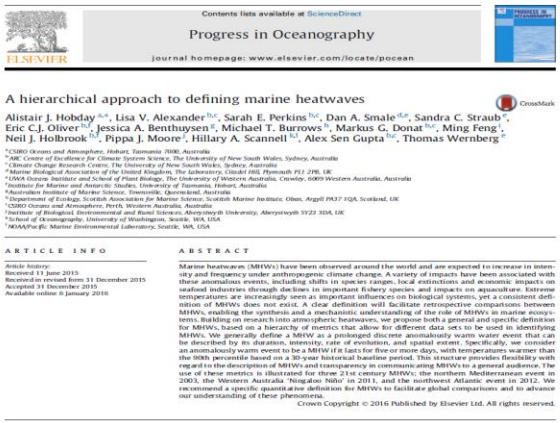
Marine heatwaves in the sub-surface using observations

Amandine Schaeffer , Michael Hemmings, Neil Malan, Alex Sen Gupta, Youtsina Elzahaby, Moninya Roughan

UNSW Sydney: school of Maths & Stats, Coastal and Regional Oceanography Laboratory, Climate Change Research Center.

An Examination of Shelf Data collected by Moorings and Other Fixed Stations in the North Pacific Ocean PICES2025

Introduction



Progress in Oceanography 141 (2016) 227–238

Contents lists available at ScienceDirect

Progress in Oceanography

journal homepage: www.elsevier.com/locate/pocean

A hierarchical approach to defining marine heatwaves

Alistair J. Hobday [a,*], Lisa V. Alexander [b,c], Sarah E. Perkins [b,c], Dan A. Smale [d,e], Sandra C. Straub [e], Eric C.J. Oliver [b,f], Jessica A. Benthuysen [g], Michael T. Burrows [h], Markus G. Donat [b,c], Ming Feng [i], Neil J. Holbrook [b,f], Pippa J. Moore [j], Hillary A. Scannell [k,l], Alex Sen Gupta [b,c], Thomas Wernberg [e]

[a] CSIRO Oceans and Atmosphere, Hobart, Tasmania 7000, Australia
[b] ARC Centre of Excellence for Climate System Science, The University of New South Wales, Sydney, Australia
[c] Climate Change Research Centre, The University of New South Wales, Sydney, Australia
[d] Marine Biological Association of the United Kingdom, The Laboratory, Citadel Hill, Plymouth PL1 2PB, UK
[e] UWA Oceans Institute and School of Plant Biology, The University of Western Australia, Crawley, 6009 Western Australia, Australia
[f] Institute for Marine and Antarctic Studies, University of Tasmania, Hobart, Australia
[g] Australian Institute of Marine Science, Townsville, Queensland, Australia
[h] Department of Ecology, Scottish Association for Marine Science, Scottish Marine Institute, Oban, Argyll PA37 1QA, Scotland, UK
[i] CSIRO Oceans and Atmosphere, Perth, Western Australia, Australia
[j] Institute of Biological, Environmental and Rural Sciences, Aberystwyth University, Aberystwyth SY23 3DA, UK
[k] School of Oceanography, University of Washington, Seattle, WA, USA
[l] NOAA/Pacific Marine Environmental Laboratory, Seattle, WA, USA

ARTICLE INFO

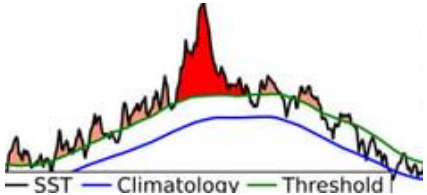
Article history:
Received 11 June 2015
Received in revised form 31 December 2015
Accepted 31 December 2015
Available online 6 January 2016

ABSTRACT

Marine heatwaves (MHWs) have been observed around the world and are expected to increase in intensity and frequency under anthropogenic climate change. A variety of impacts have been associated with these anomalous events, including shifts in species ranges, local extinctions and economic impacts on seafood industries through declines in important fishery species and impacts on aquaculture. Extreme temperatures are increasingly seen as important influences on biological systems, yet a consistent definition of MHWs does not exist. A clear definition will facilitate retrospective comparisons between MHWs, enabling the synthesis and a mechanistic understanding of the role of MHWs in marine ecosystems. Building on research into atmospheric heatwaves, we propose both a general and specific definition for MHWs, based on a hierarchy of metrics that allow for different data sets to be used in identifying MHWs. We generally define a MHW as a prolonged discrete anomalously warm water event that can be described by its duration, intensity, rate of evolution, and spatial extent. Specifically, we consider an anomalously warm event to be a MHW if it lasts for five or more days, with temperatures warmer than the 90th percentile based on a 30-year historical baseline period. This structure provides flexibility with regard to the description of MHWs and transparency in communicating MHWs to a general audience. The use of these metrics is illustrated for three 21st century MHWs: the northern Mediterranean event in 2003, the Western Australia 'Ningaloo Niño' in 2011, and the northwest Atlantic event in 2012. We recommend a specific quantitative definition for MHWs to facilitate global comparisons and to advance our understanding of these phenomena.

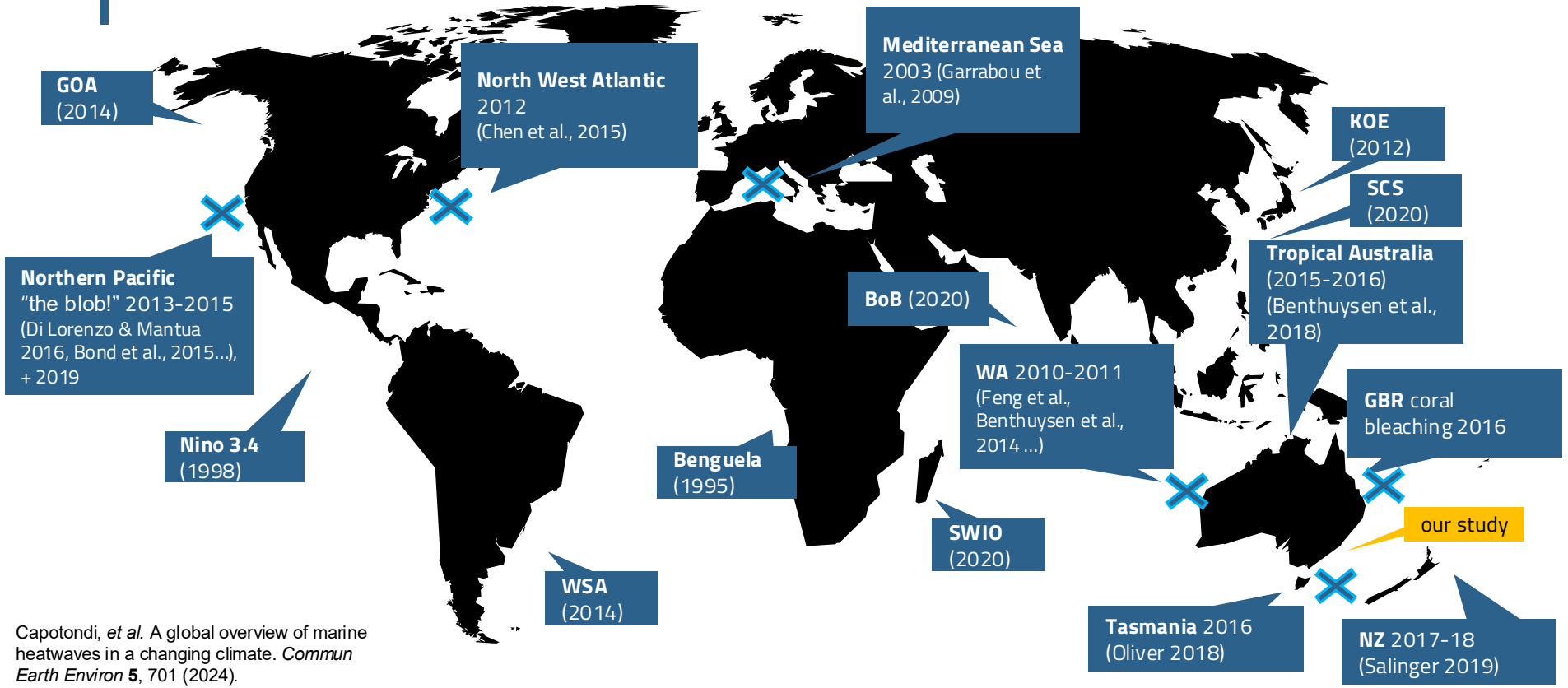
Marine heatwaves

"A discrete prolonged anomalously warm water event in a particular location" (Hobday et al., 2016)



Threshold:
90th percentile of day-of year temperature calculated over ~30 years.

Extreme Marine heatwaves (MHWs)



Capotondi, *et al.* A global overview of marine heatwaves in a changing climate. *Commun Earth Environ* **5**, 701 (2024).

MHWs are more common and critical

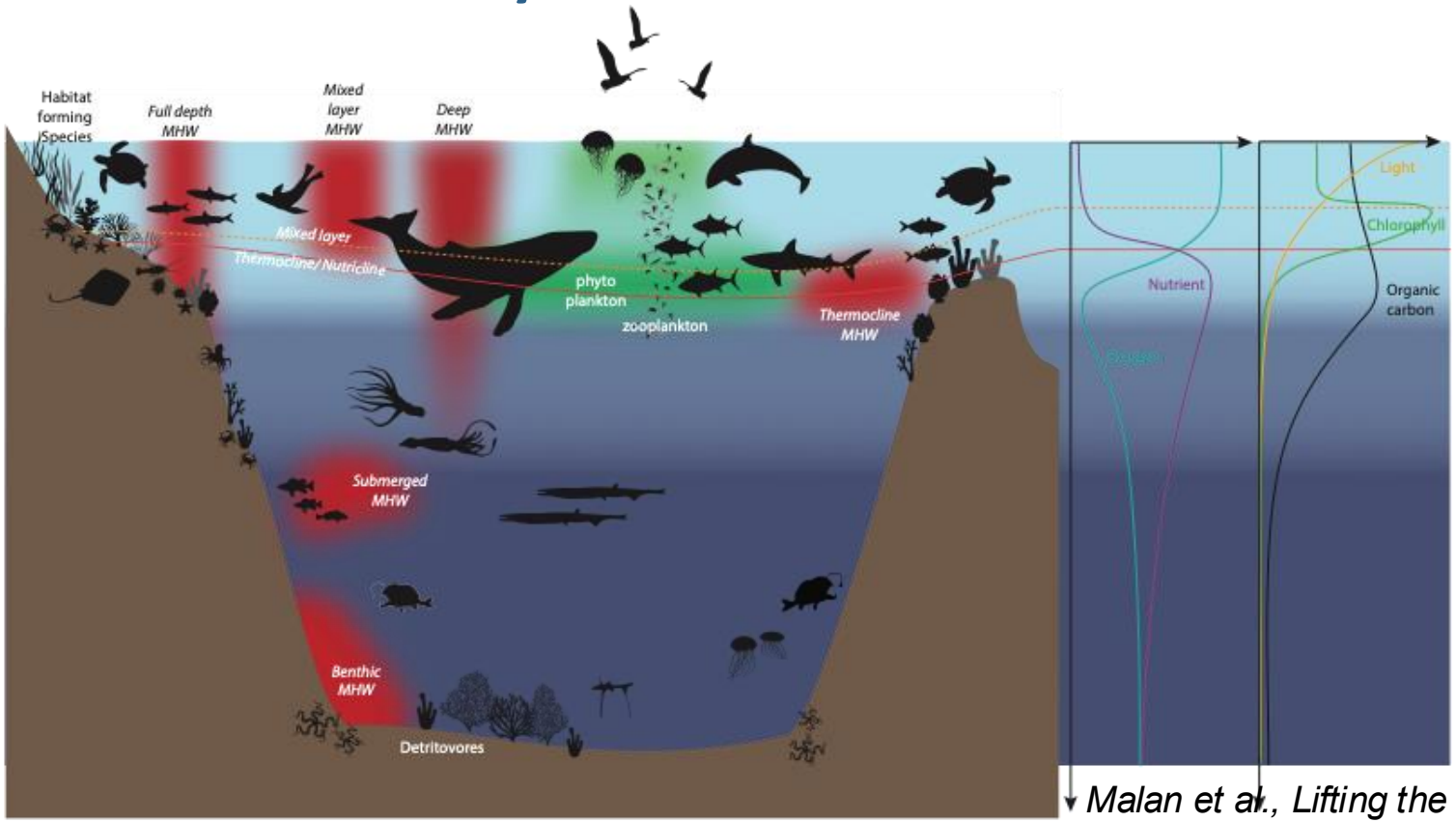
- **Globally**:
  MHWs have become more common and more intense (Oliver et al. 2018) and projected to accelerate in the future (Frolicher et al. 2018, Plecha et al. 2020, Qiu et al. 2021).

- **Impact on the ocean ecosystems** (Smale et al. 2019): mortality of benthic communities, corals, seagrass, fish and invertebrate (Garrabou et al 2009, Pearce and Feng 2013); poleward shift of warm water seaweeds and fish and habitat loss (Last et al. 2011, Wernberg et al. 2016, Verges et al. 2014).

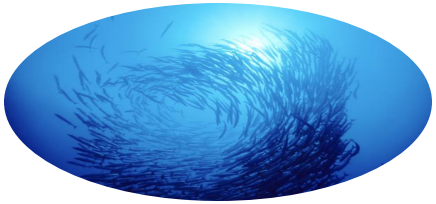
However, the vast vajority of studies used satellite Sea Surface Temperature (SST) to identify MHWs.

But not all MHWs are restricted to the surface layers (Elzahaby and Schaeffer, 2019), or have a surface signature (Schaeffer and Roughan 2017, Scannel et al 2020, Hu et al. 2021).

And most of the ecosystem is in the sub-surface



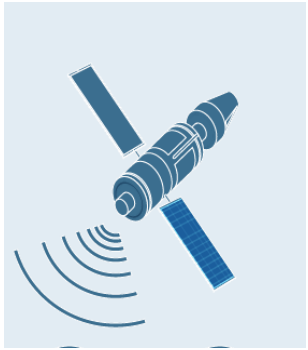
Malan et al., Lifting the Lid on MHWs, P&O 2025



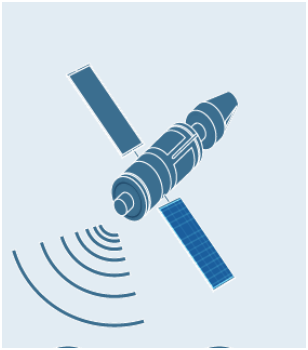
The challenges with MHWs…

- We need a baseline to define the (90th percentile) threshold
→ temporal coverage is critical (e.g. 30 years)!

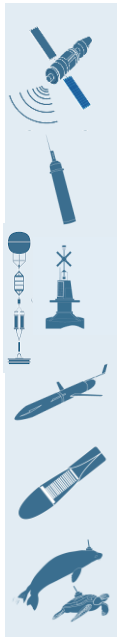
- Events of a few days can already have large impacts
→ temporal resolution is also critical (e.g. daily)!



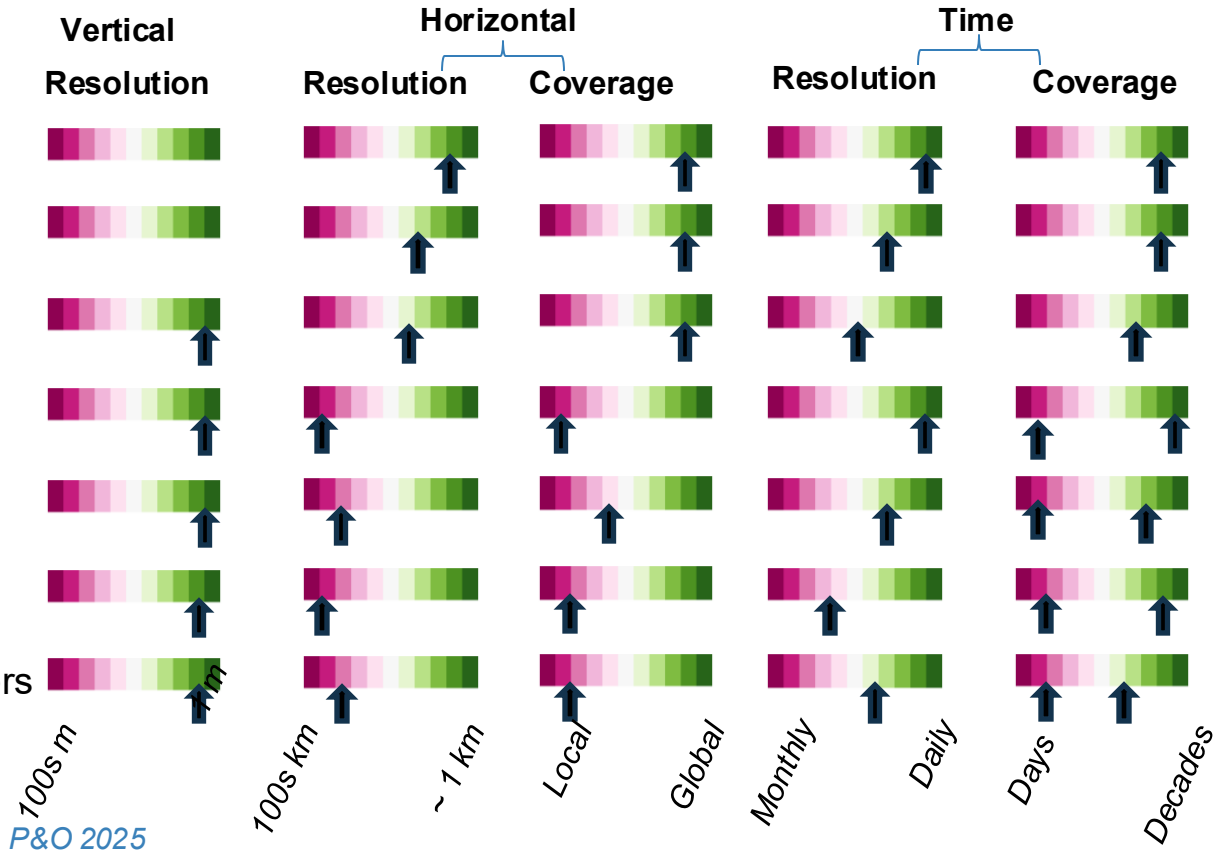
Hence the wide use of satellite SST and limited studies in the sub-surface.



Each observation platform has specific characteristics

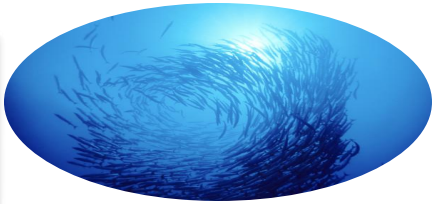


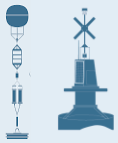
- Satellite SST
- Satellite Altimetry
- Argo profilers
- Moorings
- Ocean gliders
- XBT / CTD
- Animal borne sensors



More in Malan et al., Lifting the Lid on MHWs, P&O 2025

Outline





1. **Long-term shelf mooring: identify Marine heatwaves below the surface, their classes and drivers.**

→ What do we miss when looking at SST?

2. What other classes of MHWs exist when considering the open-ocean?

3. What if the daily multi-decadal sub-surface data does not exist?

- E.g. Building a sub-surface baseline using multi platforms.
- E.g. Focusing on the vertical structure of surface MHWs (Argo, glider).

4. Co-designing an observational system for MHWs - a GOOS initiative.

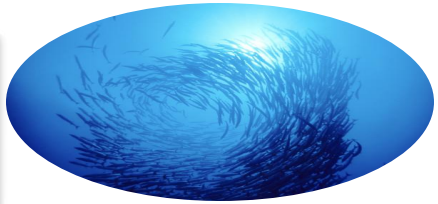
Outline

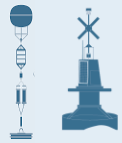

communications earth & environment

ARTICLE

OPEN

Seasonal stratification and complex local dynamics control the sub-surface structure of marine heatwaves in Eastern Australian coastal waters





1. **Long-term shelf mooring: identify Marine heatwaves below the surface, their classes and drivers.**

→ What do we miss when looking at SST?

2. What other classes of MHWs exist when considering the open-ocean?

3. What if the daily multi-decadal sub-surface data does not exist?
   - E.g. Building a sub-surface baseline using multi platforms.
   - E.g. Focusing on the vertical structure of surface MHWs (Argo, glider).

4. Co-designing an observational system for MHWs - a GOOS initiative.

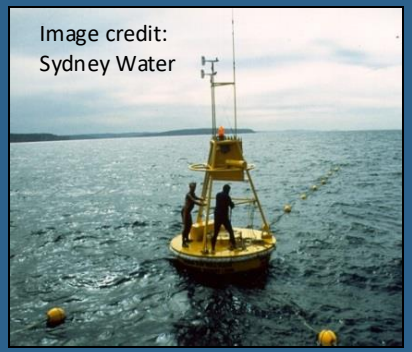
Methods

- Datasets: temperature, drivers
- Areas of interest

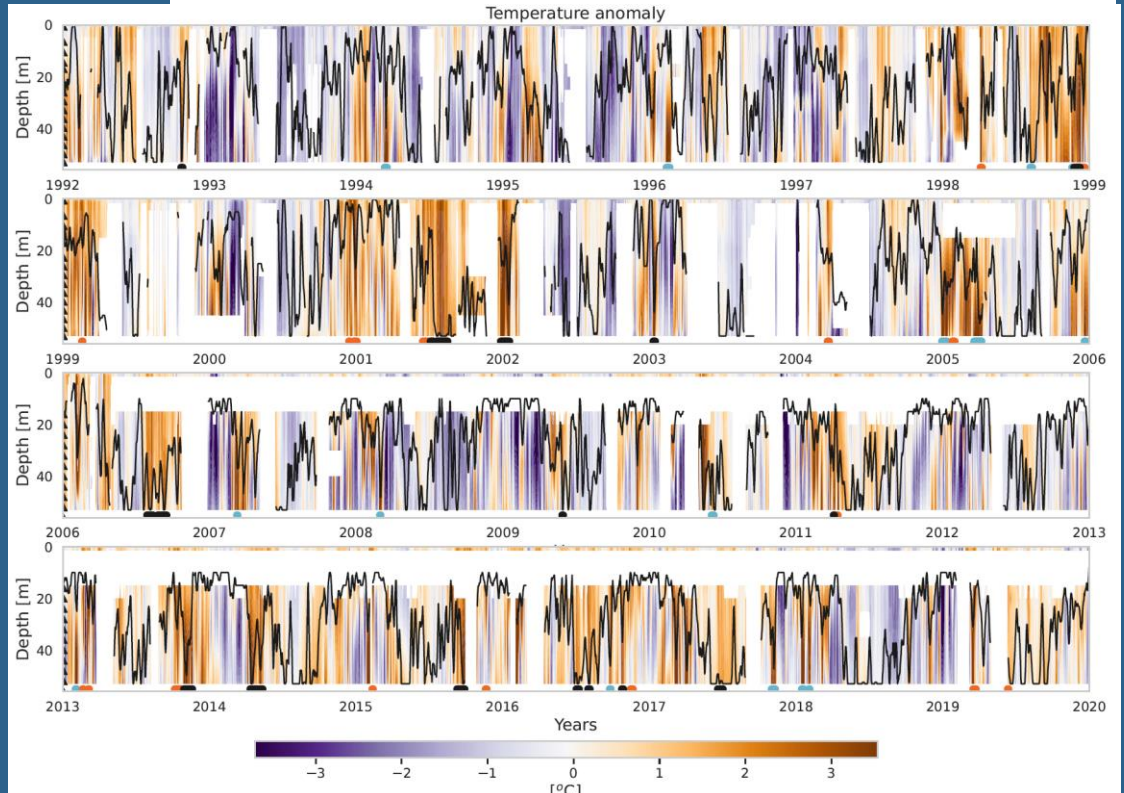
28-year daily *in situ* temperature

ORS065: mooring (Sydney Water Corp)

- 1992 – 2019 -> 28 years!
- Depth 65 m
- Temperature dz=4m, dt=1h / 5min
- Current velocity after 2006.



Temperature anomaly measurements ORS065, SST, with Mixed Layer Depth



Sea surface temperture (SST) and other datasets

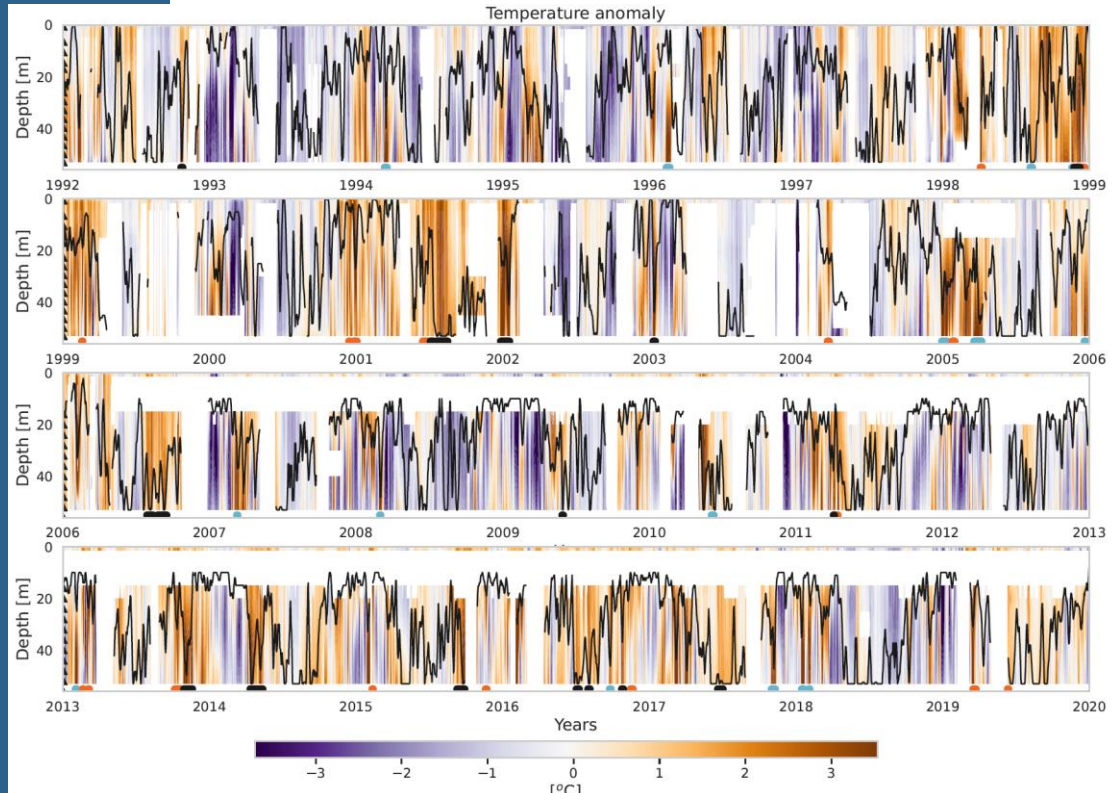
SST ESA L4 (Merchant et al., 2019)
- 0.05° resolution
- Gap free (infra-red + microwave)

Altimetry geostrophic current
- 0.2° resolution

BoM meteorological station: air temperature, wind speed & direction.

ERA5 reanalysis air-sea heat fluxes (QLAT, QSENS, QSW, QLW)
- 0.05° resolution.

Temperature anomaly measurements ORS065, SST, with Mixed Layer Depth

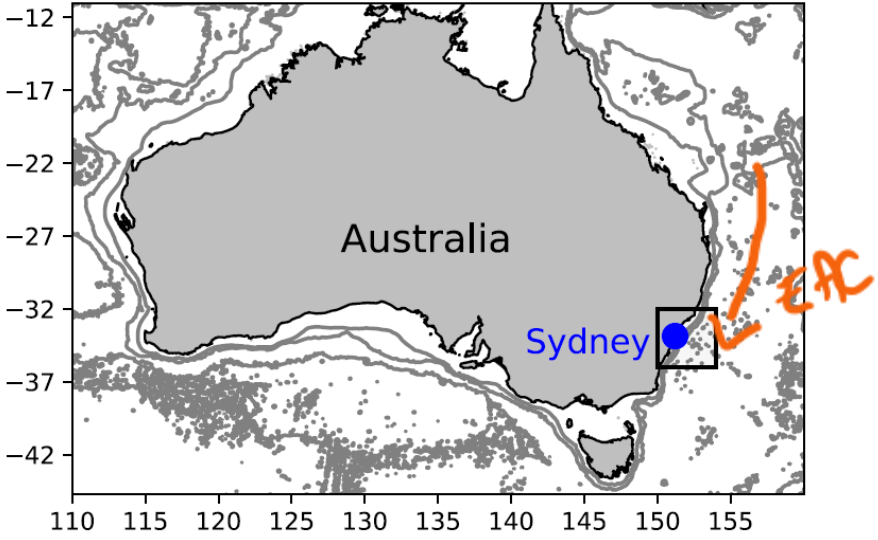


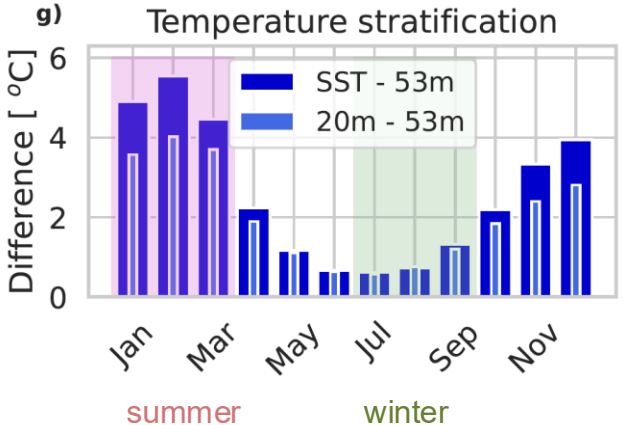
Areas of interest
Shelf off Sydney

- The East Australian Current (EAC) and eddies -> southward heat transport, geostrophic and barotropic circulation on the shelf (Schaeffer et al., 2013)

- Wind stress: mostly northward (downwelling favourable), but sporadic upwellings in summer (Rossi et al., 2014)

- Seasonal stratification:
weak in “winter”, strong in “summer”.





Results

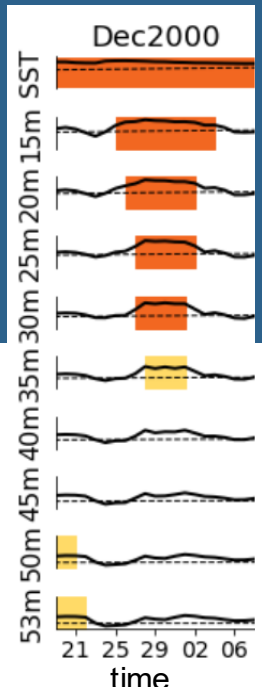
- Shallow, extended, sub-surface MHWs
- Characteristics
- Drivers

MHWs: different classes

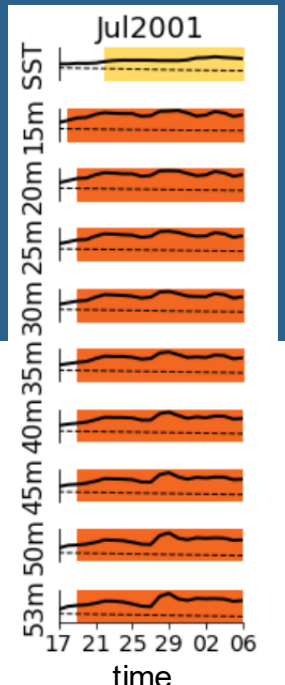
Moderate MHW

Strong MHW

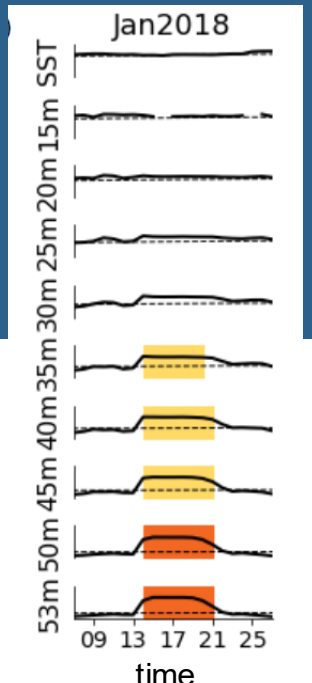
Shallow MHW



Extended MHW



Sub-surface MHW



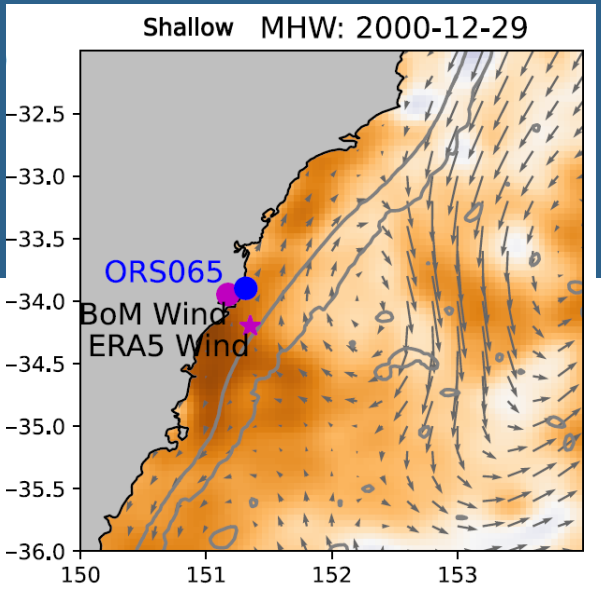
MHWs: different classes

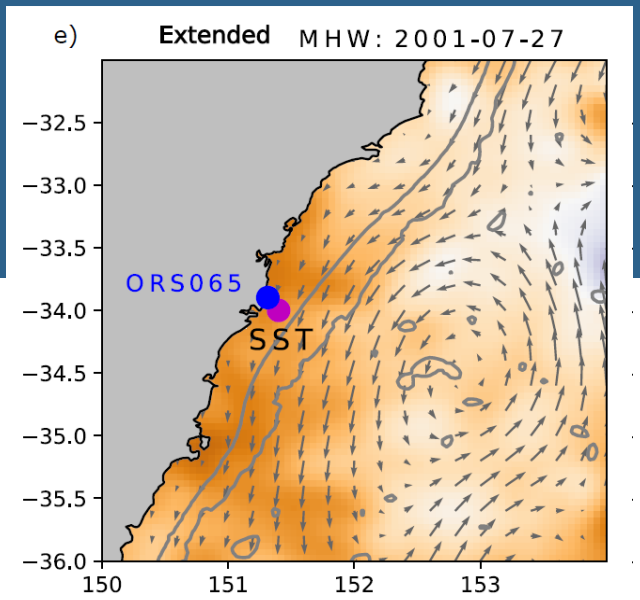
SST anomaly [°C]

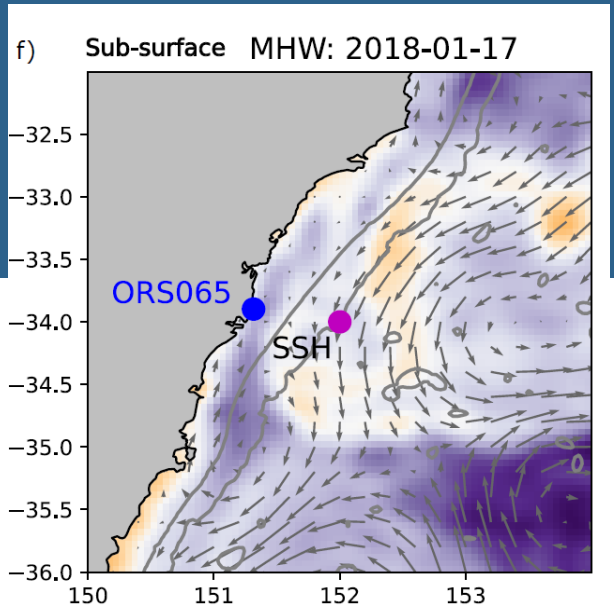
Shallow MHW

Extended MHW

Sub-surface MHW
(no surface signature!)

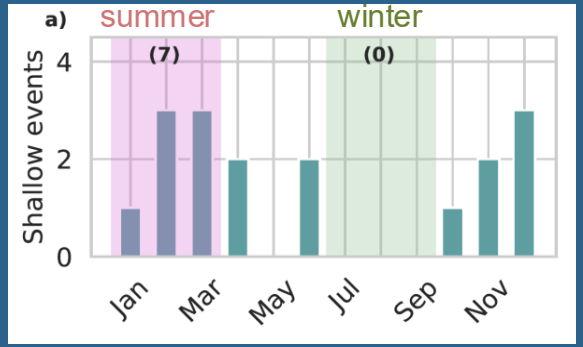


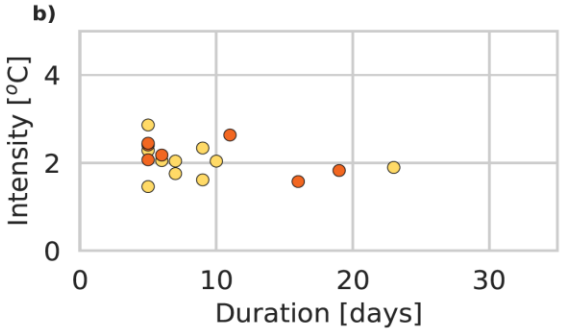




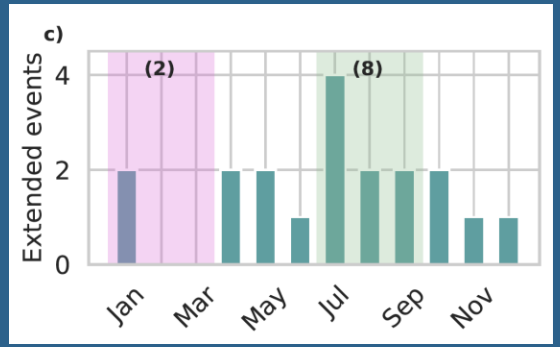
Contrasting timing, intensity and duration

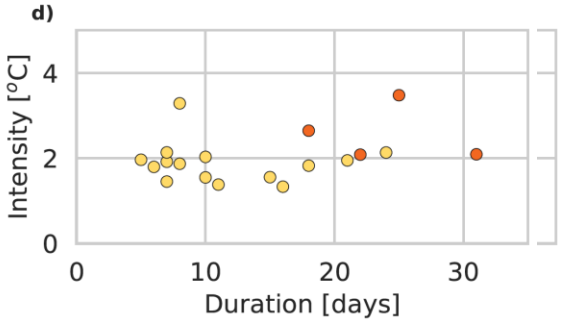
Shallow MHW



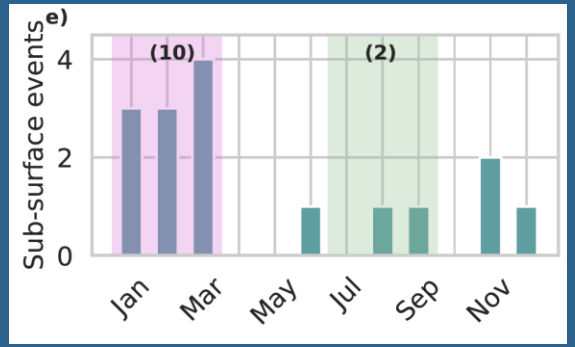


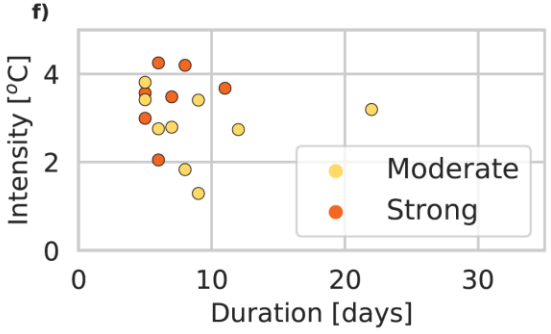
Extended MHW





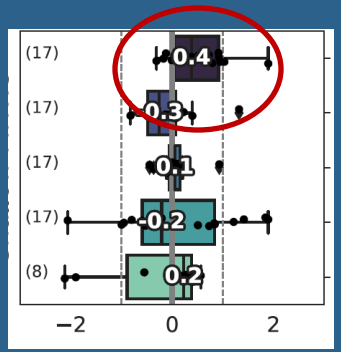
Sub-surface MHW



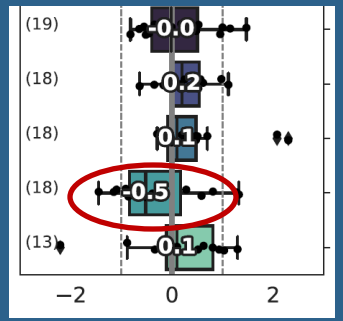


Contrasting influence of wind, currents, air-sea heat fluxes

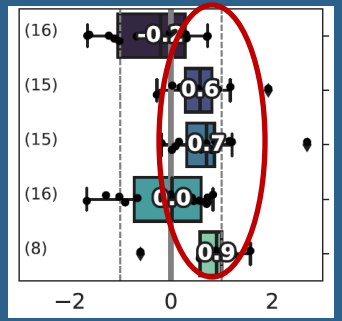
Shallow MHW



Extended MHW



Sub-surface MHW

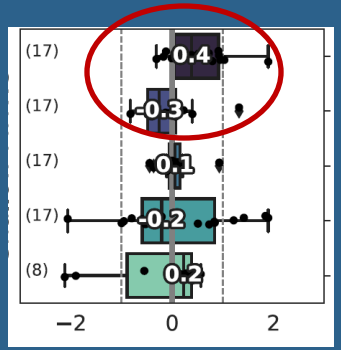


Air temperature
Wind speed
Northward wind stress
Northward geostrophic current
Northward local current

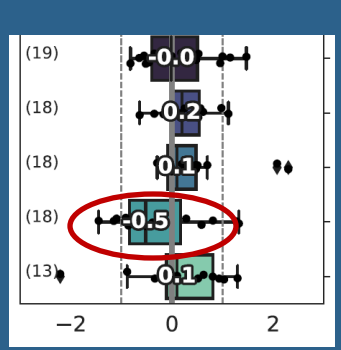
* ***Normalised anomalies*** *over the week before the peak of the events*

Contrasting influence of wind, currents, air-sea heat fluxes

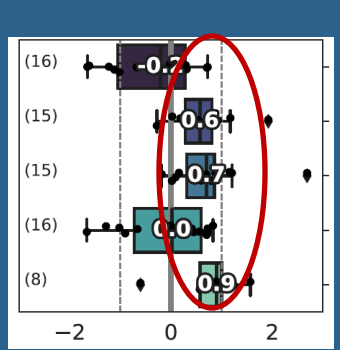
Shallow MHW



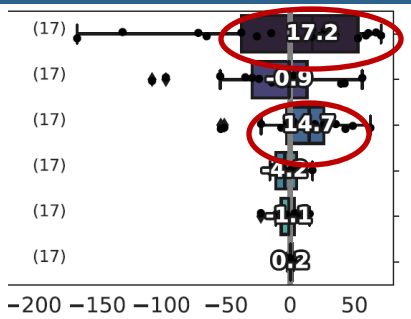
Extended MHW

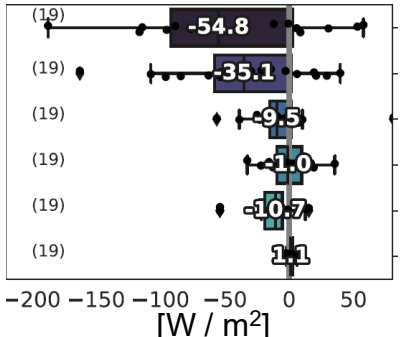


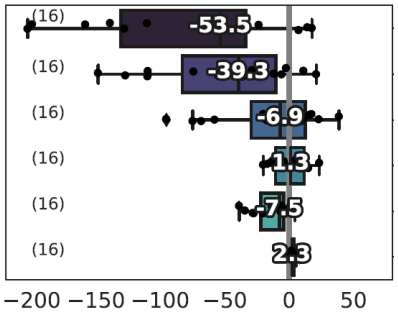
Sub-surface MHW



Air temperature
Wind speed
Northward wind stress
Northward geostrophic current
Northward local current

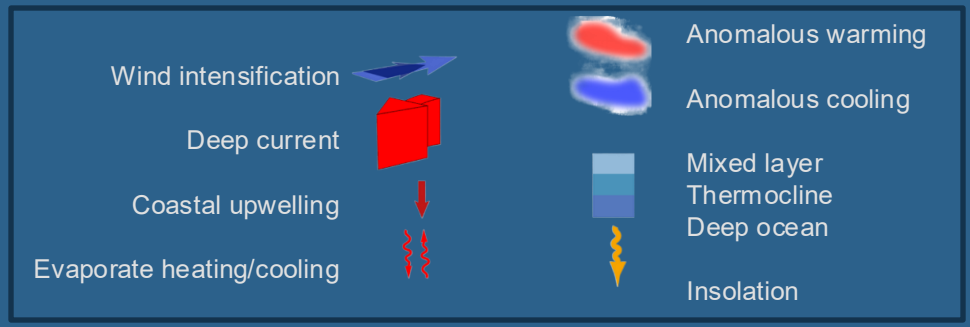




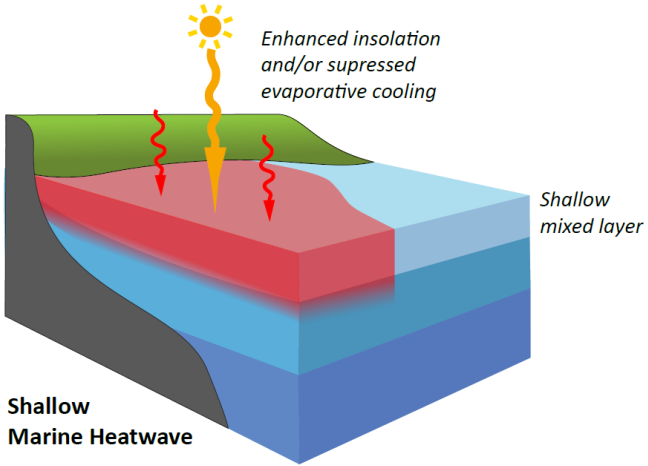


Net flux
Latent flux
Short-wave flux
Long-wave flux
Sensible flux
Northward wind

Summary of three classes

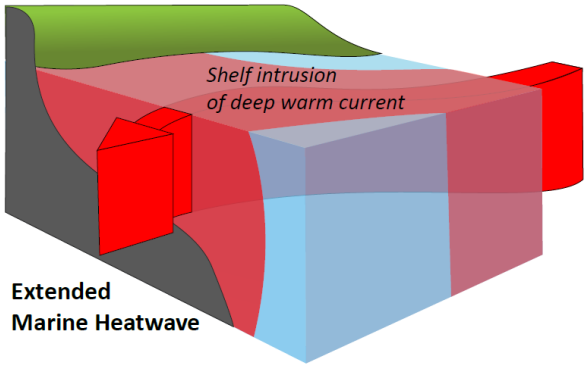


Shallow MHW



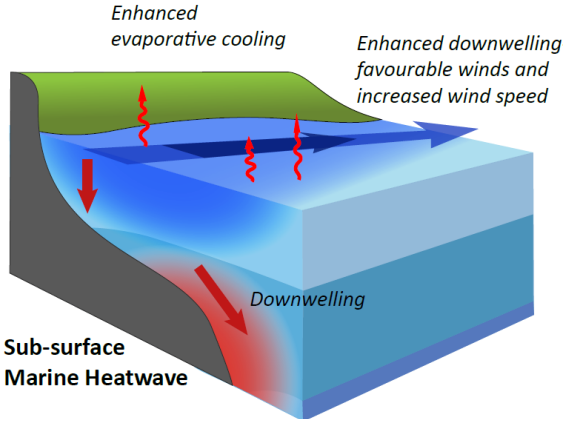
STRONGLY STRATIFIED PERIODS

Extended MHW



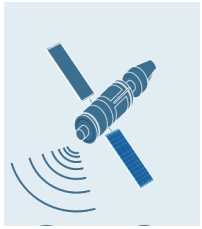
WEAKLY STRATIFIED PERIODS

Sub-surface MHW



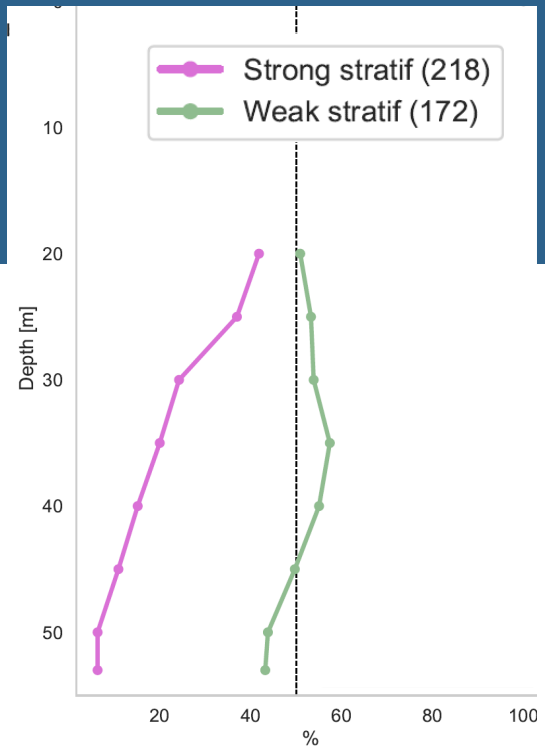
STRONGLY STRATIFIED PERIODS

So when is SST a good proxy for deep MHWs?



- Coherence of MHW days
- Inter-annual variability
- Drivers of inter-annual variability

The importance of seasonal stratification



Coherence: Percentage of surface (SST) MHW days which are also a MHW at different depth

Weak stratification (winter):

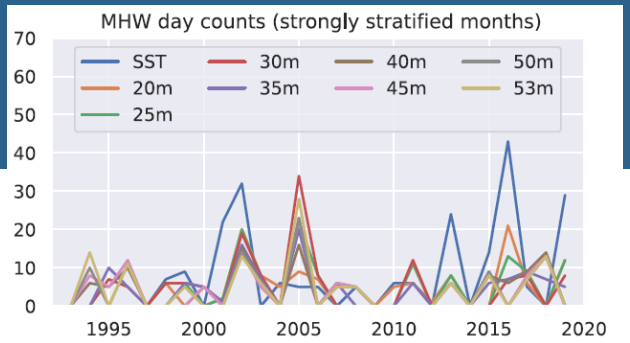
- Consistent coherence with depth.
- 43-57% of MHW days from SST are also MHWs in the sub-surface.

Strong stratification (summer):

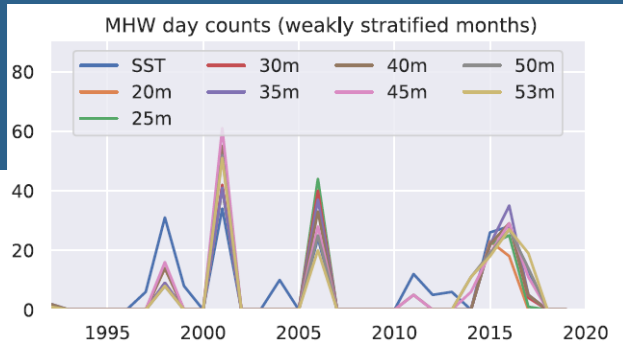
- Coherence drops with depth.
- Only 6% of MHW days at 53m co-occurring with a SST MHW.

At inter-annual time-scale…

Strong stratification:



Weak stratification:

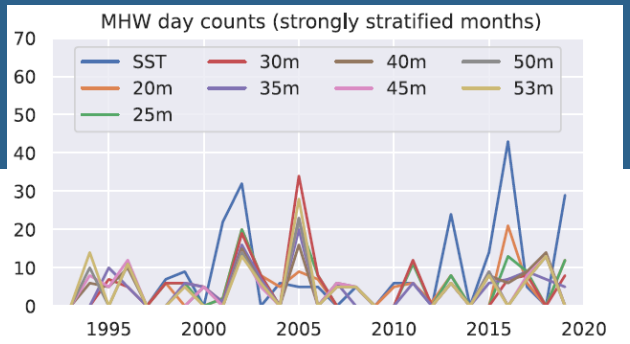


MHW day count per season:

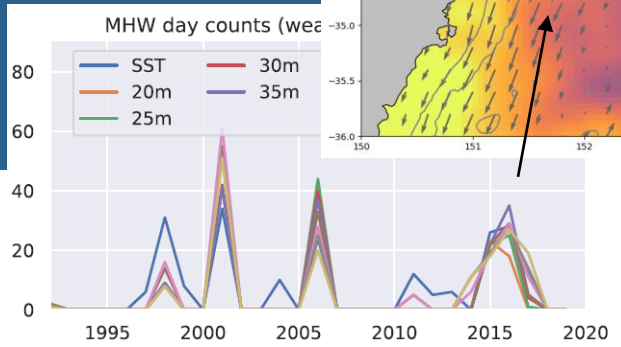
- Consistent over depth in winter (correlations > 0.8).
- Dephasing in summer (correlation <0.3 at depth>25 m).

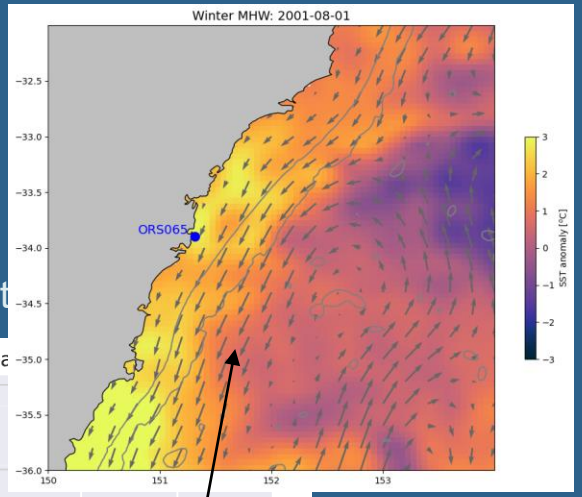
At inter-annual time-scale…

Strong stratification:

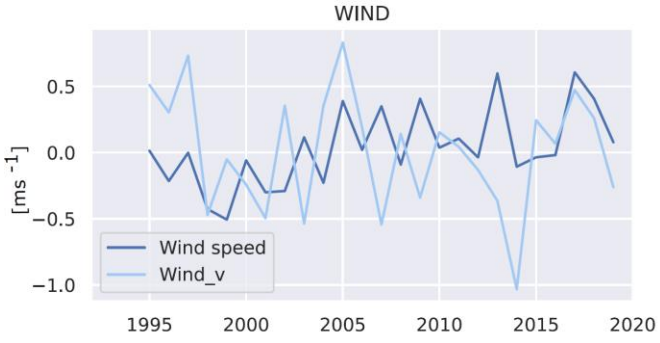


Weak strat





Correlation deep MHW days & downwelling winds ~0.5

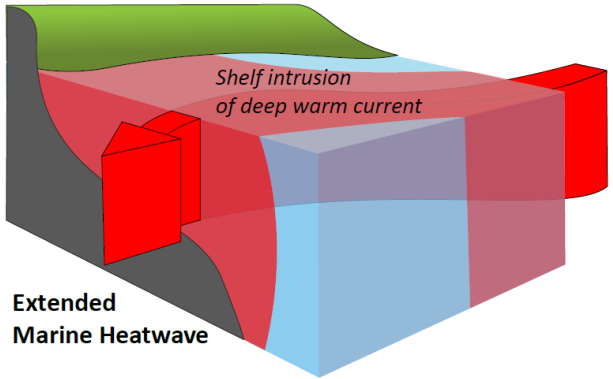


Correlation MHW days & southward geostrophic current ~0.5

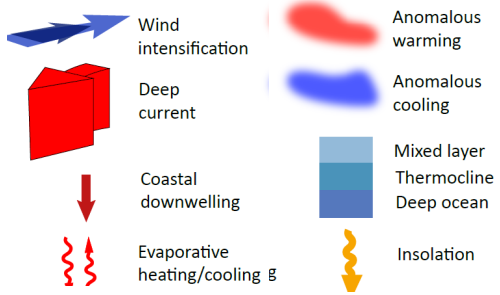
1.Conclusions

During winter weak stratification: coastal MHWs are mostly consistent over depth -> long, extended MHW events.

Good proxy for winter deep MHWs: SST and geostrophic currents.

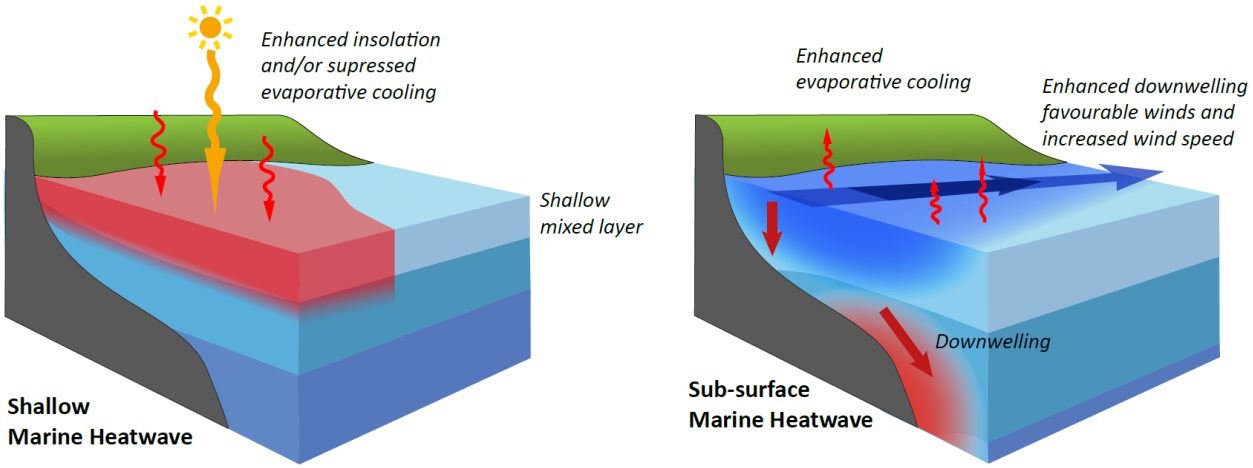


WEAKLY STRATIFIED PERIODS



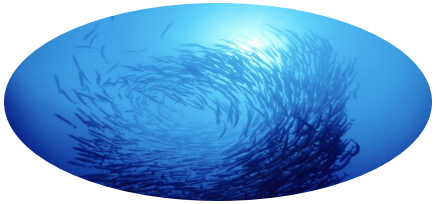
1.Conclusions

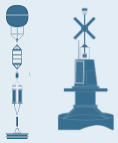
During summer strong stratification: coastal MHWs are decoupled
-> shallow MHWs
-> & sub-surface MHWs, the shortest and most intense.
Good proxy for summer deep MHWs: downwelling winds.



STRONGLY STRATIFIED PERIODS

Outline





1. Long-term shelf mooring: identify Marine heatwaves below the surface, their classes and drivers.

→ What do we miss when looking at SST?

2. **What other classes of MHWs exist when considering the open-ocean?**

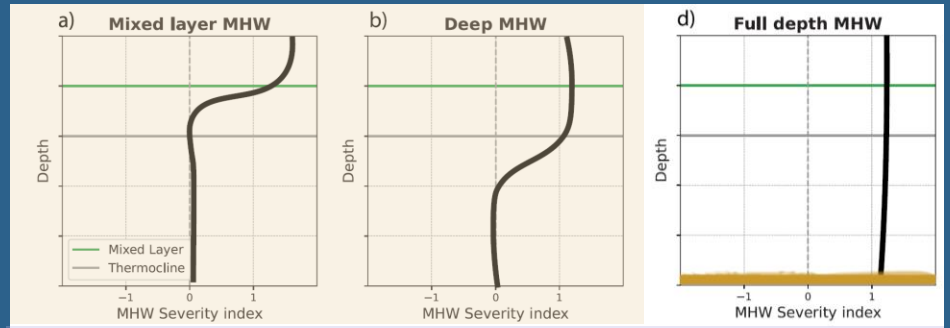
3. **What if the daily multi-decadal sub-surface data does not exist?**
   - **E.g. Building a sub-surface baseline using multi platforms.**
   - **E.g. Focusing on the vertical structure of surface MHWs (Argo, glider).**

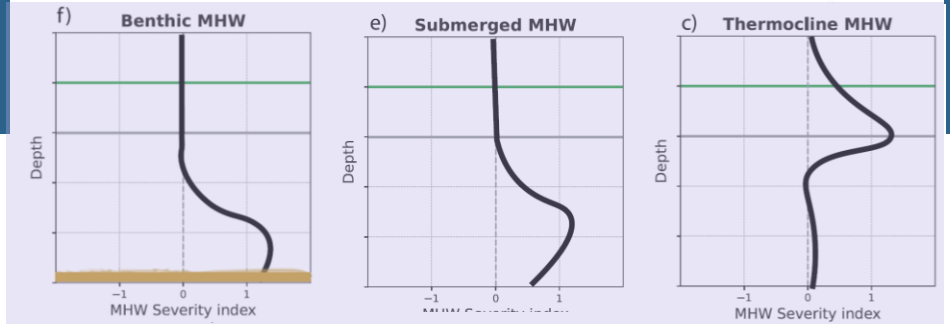
4. **Co-designing an observational system for MHWs - a GOOS initiative.**

A typology for MHWs

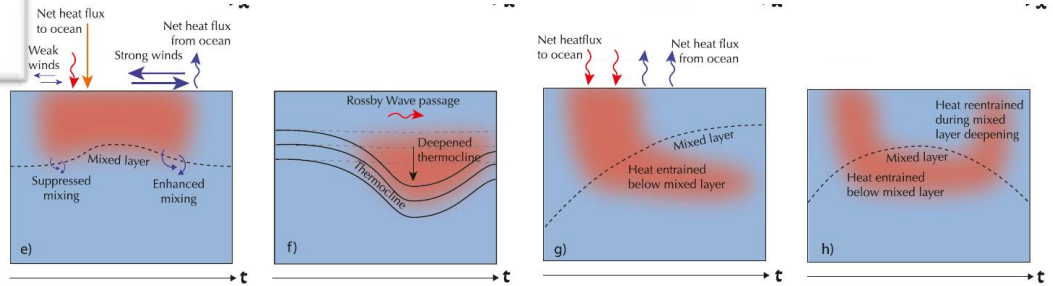
Combining typologies from previous literature, qualitative and quantitative analysis
→ typology of 6 types of vertical MHW structure.

shallow extended



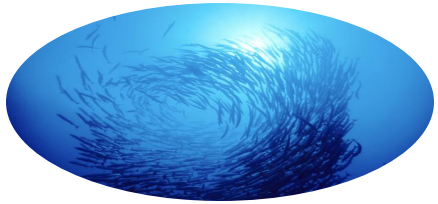


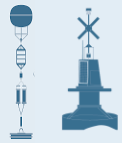
Sub-surface



Note: an event can change from type to type over its lifetime, and can also experience two types simultaneously

Outline





1. Long-term shelf mooring: identify Marine heatwaves below the surface, their classes and drivers.

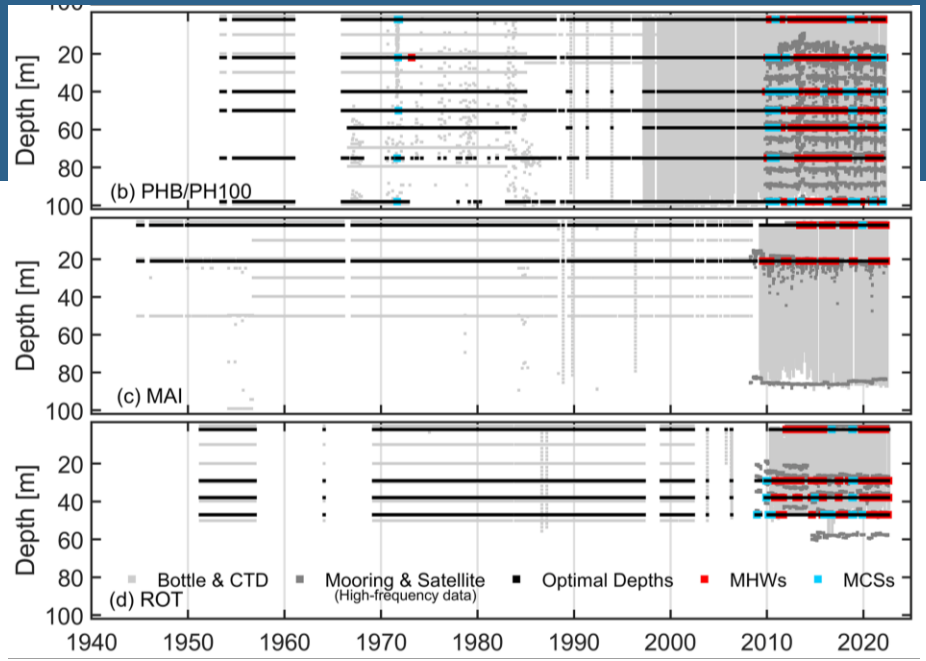
→ What do we miss when looking at SST?

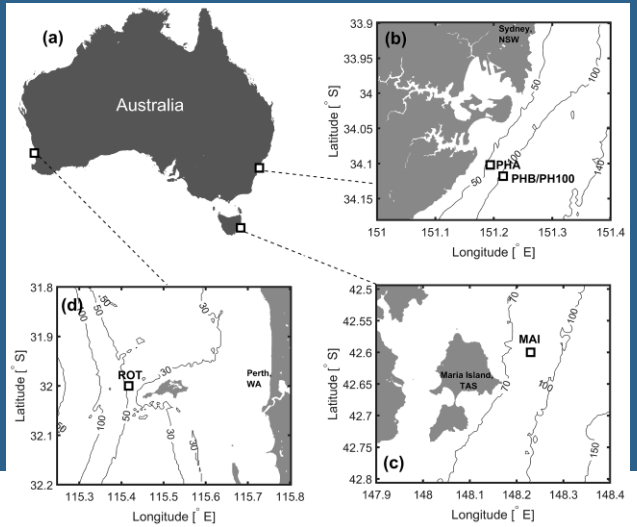
2. What other classes of MHWs exist when considering the open-ocean?

3. What if the daily multi-decadal sub-surface data does not exist?
   - E.g. Building a sub-surface baseline using multi platforms.
   - E.g. Focusing on the vertical structure of surface MHWs (Argo, glider).

4. Co-designing an observational system for MHWs - a GOOS initiative.

Multi-platform time-series

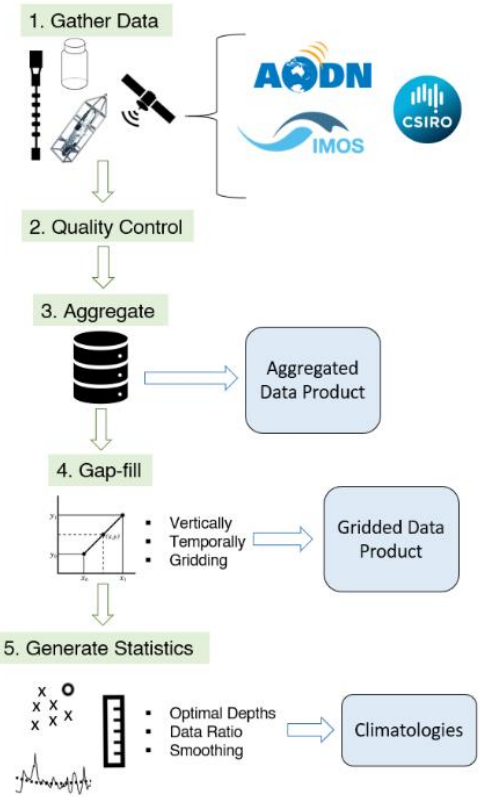


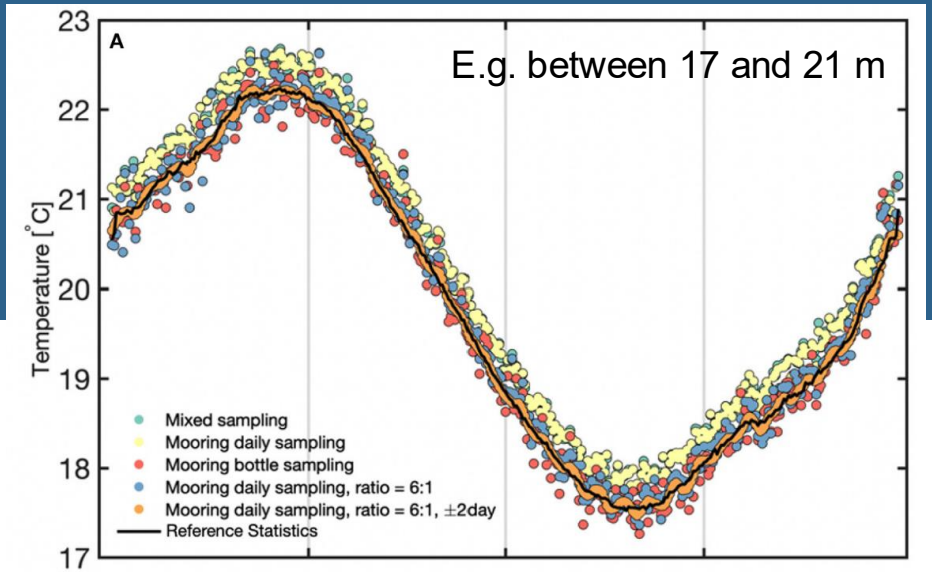


Bottle, CTD, and mooring data between 1953 and 2019

→ *Varying frequency, depth, coverage / gaps, accuracy.*

Building a climatology

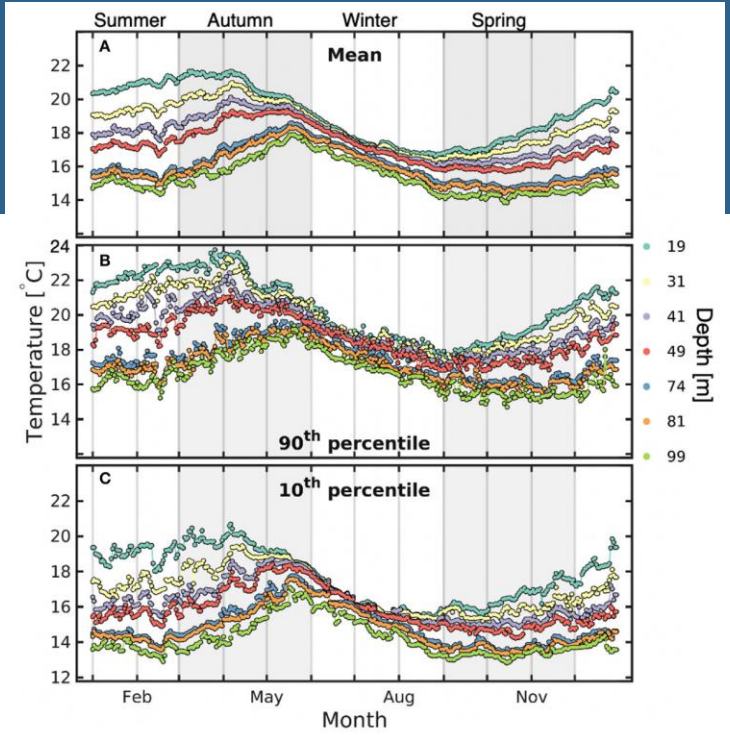


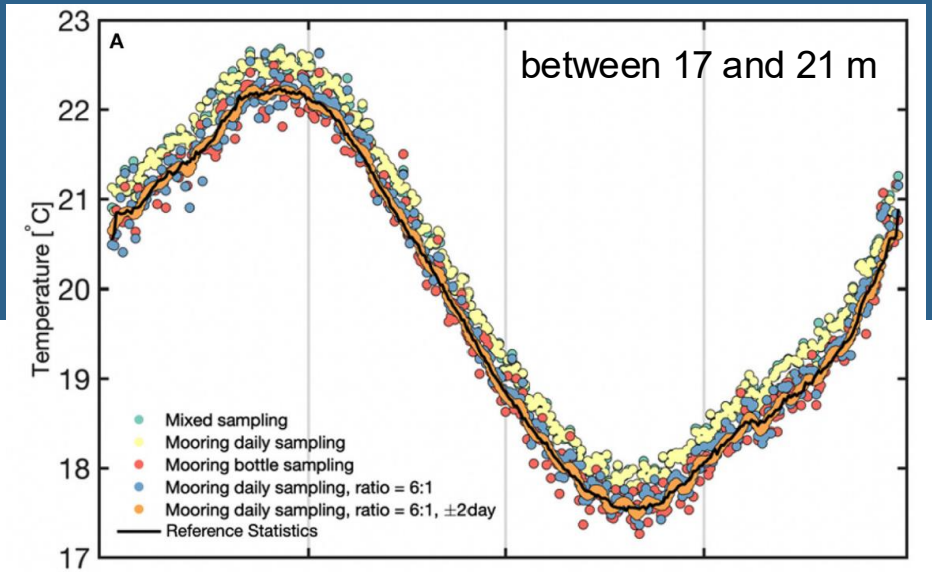


Challenge: account for differing data source sampling frequencies. Use synthetic temperature data with similar qualities to real observations.

→ Data source year ratio to under-sample mooring days (here, a bottle to mooring ratio of 6:1).
→ Time-centered moving window +- 2 days.

Building a climatology

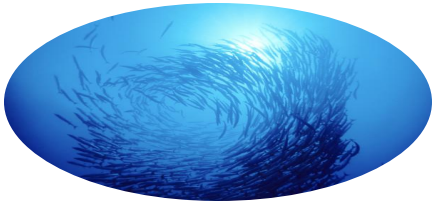




Challenge: account for differing data source sampling frequencies. Use synthetic temperature data with similar qualities to real observations.

→ Data source year ratio to under-sample mooring days (here, a bottle to mooring ratio of 6:1).
→ Time-centered moving window +- 2 days.

Outline



1. Long-term shelf mooring: identify Marine heatwaves below the surface, their classes and drivers.

→ What do we miss when looking at SST?

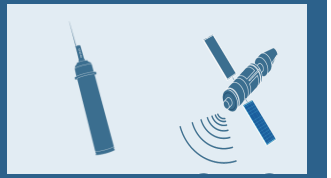
2. What other classes of MHWs exist when considering the open-ocean?

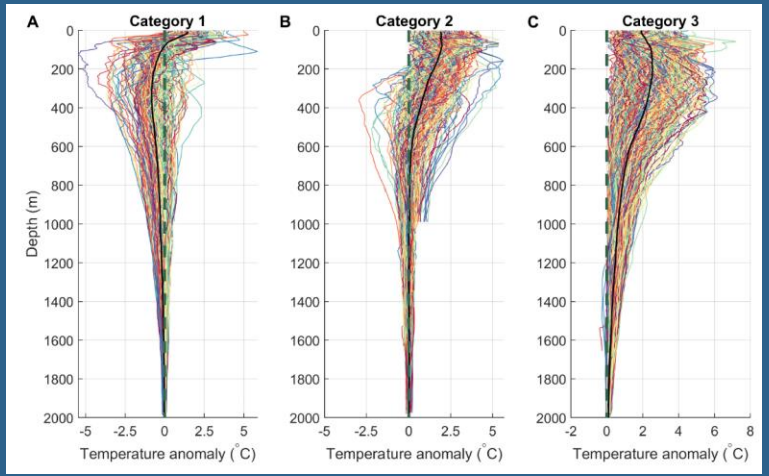
3. What if the daily multi-decadal sub-surface data does not exist?

- E.g. Building a sub-surface baseline using multi platforms.
- E.g. Focusing on the vertical structure of surface MHWs (Argo, glider).

4. Co-designing an observational system for MHWs - a GOOS initiative.

Example: vertical profiles during surface MHWs: Argo floats






Frontiers in Marine Science

Observational Insight Into the Subsurface Anomalies of Marine Heatwaves

Youstina Elzahaby and Amandine Schaeffer

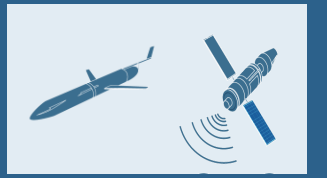
- Shallow MHWs [0–150 m] (relationship between surface temperature anomalies and depth extent)

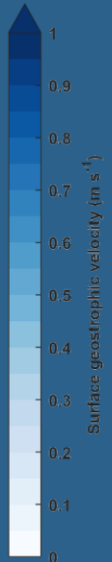
- Intermediate MHWs [150–800 m]

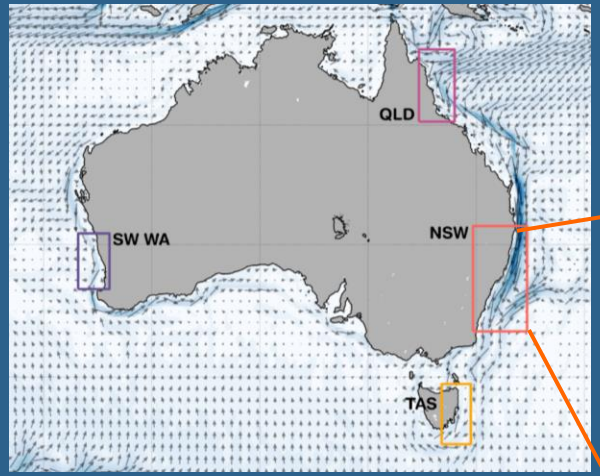
- Deep MHWs [>800 m, 45%]

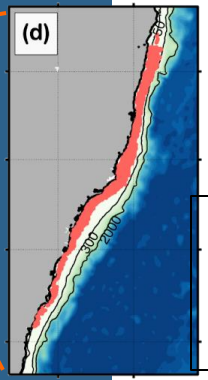
→ greater and deeper maximum temperature anomalies, dominating MHWs in winter, in warm core eddies.

Example: vertical profiles during surface MHWs: gliders (BGC)

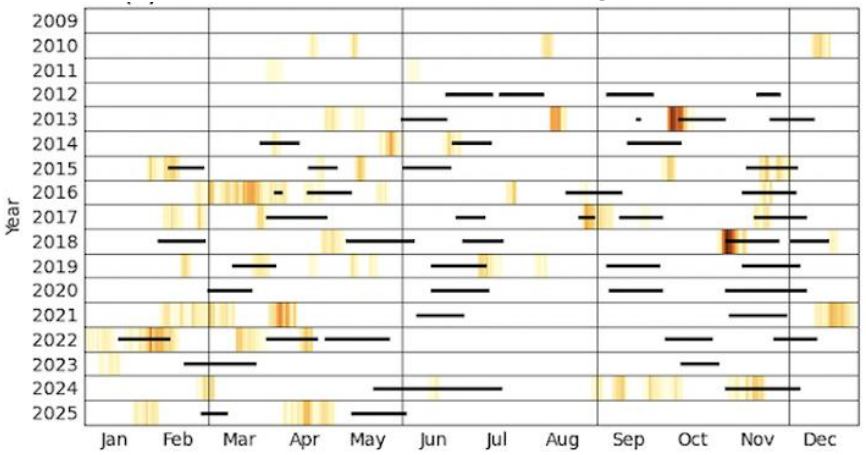


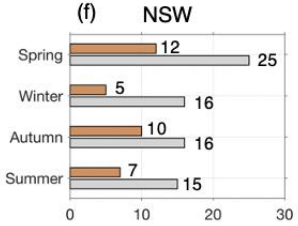






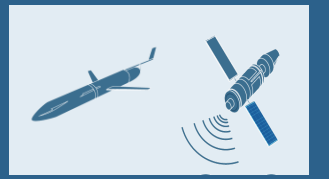
Surface MHWs from SST and glider missions

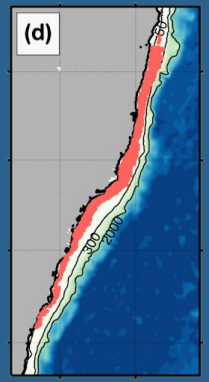




Gliding through marine heatwaves: Subsurface biogeochemical characteristics on the Australian continental shelf (in prep)
D. Mawren, J. Araujo, R. Le Gendre, F.E.K. Ghomsi, J. S. Saranya, J. A. Benthuysen, A. Schaeffer

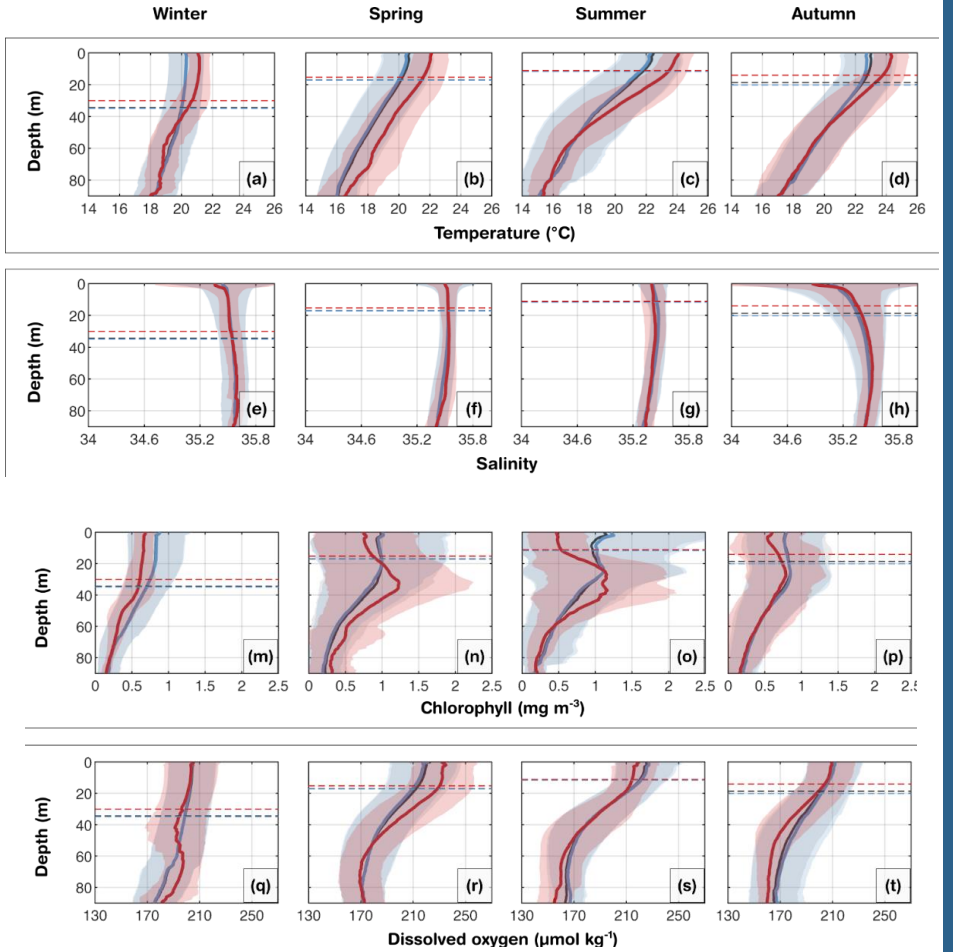
Example: vertical profiles during surface MHWs: gliders (BGC)



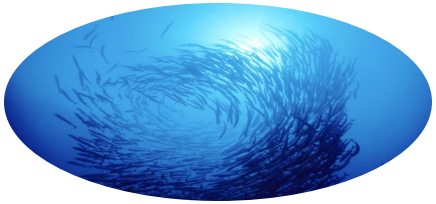


Seasonal MHWs non-MHWs

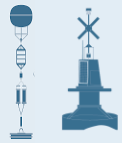
Mixed layer depth NSW region



Outline



Ocean Observing Co-Design
by The Global Ocean Observing System



1. Long-term shelf mooring: identify Marine heatwaves below the surface, their classes and drivers.

→ What do we miss when looking at SST?

2. What other classes of MHWs exist when considering the open-ocean?

3. What if the daily multi-decadal sub-surface data does not exist?
   - E.g. Building a sub-surface baseline using multi platforms.
   - E.g. Focusing on the vertical structure of surface MHWs (Argo, glider).

4. Co-designing an observational system for MHWs - a GOOS initiative.

Marine Heat Waves Exemplar

Co-Designing to Understand, Forecast, and Respond to Marine Heatwaves. Turning Science into Action for Resilient Communities.

Aims to:

Builds a co-designed framework for MHW monitoring, modelling, and user-driven services.

Strengthen community and end-user engagement integrating stakeholder in the process, ensuring systems are designed with and for the communities they serve.

Share knowledge and practices across existing examples from different regions.

CONCLUSIONS

Extremes are challenging, even more in the sub-surface!

- To observe → need long time-series and sustained observations.
- To model → very sensitive to model biases. Models are best used to study the dynamics, drivers of large events, sensitivity, and predictions.
- To reproduce (reanalysis products): as good as the constraining observations are → need observations in the sub-surface.
- To forecast!

Let's not forget why MHW matters for the health of our environment, people and economies.

Image credit: www.mercator-ocean.fr

Questions?

Acknowledgements:
Sydney Water corporation and Clive Holden (Oceanographic Field Services Pty Ltd) for ORS065, NSW-IMOS mooring team, everyone involved in field work. "MarineHeatWaves" module for python was written by Eric C. J. Oliver.; CLIVAR MHW research focus group.

More details:

Schaeffer, Sen Gupta, & Roughan: Seasonal stratification and complex local dynamics control the sub-surface structure of marine heatwaves in Eastern Australian coastal waters. Commun Earth Environ 4, 304 (2023).

Malan, et al.: Lifting the lid on Marine Heatwaves, Progress in Oceanography, 239: 103539 (2025)

Capotondi, et al. A global overview of marine heatwaves in a changing climate. Commun Earth Environ 5, 701 (2024).

Hemming, Roughan, & Schaeffer: Daily Subsurface Ocean Temperature Climatology Using Multiple Data Sources: New Methodology, Frontiers in Marine Science, 7, 485, (2020);
Hemming, Roughan, & Schaeffer Exploring multi-decadal time series of temperature extremes in Australian coastal waters, Earth Syst. Sci. Data, 16, 887–901 . (2024)

Elzahaby, & Schaeffer: Observational Insight Into the Subsurface Anomalies of Marine Heatwaves, Frontiers in Marine Science, 6, 745 (2019)