Australian Government

Australian Institute of Marine Science

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Australian Institute of Marine Science

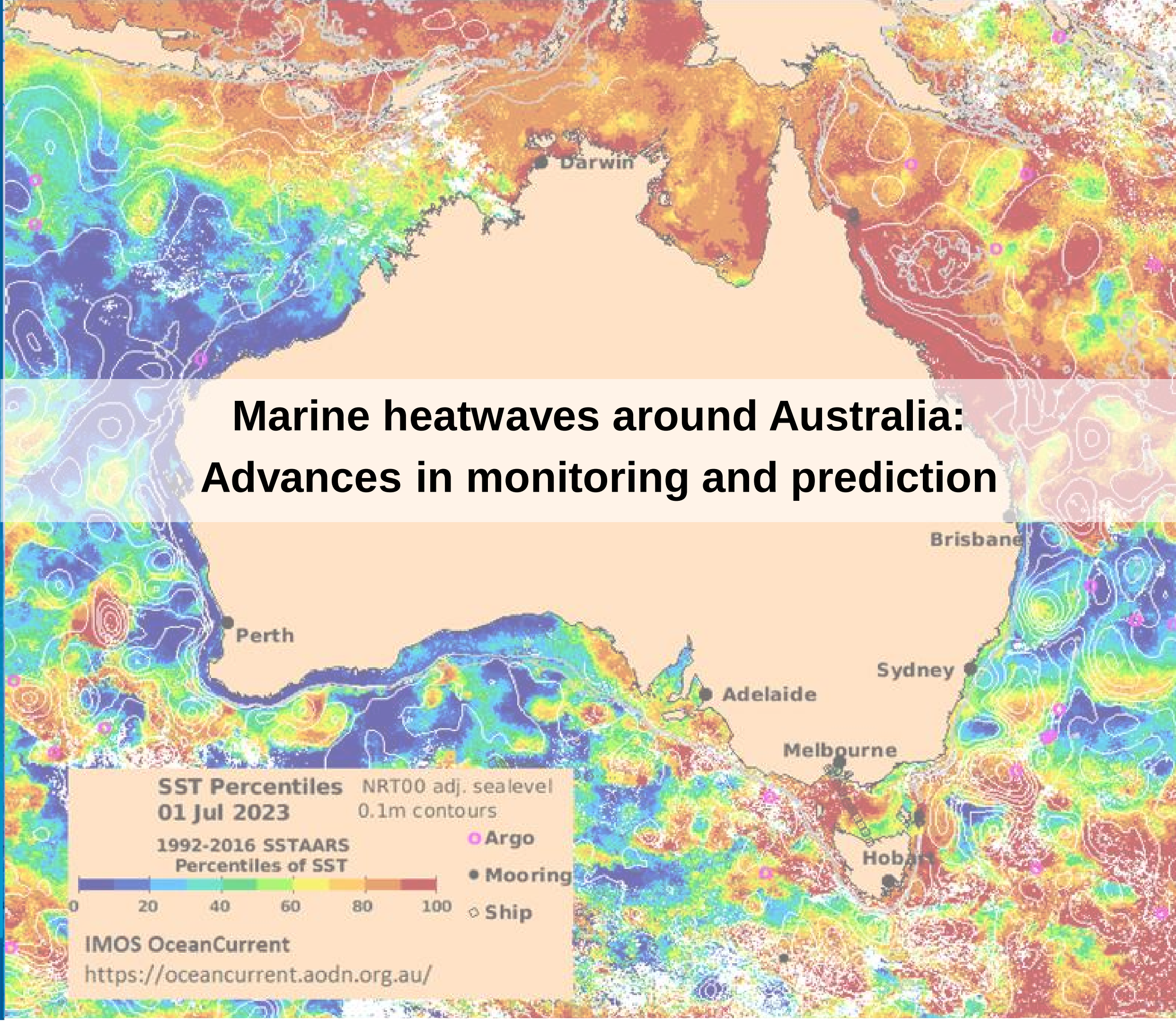
Indian Ocean Marine Research Centre, Perth, Australia

2023 US CLIVAR Summit

1 August 2023

Tracking Earth Energy Imbalance and Marine Heatwaves across the Global Sunlit Ocean

Marine heatwaves around Australia: Advances in monitoring and prediction



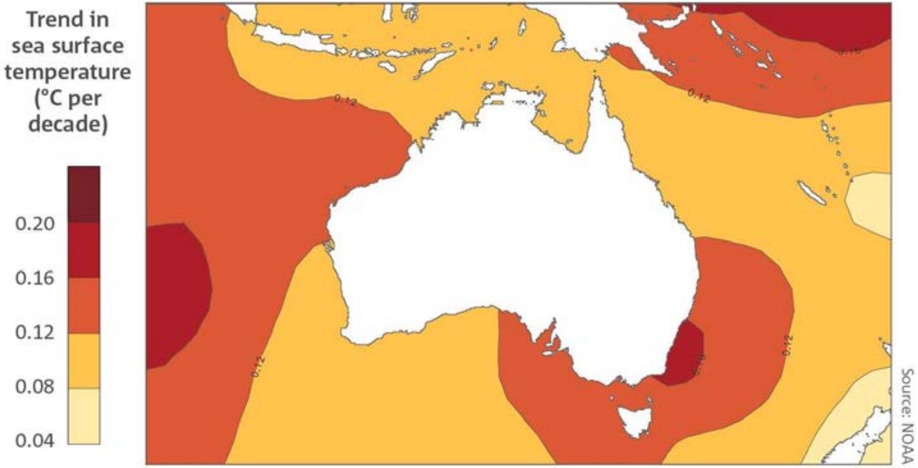
AIMS: Australia's tropical marine research agency.

Addressing the challenge of marine heatwaves for Australia

How can we improve monitoring and prediction of marine heatwaves to meet stakeholder needs?

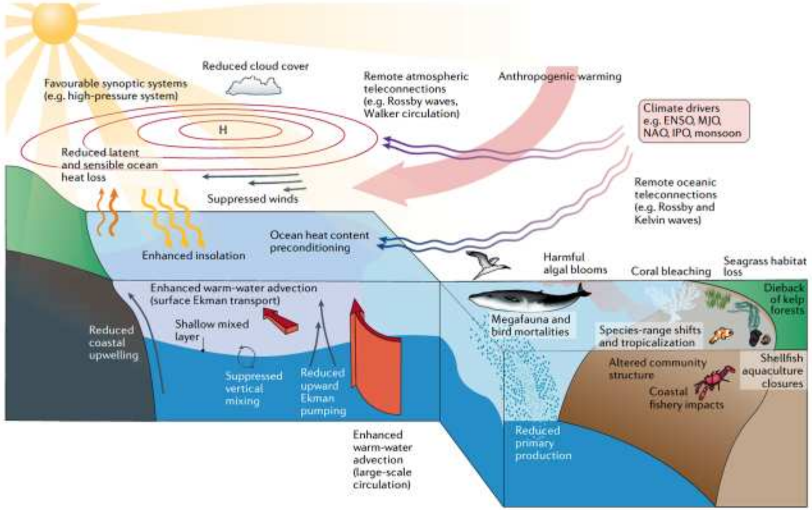
Understanding why marine heatwaves occur via long-term warming trends, climate modes of variability, and their physical processes offer a pathway to prediction.

Long-term SST trends



2022 State of the Climate; 1950 - 2021
http://www.bom.gov.au/state-of-the-climate/

Marine heatwave drivers and impacts



Holbrook et al. 2020,
Nature Reviews Earth & Environment

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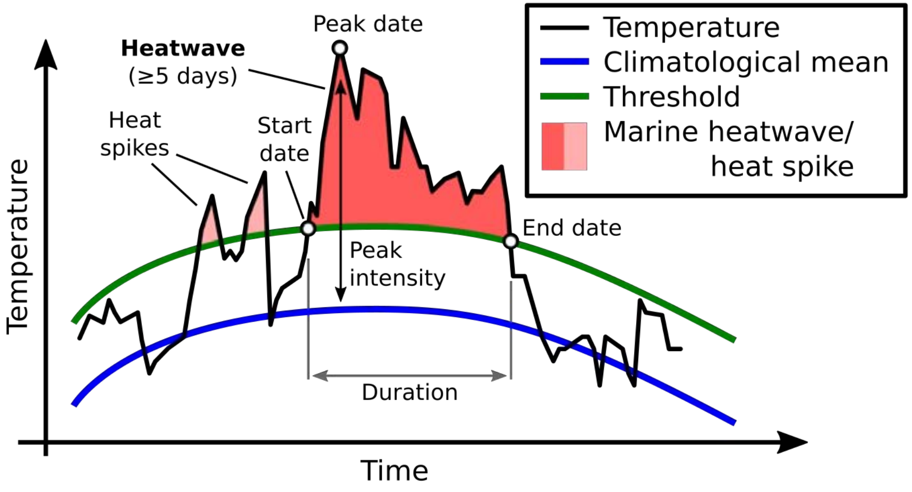
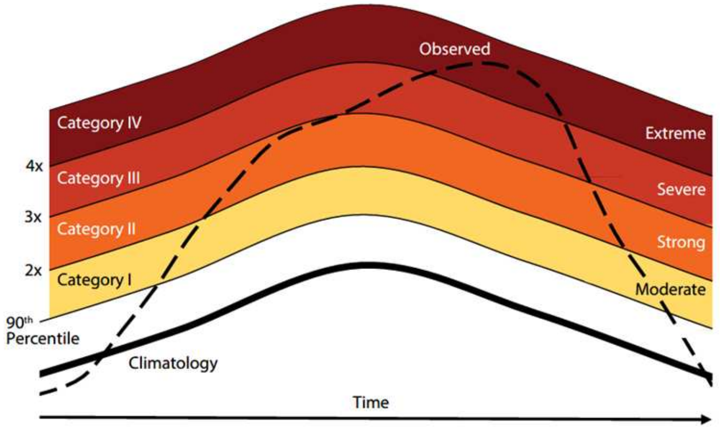
What are marine heatwaves?

Defining marine heatwaves



Hobday et al. 2016

Marine heatwave severity



Hobday et al. 2018

http://www.marineheatwaves.org/

https://github.com/ecjoliver/marineHeatWaves

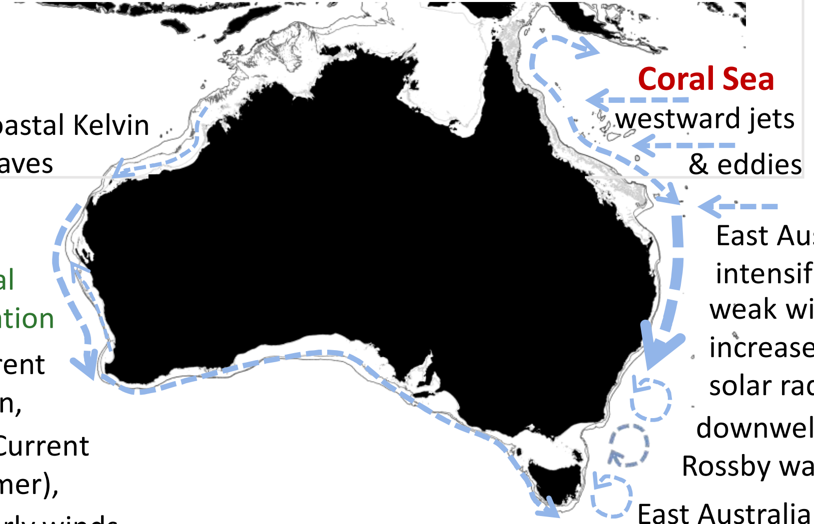
A **marine heatwave** (MHW) is defined to be **a discrete prolonged anomalously warm water event at a particular location**.

Specifically, **SSTs above the seasonally-varying 90th percentile** that persist **for at least 5 days**.

Marine heatwave drivers and processes

El Niño, Madden Julian Oscillation, Indian Ocean Dipole

Air-sea heat flux (prolonged clear skies and still winds) and shallow surface mixed layer, monsoon timing in summer, timing and spatial extent of tropical cyclones



Currents affecting Australian marine heatwaves

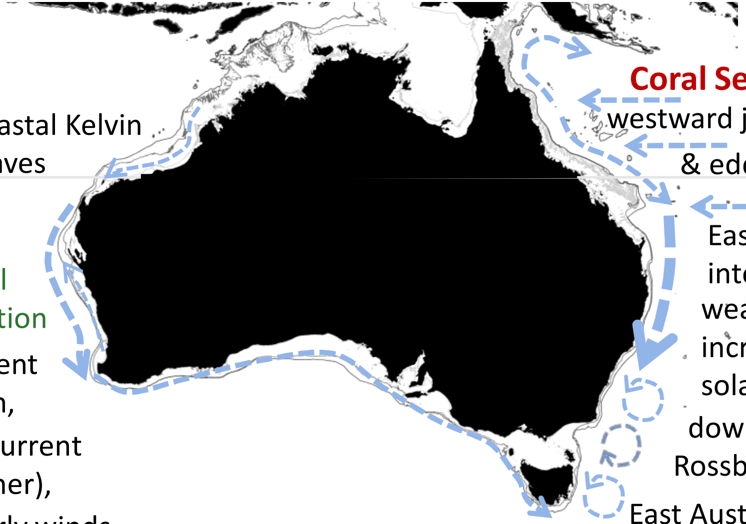
Bathymetry: GeoScience Australia 2009; 20, 100, 200 m contours

Marine heatwave drivers and processes and notable events

El Niño, Madden Julian Oscillation, Indian Ocean Dipole

Air-sea heat flux (prolonged clear skies and still winds) and shallow surface mixed layer, monsoon timing in summer, timing and spatial extent of tropical cyclones

Indonesian Seas



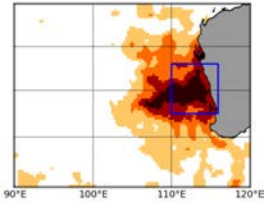
Indian Ocean

coastal Kelvin waves

Coral Sea

westward jets & eddies

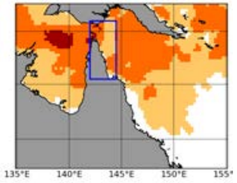
2011 Western Australia



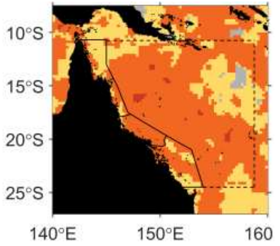
La Niña
+ IOD
– Interdecadal Pacific Oscillation

Leeuwin Current intensification,
weak Capes Current (austral summer),
weak southerly winds

2015/16 Northern Australia



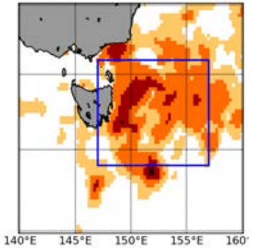
2020 Great Barrier Reef and Coral Sea

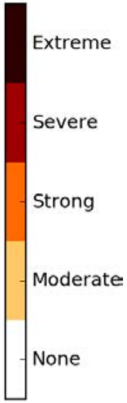


East Australian Current intensification,
weak winds,
increased downward solar radiation,
downwelling Rossby waves

+ Southern Annular Mode
La Niña

2015/16 Tasman Sea





East Australian Current Extension intensification,
long-lived warm eddies

Currents affecting Australian marine heatwaves
Bathymetry: GeoScience Australia 2009; 20, 100, 200 m contours

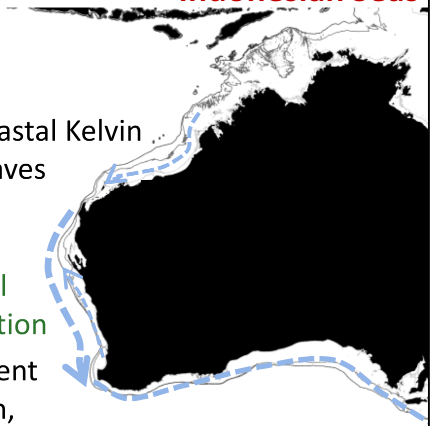
Hobday et al. 2018, Oceanography
Holbrook et al. 2019, Nature Communications
Benthuysen et al. 2020, Env. Research Letters
Holbrook et al. 2020, Nature Reviews Earth & Env.

Marine heatwave drivers and processes and notable events

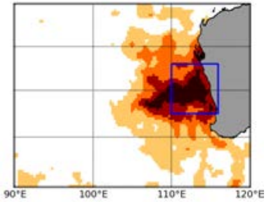
Indonesian Seas

Indian Ocean

coastal Kelvin waves



2011 Western Australia



La Niña
+ IOD
– Interdecadal Pacific Oscillation

Leeuwin Current intensification,
weak Capes Current (austral summer),
weak southerly winds

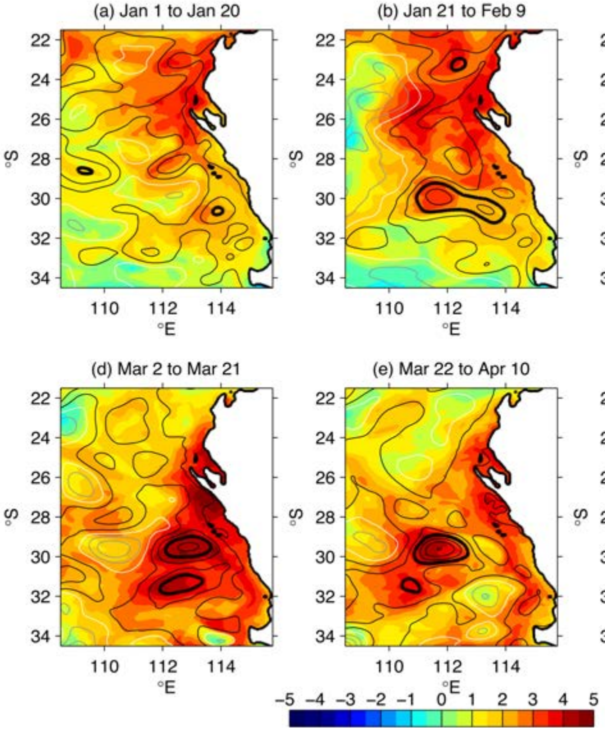
Marine heatwaves off Western Australia (WA)

- **Remote forcing**: austral summer warm SSTs significantly correlated with positive spring SSH anomalies in the western equatorial Pacific Ocean.
- SSH anomalies transmitted via equatorial and coastal waveguides, thereby strengthening the Leeuwin Current, emphasizing the role of **La Niña** (Feng et al. 2003; Feng et al. 2013).
- Negative **Interdecadal Pacific Oscillation** – decadal increase in MHWs since 1990s (Feng et al. 2014).
- **Local forcing**: air-sea feedback leads to cyclonic atmospheric anomalies that reduce the southerly winds off WA, decreasing latent heat loss and promoting a stronger Leeuwin Current (Feng et al. 2013; Kataoka et al. 2014; Zinke et al. 2014).
- Positive **Indian Ocean Dipole** increases MHW likelihood (Zhang et al. 2018; Wang et al. 2023).

2011 Western Australia (Ningaloo Niño)

Integrated Marine Observing System (IMOS)
https://www.imos.org.au/

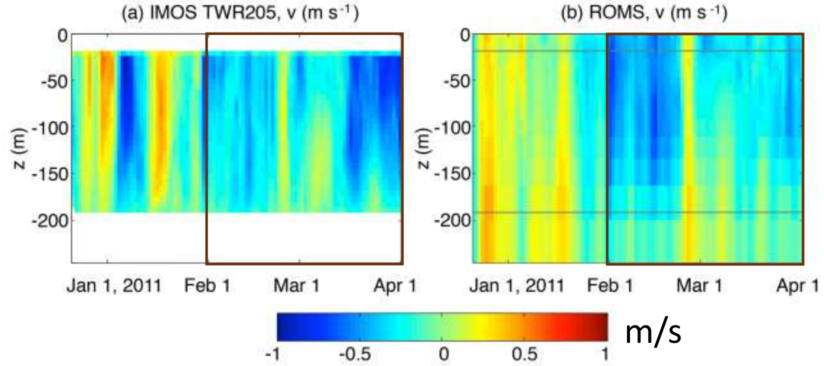
SST & surface elevation anomalies (2011 vs 2009, 2010)



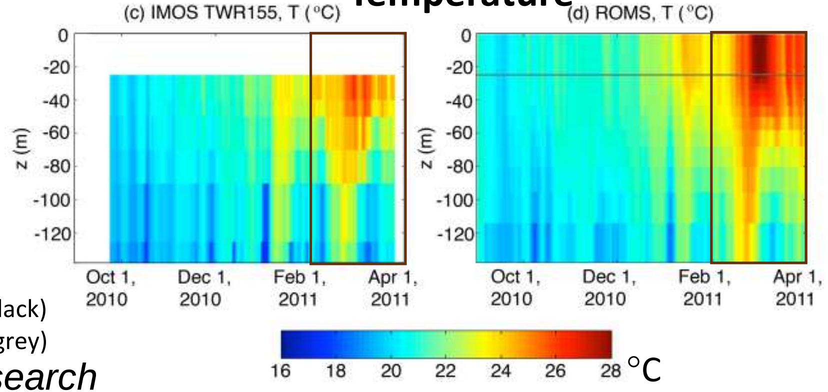
c.i. = 0.1 m for positive (black)
negative (grey)

☆ IMOS Two Rocks moorings **ROMS model**

Meridional velocity



Temperature



Benthuysen, Feng, Zhong 2014, Continental Shelf Research

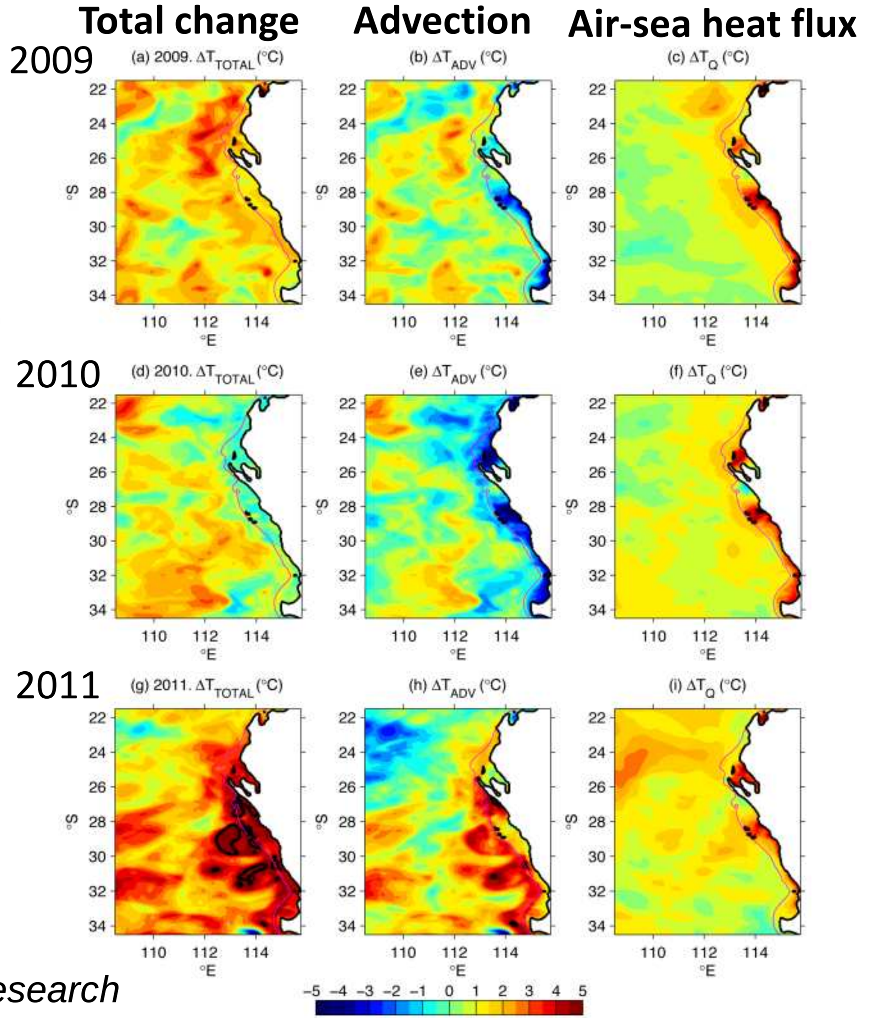
2011 Western Australia (Ningaloo Niño)

Depth-averaged temperature budget

$$\underbrace{\frac{1}{H}\int^{\Delta t}\int^{H}\left(\frac{\partial T}{\partial t}\right)dzdt}_{\Delta T_{TOTAL}} \approx \underbrace{-\frac{1}{H}\int^{\Delta t}\int^{H}(\mathbf{u}\cdot\nabla T)dzdt}_{\Delta T_{ADV}} + \underbrace{\frac{1}{H}\int^{\Delta t}\int^{H}\frac{\partial}{\partial z}\left(\kappa_V\frac{\partial T}{\partial z}\right)dzdt}_{\Delta T_Q}$$

Total change in temperature | **Change due to advection** | **Change due to air-sea heat flux**

Change in upper ocean temperature (H = 60 m) from 1 January to 1 March.



Benthuysen, Feng, Zhong 2014, Continental Shelf Research

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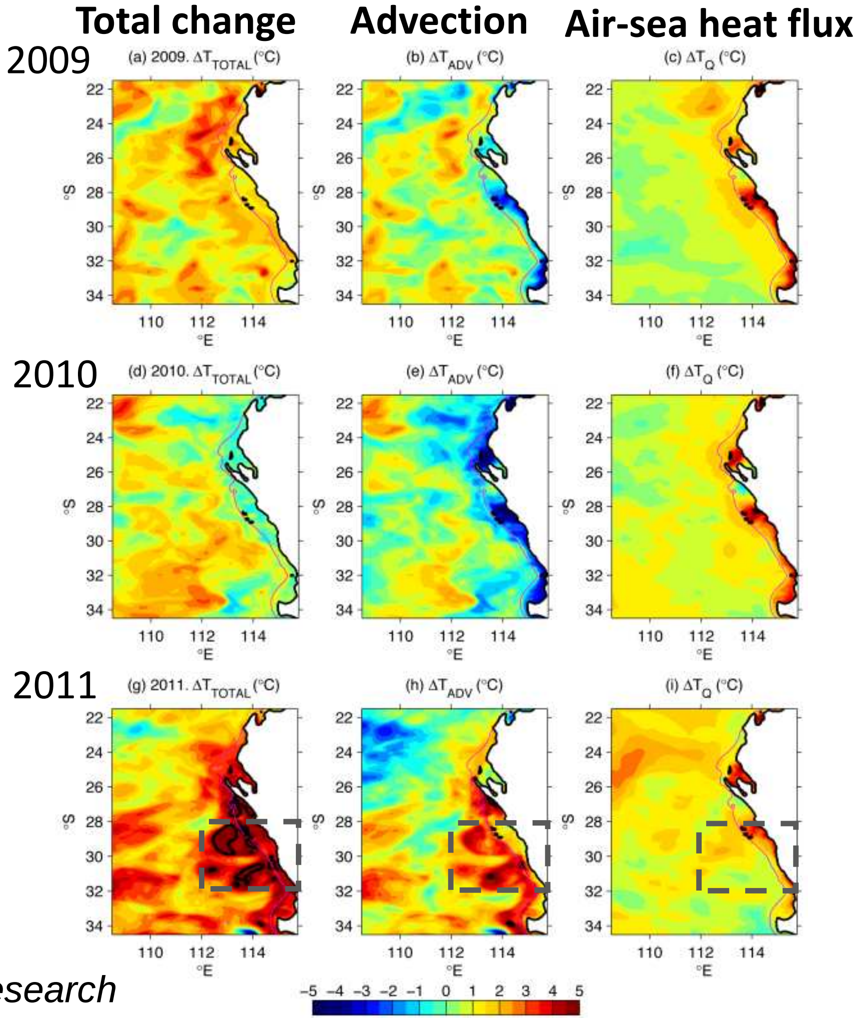
Total change in temperature | **Change due to advection** | **Change due to air-sea heat flux**

Warming caused by poleward advection (≈ 2/3) and air-sea heat flux (≈ 1/3).

The Leeuwin Current intensified due to remote forcing by equatorial easterly wind anomalies and local weakening of southerly winds.



Benthuysen, Feng, Zhong 2014, Continental Shelf Research

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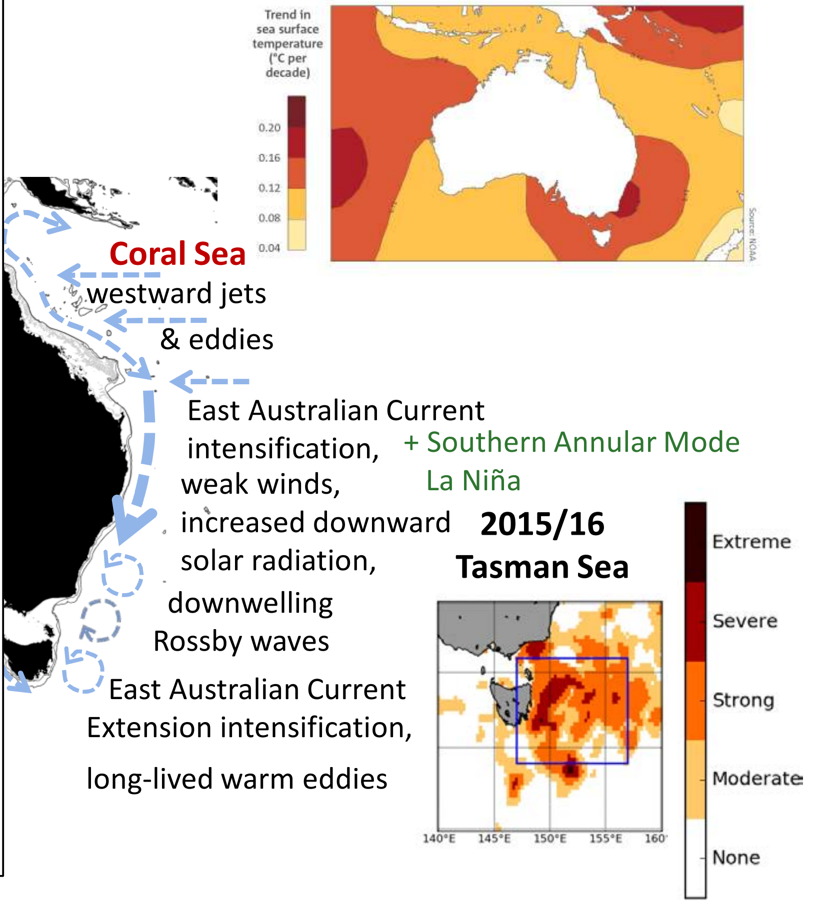
Marine heatwave drivers and processes and notable events

Marine heatwaves in the Tasman Sea

- **Ocean warming hotspot** (2× global rate; BOM 2022); trend found in other WBC extensions (Wu et al. 2012).
- **Atmospheric forcing**: positive phase of the asymmetric **Southern Annular Mode** promotes marine heatwaves and is more likely during **La Niña** (Gregory et al. 2023).
- Blocking high pressure causes weak winds and reduced vertical mixing, enhancing warming (Salinger et al. 2019).
- **Ocean processes**: East Australian Current Extension intensification (Z. Li et al. 2020; J. Li et al. 2022).
- Downwelling Rossby waves with reduced upstream return flow increases ocean heat content (J. Li et al. 2022).
- Enhanced ocean heat content is associated with marine heatwave occurrences and can serve as a measure of likelihood (Behrens et al. 2019).



2015/16 Tasman Sea marine heatwave

9 Sep 2015 – 16 May 2016

An unprecedented marine heatwave:

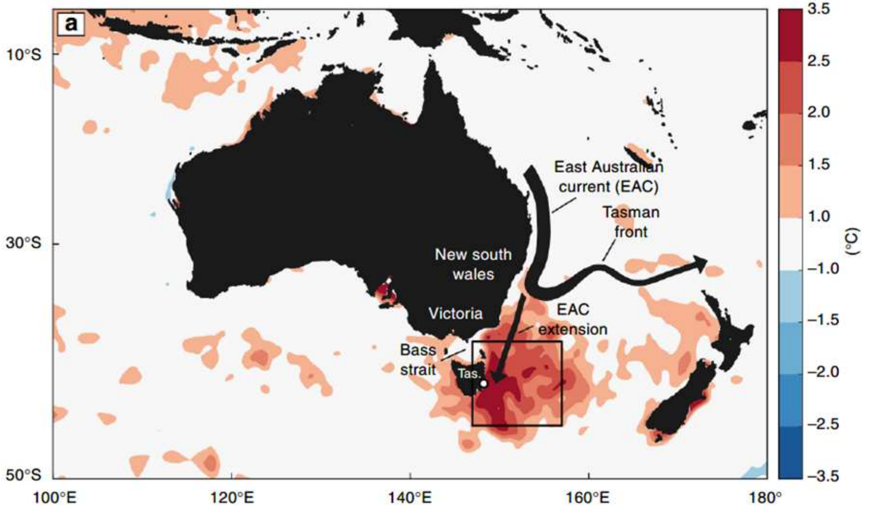
Duration (251 days)

Maximum Intensity (2.9°C)

Impacts:

- Out-of-range species observed,
- Dead abalone,
- Reduced salmon farm performance,
- Thinning of giant kelp forests

Mean 2015-2016 Dec-Feb SST Anomaly



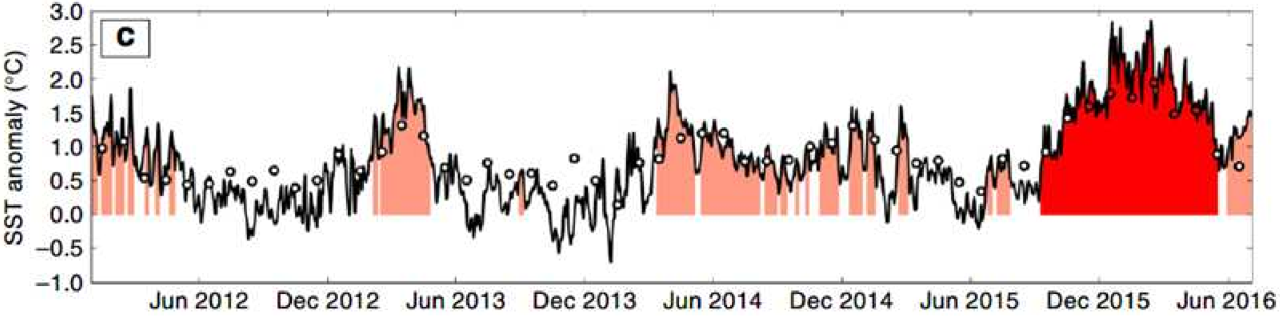
Marine heatwave

Most intense event

-- daily NOAA OISST V2

○ monthly HadISST

1982 – 2005 reference period



Oliver et al. 2017, Nature Communications

2015/16 Tasman Sea marine heatwave

IMOS Maria Island National Reference Station

- 20 m temperature
- Full-depth velocities

IMAS (UTas) nearshore temperature sites

- 6-20 m depth
- Greatest intensity over ~10-year record
- Indicate southward flows in early 2016

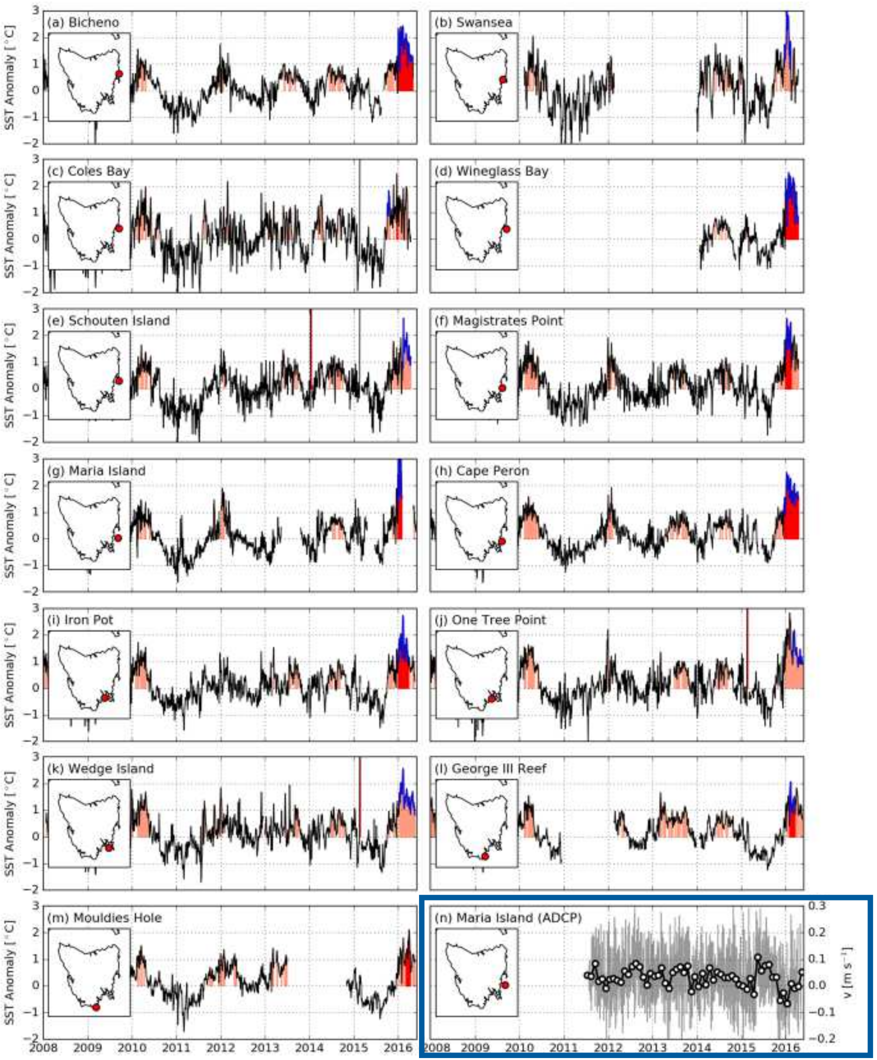
Marine heatwave

Most intense marine heatwave

Longest marine heatwave

Bluelink OceanMAPS (0.1°):
Warming caused by poleward advection (80%) and air-sea heat flux (20%) by mid-February.

Oliver et al. 2017, Nature Communications



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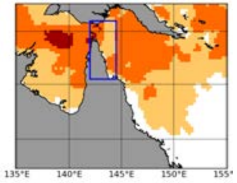
El Niño, Madden Julian Oscillation, Indian Ocean Dipole

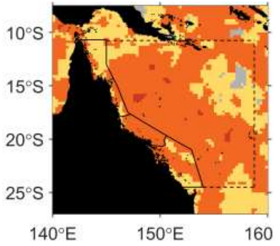
Air-sea heat flux (prolonged clear skies and still winds)
and shallow surface mixed layer, monsoon timing in summer,
timing and spatial extent of tropical cyclones

Indian Ocean

2015/16 Northern Australia



2020 Great Barrier Reef and Coral Sea

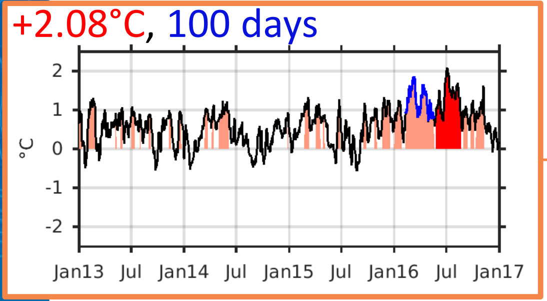


Marine heatwaves off Northern Australia

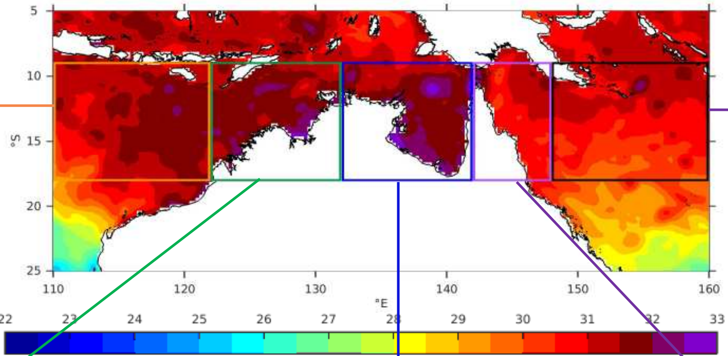
- **El Niño** modifies atmospheric circulation, promoting marine heatwaves owing to increased solar radiation, with reduced cloud cover, and a weaker Australian monsoon (e.g. Zhang et al. 2017).
- The **Madden Julian Oscillation** modulates marine heatwave variability (Zhang et al. 2017; Benthuysen et al. 2018).
- Strong negative **Indian Ocean Dipole** contributed to warming during winter 2016 (Benthuysen et al. 2018).
- Strong positive **Indian Ocean Dipole** contributed to warming in the Great Barrier Reef during summer 2019/20 with a delayed monsoon onset, in addition to reduced cloud cover and weakened winds (BOM 2020).
- Timing of extreme weather events and tropical cyclones can affect marine heatwave characteristics, such as dampening marine heatwaves, if they occur (Benthuysen et al. 2018).

2015/16 Northern Australia marine heatwave

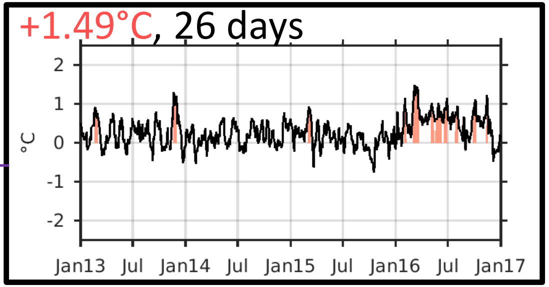
Indonesian-Australian Basin



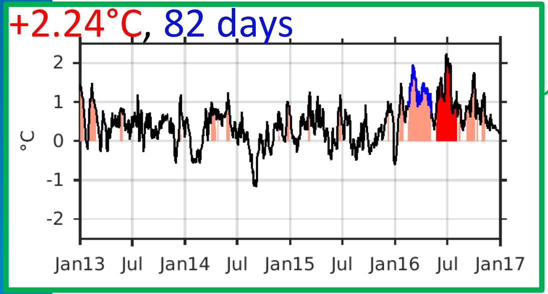
Maximum sea surface temperature austral summer 2015-2016



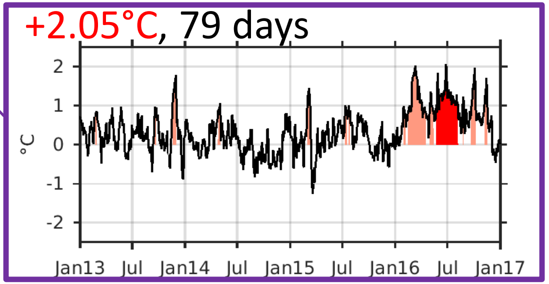
Coral Sea



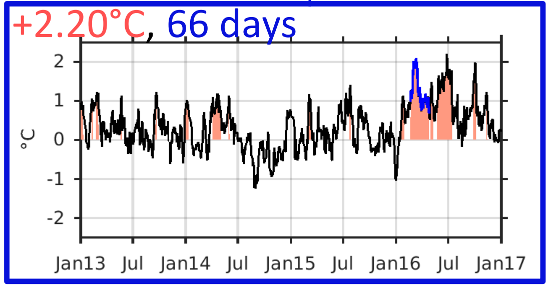
Kimberley Shelf, Timor Sea



Torres Strait, N GBR, W Coral Sea



S Arafura Sea, Gulf of Carpentaria



Marine heatwave (MHW)
Most intense MHW
Longest MHW

NOAA OISST V2
(1 Sep 1981 – 31 Dec 2016;
1982 – 2015 reference period)
Benthuysen, Oliver, Feng, Marshall 2018, JGR: Oceans

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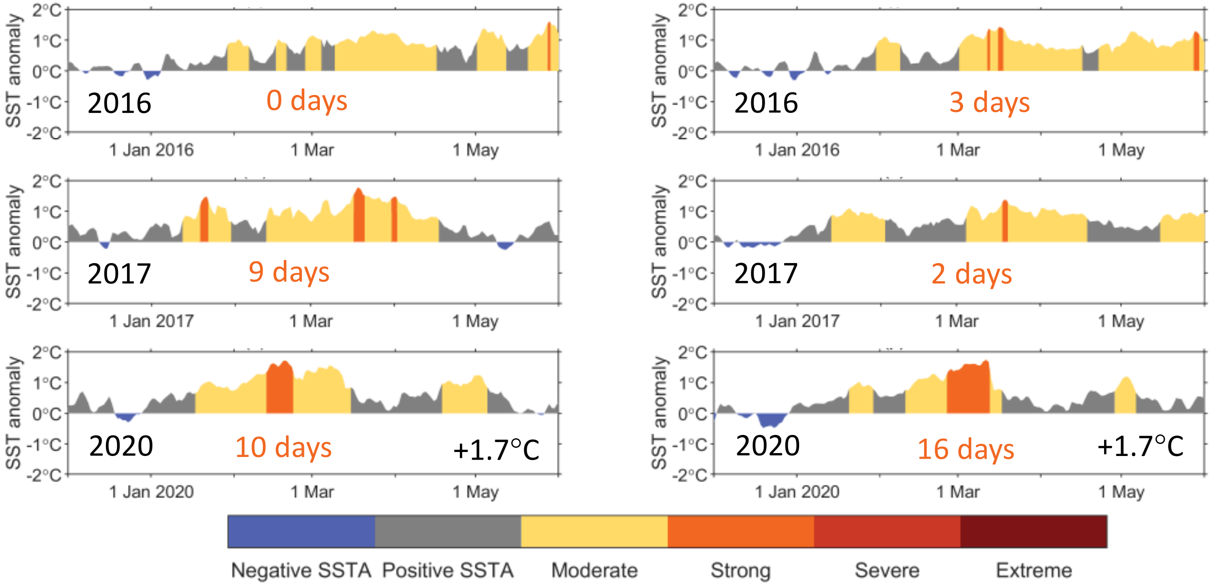
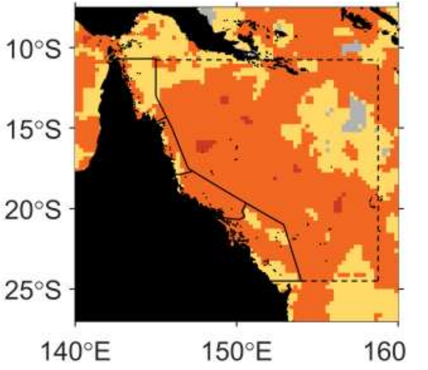
2016, 2017, 2020 Great Barrier Reef and Coral Sea marine heatwaves

SST anomaly

Great Barrier Reef Marine Park | **Coral Sea**



Summer 2020 Category



NOAA daily OISST V2.1
Reference period: 1990-2012

Benthuysen et al. 2021, Vol. 4. Observations and predictions of marine heatwaves

See: Compilation of temperature data during 2016 and 2017 mass coral bleaching events
https://eatlas.org.au/nesp-twq-4/drivers-of-bleaching-4-2

NESP TWQ Hub – Project 4.2: https://nesptropical.edu.au/index.php/final-reports-round-4/

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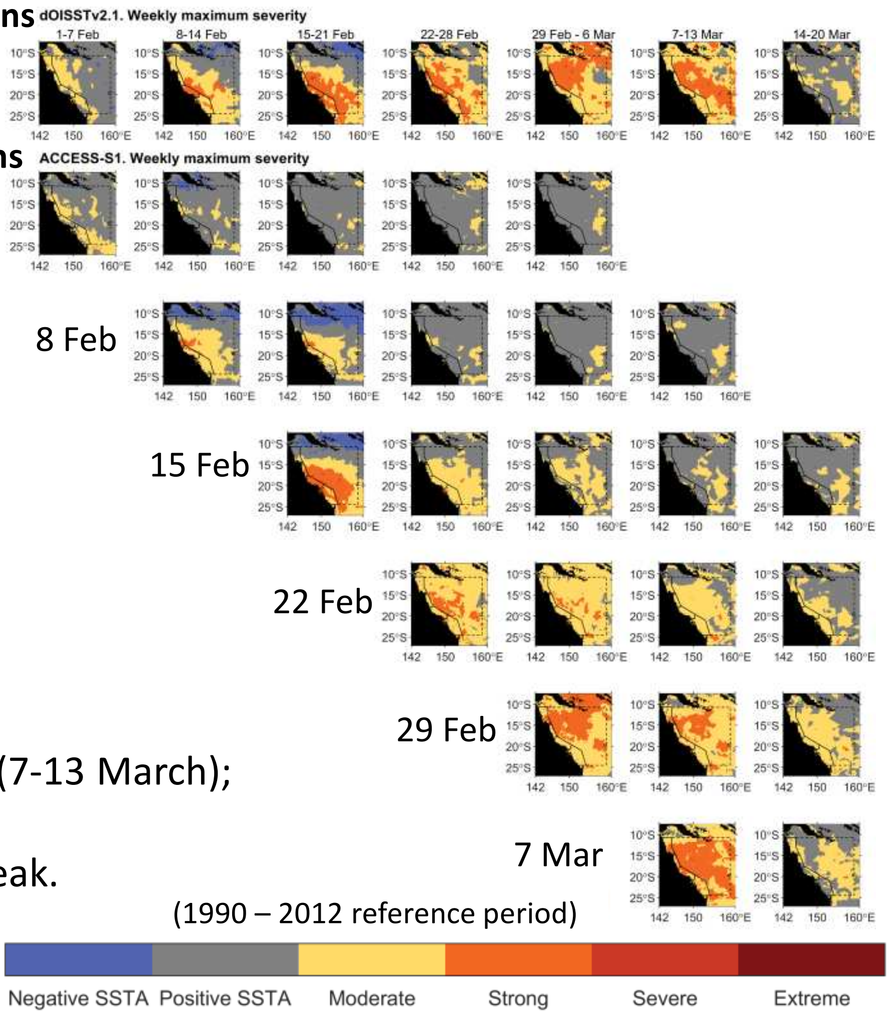
Australian Institute of Marine Science
National Environmental Science Programme
Tropical Water Quality Hub

Evaluating the 2020 Great Barrier Reef and Coral Sea marine heatwave predictions

Australian Community Climate Earth-System Simulator – Seasonal (ACCESS-S1)

The ACCESS-S1 ensemble mean SST anomalies:

- underpredicted the maximum severity's development phase;
- captured the broad extent with unusually warm SST anomalies (marine heatwave severity);
- reached the maximum severity during the initial week of prediction for the GBR Marine Park (15-21 February) and Coral Sea (7-13 March);
- tended to cool after their severities reach their peak.



Benthuysen et al. (2021), Environmental Research Letters

*Note: ACCESS-S2 now operational.

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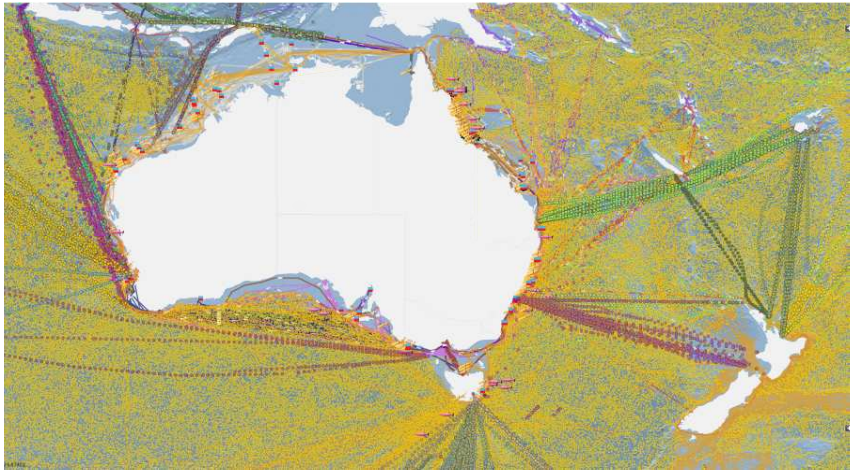
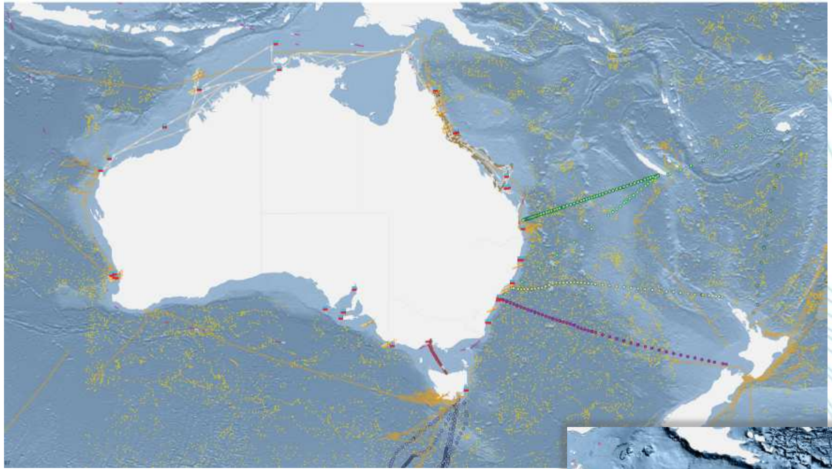
Is Australia's ocean temperature network sufficient for tracking marine heatwaves?

1 January 2006 – 13 July 2023



1 July 2022 – 30 June 2023



Integrated Marine Observing System (IMOS) temperature observations:

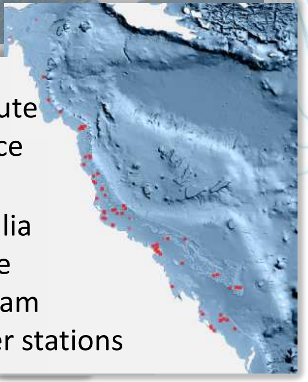
<u>Bluewater</u>:

Argo (0 - 2000 m; yellow dot)
XBT (0 - 800 m; multi-colour)
Seagliders (0 - ~1000 m, pink)
Satellite remote sensing

<u>Shelf</u>:

Ships of Opportunity (multi-colour; orange)
Moorings (red/blue square)
Slocum gliders (0- ~200 m, yellow)
Satellite remote sensing
Wireless sensor networks (Great Barrier Reef)

Australian Institute of Marine Science (AIMS) Northern Australia Sea Temperature Observing Program and reef weather stations



Drifter observations and CTD stations not included but have poor distribution in northern seas.

Australian Ocean Data Network Portal: https://portal.aodn.org.au/
IMOS OceanCurrent: https://oceancurrent.aodn.org.au/

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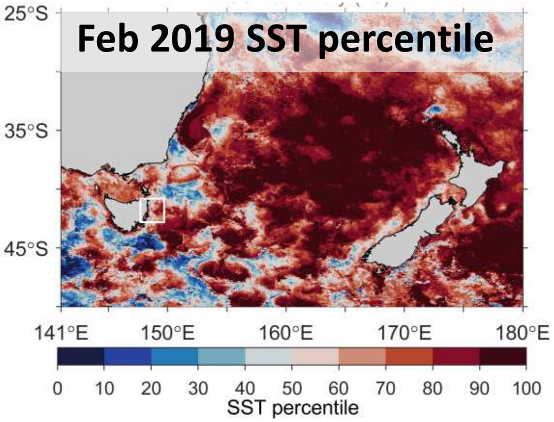
National collaboration for sampling marine heatwaves with gliders

Integrated Marine Observing System (IMOS) –
Event Based Sampling (December 2018 – present)
https://imos.org.au/facilities/oceangliders/event-based-sampling

Event Based Sampling

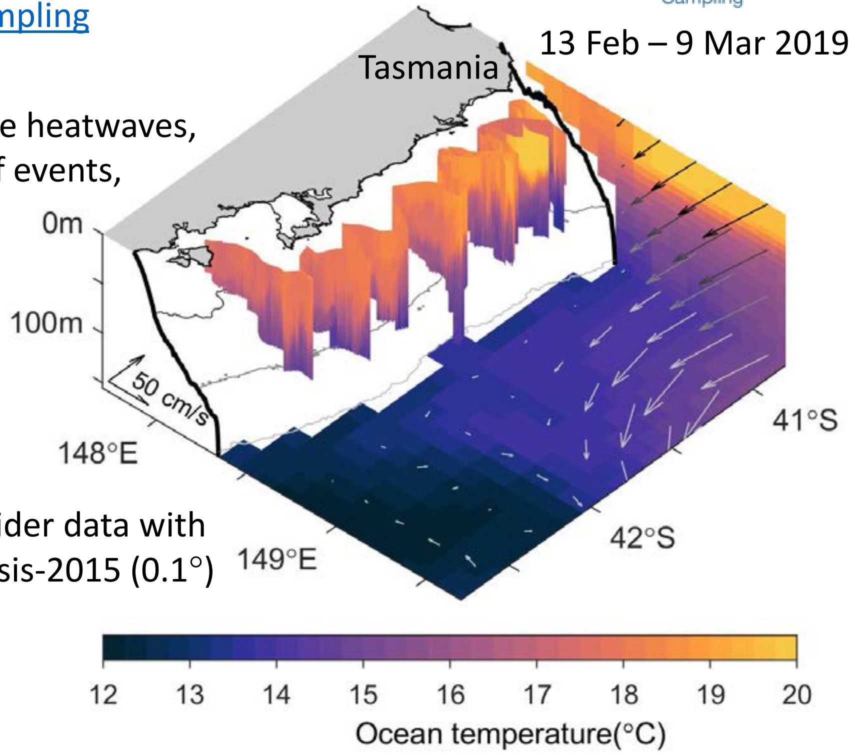
Guiding principles:

- Identify and monitor indicators and predictors of marine heatwaves,
- Collate, review, and evaluate evidence and likelihood of events,
- Develop a deployment plan,
- Prioritise deployment locations nationally.



SST Atlas of Australian Regional Seas
(SSTAARS climatology; Wijffels et al. 2018)

13 Feb – 9 Mar 2019



Near-real time glider data with
Bluelink ReANalysis-2015 (0.1°)

Holbrook et al. 2020, Nature Reviews Earth & Environment

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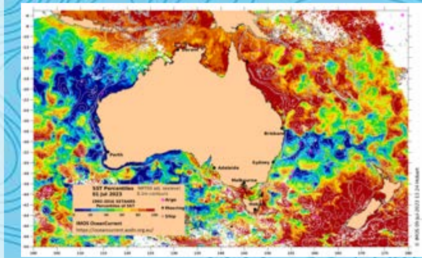
Summary

- **New frameworks and methods** developed for characterising marine heatwaves
- **Long-term and targeted sampling** are key: including near-real time & subsurface
- **Surface to subsurface climatologies**: mean values and percentiles useful for contextualizing temperature extremes
- **Regional-scale to fine-scale modelling** offer opportunities to diagnose mechanisms and can be used to build predictive models
- **Monitoring current conditions and outlooks** and communicating risks are important for proactive decision making, e.g. by marine industries to reduce impacts

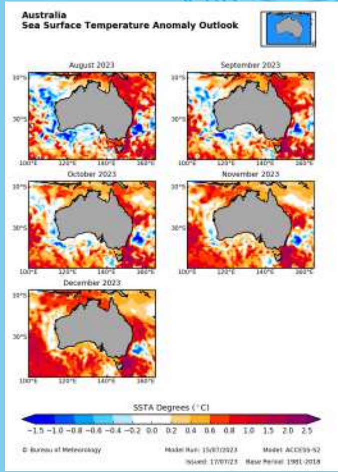
Monitoring Current conditions

https://oceancurrent.aodn.org.au/



Seasonal predictions

http://www.bom.gov.au/oceanography/oceantemp/sst-outlook-map.shtml



Jessica Benthuysen
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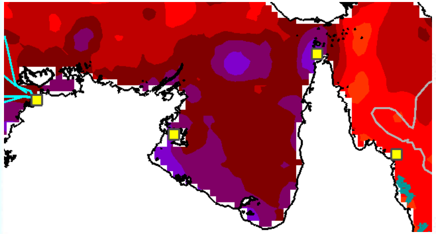
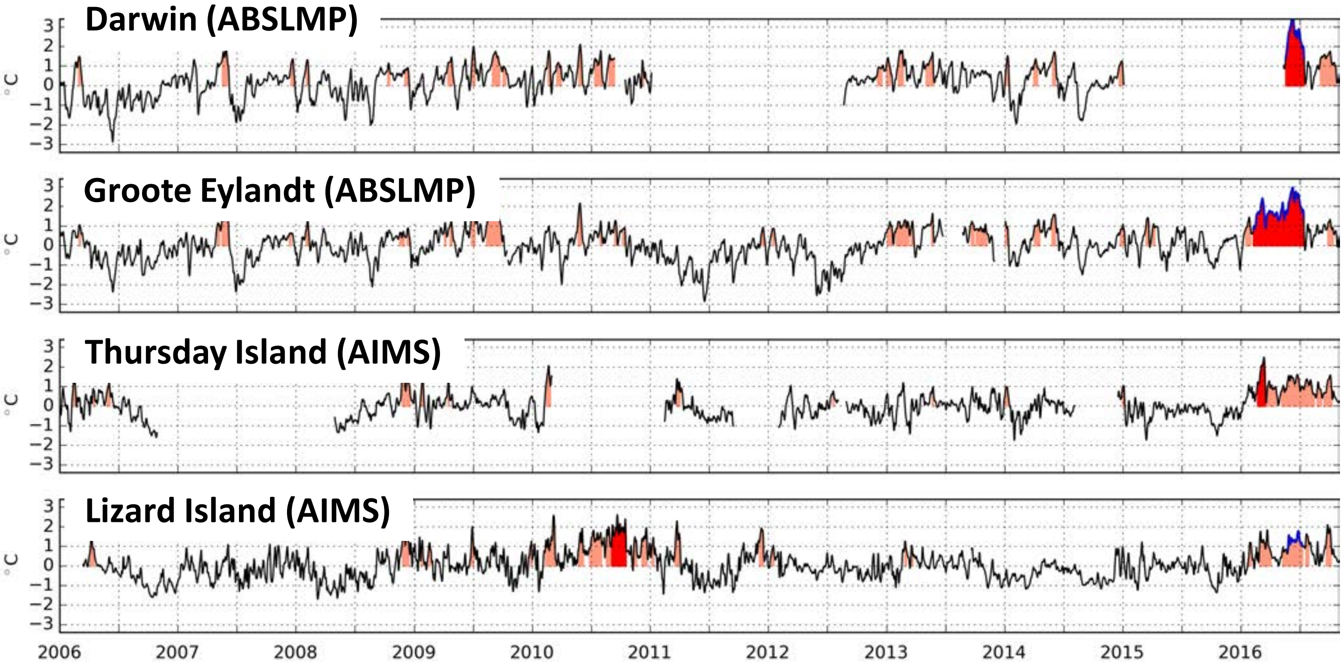
Benthuysen 2020,
"Planning for marine heatwaves around Australia",
CSIRO Report on Climate and Disaster Resilience

2015/16 Northern Australia marine heatwave

Long-term in situ temperature records



Marine heatwave (MHW)
Most intense MHW
Longest MHW



ABSLMP: Australian Baseline Sea Level Monitoring Project
AIMS: Australian Institute of Marine Science
Benthuysen, Oliver, Feng, Marshall 2018, JGR: Oceans

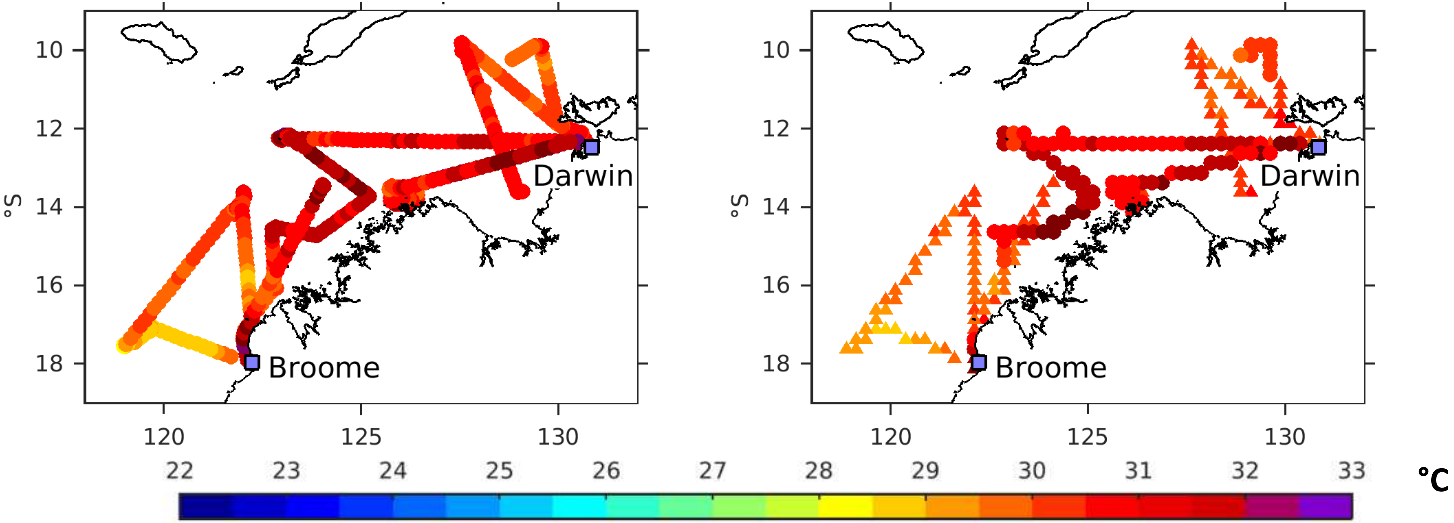
2015/16 Northern Australia marine heatwave

IMOS Ships of Opportunity –

Sensors on Tropical Research Vessels:

Tracking marine heatwaves in near real time

AIMS R/V Solander in situ temperature | **NOAA OISST V2 temperature**



1 January – 31 March 2016

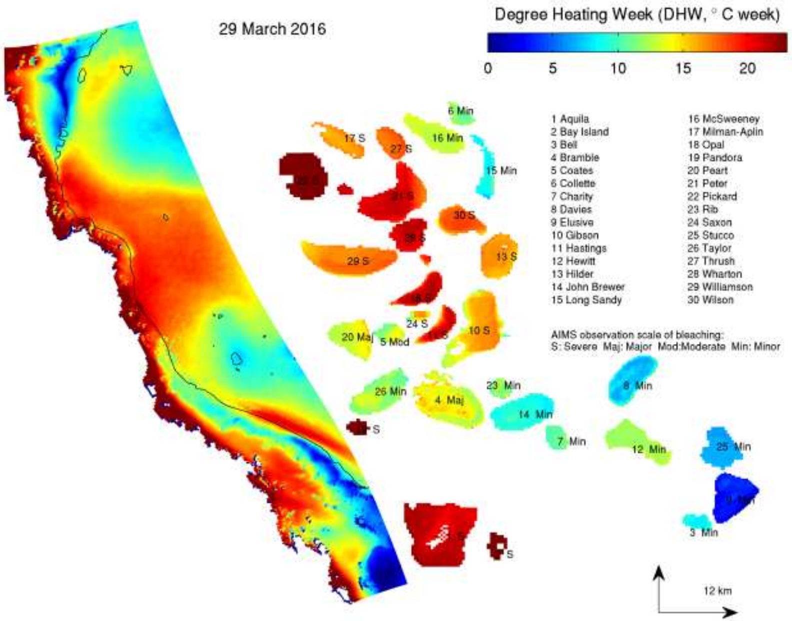
▲ **Not in a marine heatwave**

● **In a marine heatwave**

Benthuysen, Oliver, Feng, Marshall 2018, JGR: Oceans

More recently: IMOS OceanCurrent (http://oceancurrent.imos.org.au/)
SST Atlas of Australian Regional Seas (SSTAARS climatology)

Hydrodynamic models used to assess coral bleaching from shelf to reef-scale – 2015/2016 Great Barrier Reef marine heatwave



Baird et al. from https://research.csiro.au/ereefs/models/

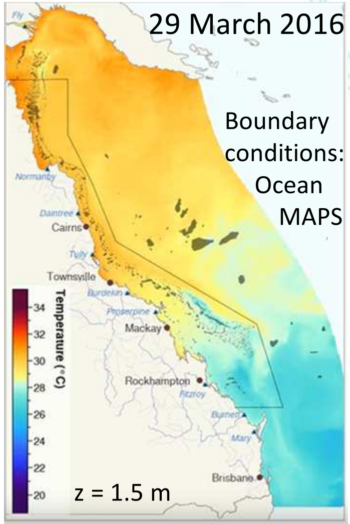
eReefs, GBR4v2 (~4km) and RECOM (Relocatable Ocean Model)

http://ereefs.info/

AIMS eReefs Visualisation Portal

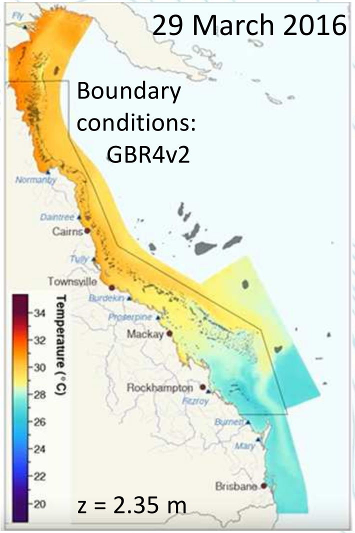
https://ereefs.aims.gov.au/

eReefs GBR4v2 (4km)
(Sep 2010 – NRT)



Forced by: Australian Bureau of Meteorology's OceanMAPS (10 km) ACCESS-A (12 km)

eReefs GBR1v2 (1km)
(Dec 2014 – NRT)



Model outputs:

- ocean velocity, SSH, temperature, salinity;
- water chemistry and water quality variables;
- macroalgae, seagrass, coral (symbiont, calcification, DHWs)

Vertical resolution:

- **OceanMAPS:** 5 m to 40 m depth; 10 m to 200 m depth; 24 values
- **GBR1v2:** 1-6 m to 27 m depth; 8-30 m to 210 m depth; 18 values

Australian Government

Australian Institute of Marine Science