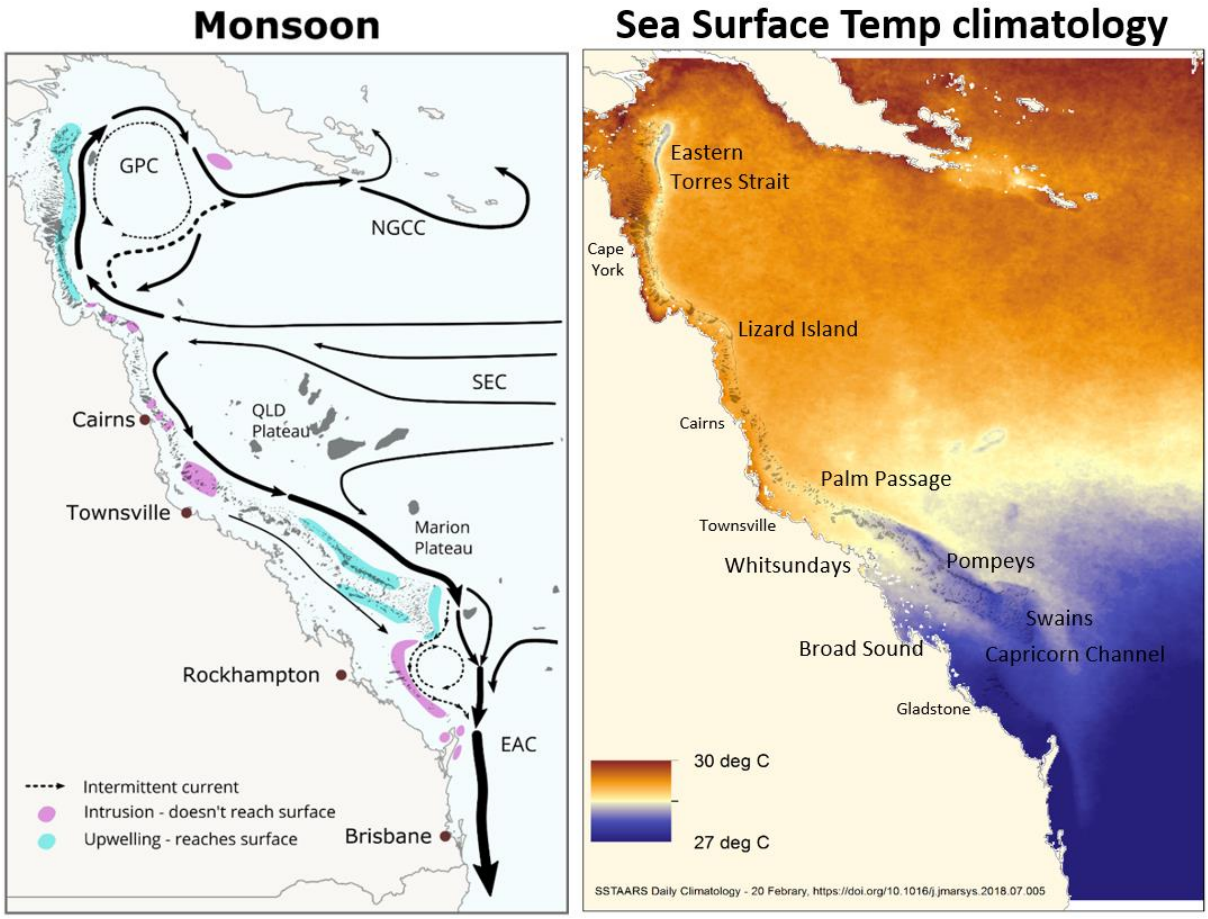


Figure 36: Schematic of Coral Sea circulation, upwelling and intrusions during the monsoon season (left) and SSTAARS climatology snapshot for mid-February (Right). Visualisation courtesy of Eric Lawrey, AIMS.

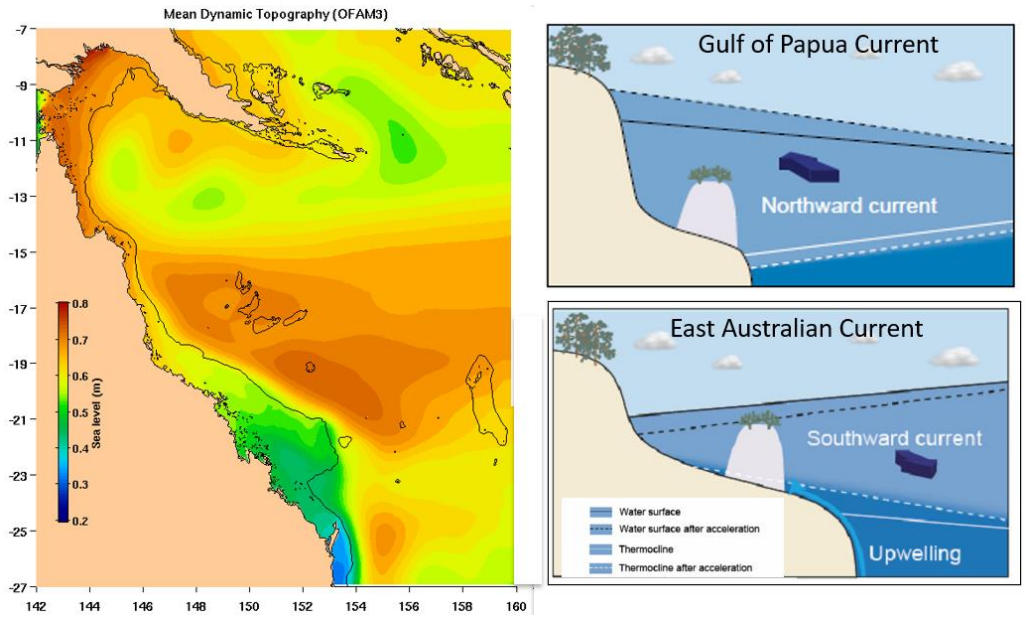


Figure 37: Map of the mean dynamic topography of the ocean surface from IMOS OceanCurrent (left) and a cross-section of the Gulf of Papua Current and its thermocline (top right) and the East Australian Current (bottom right) adapted from Steinberg (2007).

Figure 37 shows the mean dynamic topography of the ocean surface which illustrates that the major currents are in geostrophic balance with a sea level slope perpendicular to the ocean current direction. For the Gulf of Papua current, there is a higher sea level to the west of the northward flow. Concurrently, the thermocline deepens to the west making cooler water deeper at the continental shelf break. In contrast the southward EAC has higher sea level to the east with lower sea levels to the west. This sea level slope makes the EAC favourable to upwelling as the raised thermocline along the continental shelf means that cooler water is drawn across the outer shelf. During periods of reduced south-easterly trade winds, the EAC can strengthen, bringing cold water onto the continental shelf.

3.4.1 The Pompeys-Swains cool region

The mechanisms in play here causing cooling in this region during the summer are relatively well understood and are mainly due to the interaction of two physical oceanographic phenomena: upwelling from the EAC and strong tidal mixing. Tidal currents mix the water column through turbulence generated by the friction of the seafloor or reef slopes. The stronger the current the higher up in the water column the mixing occurs. Winds cause mixing from the surface downwards and often the two can combine to mix the entire water column on the continental shelf as is experienced in winter. During bleaching periods however winds are low and so the tides and boundary currents are the only reliable source of energy for water column mixing that can affect a warming surface layer (Steinberg et al., 2007).

The tides in this region are the largest on Australia's east coast due to the wide shelf (~250km) and the reef barrier posed by the Pompeys and Swains forcing tides to come from both the north where the reef matrix is more open and from the Capricorn Channel in the south. These tides meet off Broad Sound (Figure 36) causing a constructive interference that increases the sea level response (Bode, 1986). The strong tidal currents can be seen flooding into the Broad Sound embayment in Figure 38 on the right-hand side. As described in the previous section the EAC will lift cool water up onto the shelf. Flooding tides can then move cool water across shelf through the many narrow channels between the densely packed reefs in this region.

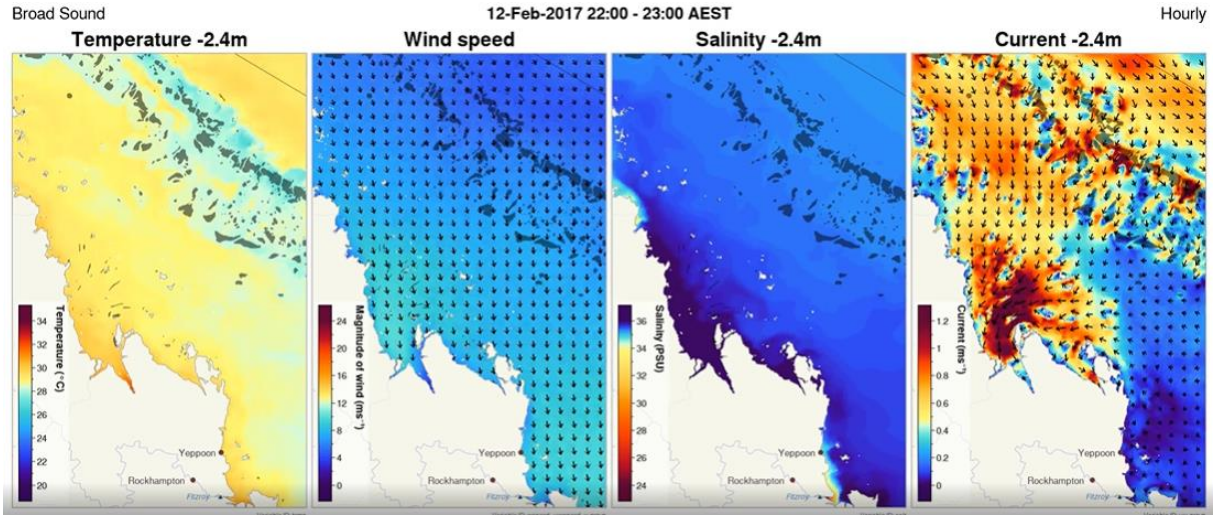


Figure 38: Snapshot of eReefs 1km hydrodynamic model showing (left to right) Temperature, Wind speed (from ACCESS-R), Salinity and Currents for February 12, 2017 at 2200 AEST (https://ereefs.aims.gov.au/ereefs-aims/gbr1/temp-wind-salt-current).

Figure 38 shows the cooler waters amongst the outer-shelf reef complexes that are a stark contrast to the warmer coastal and offshore EAC waters.

Cold water intrusions do occur in the north and central GBR where the EAC begins (Figure 36, Berkelmans et al., 2010). However less vigorous tidal mixing and less dense reef matrices means that the water does not necessarily reach the surface and to the shallower corals atop the reefs (Benthuysen et al., 2016, Berkelmans et al., 2010)

3.4.2 Eastern Torres Strait and the far northern GBR cool region

In contrast to the Pompeys-Swains region, the reasons for the cooler Eastern Torres Strait and far northern GBR are more complex and are a result of an interplay of multiple physical oceanographic mechanisms. One commonality however is the strong tidal currents of the Torres Strait and the channelling of flow in between the narrowly spaced reefs.

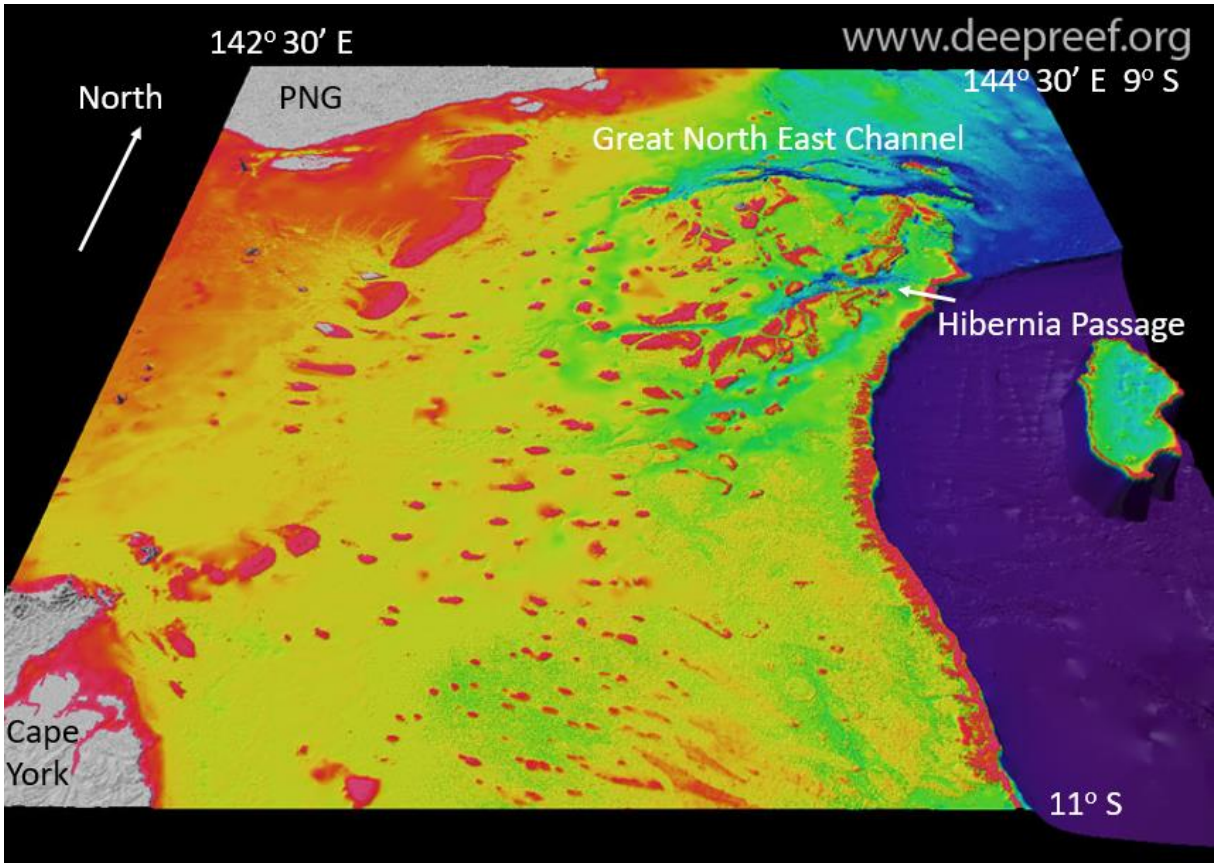


Figure 39: Bathymetry of the Torres Strait). Cape York can be seen at the bottom left and Papua New Guinea at the top in grey. Shallow waters and reef tops are shown in red, Deep . (Adapted from Source: www.deepreef.org/gallery/3d-visualisation.html, Beaman 2017)

The topography of the outer shelf to the east is quite complex, with an almost vertical drop-off from the tightly packed ribbon reefs east of Cape York that are oriented along NNW-SSE (Figure 39). Moving along the shelf break (to the north), as the Papua New Guinea shelf is approached and the shelf break veers to the ENE just north of the entrance to Hibernia Passage with a gentler slope up onto the shelf with deep channels such as the Great North East Channel that can bring waters westwards, well onto the shelf toward the Torres Strait.

As explained in the earlier section the northward Gulf of Papua Current suppresses the thermocline making the cooler water much deeper than it is for the reefs adjacent to the EAC.

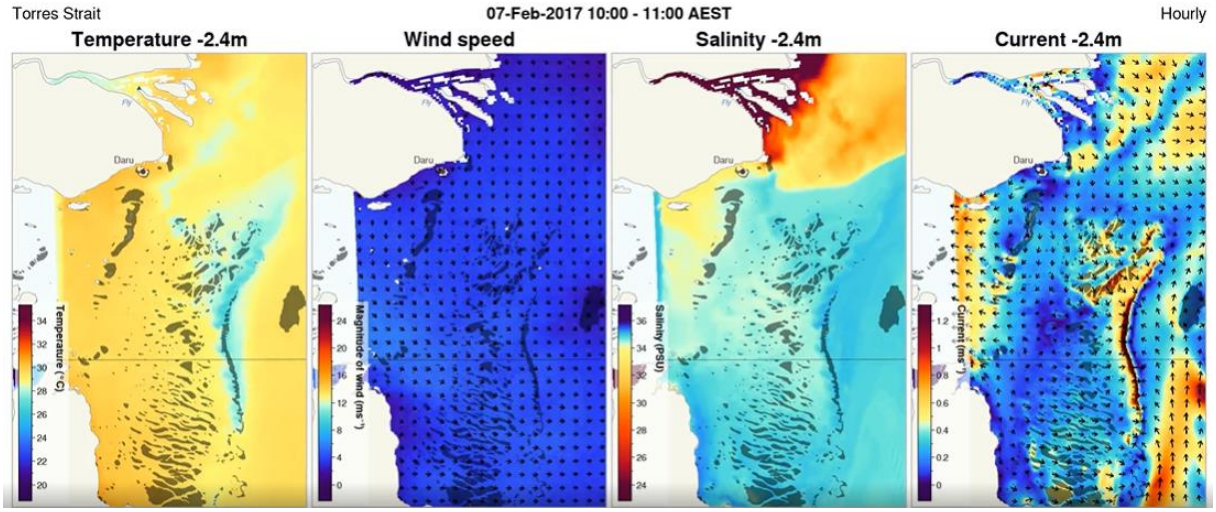


Figure 40: Snapshot of eReefs 1km hydrodynamic model showing (left to right) temperature, wind speed (from ACCESS-R), salinity and ocean and tidal currents for February 7, 2017 at 1000 AEST (https://ereefs.aims.gov.au/ereefs-aims/gbr1/temp-wind-salt-current).

The eReefs 1km hourly model animations reveal the strong tidal flood and ebbs in the regions with high current regions in the Strait and also along the outer barrier reefs and the region of deep channels (Figure 40 on the right). Off the shelf a strong flow can be seen from the Gulf of Papua Current which usually follows the shelf break towards the north. However, in this instance the main flow has moved away from the shelf break. This deflection is due to the shelf edge at the southern end of Figure 40, deflecting the main current further to the NNE as the shelf break further north inflects back toward the west. That separation of the main flow away from the shelf break creates a divergence of the flow that allows water from depth to move upwards in the lee of that change in shelf slope topography curvature. The deeper and gentler slope to the north, where the slope curves more directing the main flow to the ENE, is also a mechanism for the deeper water to flow up onto the shelf.

The southeast trade winds have the effect of forcing the surface waters to the left of the main flow resulting in a deeper thermocline due to classical Ekman transport. However, any reduced strength of that flow or even a reversal through the northwest monsoon would allow the thermocline to lift in response, thereby bringing the cooler deeper waters more in reach of the shelf break reefs. This process is assisted in the area to the north with the gently deepening continental shelf towards the shelf edge and where of the shelf break tracks to the ENE (Just south of the mouth of Hibernia Passage). This deeper outer shelf provides a conduit for that water onto the shelf.

The North Vanuatu Jet is the main westward current from the Coral Sea that flows into the Gulf of Papua Current (Ridgway et al. 2018). Ubiquitous eddies also play a role in sea surface variability in that region. Figure 37 shows that the prevailing or climatological expectation is for an anti-clockwise Gulf of Papua gyre (centred on 12^{o} S, 145^{o} 30’ E) with a low central sea level height. However, there are occasions when the reverse is true. In July 2015, a small eddy was detected in the Solomon Sea that moved westwards over the following months until it reached the Gulf of Papua in January 2016. Figure 41 reveals that instead of the expected lower sea

level in the centre of the Gulf, sea level anomalies were high which indicating a cyclonic circulation that is north to south along the shelf break. This flow reversal lifts the thermocline along the shelf break and so can bring significant cooler water toward the surface in that region.

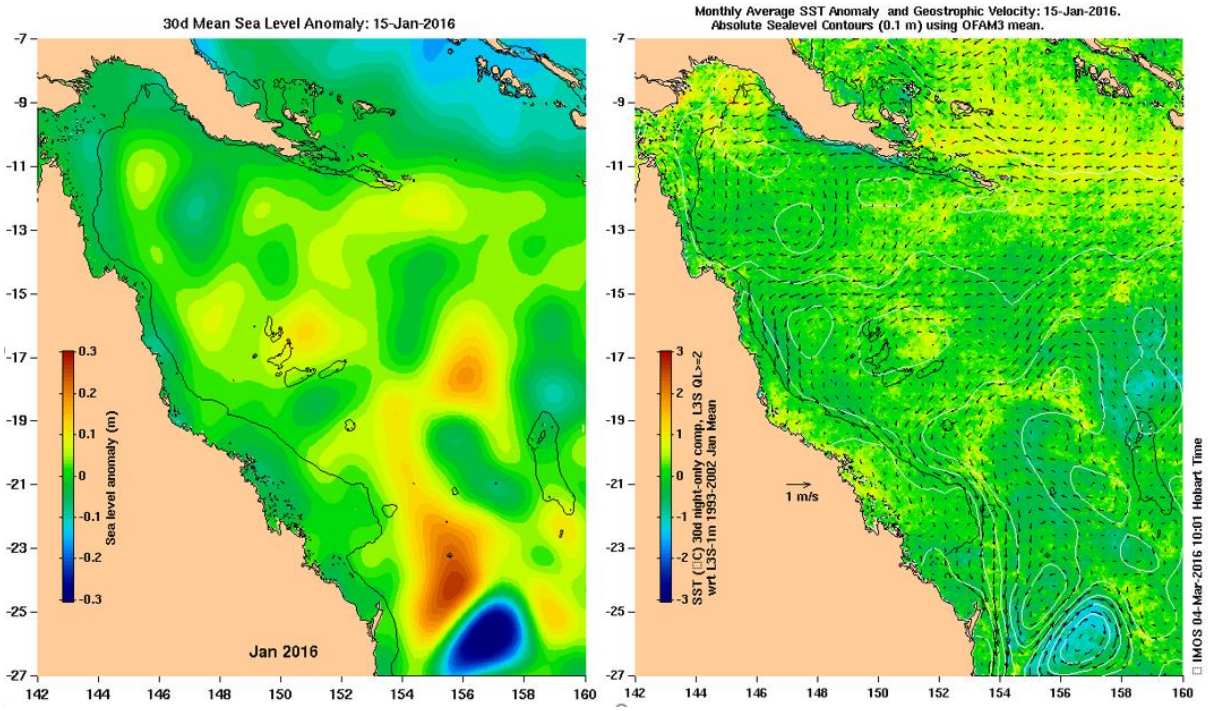


Figure 41: The January 2016 monthly mean sea level anomaly (left) and the monthly SST anomaly with geostrophic currents overlaid as black arrows (right). Graphic courtesy of IMOS OceanCurrent.

The final mechanism described here are internal waves (Storlazzi et al., 2020) that can exist whenever there is stratification. They can be generated from interaction with topography through tides, atmospheric disturbances such as tropical lows and cyclones. Once generated they can travel across ocean basins and also as continental shelf waves along the shelf break. As the thermocline is where the thermal gradient is largest, internal waves can be detected through monitoring temperature and currents through the water column or through modelling.

Given the lack of observational data for this region we employ a model to illustrate this phenomenom. A suite of nested 3D hydrodynamic models have been applied to the GBR from the global BlueLink> Ocean Forecasting Australia Model for ocean circulation (10km horizontal grid resolution, Oke et al., 2012), eReefs (4km and 1km) whole of GBR that includes tides (Steven et al., 2019) and higher resolution reef scale models by Delft (https://oss.deltares.nl/web/delft3d) and RECOM (Baird et al., 2020). Figure 42 shows an application of the Delft 3D model to the Eastern Torres Strait. Over a tidal flood current a sequence on the right-hand side shows an initially depressed thermocline lifting to reach the shelf edge and then flow the cooler water across the outer continental shelf amongst the reefs (Figure 42). If there is sufficient wind, channelling of flow and or tidal current then that water can be mixed up to the surface.

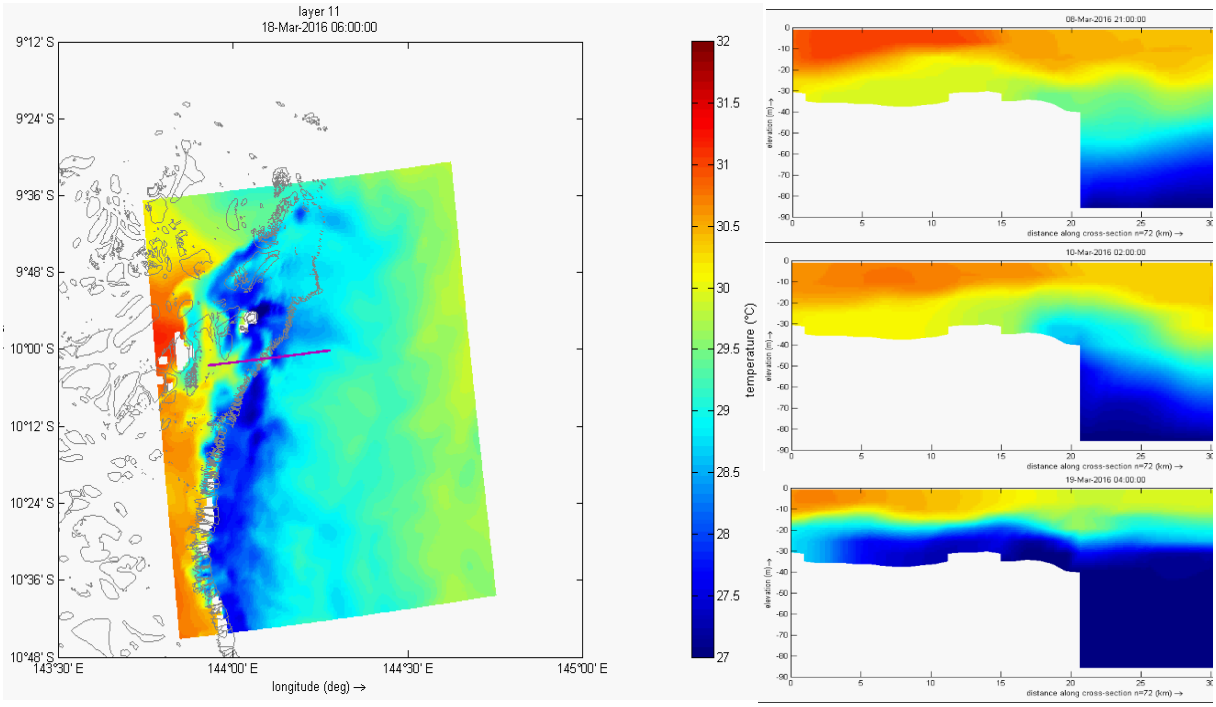


Figure 42: High resolution modelling of the shelf break of the far northern GBR and eastern Torres Strait. Temperature at 20m below the surface (left panel) and sequence of thermocline uplift over the shelf break (right panel).

4.0 RECOMMENDATIONS AND CONCLUSION

This project has compiled as much of the publicly available temperature observations from multiple platforms to allow researchers a more convenient access point to the GBR data for the 2015-17 bleaching years, and a list of products to continue monitoring the GBR.

Whilst satellite derived products provide very good surface products, gaps mainly due to the presence of clouds and water vapour can be significant and so product quality can be at risk. The continued in situ monitoring of coral reefs and ocean is therefore important to validate these products and fill in those cloudy periods. Coral reef slope transects of loggers, gliders and moorings that extend observations through the water column are critical (though sparse) to understand the vertical extent of the heat and calibrate and validate the performance of 3D models such as eReefs. Long-term monitoring is also necessary to assess the normal conditions (climatology) and evidence extremes.

Continued long-term pelagic and benthic physical and ecological monitoring of the Great Barrier Reef is needed with a strategy to fill a number of observational gaps– especially in the remote reefs off Cape York, eastern Torres Strait, the Swains and Pompey reefs.

The computation of climatologies from in situ observations allow the ability to calculate the accumulated heat stress at each logger location. Where in situ observations coincide with in situ coral bleaching observations a detailed thermal history can be used to validate and improve metrics to assess that location's sensitivity to bleaching. One such metric is the time integrated bleaching curves (Berkelmans (2002); https://data.aims.gov.au/aimsrtds/coralbleaching.xhtml) which have only been applied to a few sites using data only from the 1998 coral bleaching event that was coastal and not as widespread as later events.

The comparison between in situ temperature loggers and the eReefs 1km model reveal that the model had some bias and less variability that varied spatially along and across the GBR. These differences indicates the need for continued development of the eReefs hydrodynamic model to improve its performance at coral reef locations. Downscaled Climate modelling utilising models such as eReefs is also necessary to identify any regional and fine-scale changes in temperature, circulation and mixing.

The temperature observations and their climatologies have been used to assess bleaching responses as a part of NESP 5.7 (Cantin et. al., 2020) and provide validation for the products developed in volumes 2 and 3 of this NESP 4.2 project (Langlais et. al., 2021 and Klein et. al., 2021 respectively).

Climate is changing rapidly for tropical coral reef ecosystems, which are already showing their vulnerability. With the observed increase in global average temperatures, corals live near their upper thermal tolerances. This threshold means when ocean temperatures increase again, particularly during summer months, beyond this limit, corals will exceed these thresholds and move to a state of thermal stress. To reduce the number and severity of coral bleaching events, global warming needs to be limited to well below 1.5^{o}C (IPCC, 2018).

In conclusion, this study has provided evidence of a number of meteorological and oceanographic processes that can help explain the spatial coral bleaching responses along the GBR:

- Mass coral bleaching is occurring more frequently due to rising ocean temperatures and the persistence of doldrum like weather due to a suppressed monsoon, lower cloud cover and winds.
- Weather events such as wind and swell generated from close or distant tropical cyclones can mix the water column and cool the reef waters.
- Episodic physical oceanographic processes can work in concert with complex reef topography and tides to produce significant large scale refugia for corals that are persistently cooler

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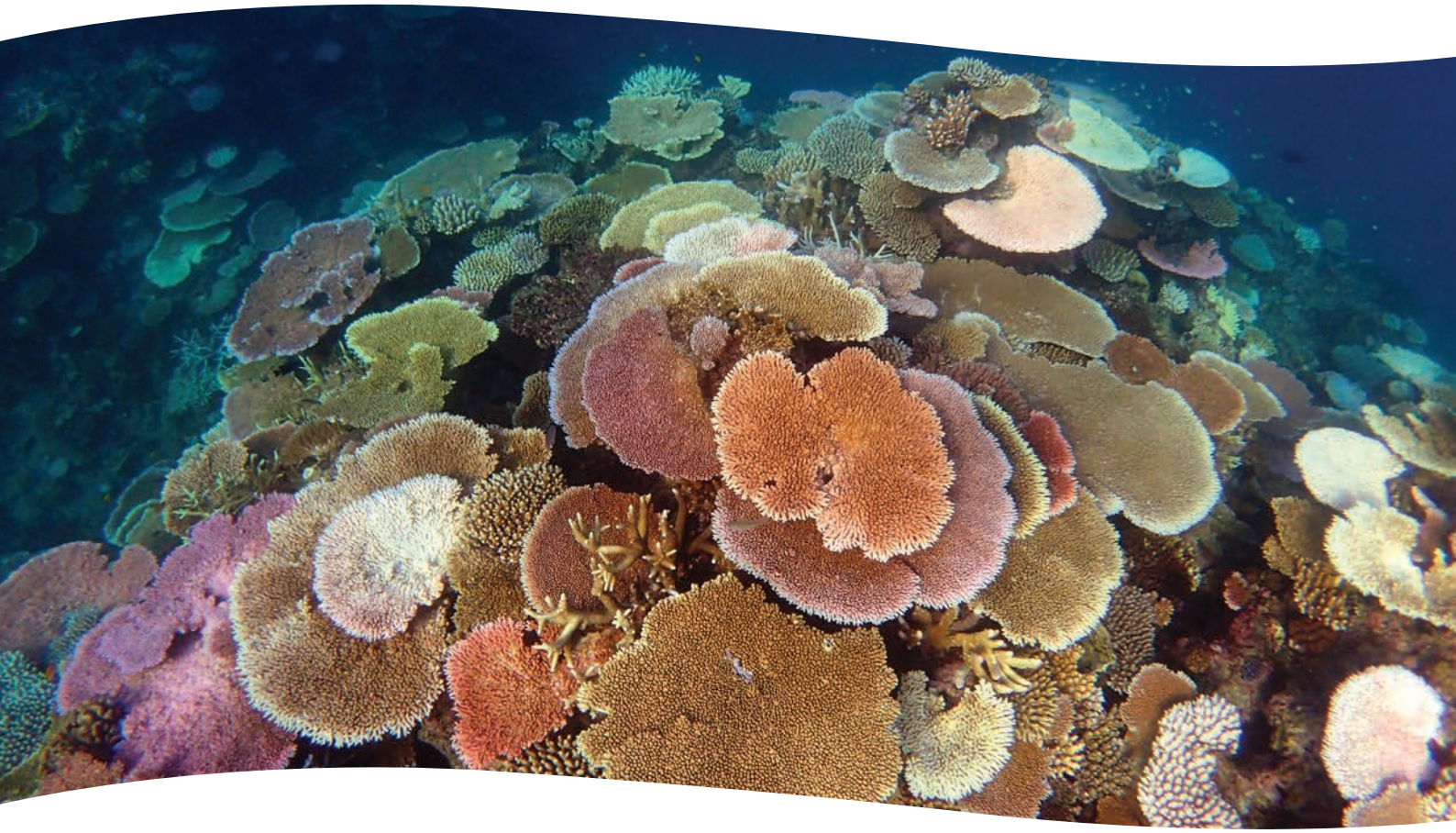
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