climate extremes
ARC centre of excellence

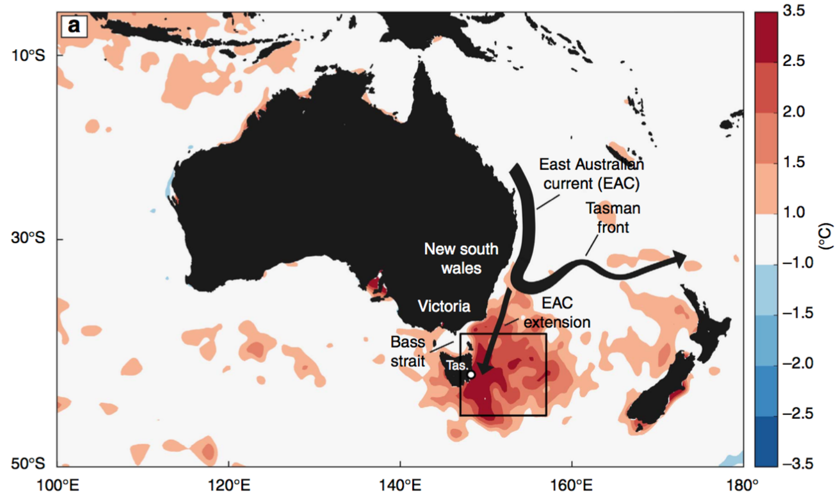
UNIVERSITY of TASMANIA

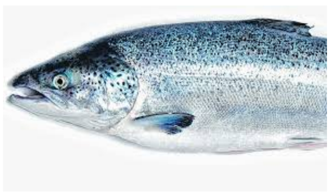
IMAS
INSTITUTE FOR MARINE & ANTARCTIC STUDIES

Marine Heatwaves

Lecturer: Professor Neil Holbrook

Institute for Marine and Antarctic Studies, University of Tasmania



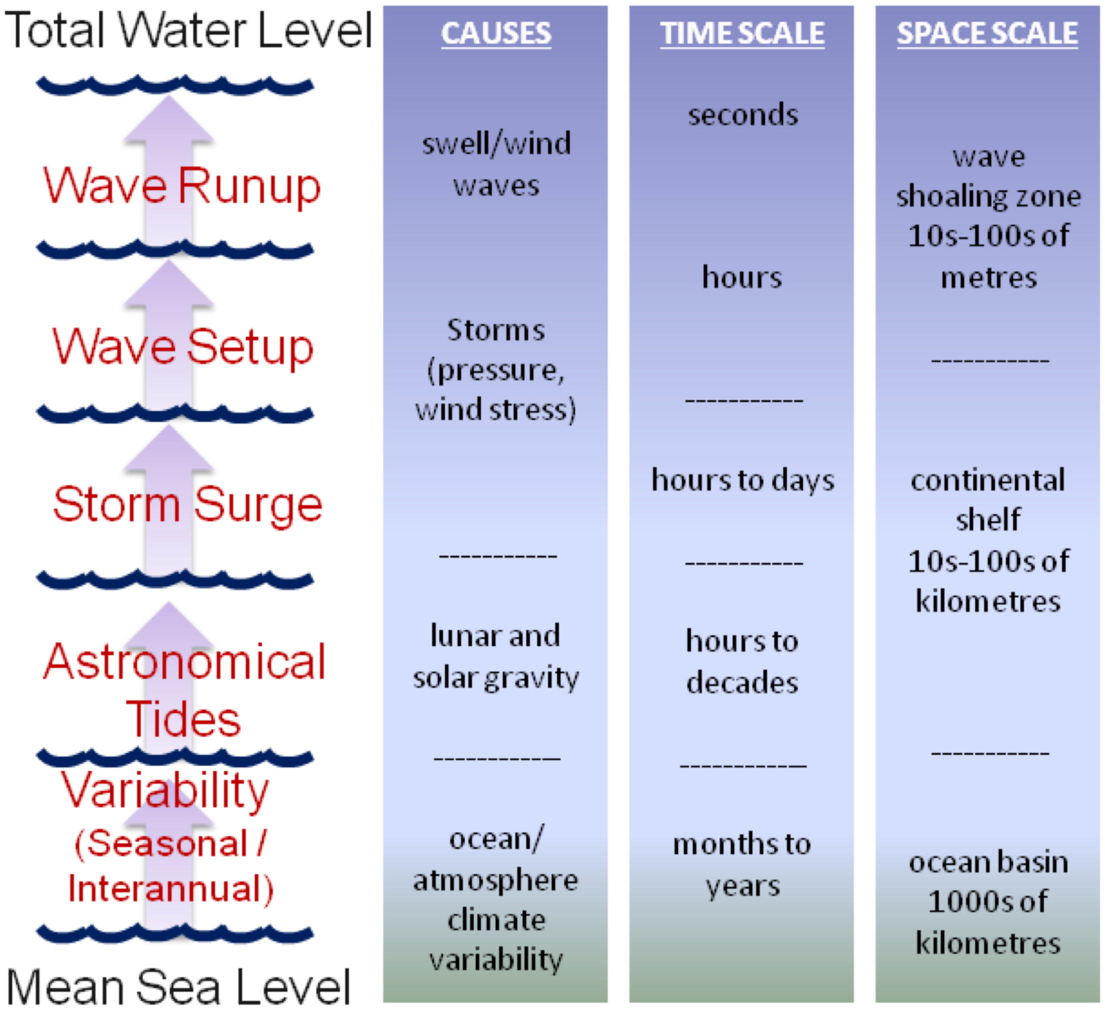


Outline

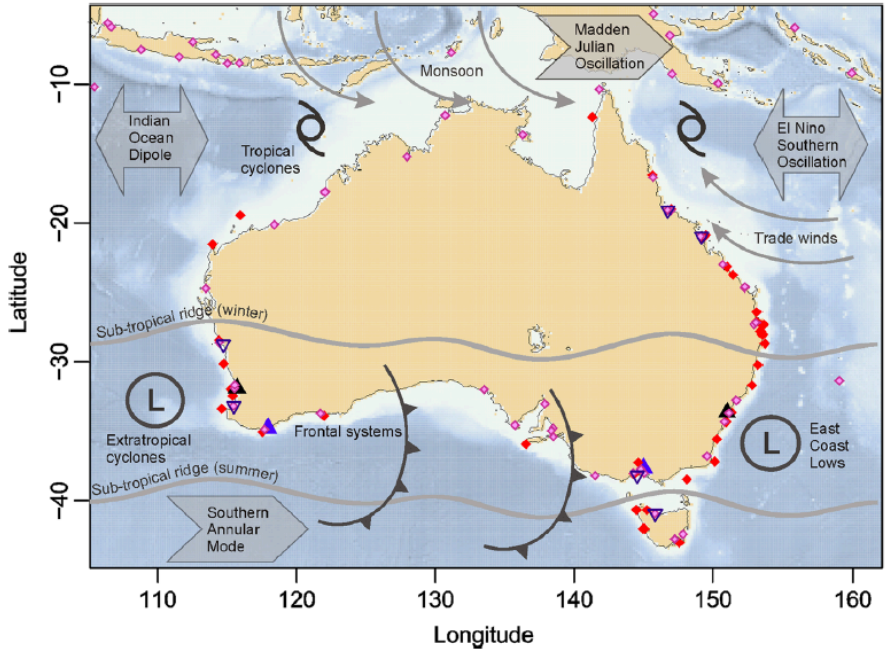
1. Background
    1. Extremes in the ocean (including marine heatwaves)
    2. Recent history/timeline
    3. Impacts from recent events
2. Marine Heatwave Definition
3. Marine Heatwave Characteristics and Historical Trends
4. Marine Heatwave Drivers
5. Categorising and Naming Marine Heatwaves
6. Predictability, Prediction and Projections
7. Summary – Take Home Messages
8. Marine Heatwave Event Attribution under Climate Change (extra)

1. Background

1.1 Extremes in the ocean
Sea Level

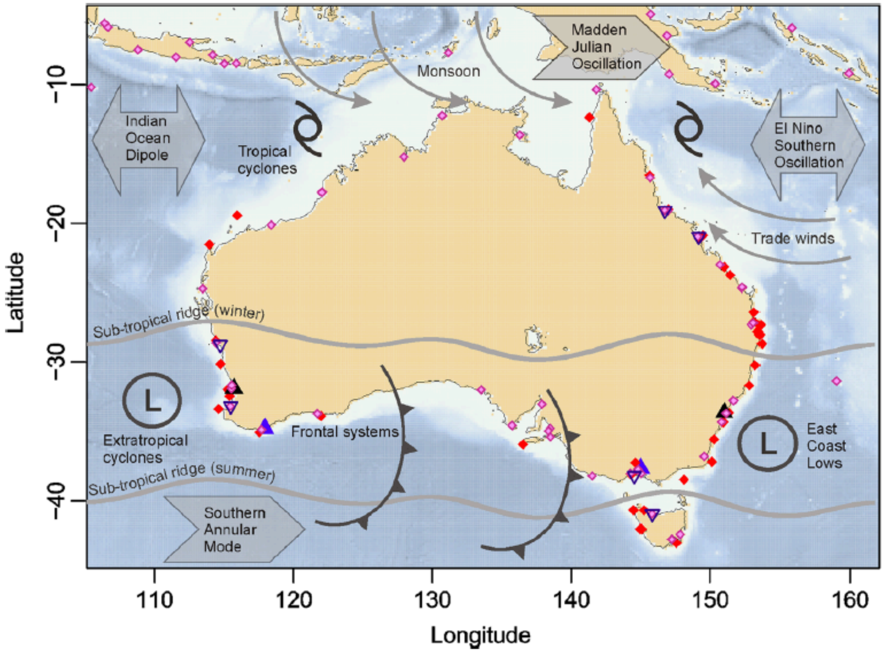


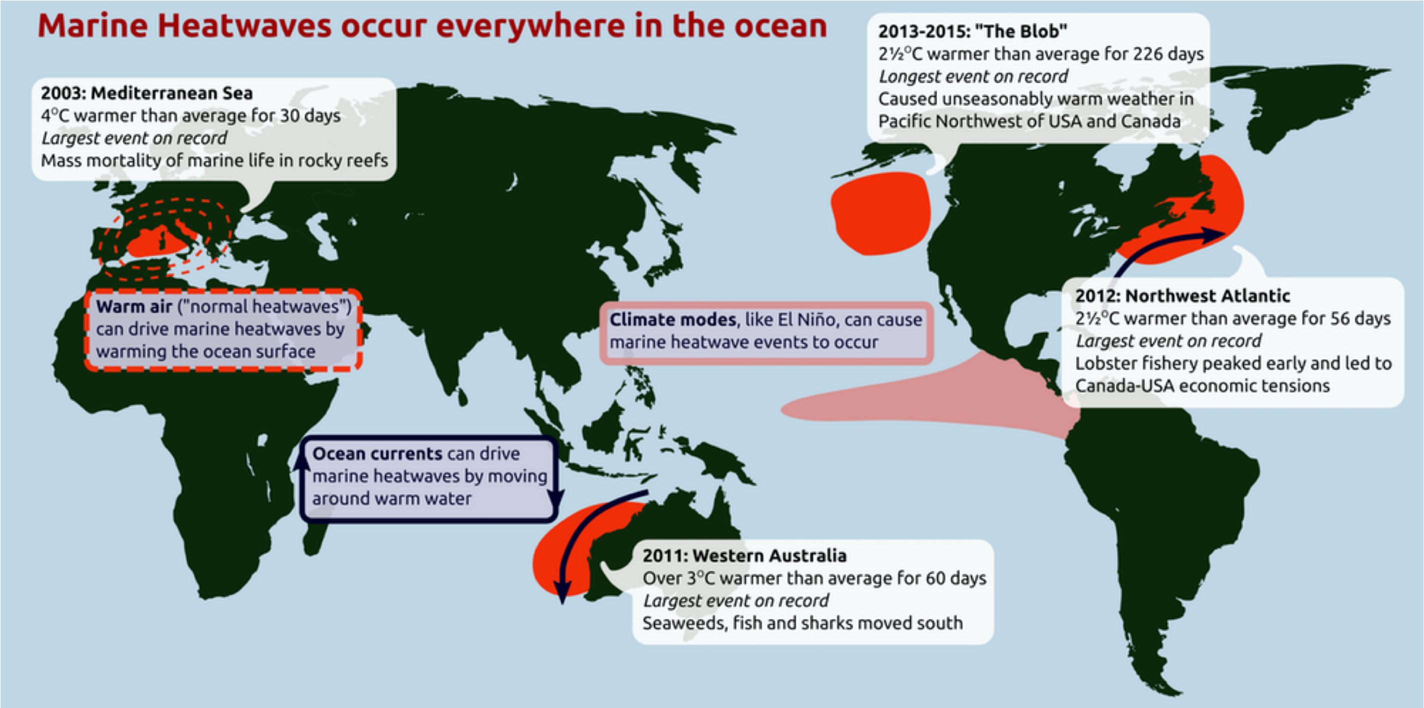
Source: McInnes et al. (2016)



via https://www.news.com.au/technology/environment/

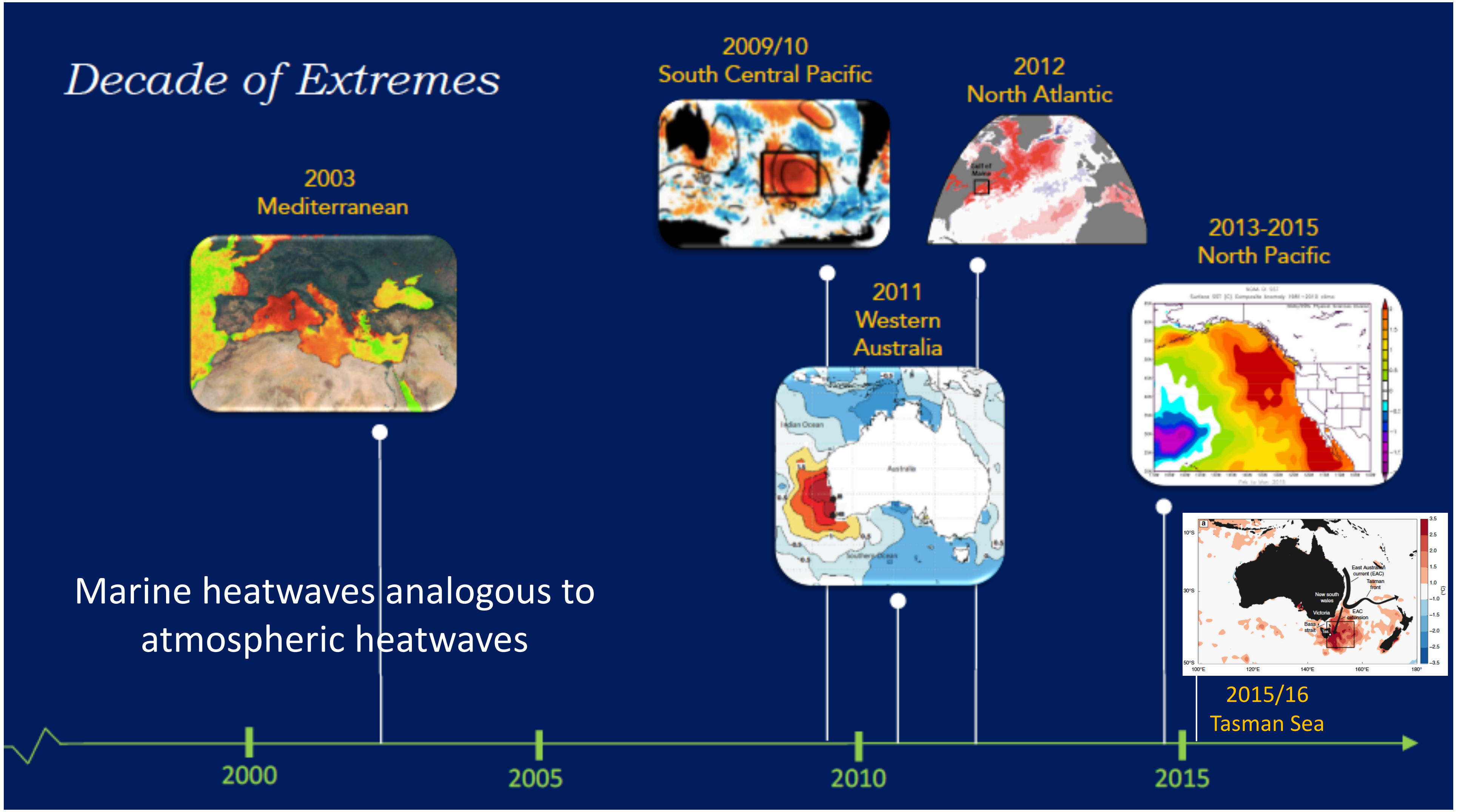
1.1 Extremes in the ocean
Marine Heatwaves





Oliver, Hobday, Smale, Holbrook, Wernberg, 2018:
The Conversation +
www.marineheatwaves.org

1.2 Recent history/timeline



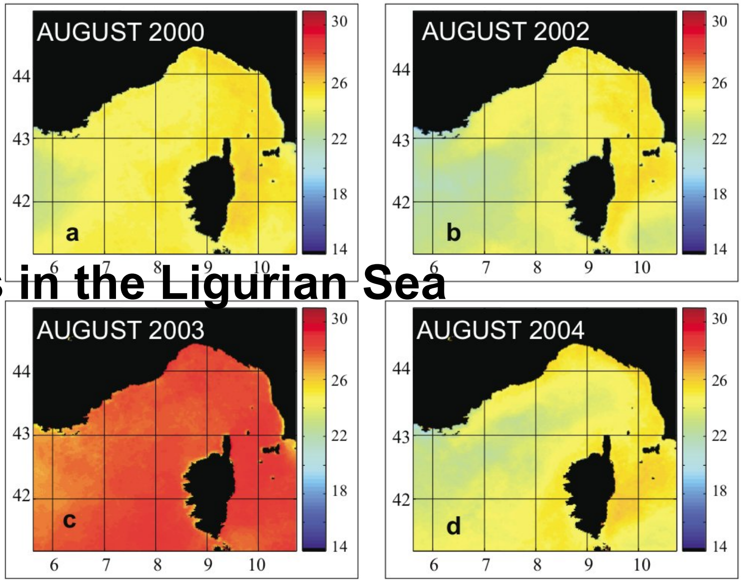
Modified after presentation by Hillary Scannell (2017)

1.3 Impacts from recent events

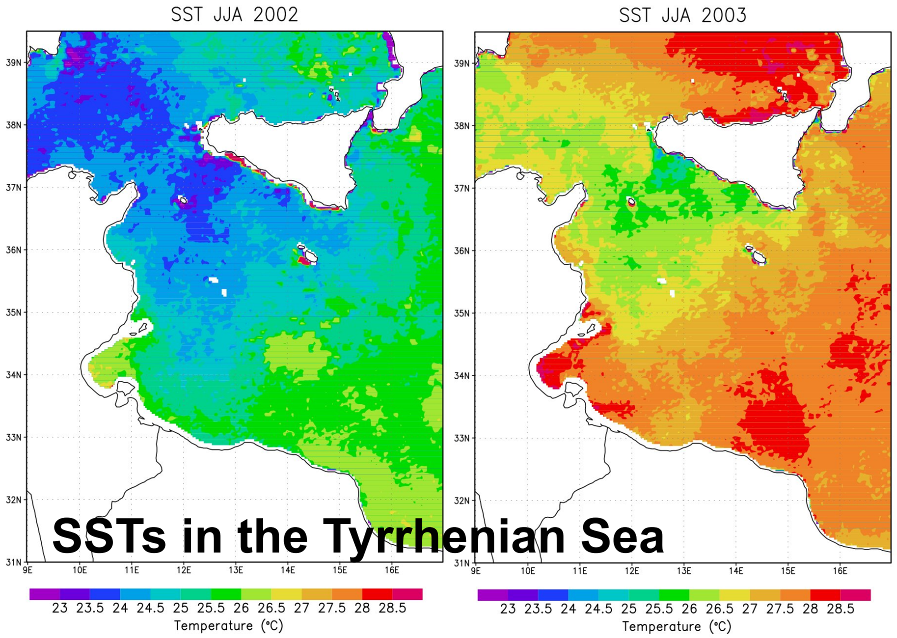
2003 Mediterranean Sea marine heatwave

Sparnocchia et al. (2006), *Annalles Geophysicae*, **24**, 443-452
Olita et al. (2007), *Ocean Science*, **3**, 273-289
Garrabou et al. (2009), *Global Change Biology*, **15**, 1090-1103

- In **summer 2003** a **record heatwave** experienced in **Europe!**
  => Mediterranean Sea
- **Ligurian Sea** SST 28^{O}-28.5^{O}C (August)
  2-3^{O}C higher than previous summers
  (Sparnocchia et al. 2006)
- **Tyrrhenian Sea** >29.5^{O}C, **June SST anomaly ~2.5^{O}C** (Olita et al. 2007)
- Warming in upper layers (<20 m depth), anomalously cold below this depth
- <u>Cause</u>: **anomalous air-sea heat flux**: *high air temperatures* (the atmospheric heatwave) and *low wind speeds*
- This **marine heatwave (MHW)** linked to mass mortality of **rocky reef communities** (Garrabou et al. 2009)



SSTs in the Ligurian Sea



SSTs in the Tyrrhenian Sea

2011 Western Australia marine heatwave

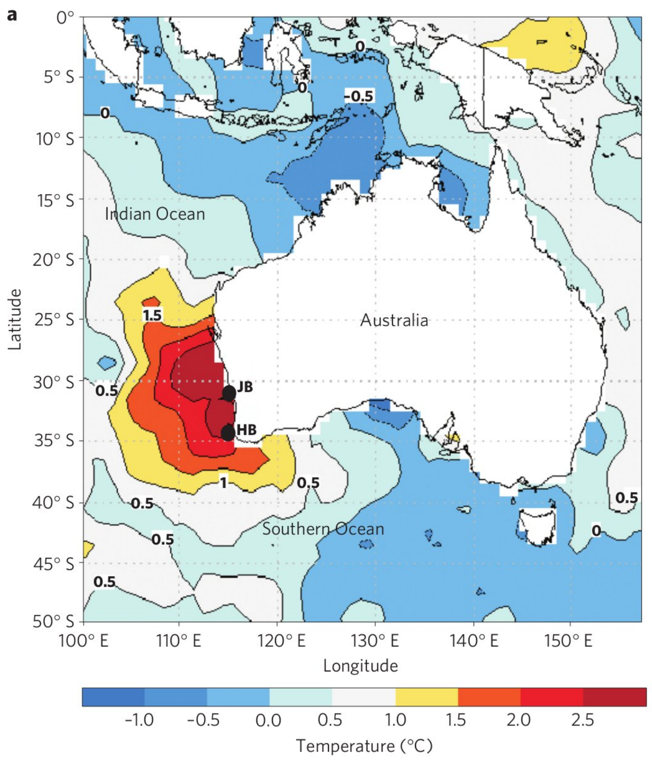
Pearce and Feng (2013), *J Marine Systs*, **111-112**, 139-156
Feng et al. (2013), *Scientific Reports*, **3**, 1277
Wernberg et al. (2013), *Nature Climate Change*, **3**, 78-82

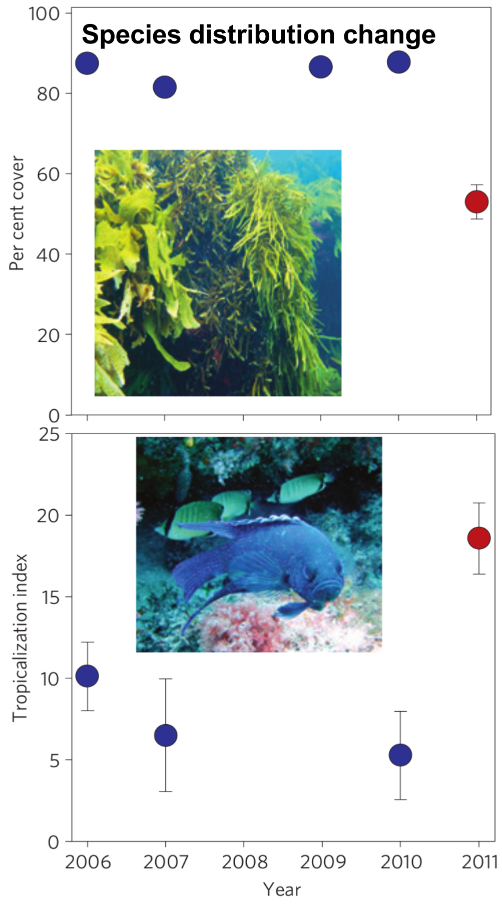
- In **summer 2010/2011** an unprecedented **marine heatwave** documented off **Western Australia (WA)**

- SSTA **~3^{o}C above seasonal values** along WA coast (Ningaloo at 22^{o}S to Cape Leeuwin at 34^{o}S) and >200 km offshore (Pearce & Feng 2013)

- Feng et al. (2013) identified event as a **"Ningaloo Niño"**
  => warming due to warm water surge south along the coast due to Leeuwin current

- Remotely forced via near-record 2010/11 **La Niña** and **regional wind changes**

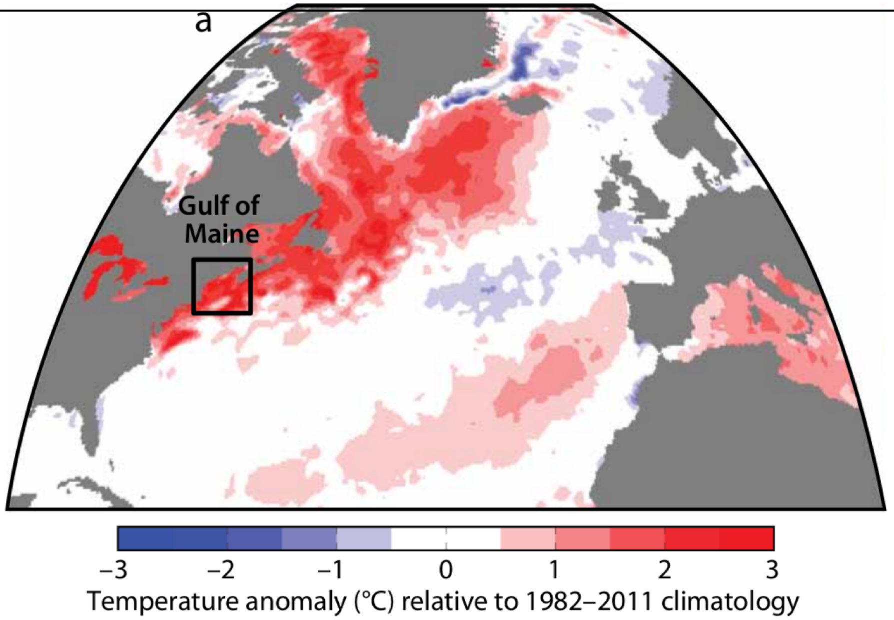


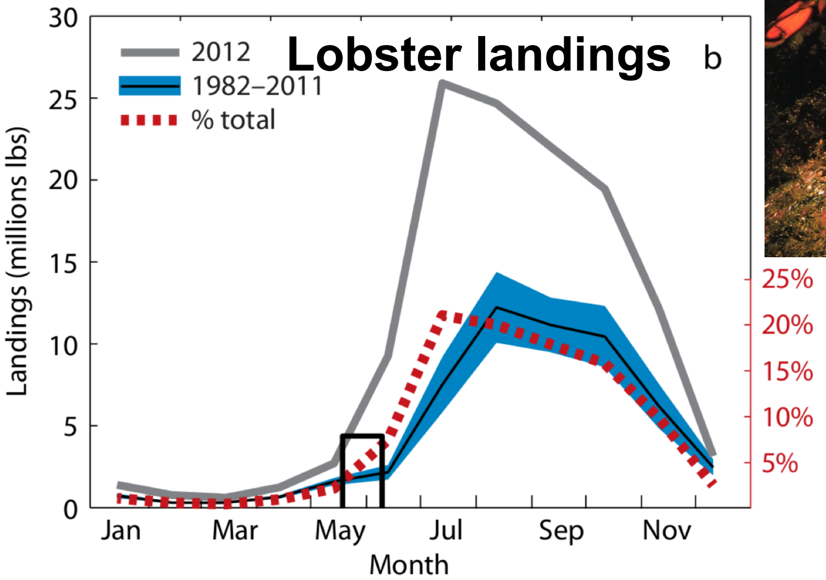


Wernberg et al. (2013) noted significant observable impacts on biodiversity including temperate seaweeds, sessile invertebrates, and demersal fish
=> "**tropicalization**" of fish communities

2012 Northwest Atlantic marine heatwave

- In **Boreal summer 2012**, the **northwest Atlantic** also experienced a **heatwave**
- SST anomalies peaked at 3^{O}C above seasonal value along a stretch of eastern Canada and USA (Mills et al. 2013)
- Linked to **atmospheric warming** and anomalous position of the **Gulf Stream**
- Dramatic impact on **lobster fishery**:
  - Lobster fishery season peaked early
  - Increased catch sizes lowered price
  - Processing plants were flooded
  - Increased Canada-US economic tensions

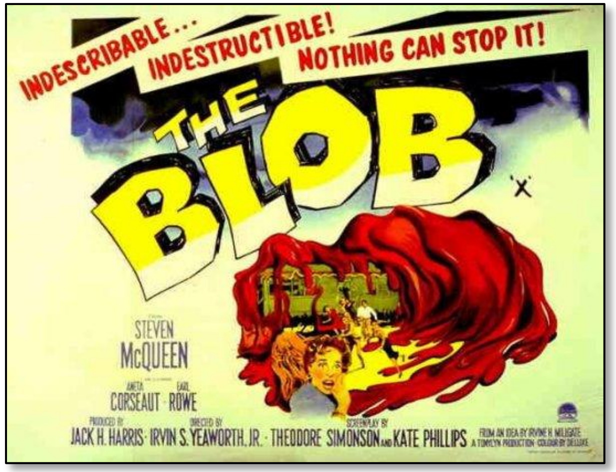




Mills et al. (2013), *Oceanography*, **26**(2), 60-64
Chen et al. (2014), *J Geophys Res - Oceans*, **119**, 1-10
Chen et al. (2015), *J Geophys Res - Oceans*, **120**, 4324-4339

2014/15 Northeast Pacific MHW ('The Blob')

Di Lorenzo E and N Mantua, 2016: Multi-year persistence of the 2014/15 North Pacific marine heatwave. *Nature Climate Change*, DOI:10.1038/NCLIMATE3082.



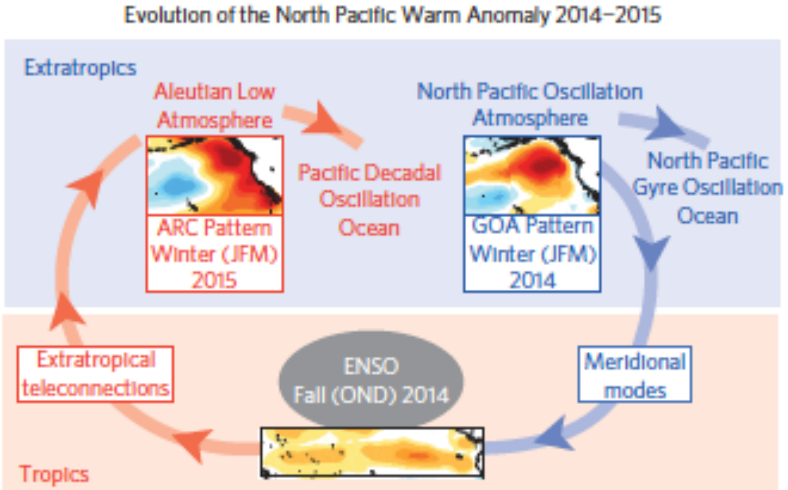


Figure 4 | Climate hypothesis to explain the generation, evolution and persistence of the North Pacific warm anomaly between the winters of 2013/14 and 2014/15.

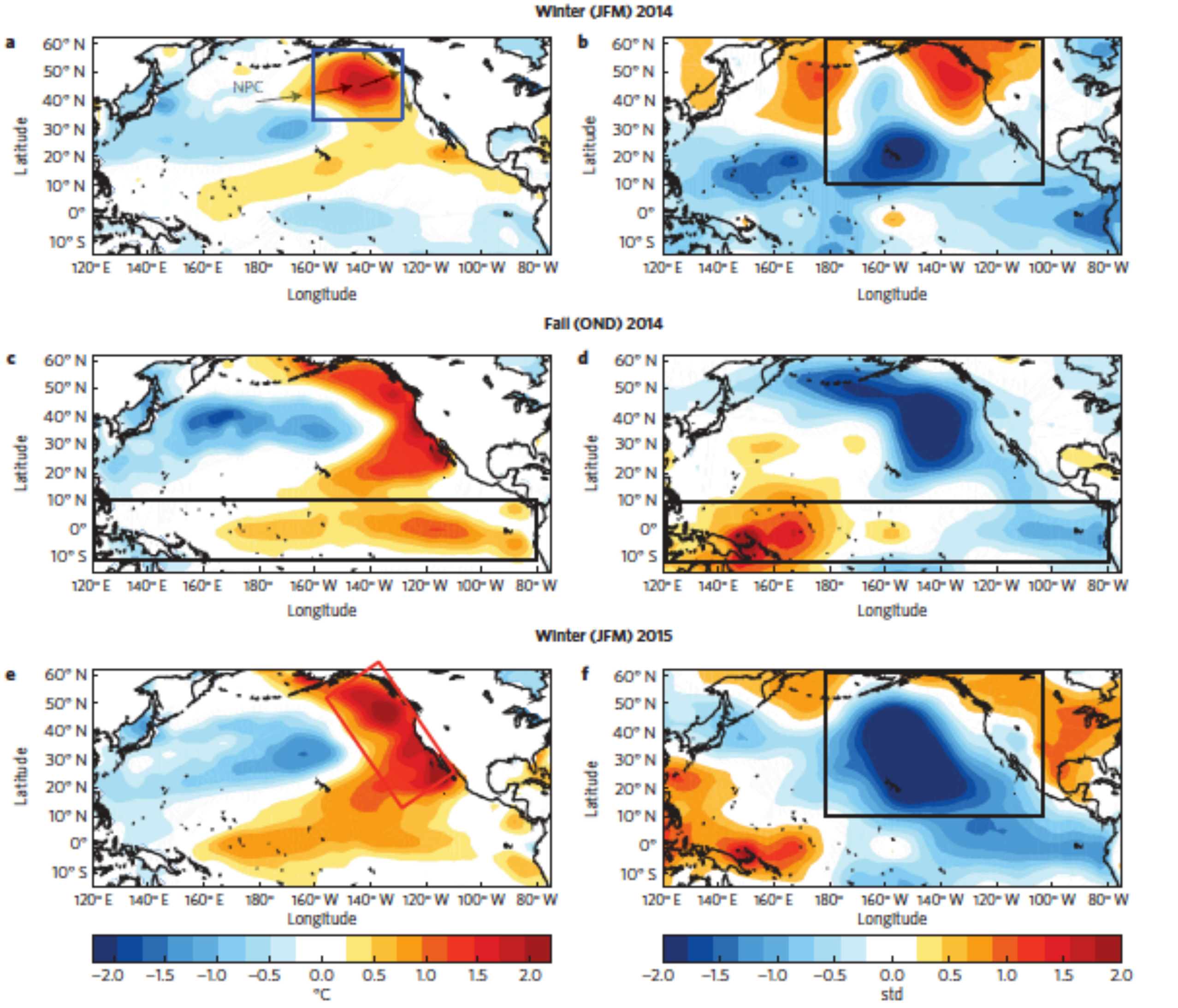
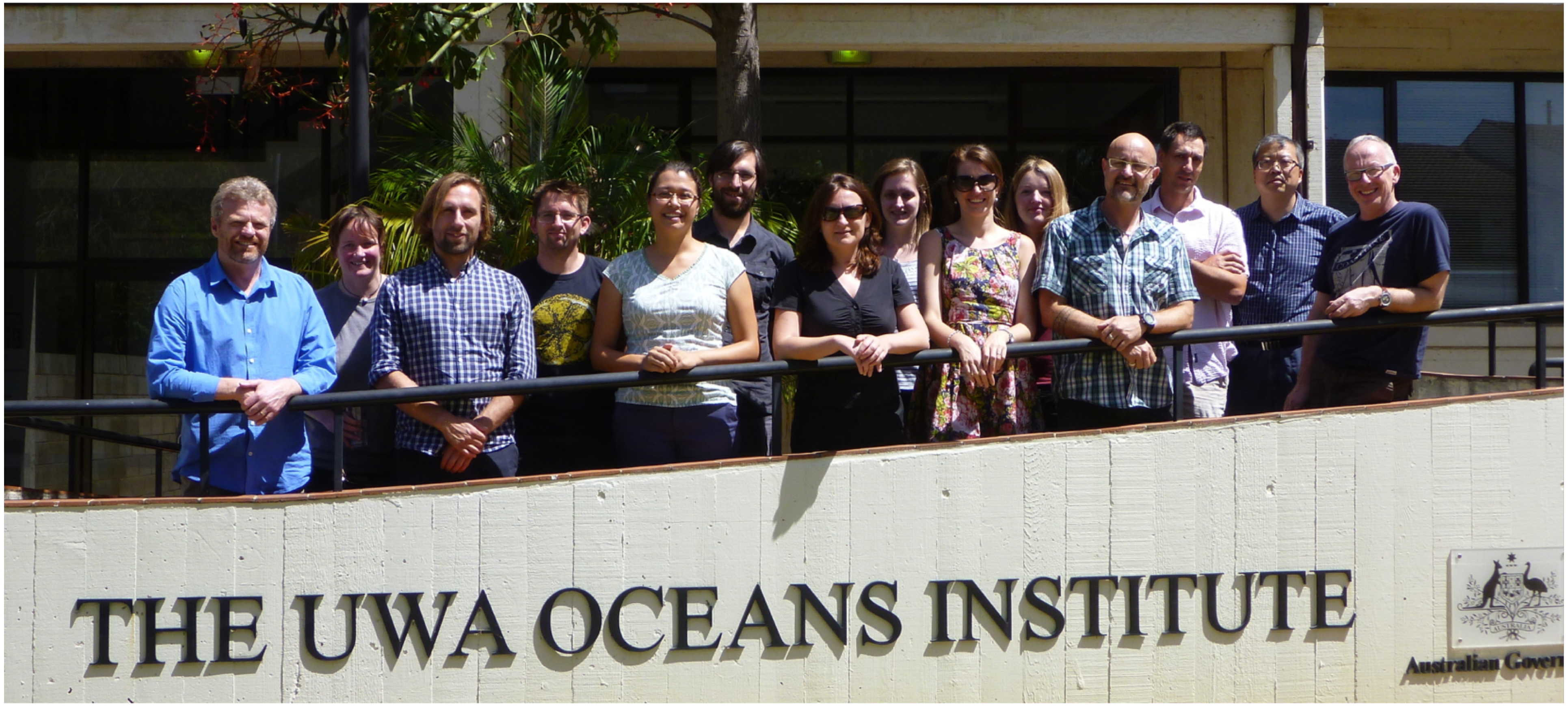


Figure 1 | Evolution of seasonal NOAA SSTa and NCEP SLPa during 2014 and 2015. a,b, January–February–March (JFM) 2014 SSTa and SLPa, respectively. **c,d**, October–November–December (OND) 2014 SSTa and SLPa, respectively. **e,f**, JFM 2015 SSTa and SLPa, respectively. The blue box in **a** denotes region used to compute the GOA SSTa index. The red box in **e** denotes region used to compute the ARC SSTa index. The mean position and direction of the North Pacific Current (NPC) and gyre circulation in the North Pacific Ocean is indicated with the grey arrows in panel **a**. Std: units of standard deviation.



International cross-disciplinary workshop held January 2015 in Perth, Australia **“Marine Heatwaves – Physical drivers and properties Workshop”** focused on three key research themes:

- **Defining marine heatwaves**
- **Drivers of marine heatwaves: a global assessment**
- **Long-term trends in marine heatwaves globally**

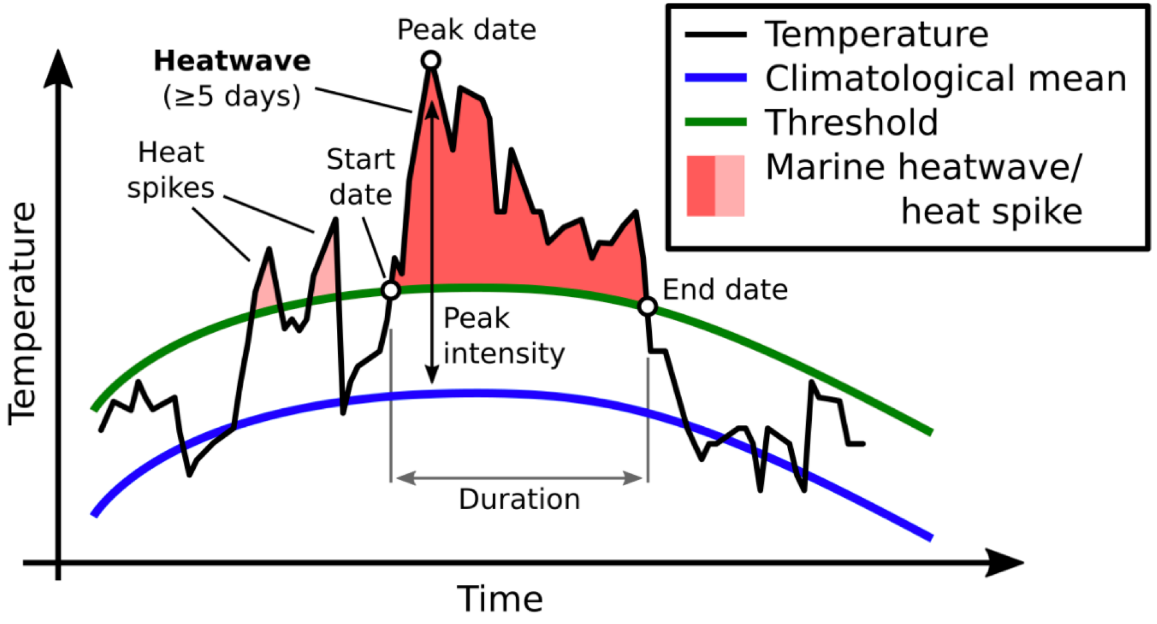
2. Marine Heatwave Definition

2. Marine Heatwave Definition

- The definition of a marine heatwave (MHW): Hobday et al. (2016)

A prolonged discrete anomalously warm water event in a particular location

- prolonged → persistence for at least five days
- discrete → well-defined start and end dates
- anomalously warm → warmer than 90th percentile in a 30-yr baseline climatology



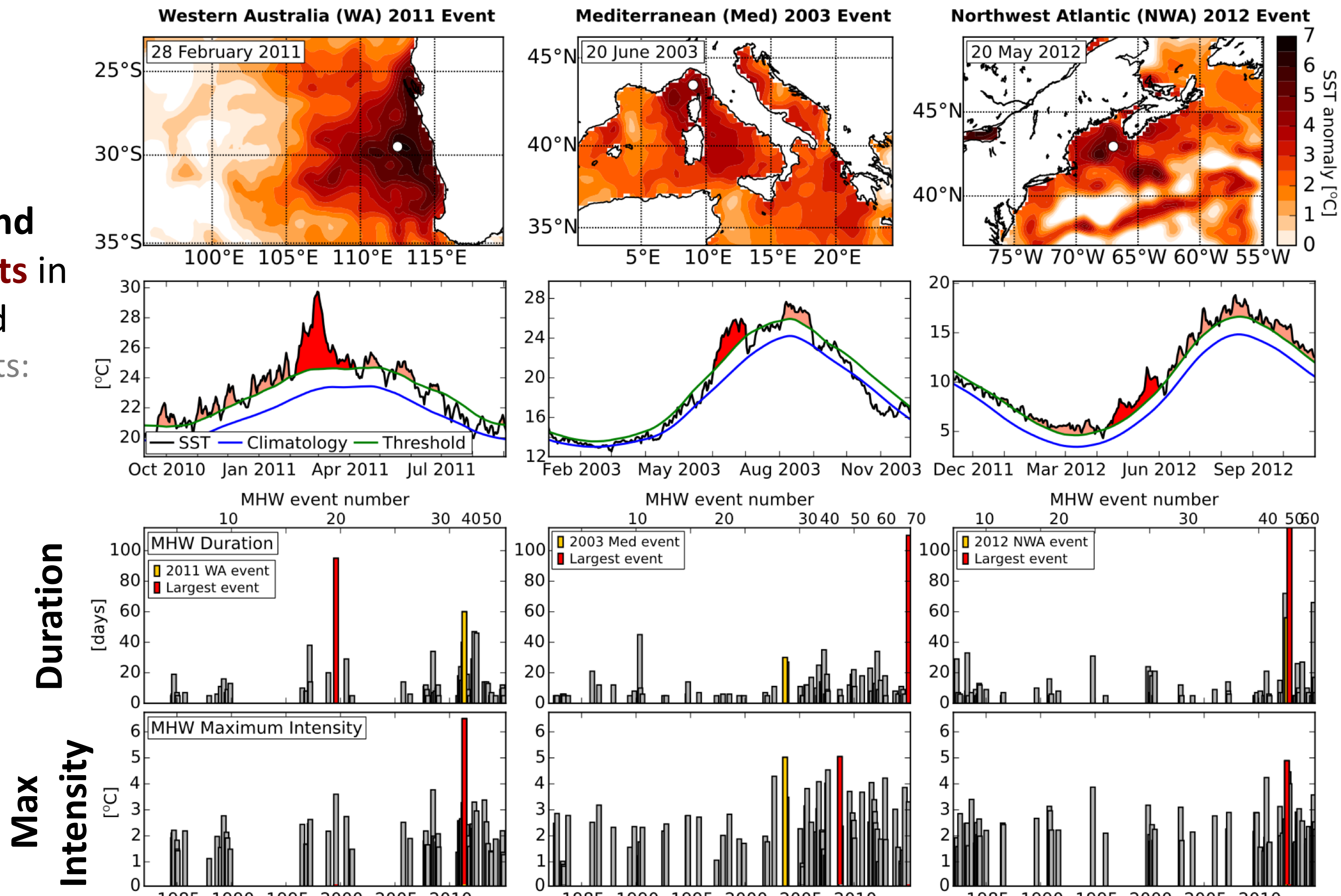
http://www.marineheatwaves.org/all-about-mhws.html

Hobday et al. 2016: A hierarchical approach to defining marine heatwaves. *Progress in Oceanography,* **141**, 227-238.
AND **www.marineheatwaves.org**

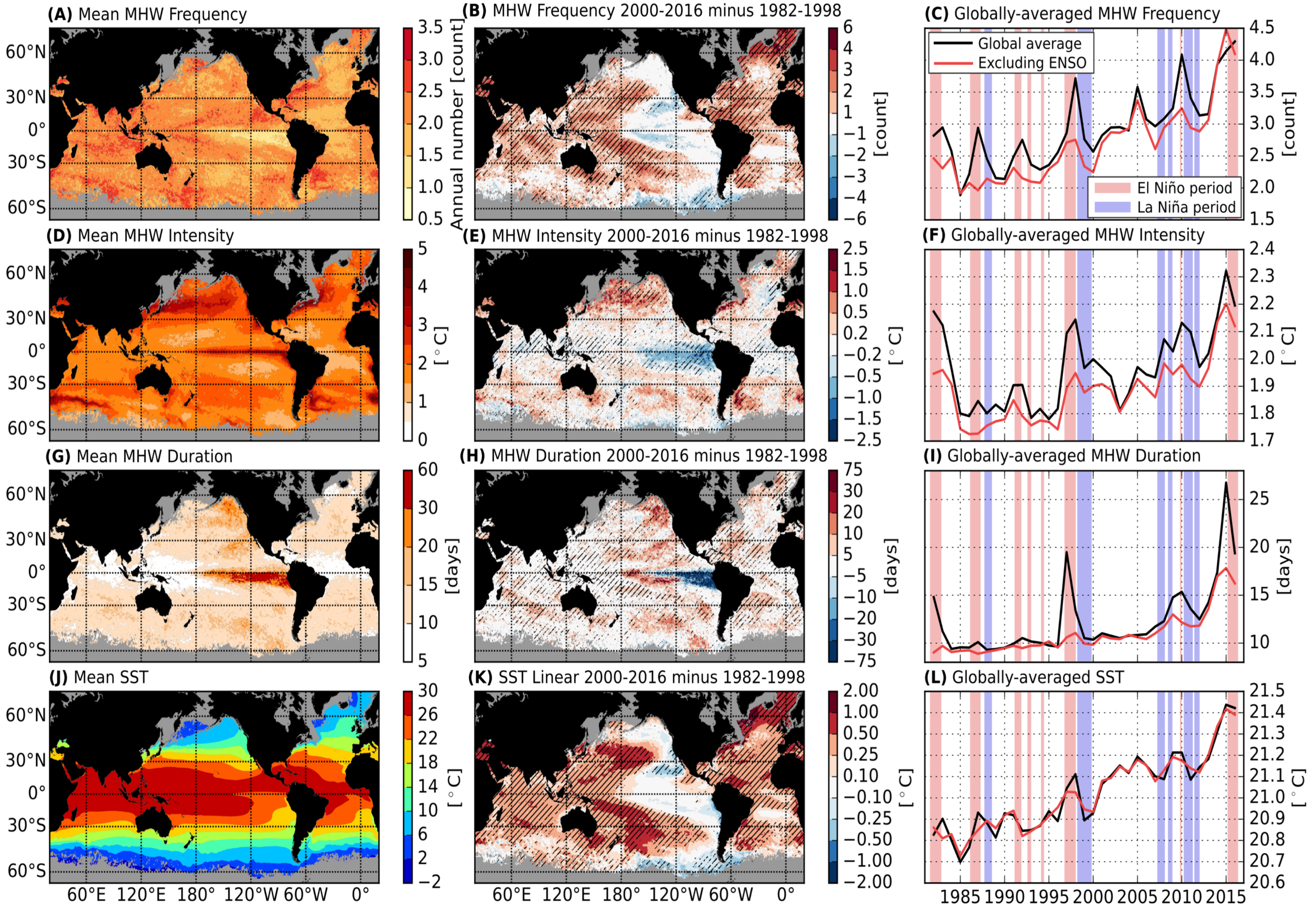
3. Marine Heatwave Characteristics and Historical Trends

2. Marine Heatwave Characteristics and Historical Trends

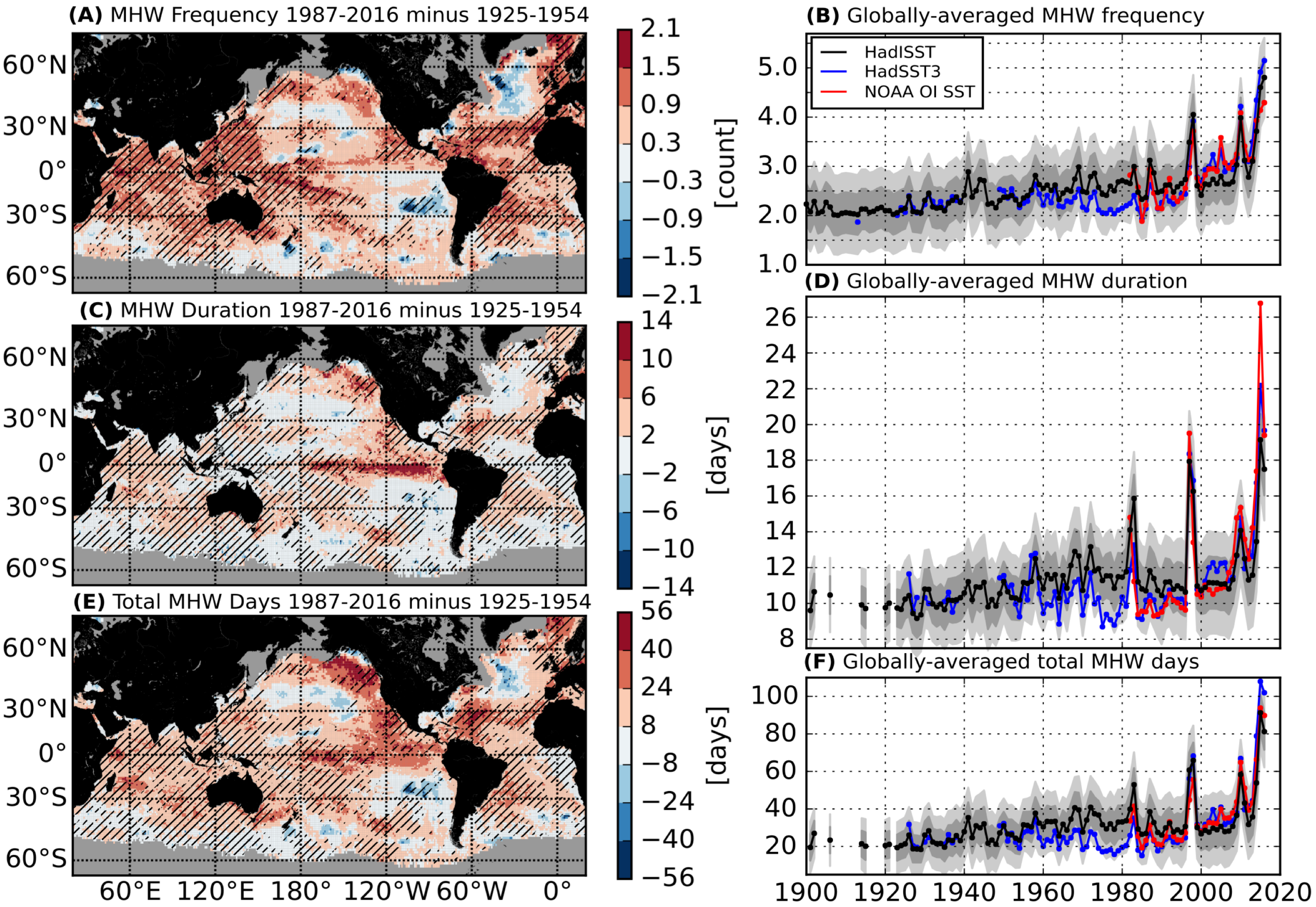
Can **identify, re-examine and quantify historical events** in the observational record (satellite SST measurements: NOAA OI SST)



Oliver ECJ et al., 2018: Longer and more frequent marine heatwaves over the past century. *Nature Communications*, DOI:10.1038/s41467-018-03732-9.



Oliver ECJ et al., 2018: Longer and more frequent marine heatwaves over the past century. *Nature Communications*, DOI:10.1038/s41467-018-03732-9.



Subsurface intensification of marine heatwaves

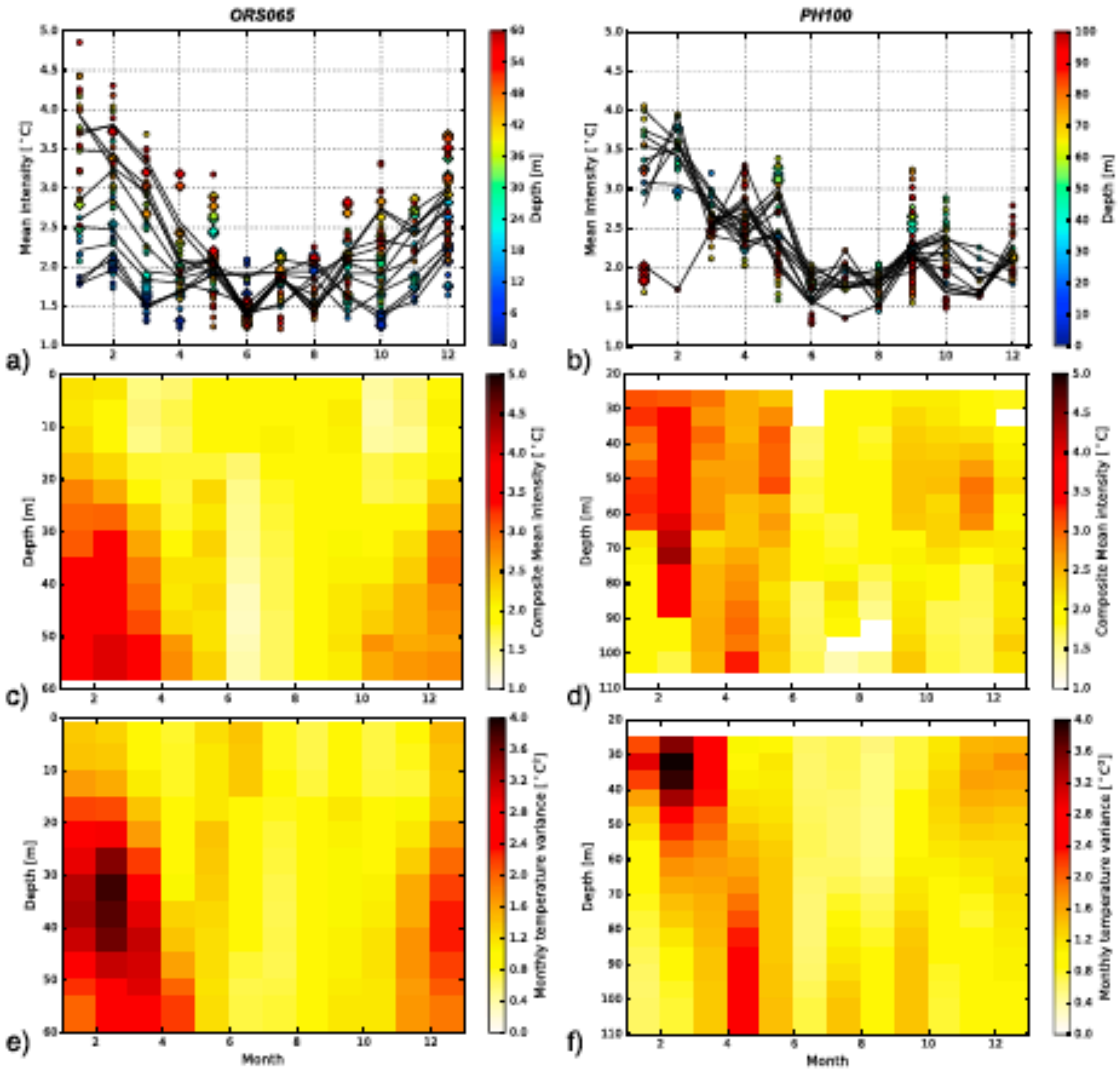


Figure 4. Mean intensity of MHW events as a function of their start month at (a) ORS065 and (b) PH100. Colors show the depth of the event, solid lines link the composite values for each depth and month. Diamonds refer to long events (> 10 days). Composite mean intensity during MHWs binned by depth and month at (c) ORS065 and (d) PH100. White cells show depths and months with no events. Temperature variance over the climatological period binned by depth and months at (e) ORS065 and (f) PH100.

Schaeffer A and M Roughan, 2017: Subsurface intensification of marine heatwaves off southeast Australia: The role of stratification and local winds, *Geophysical Research Letters*, **44**, doi:10.1002/2017GL073714.

4. Marine Heatwave Drivers …

What drives marine heatwave events?

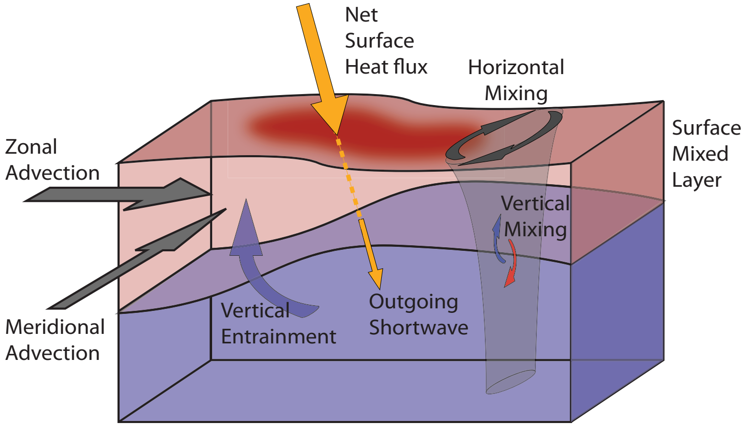
- Define '***drivers***' to be the set of causative mechanisms that combine to produce a MHW event!

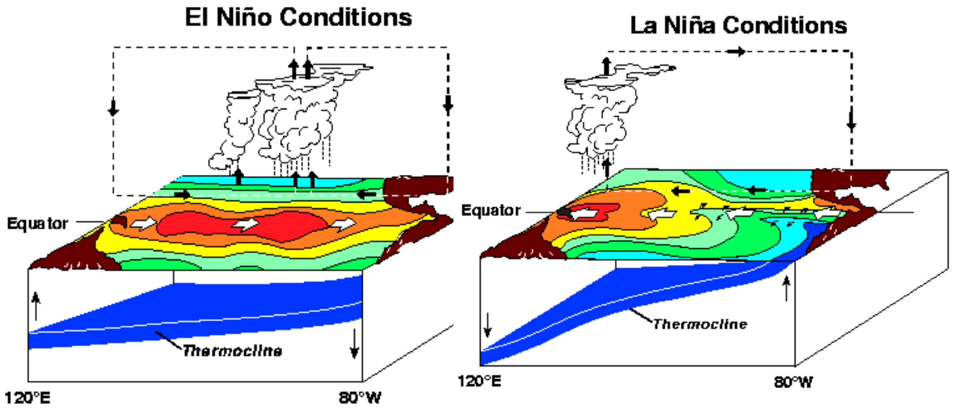
- **Drivers** comprise:

  - ***local processes***

  - possible large-scale ***climate forcing*** mechanisms (**climate modes**) via ***teleconnection processes***

Based on Holbrook et al. (submitted)





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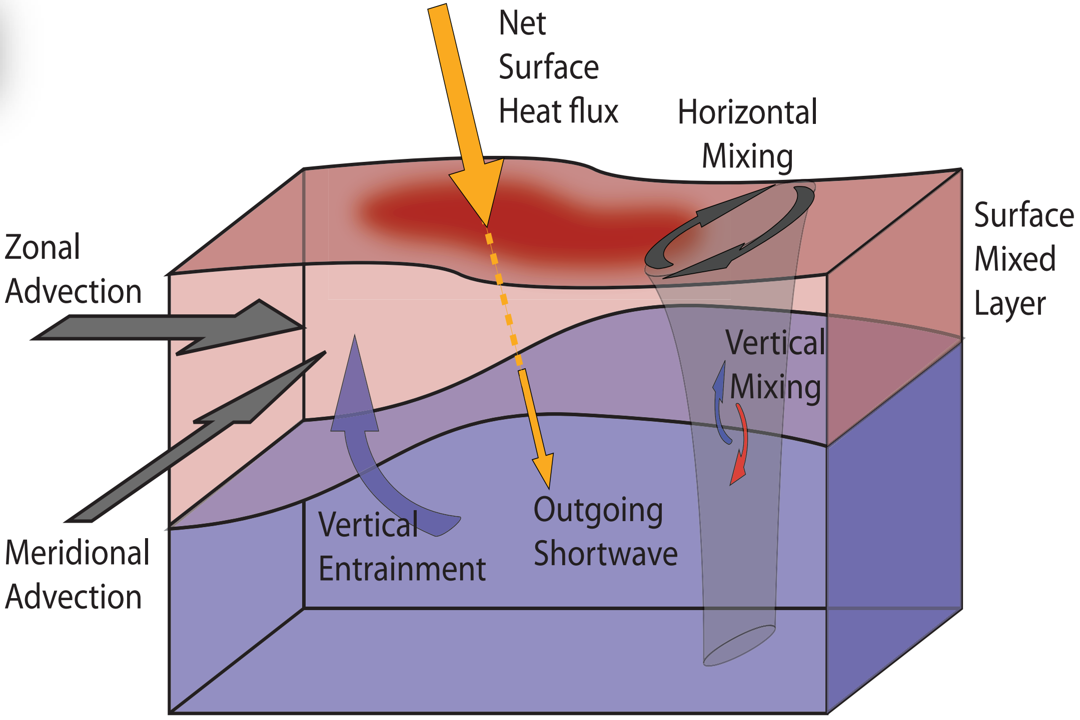

$$\underbrace{\frac{d\langle T\rangle}{dt}}_{RATE_V} = \underbrace{-\langle u_H \cdot \nabla_H T\rangle}_{ADV_H} + \underbrace{\frac{1}{A}\int^{A} \frac{Q}{h}\, dA}_{Q_V} + \underbrace{\langle \nabla_H \cdot (\kappa_H \nabla_H T)\rangle - \langle w \frac{dT}{dz}\rangle - \frac{1}{A}\int^{A} \left(\kappa_V \frac{dT}{dz}\right)_{-h} dA}_{Residual}$$

Temperature budget equation: from Li et al. (in prep).

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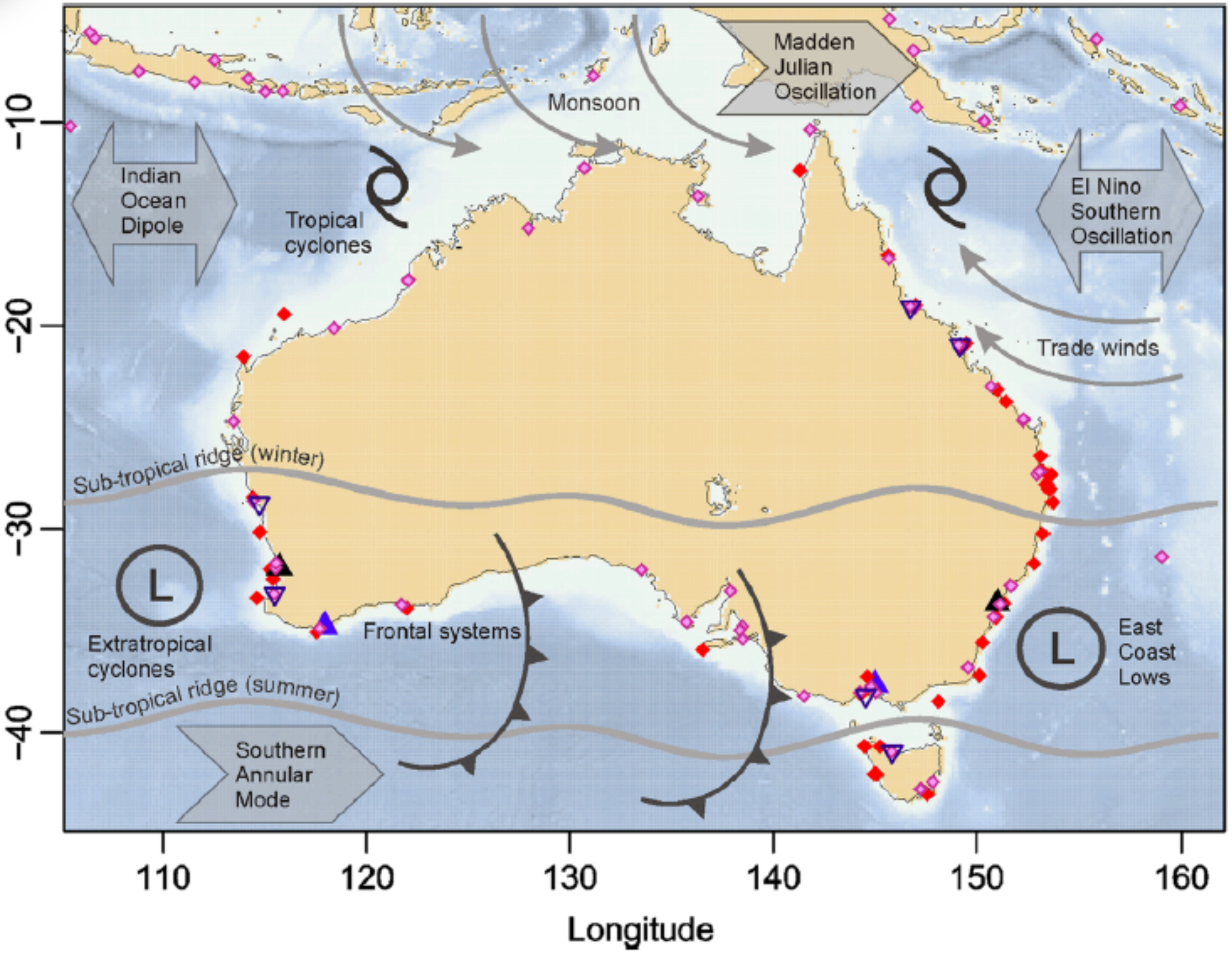


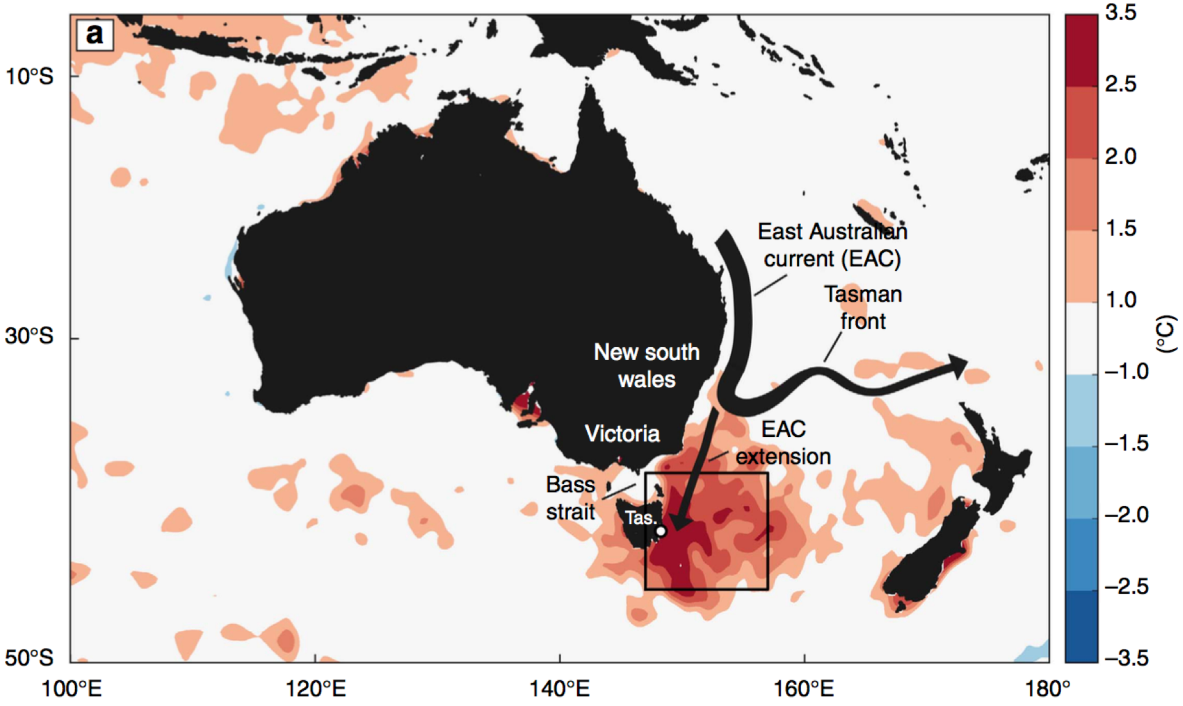
Source: McInnes et al. (2016, *Climatic Change*)

The 2015/16 Tasman Sea MHW

- the longest and most intense MHW on record
- started from Sep 9th 2015 and ended on May 16th 2016
- lasted for 251 days
- a maximum intensity of 2.9 ℃

- Profound impacts on marine ecosystem and economy
- .e.g. Pacific oyster, blacklip abalone and farmed Atlantic salmon



Oliver ECJ, JA Benthuysen, NL Bindoff, AJ Hobday, NJ Holbrook, CN Mundy and SE Perkins-Kirkpatrick, 2017: The unprecedented 2015/16 Tasman Sea marine heatwave. *Nature Communications*, **8**, 16101.

What happened?

- In the summer of 2015/16, an unprecedented marine heatwave (MHW) occurred off southeast Australia
- Lasted for 251 days (i.e. >8 months) from 9 September 2015 to 15 May 2016, with a maximum intensity of 2.9^{o}C above seasonal values averaged over a vast region
- To give a sense of the scale of this MHW, during the summer of 2015/16 temperatures were >1^{o}C above climatological averages over an area ~21x the size of Tasmania, >2^{o}C over an area ~7x the size of Tasmania, and >3^{o}C over an area about half the size of Tasmania

Observed impacts?

- Abalone died, lethal virus in Pacific oyster, and poor performance of Atlantic salmon
- Greater amount of out-of-range fish species than in recent years
- Swimmers and surfers noted the unusual warmth in Tasmanian waters

What caused the event?

- From temperature budget analysis, we found that the dominant factor causing this MHW was due to the very strong southward East Australian Current (EAC) Extension at the time

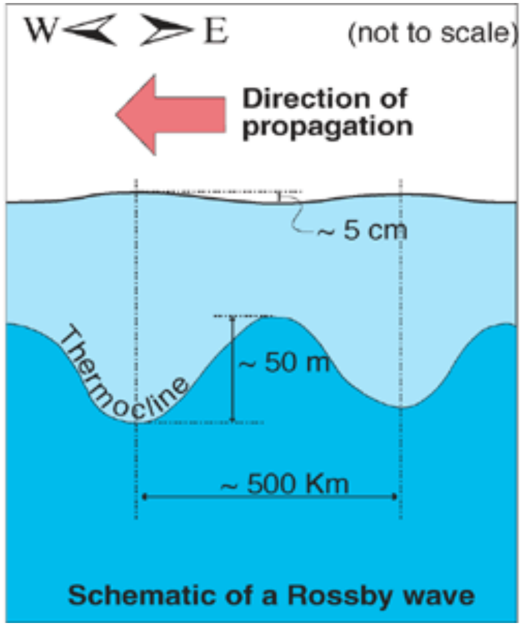
What else do we know?

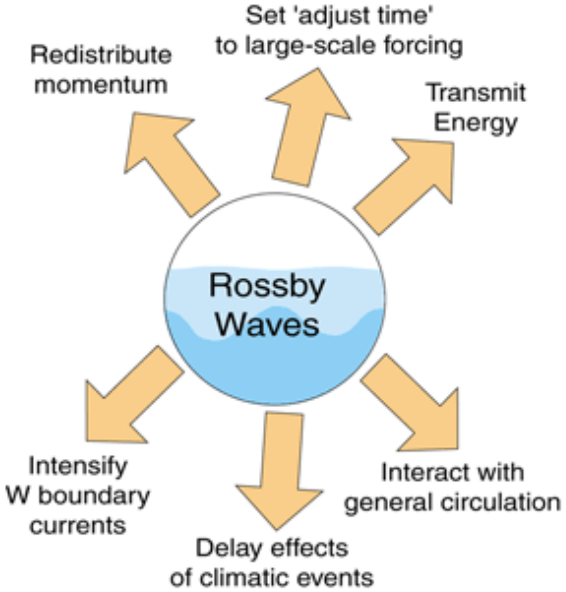
- In 2015 and 2016, approximately one quarter of the ocean surface area experienced a MHW that was either the longest or most intense recorded during the satellite era since records began in 1982
- The EAC Extension has become stronger over the past 70 or so years, causing a multi-decadal warming of the western Tasman Sea
- 2015/16 coincided with an extreme El Nino event, which would have had a substantial influence on warming SSTs in the tropics
- El Nino tends to play a weak to modest role in EAC transport variations

Did humans play a role in the event?

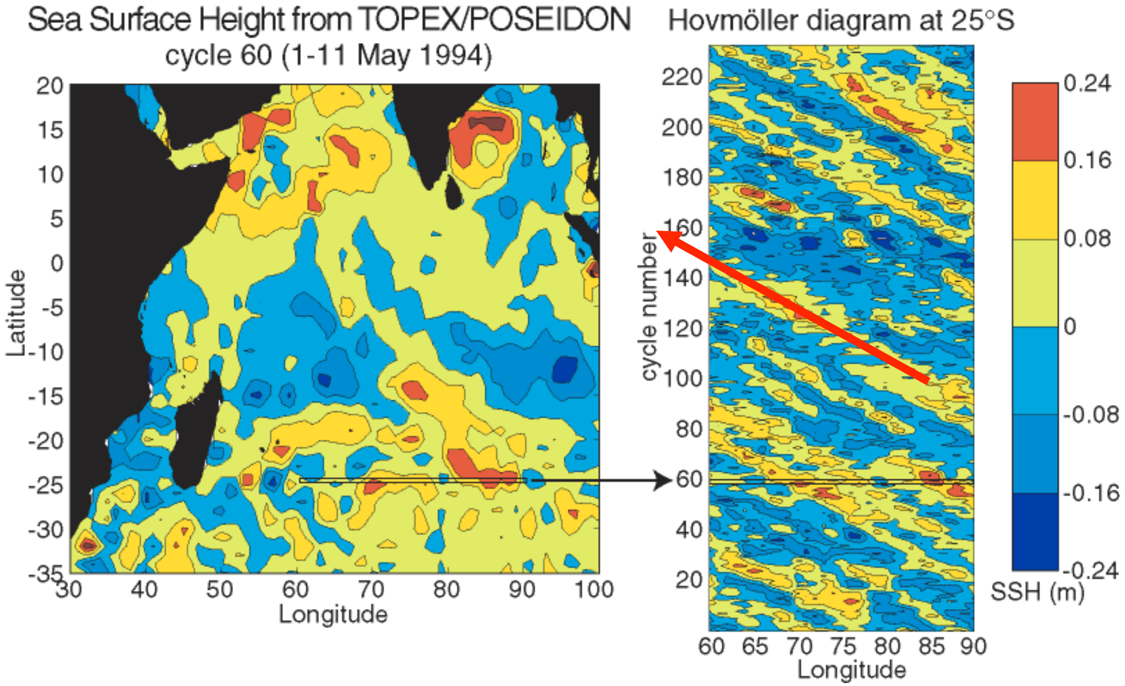
- From a Fraction of Attributable Risk (FAR) analysis, based on global climate model historical simulations and the record of observations, we found that it is very likely (>90% confidence) that the occurrence of an extreme warming event of this intensity is >6 (>6.8) times as likely due to the influence of anthropogenic climate change
- Further, we found it is very likely that the occurrence of an extreme warming event of this duration is >330 times as likely due to the influence of anthropogenic climate change

Rossby waves



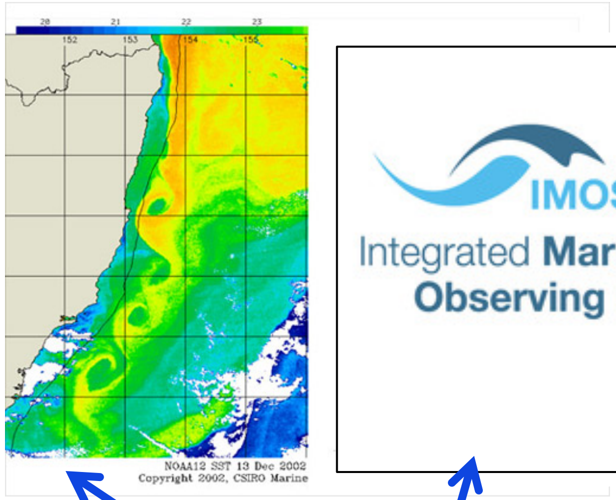


- Owe their existence to the shape and rotation of the Earth
- Horizontal scales: ~100s-1000s km
- Vertical scales: SSH ~10cm; thermocline depth variations ~100m [i.e., 1:1000]
- Propagate westwards
- Speeds [~cm s^{-1}] decrease polewards
  - ~9-12 mth to cross Pacific Ocean near equator
  - ~7 yr to cross Pacific Ocean at 30° lat.
  - >20 yr to cross Pacific Ocean at ~40°+ lat.

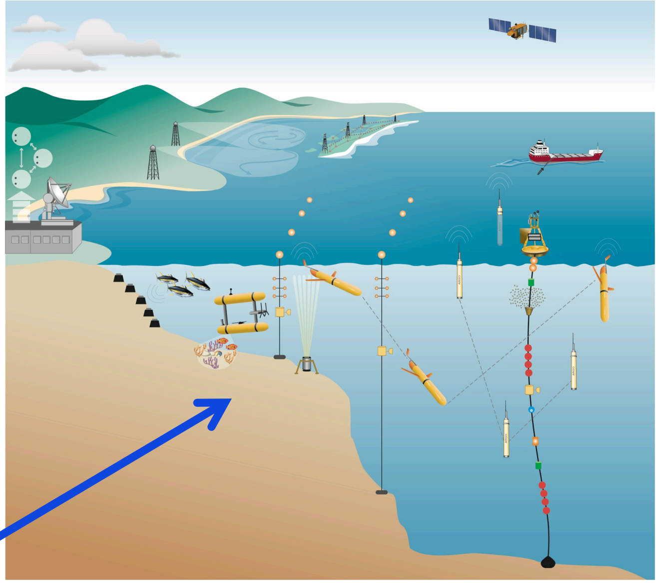


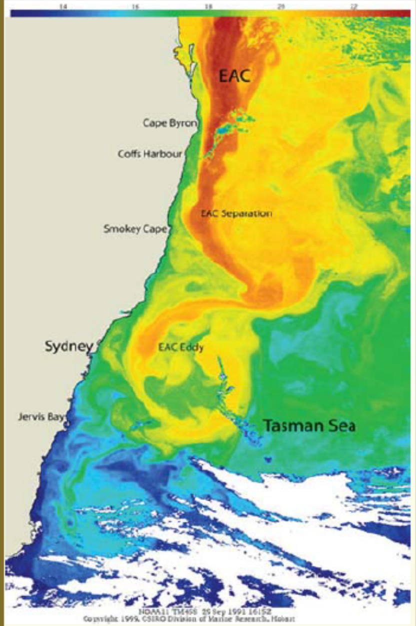
Source: www.soc.soton.ac.uk/JRD/SAT/Rossby/Rossbyintro.html

EAC eddies, observations and predictions



IMOS
Integrated Marine Observing System

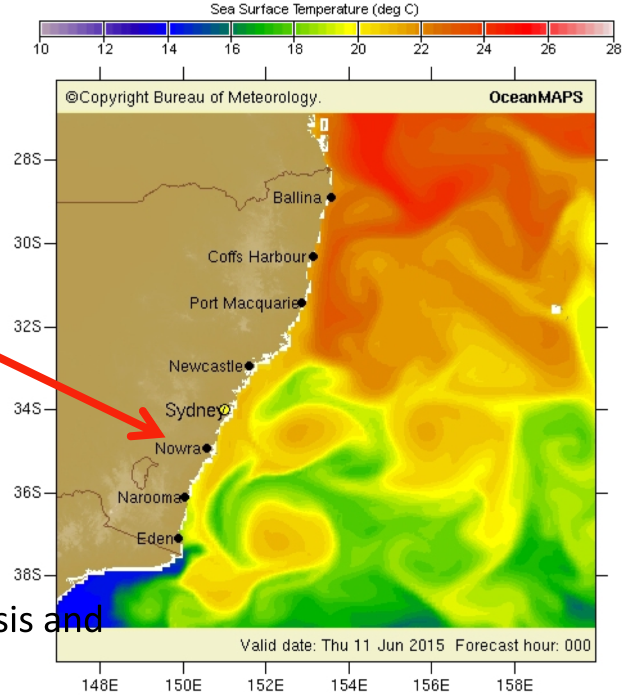




The warm waters from Coral Sea travel the East Australian Current mixing with the temperate waters of the Tasman Sea (Source: IMOS 2011)

observing

and predicting



Marine National Facility

OceanMAPS
Ocean Modelling, Analysis and Prediction System

5. Categorising + Naming Marine Heatwaves

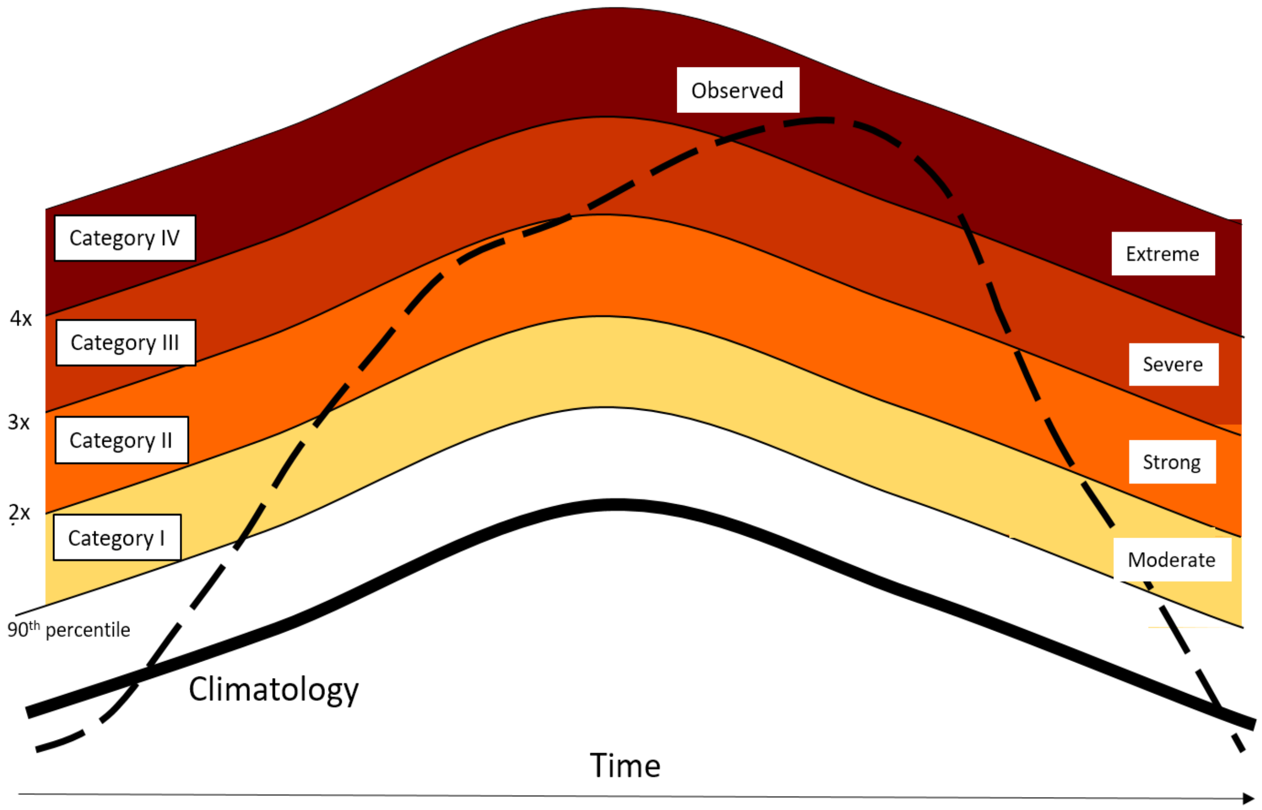
TABLE 1. Examples of naming and categorization schemes used for extreme events and natural disasters. Single events may have attracted a name in popular media, without formal naming.

	WITH FORMAL NAMING	WITHOUT FORMAL NAMING
With category/ scale	• Hurricanes (Saffir-Simpson scale, e.g., Katrina, Category 5) • Earthquakes (Richter scale, e.g., Kobe) • Storms (UK since 2015, e.g., Abigail)	• Atmospheric heatwaves (e.g., heatwave index, but European heatwave (2003)) • Storms (e.g., Beaufort wind scale) • Droughts (e.g., Palmer drought severity index)
Without category/ scale	• Fires (e.g., Black Saturday) • Droughts (e.g., Millennium Drought in Australia, Dust Bowl in USA)	• Deoxygenation events • Hail storms • Floods (but, e.g., 1931 China floods) • Acidification events • Marine heatwaves

Hobday AJ, ECJ Oliver, A Sen Gupta, JA Benthuysen, MT Burrows, MG Donat, NJ Holbrook, PJ Moore, MS Thomsen, T Wernberg and DA Smale, 2018: *Oceanography,* **31**(2), DOI:10.5670/oceanog.2018.205.

5. Categorising + Naming Marine Heatwaves

Categories



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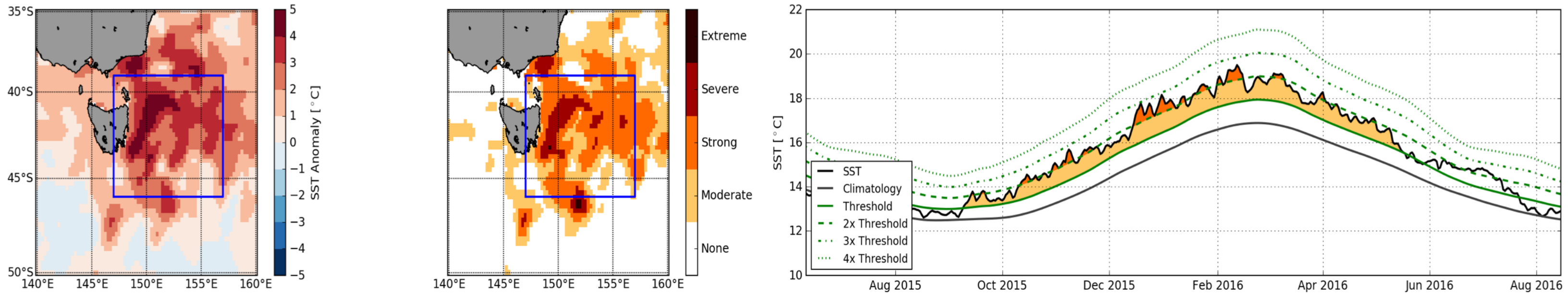
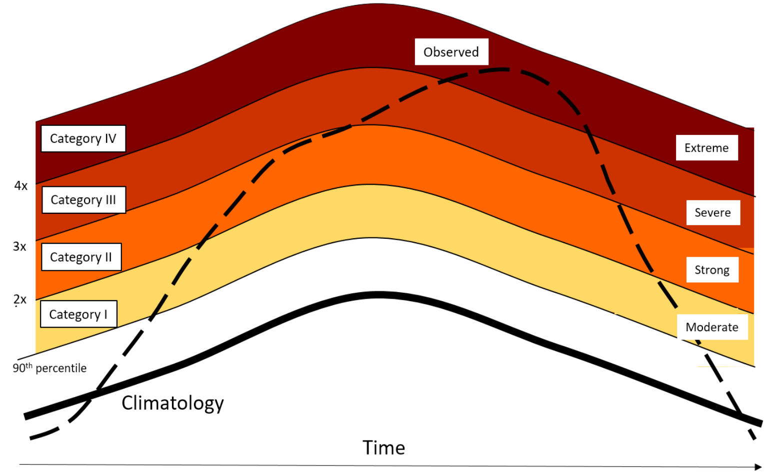
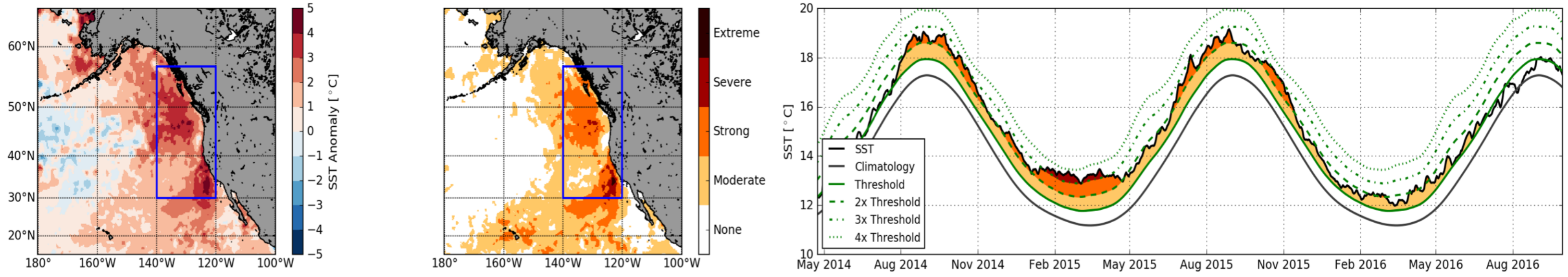
Tasman Sea 2015/16





Northeast Pacific 2014-16



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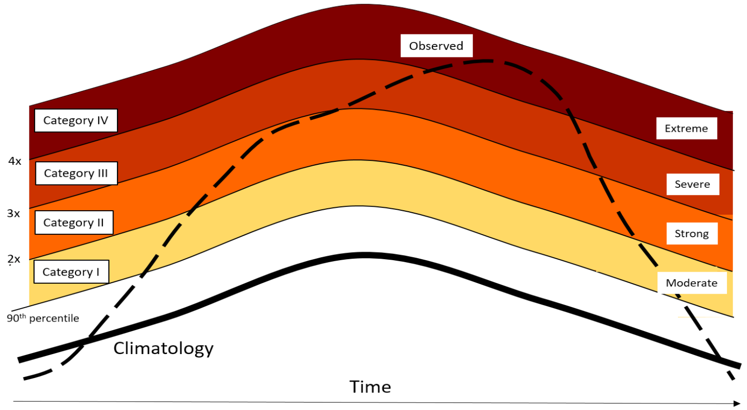


Hobday AJ, ECJ Oliver, A Sen Gupta, JA Benthuysen, MT Burrows, MG Donat, NJ Holbrook, PJ Moore, MS Thomsen, T Wernberg and DA Smale, 2018: *Oceanography,* **31**(2), DOI:10.5670/oceanog.2018.205.

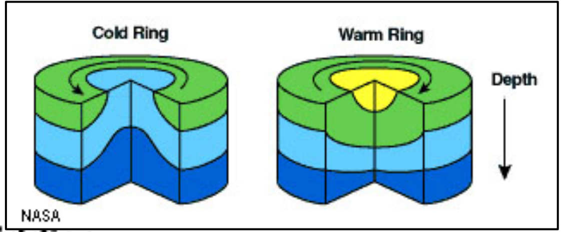
Table 2. Examples of recent marine heatwaves (MHWs) classified into four categories of increasing severity and associated heatwave metrics (for event regions, see Figure 3). The entry for each event lists the date of peak intensity, the category and intensity (I_{max}, °C) on that date, the total duration of the event (days), the proportion (p, %) of time spent in each of the four MHW categories over the duration of the event, and the season in which the event occurred. Note that the proportions do not always add up to 100% due to the presence of "gap days" linking successive events (see Hobday et al., 2016), days that are not classified into any of the four categories.

	Event	Peak Date	I_{max}	Duration	$p_{moderate}$	p_{strong}	p_{severe}	$p_{extreme}$	Season	Biological Studies
Category I (Moderate)	Mediterranean Sea 1999	Sep 27, 1999	1.92	8	100	–	–	–	Autumn	Cerrano et al., 2000 Garrabou et al., 2001 Linares et al., 2005 Coma et al., 2009
Category II (Strong)	Mediterranean Sea 2003	Jun 14, 2003	4.38	31	58	42	–	–	Early Summer	Crisci et al., 2011
	Mediterranean Sea 2006	Jul 26, 2006	3.99	33	76	21	–	–	Summer	Kersting et al., 2013 Marba and Duarte, 2010
	Tasman Sea 2015	Dec 19, 2015	2.70	252	59	41	–	–	Spring/Summer	Oliver et al., 2017
	Great Barrier Reef 2016	Mar 11, 2016	2.15	55	55	45	–	–	Summer/Autumn	Hughes et al., 2017
Category III (Severe)	Western Australia 1999	Jul 25, 1999	2.13	132	86	12	2	–	Winter	None available
	Northwest Atlantic 2012	May 20, 2012	4.30	132	76	23	2	–	Winter/Spring	Mills et al., 2013
	Northeast Pacific Blob 2015	Jul 13, 2015	2.56	711	44	43	13	–	Year-round	Cavole et al., 2016 Bond et al., 2015 McCabe et al., 2016
	Santa Barbara 2015	Oct 13, 2015	5.10	93	44	41	13	–	Summer	Reed et al., 2016
Category IV (Extreme)	Western Australia 2011	May 20, 2011	4.89	66	42	33	12	12	Summer	Wernberg et al., 2013

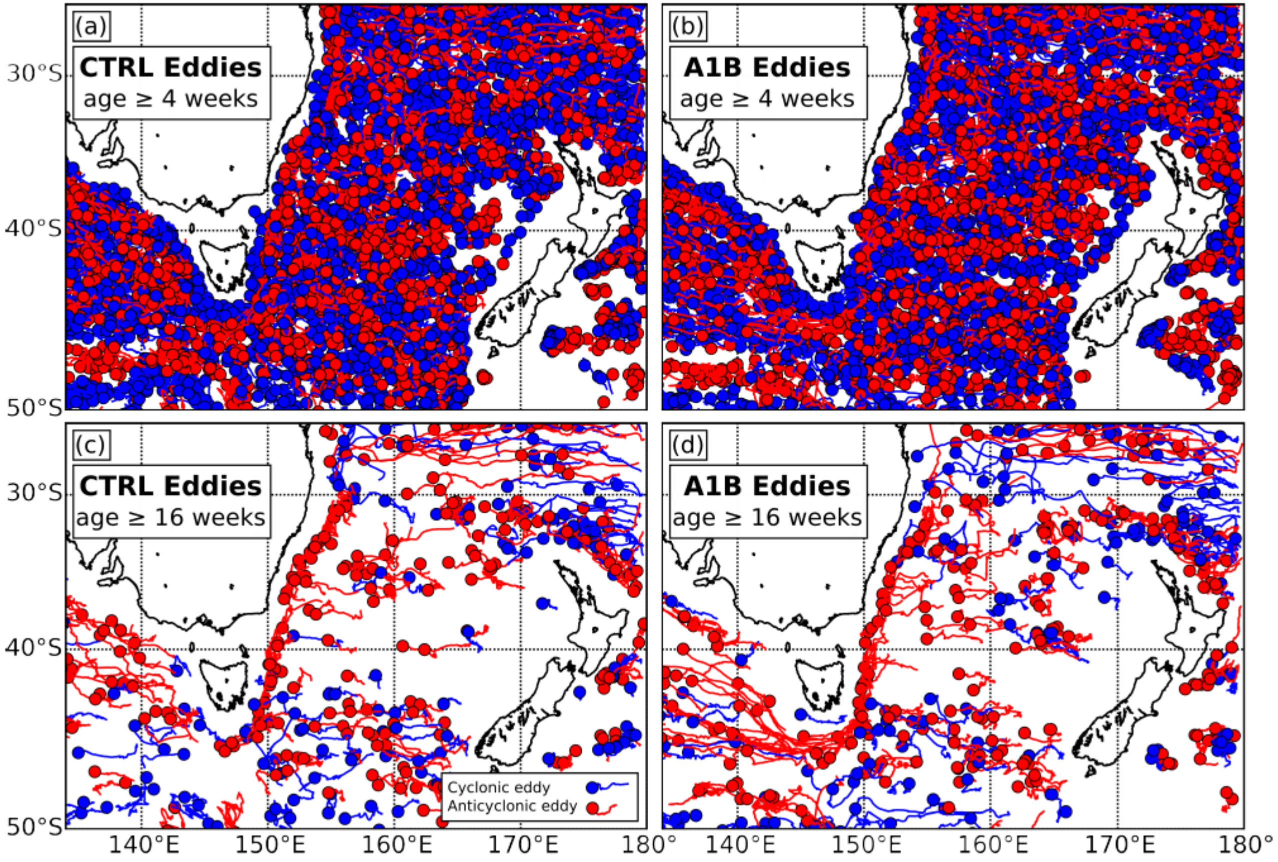
6. Predictability, Prediction and Projections …

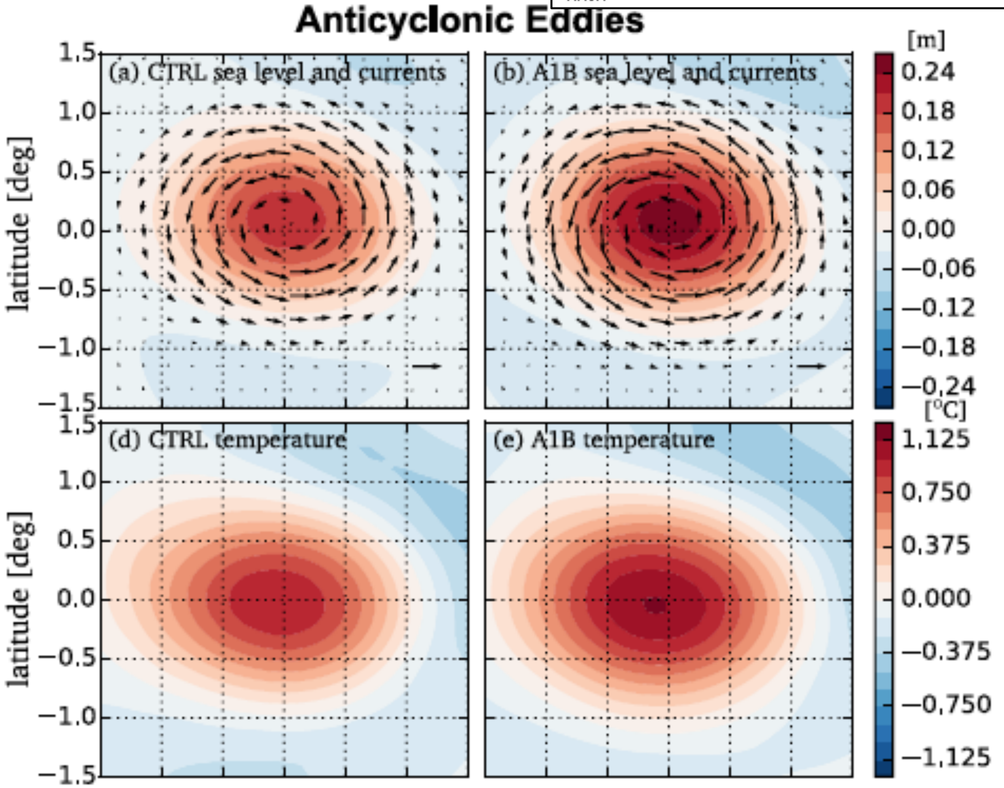
- Ocean temperature extremes (OTEs) and MHW Predictability and Prediction
  - Potential Predictability
    - OTEs re NESP ESCC Project 2.3 comp.2 (Holbrook, Cougnon, Oliver)
    - Tasmania's eastern shelf (Oliver et al. 2018, Prog Oceanogr)
    - Large-scale forcing of Tasman Sea MHWs (Zeya Li et al.)
  - Prediction (forecasting)
    - Statistical – Self Organising Maps (SOM) 7-day forecasts (Zijie Zhao et al.)
    - Deterministic – Decadal Prediction System CAFÉ (Terry O'Kane et al.)
- MHW Projections under Climate Change
  - Froelicher et al. (2018, Nature in press)
- Process-based understanding of MHWs
  - CLEX RP2 Project 2.4!!

6. Predictability, Prediction and Projections …



Cyclonic (blue) and **anticyclonic (red)** eddies tracked using Chelton et al. (2011) sea level algorithm



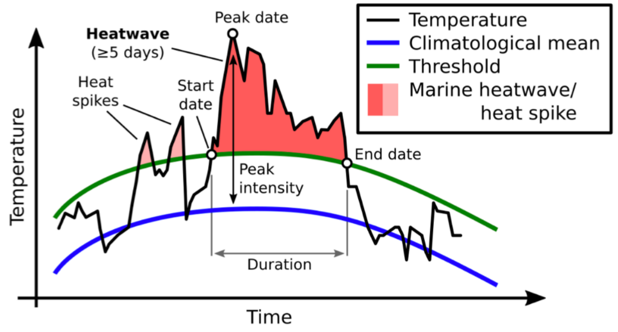


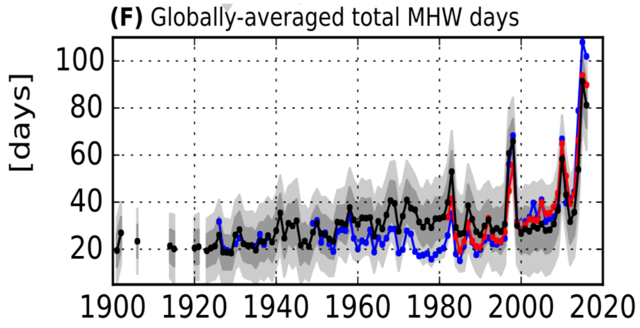
Marked **increase** in number of long-lived **anticyclonic (warm core) eddies** in EAC Extension region, and possibly an increase in eddies passing through the Tasman Leakage

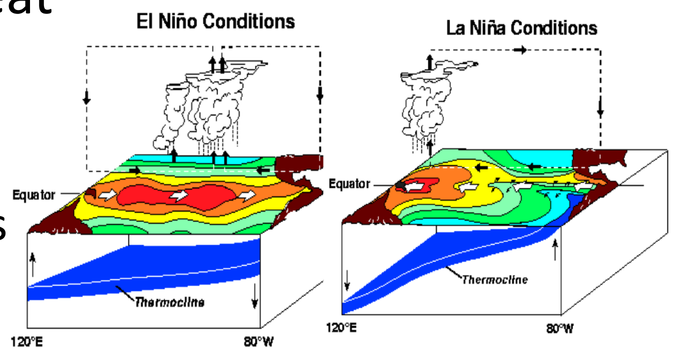
Oliver ECJ, TJ O'Kane and NJ Holbrook, 2015: Projected changes to Tasman Sea eddies in a future climate. *Journal of Geophysical Research – Oceans*, **120**, 7150-7165, doi:10.1002/2015JC010993.

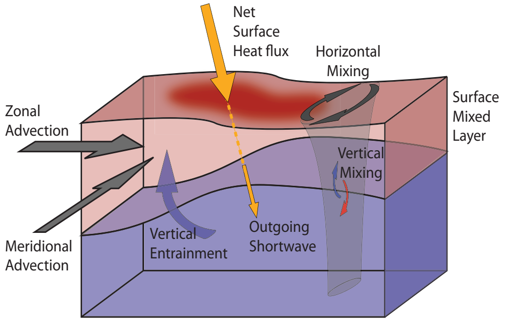
7. Summary - Take Home Messages

- Our understanding of marine heatwaves (MHWs) is in its infancy
- We now have a working definition to unify estimates of MHW frequency, intensity and duration globally
- MHWs have been increasing in frequency, intensity and duration => expected to continue into the future
- Drivers of MHWs include climate modes + oceanic teleconnections and local processes (air-sea heat flux, advection + small scale)
- Little knowledge of
    - MHWs in the ocean subsurface, or their dynamics
    - Marine cold spells
- Great opportunity for CLEX => process-based understanding => improve predictability

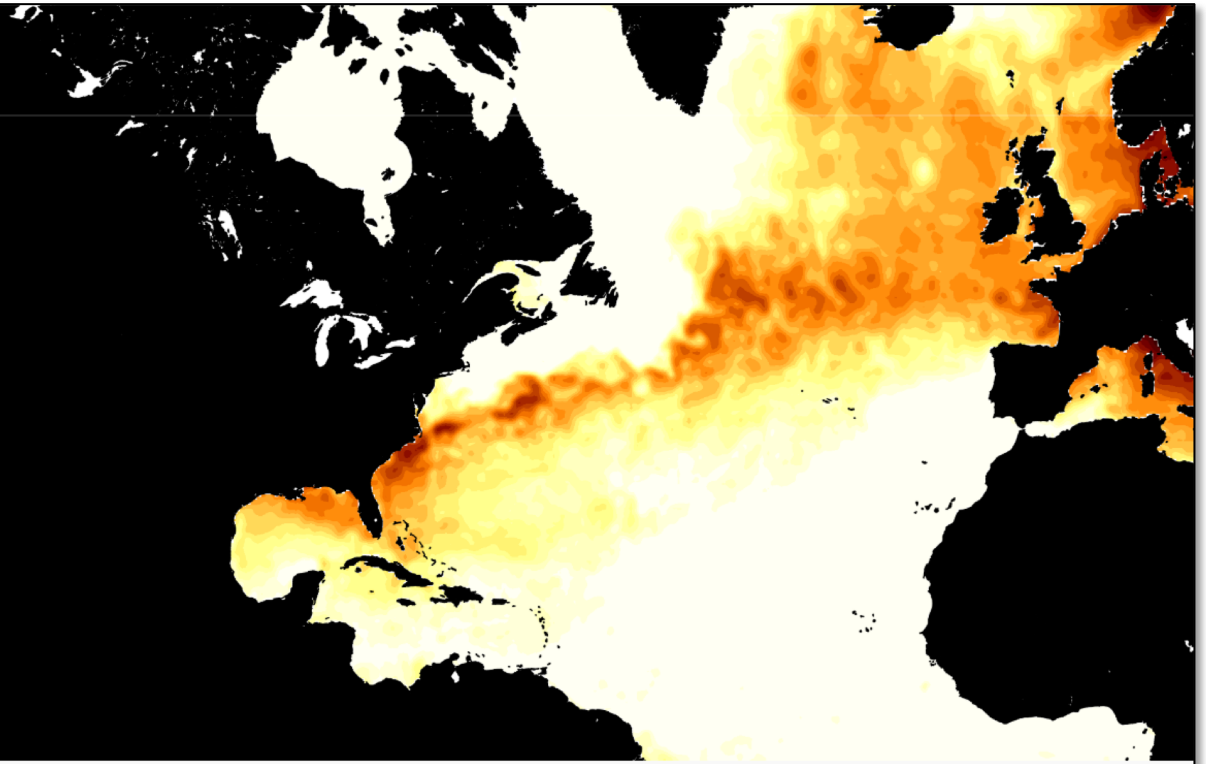








MENU   MARINE HEATWAVES



MARINE HEATWAVES

International Working Group

We are a group of scientists, spanning several continents and fields of study, dedicated to understanding marine heatwaves: their physical drivers, climatological properties, and ecological impacts.

www.marineheatwaves.org

Additional Slides …

8. Marine Heatwave CC Event Attribution …

MHW Event Attribution (Fraction of Attributable Risk (FAR) Analysis)

Oliver et al. (2017), Nature Communications **8**, 16101

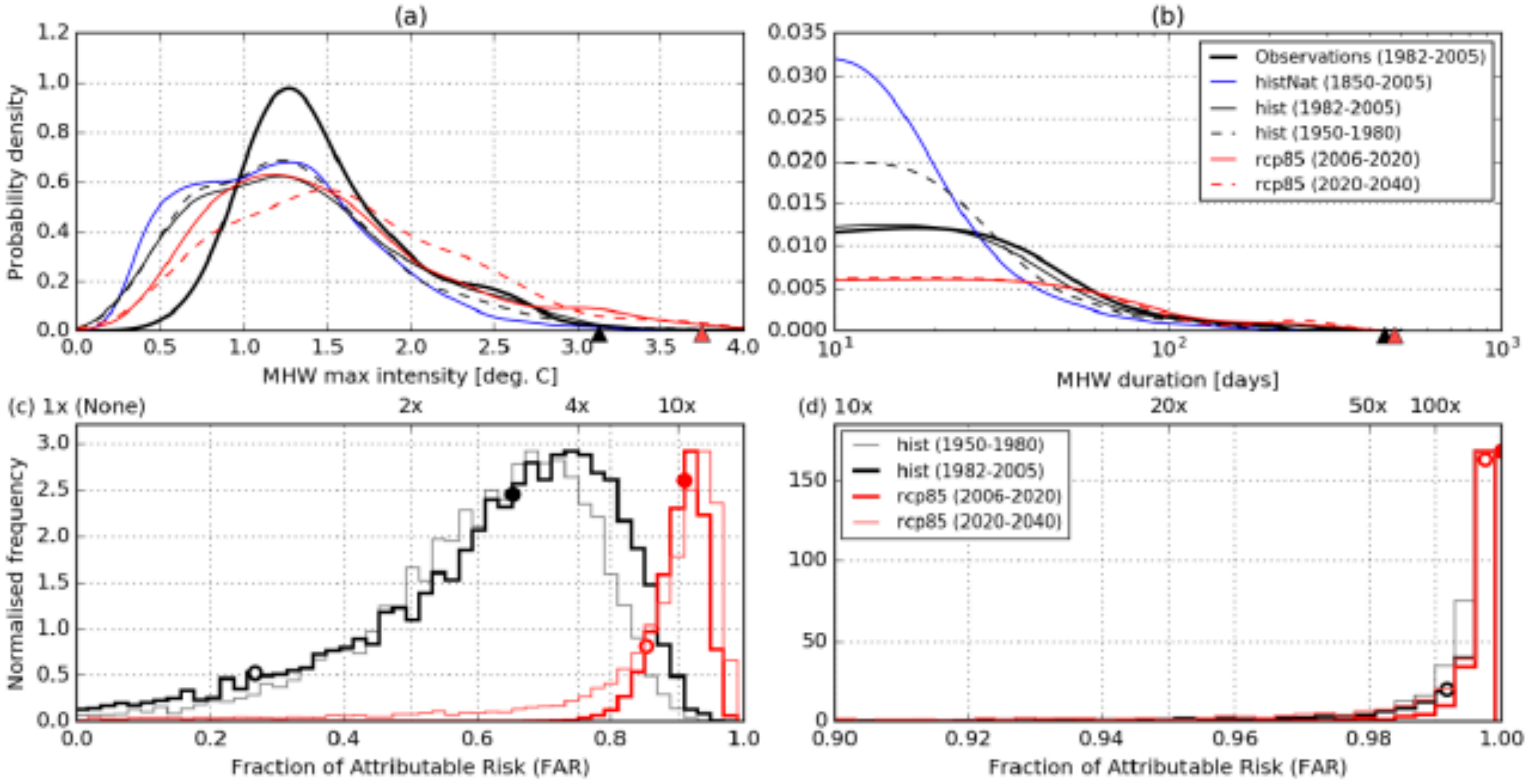


Figure 7. Attribution of 2015/16 Tasman Sea marine heatwave (MHW) event using global climate models. The probability distributions of the (a) maximum intensity and (b) duration of all MHWs detected from the observations (thick black line) and the ensemble of CMIP5 historical simulations over 1982-2005 (thin black line) and over 1950-1980 (dashed black line), historicalNat simulations (blue line), and RCP8.5 simulations over 2006-2020 (red line) and over 2020-2040 (dashed red line), using a baseline climatology of 1881-1910. The black and red triangles indicate the properties of the event being attributed and of the 2015/16 event, respectively (the latter is not shown for duration as it is too large). The distribution of Fraction of Attributable Risk (FAR) values for a MHW of (c) maximum intensity 3.1° C or (d) duration of 446 days from the historical and RCP8.5 runs over four separate time periods.