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Keynote Forum: Tuesday 25 October 2016

Marine heatwaves: Definition, drivers and global trends

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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*

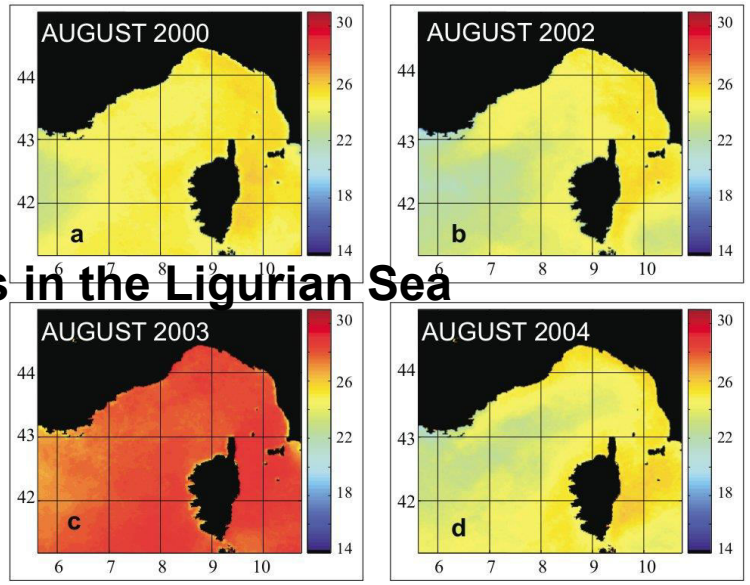
- **Ligurian Sea** SST 28^{O}-28.5^{O}C (August) **2-3^{O}C higher** than previous summers (Sparnocchia et al. 2006)

- **Tyrrhenian Sea** >29.5^{O}C, **June SST anomaly ~2.5^{O}C** (Olita et al. 2007)

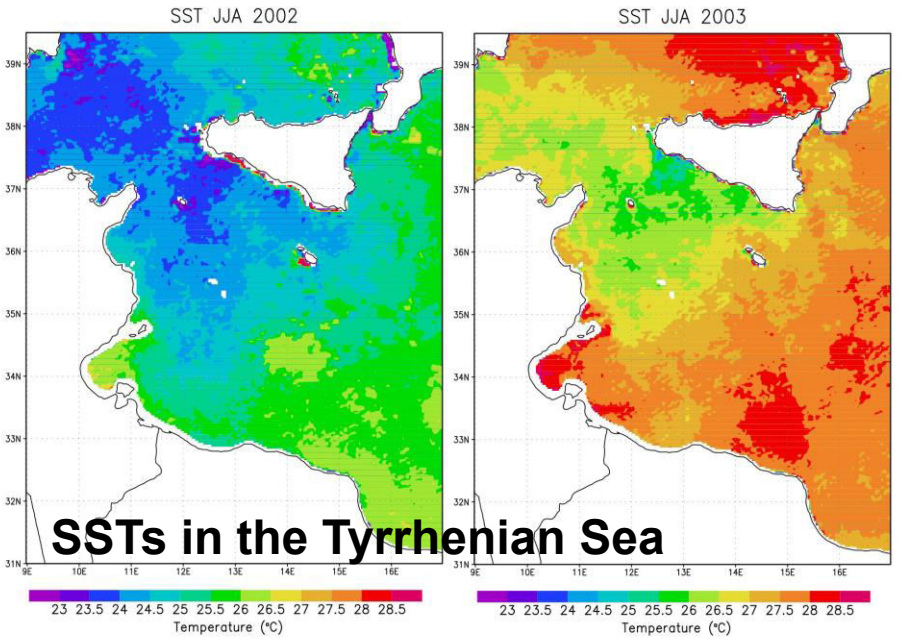
- Warming in upper layers (<20 m depth), anomalously cold below this depth

- <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)



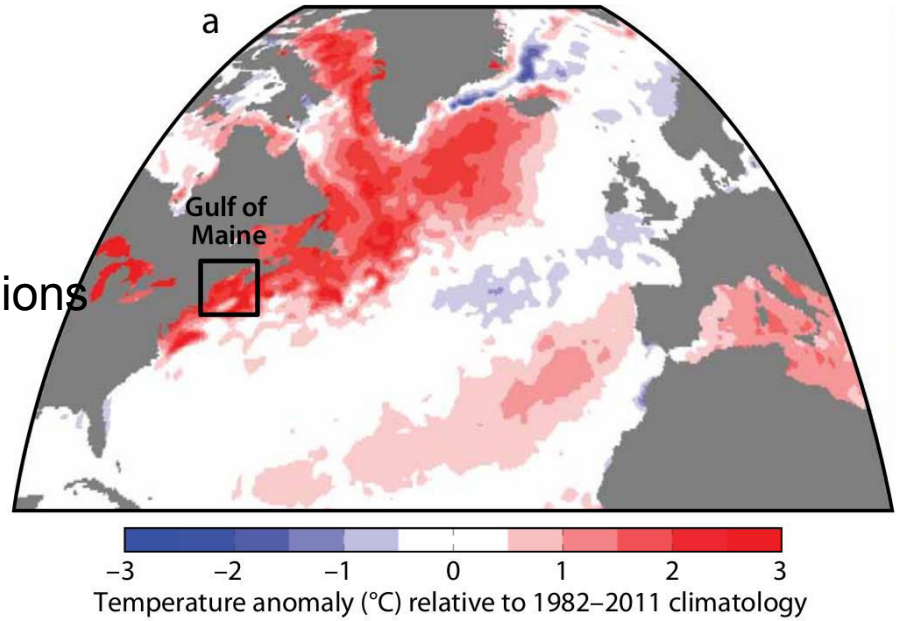
SSTs in the Ligurian Sea

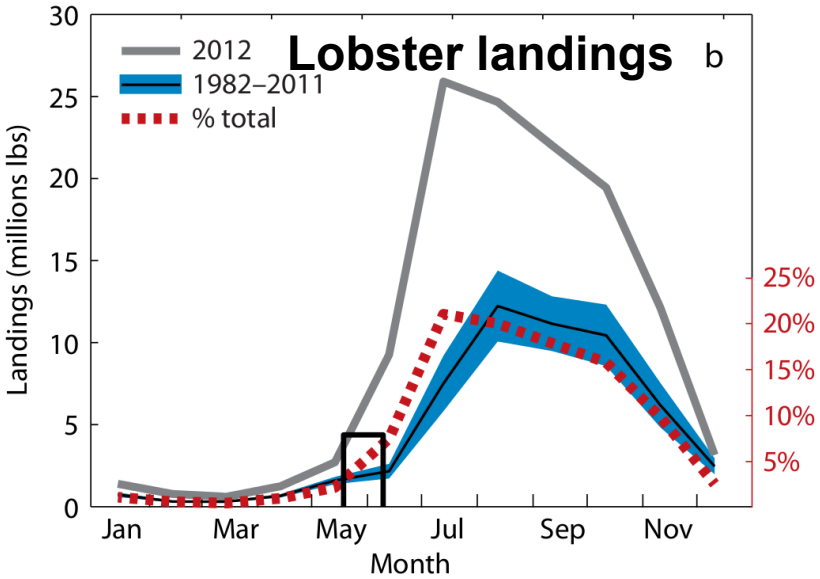


SSTs in the Tyrrhenian Sea

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

- 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







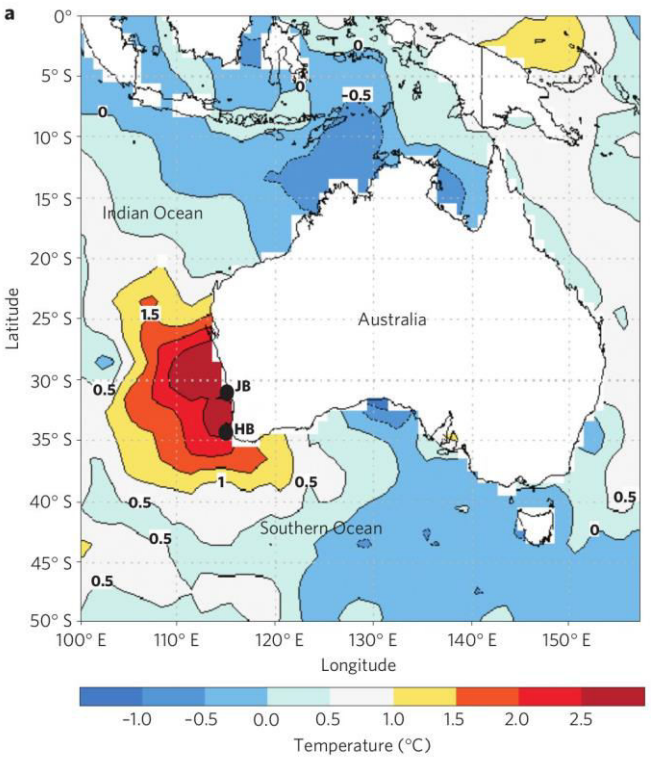
Pearce and Feng (2013), *J Marine Systems*, **111-112**, 139-156
Feng et al. (2013), *Scientific Reports*, **3**, 1277
Wernberg et al. (2013), *Nature Climate Change*, **3**, 78-82

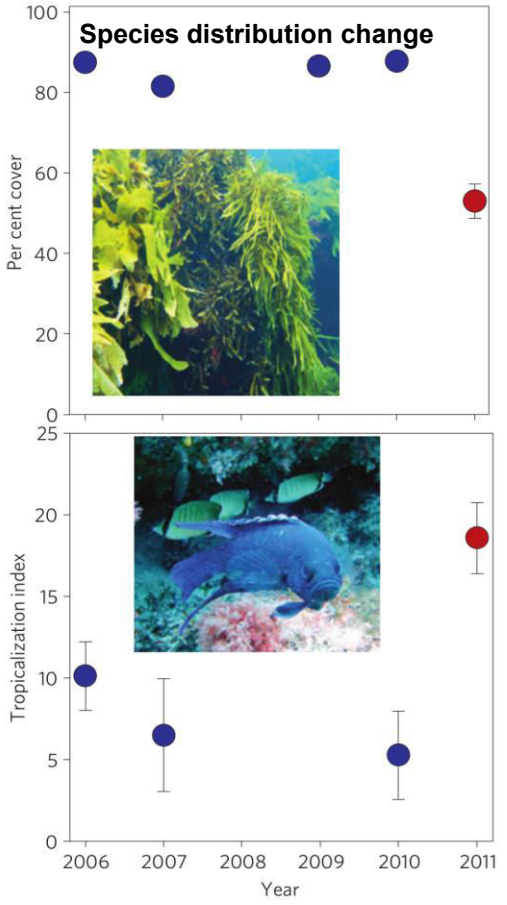
In **summer 2010/2011** an unprecedented **marine heatwave** documented off **Western Australia (WA)**

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**



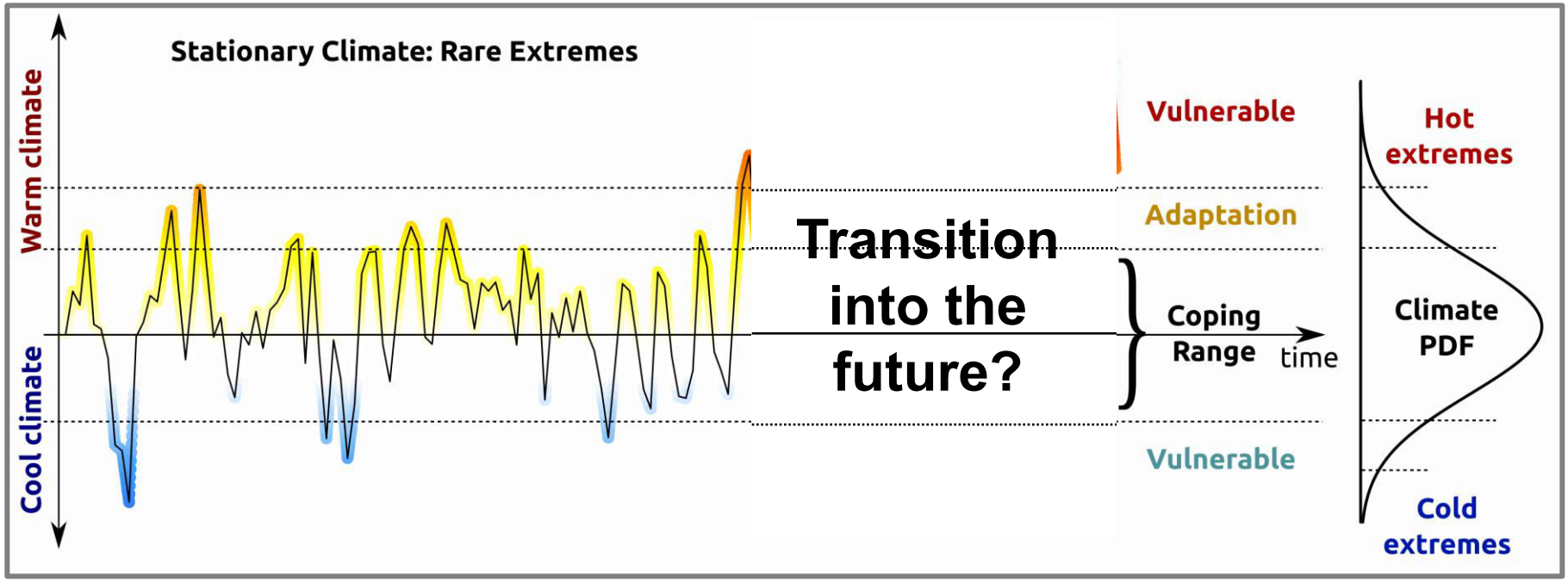


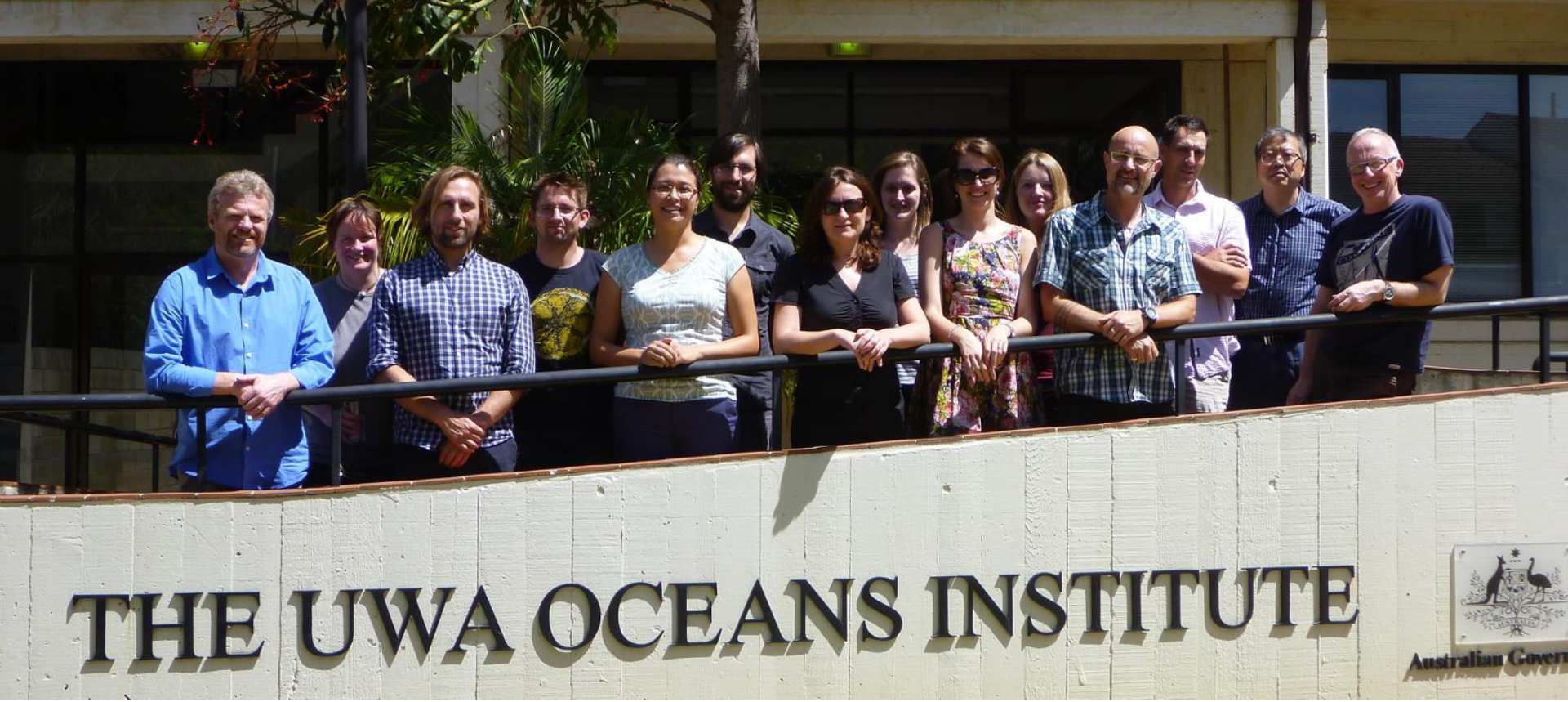
Wernberg et al. (2013) noted significant observable impacts on biodiversity including temperate seaweeds, sessile invertebrates, and demersal fish => "**tropicalization**" of fish communities

Introduction

- **Marine extremes** have been examined for decades, but studies have focused on very few physical variables (mainly **sea levels**, **wave heights**)
- **Ocean temperature extremes** demonstrated to impact **ecosystems** (e.g. *2011 WA event*) and **fisheries** (e.g., *2012 NW Atlantic event*)
- Recent substantial ecological impacts suggest that perhaps the intensity and/or frequency of MHWs may be changing with our warming climate!?

How to define MHWs? **What drives MHWs?** **Global trends in MHWs?**





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 (Hobday, Holbrook et al. 2016, *Prog. Oceanogr.*)
- Drivers of marine heatwaves: a global assessment (Holbrook et al., *in prep.*)
- Long-term trends in marine heatwaves globally (Oliver, Holbrook et al., *in prep.*)

1. How to define MHWs?

- A **marine heatwave (MHW) definition** has been proposed (Hobday et al. 2016)
  => a ***"discrete prolonged anomalously warm water event"*** at a particular location
  - **'discrete'**: well-defined start and end times
  - **'prolonged'**: persist for at least 5 days
  - **'anomalously warm'**: temperatures >90th percentile relative to climatology

Definition facilitates a set of metrics, including:

- **Intensity** [^{O}C]
  - both maximum and event-mean
- **Duration** [days]
  - Time from start to end dates

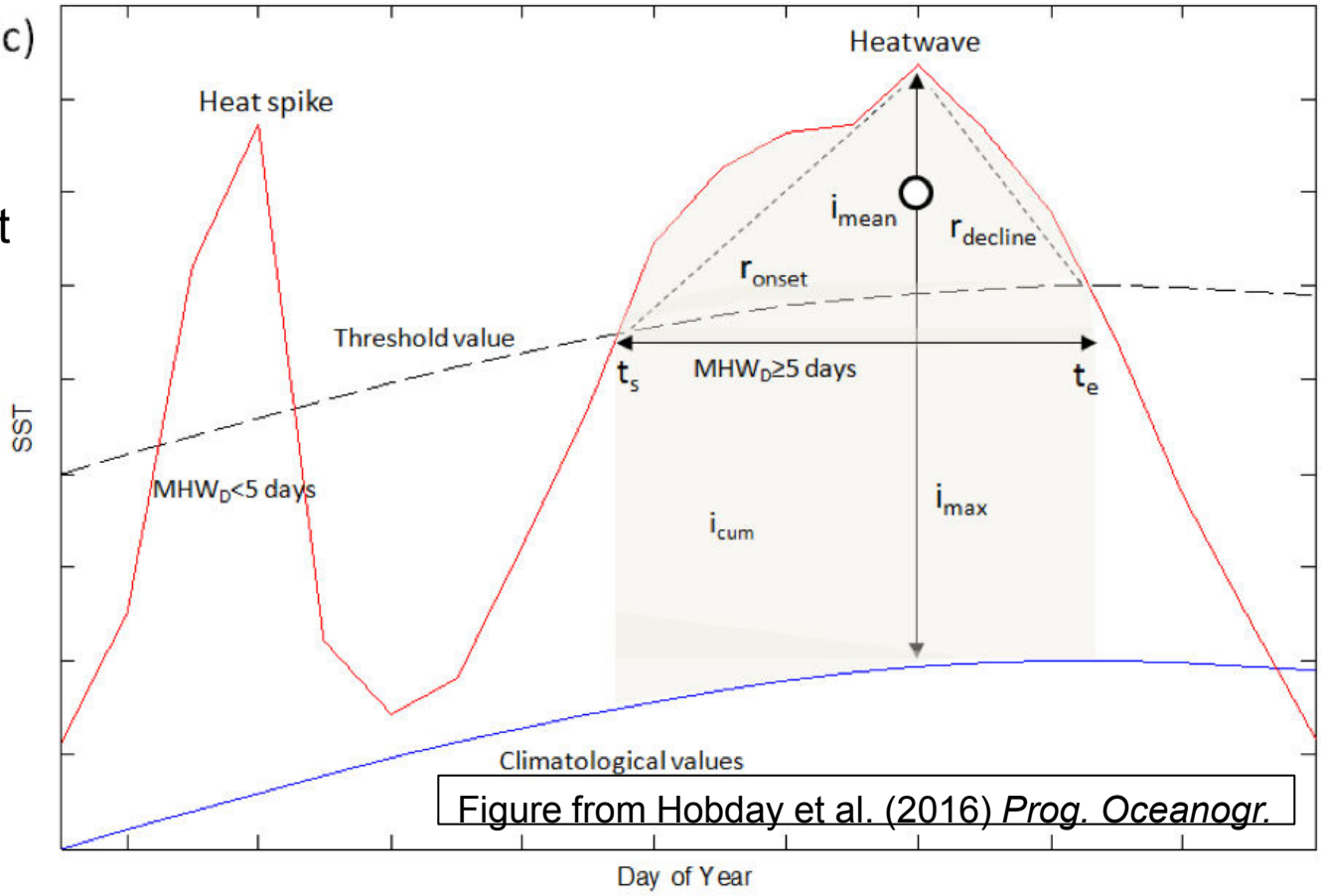
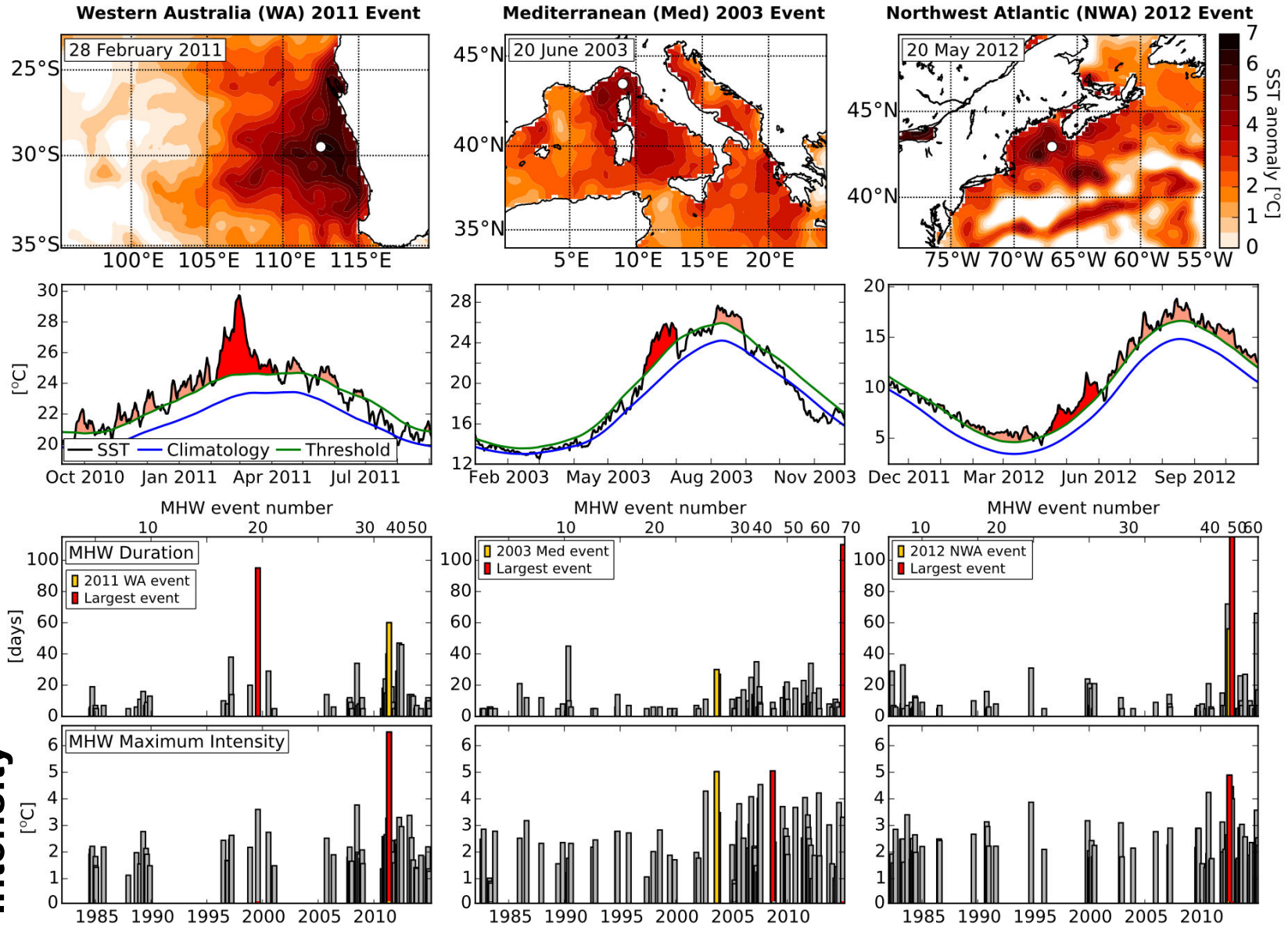


Figure from Hobday et al. (2016) *Prog. Oceanogr.*

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



2. What drives MHWs?

What are the climatic '*drivers*' and/or oceanographic '*processes*' that modulate/cause marine heatwave events?

- Define '***drivers***' to be the climatic or meteorological forcing components of MHW events => including large scale modes of climate variability!



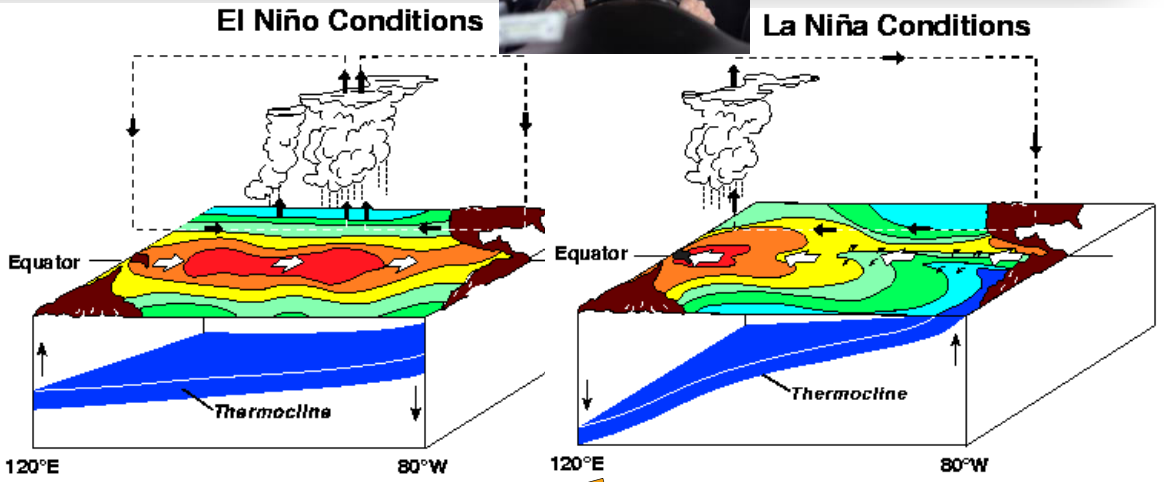
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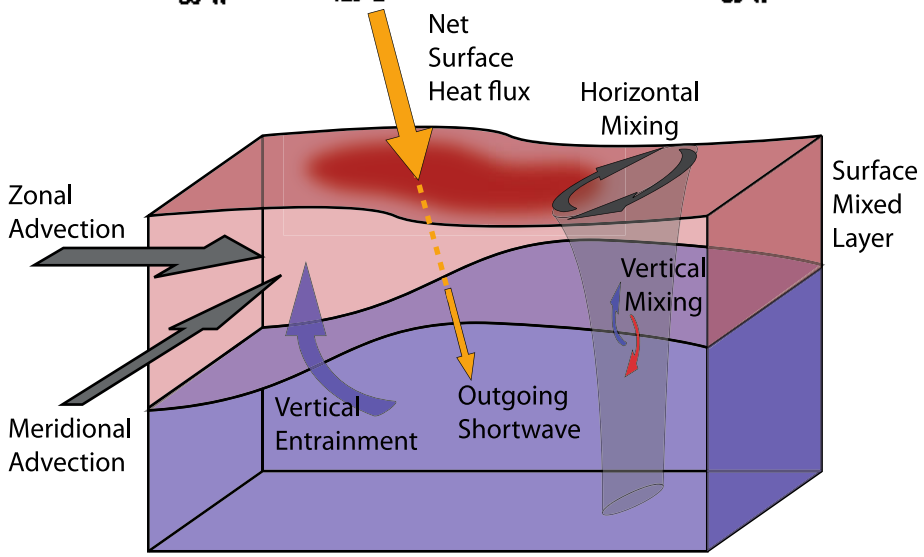


- Define '***drivers***' to be the climatic or meteorological forcing components of MHW events => including large scale modes of climate variability!

(El Niño – Southern Oscillation, North Atlantic Oscillation, etc.)



- Define '***processes***' to be the local factors that affect the evolution of ocean temperature within the surface mixed layer



2.1 Approach

Here we have

1)undertaken a systematic and comprehensive search of observed MHW events reported in the peer-reviewed literature since 1950



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2)performed a **meta-analysis** of these events to identify the characteristic large-scale **drivers** and local-scale **processes** that caused them

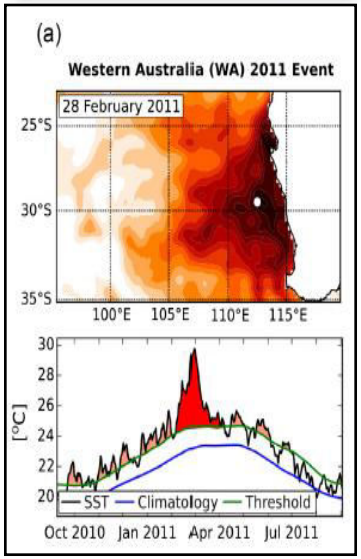
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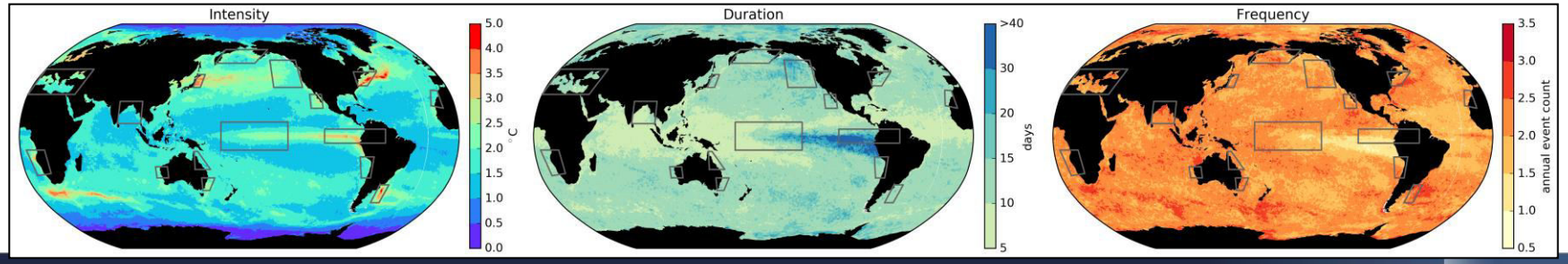
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3)uniformly analysed the **intensity**, **duration** and **spatial extent** of the identified events in high frequency sea surface temperatures from satellite data, and



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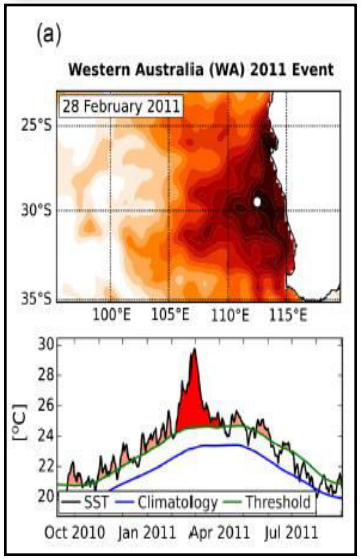
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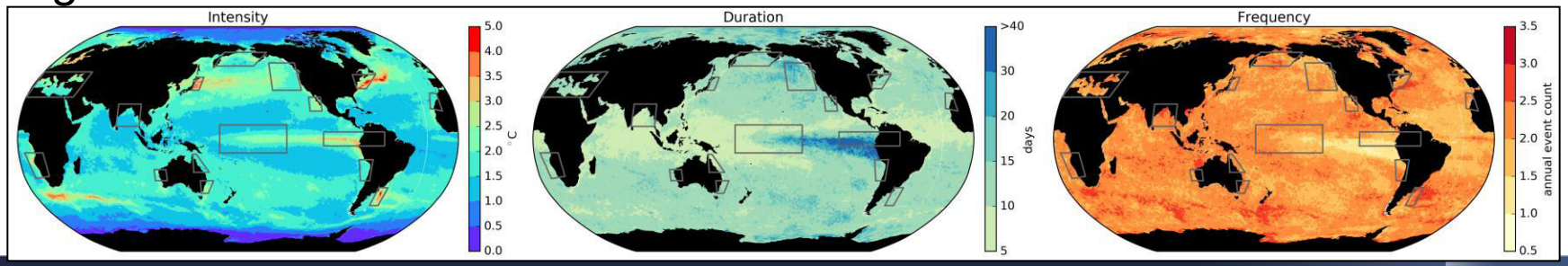


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4)Estimated **suppression** or **enhancement** of MHWs around the globe related to climate mode drivers





2.2 Literature Search

- Comprehensive search of the literature in ***Web of Science*** and ***Google Scholar***
  - *<u>Keywords</u>: sea surface temperature, extreme event, temperature anomaly, heatwave (and heat wave) / anomaly*



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Table S1. Literature review criteria for marine heatwave case studies informed by the hierarchical marine heatwave framework of Hobday et al.[11].

Marine Heatwave Literature Review Criteria	
1.	Expressed or measured through sea surface temperature
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- **174 relevant refereed publications identified since 1950!**

Confidence Level Analysis: identified 'Drivers' and 'Processes'

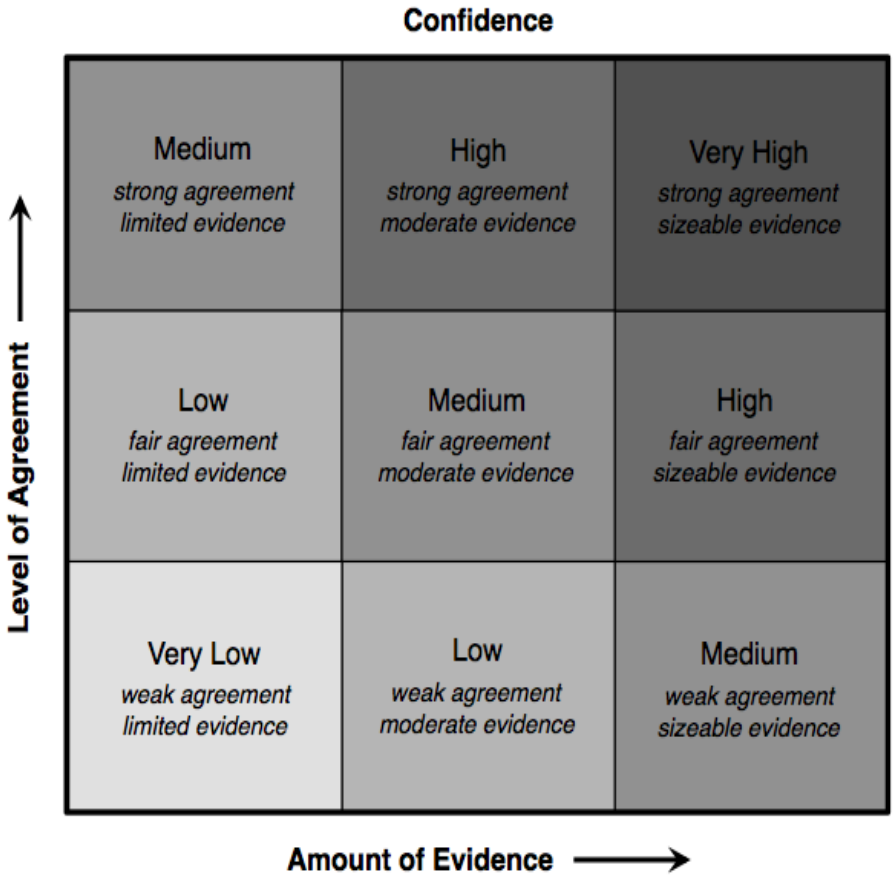
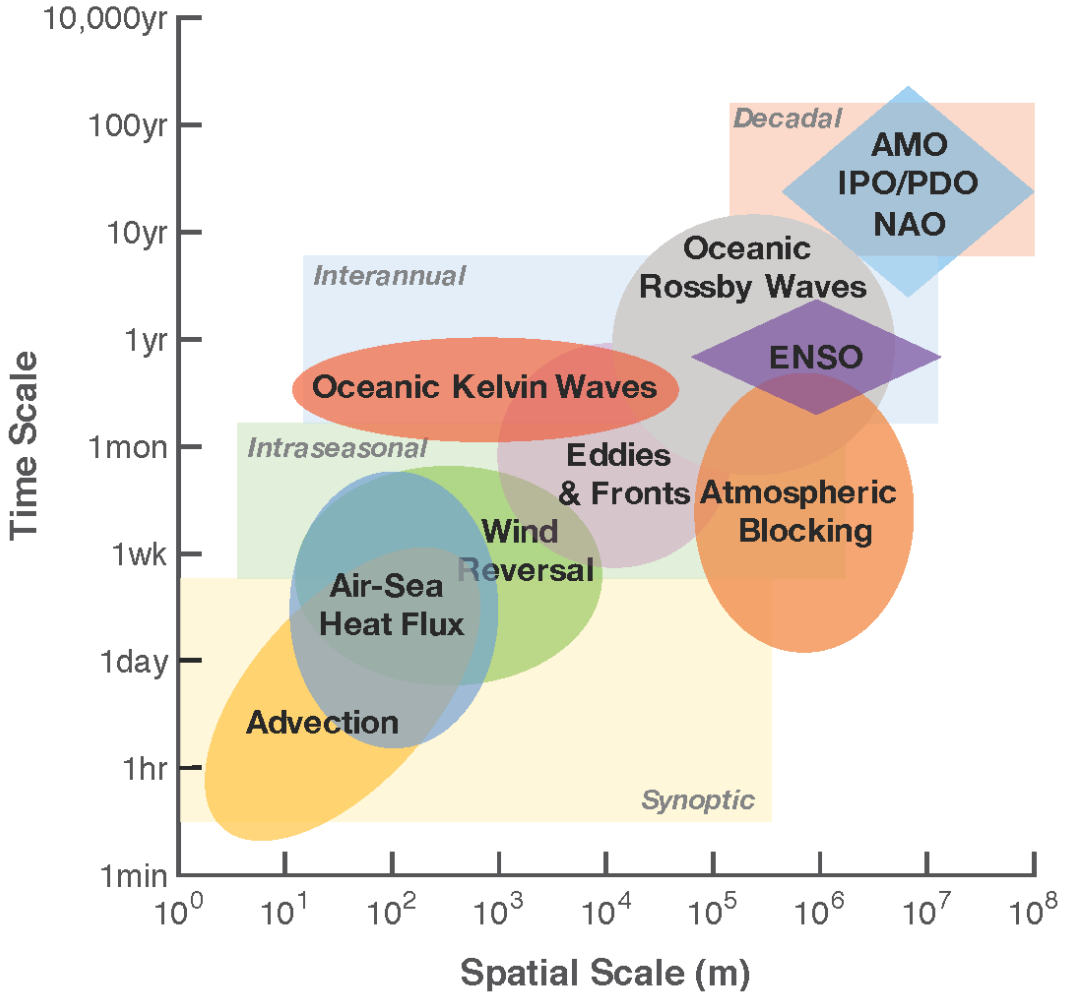




Figure. Qualitative confidence matrix based on ***level of agreement*** and the ***amount of evidence*** available. Modified from the IPCC AR5.

Marine Heatwave Drivers and Processes identified from the literature



2.3 Meta-analysis: EBC example

Interannual Drivers
- La Niña
- Ningaloo Niño

Interannual (Ocean) Processes
- ocean advection
- air-sea heat flux

Decadal Drivers
- negative Pacific Decadal Oscillation index

		Timescale									
		Synoptic		Seasonal to Intraseasonal		Interannual		Decadal			
Typology	Case Study*	Driver	Process	Driver	Process	Driver	Process	Drive	Process	Driver Confidence^	Process Confidence^
EBC	Benguela [52,64,78,65,79,60]			ABFZ, RNW, KWO, MJO	ADV, ASHF	BN, RNW, WWA, KWO	ADV, TD			Very High	Very High
	Leeuwin [67,69,66,9,80,81]			RASC, nSLP, RSW	ADV, EHF, ASHF, TD	LN, NN, SLA, EWA	ADV, ASHF	nPDO, SO	ASHF	Very High	Very High
	California [58,82,74,83,84,57,85–88,73]			SWA, RNW	ADV, ASHF, TD	EPEN, CN, REW, nSLP	ASHF, TD, ADV			Medium	Low
	Iberian / Canary [89–92]	AB	ASHF	nNAO, RASC, SWA	ADV, ASHF	JS	ASHF			Medium	Medium
	Humboldt / Peru [93,94]			KWO, RSW	TD, ADV, ASHF	EPEN, REW	ADV, ASHF			Medium	Medium

Subannual/annual Drivers
- negative North Atlantic Oscillation index
- regional air-sea coupling
- southerly wind anomaly

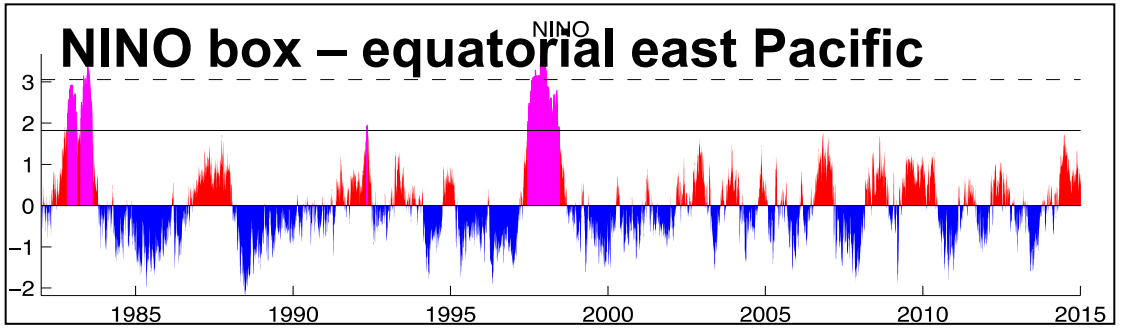
Interannual Drivers
- Eastern Pacific El Niño
- California Niño
- Relaxation of easterly winds
- Negative sea level pressure anomaly

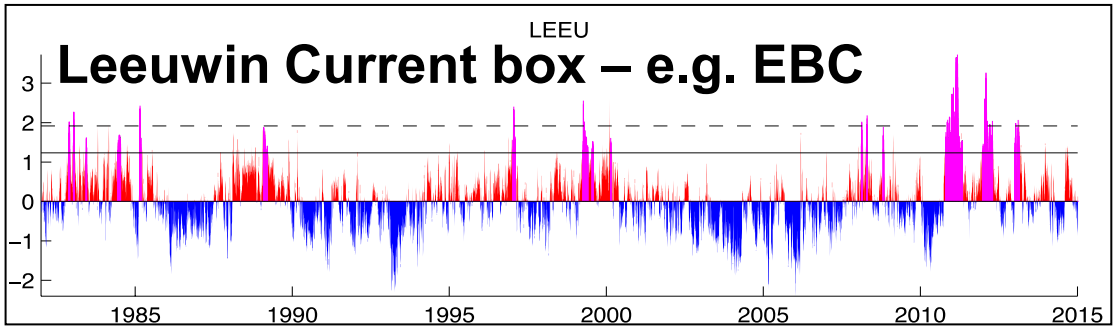
^ Confidence based on ***level of agreement*** & ***amount of evidence*** of MHW drivers and processes

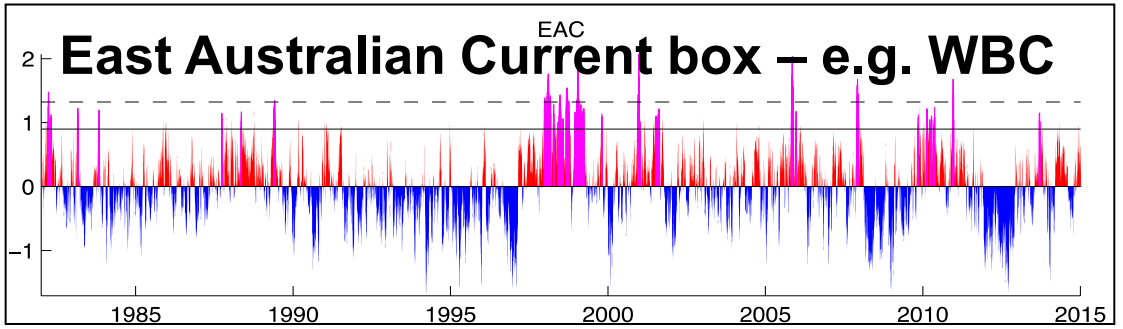
regional SSTA time series

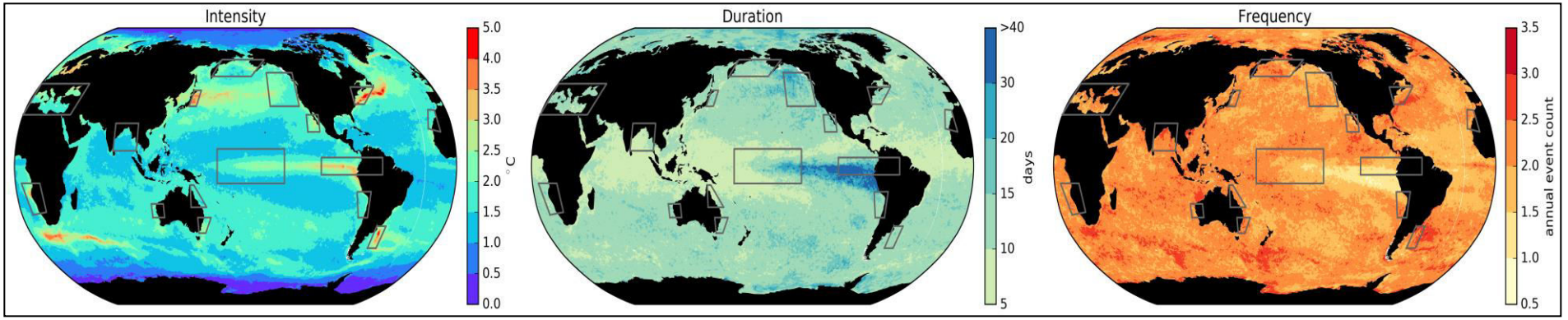
Identified regions include:

- Tropics
- Mid to high latitudes
- Western boundary currents
- Eastern boundary currents





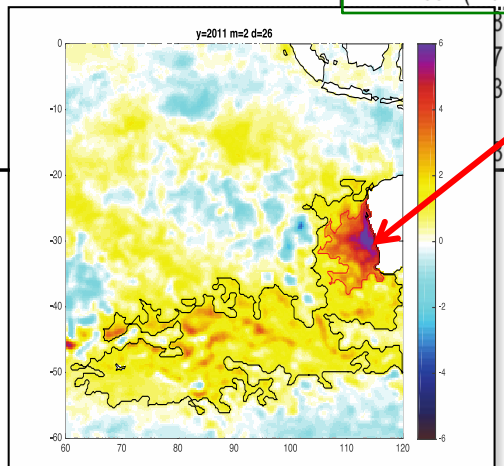


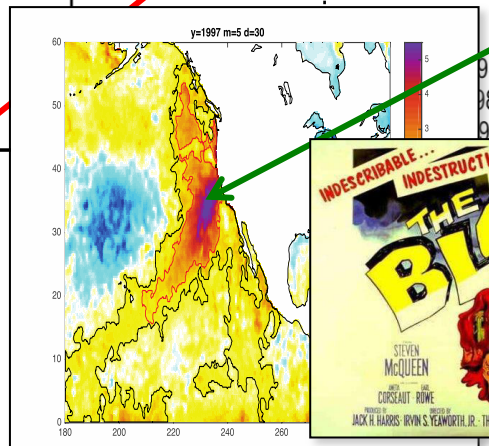


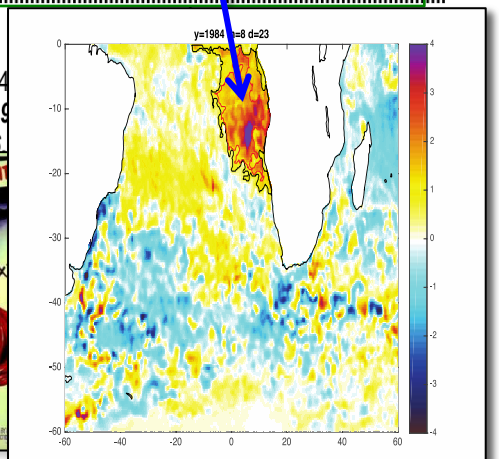
Marine Heatwave Metrics

from analysis of AVHRR SSTA corresponding to case studies

Typology	Case Study	Marine Heatwaves (References)	Metrics: Start Date (>98%)	Metrics: End Date (<98%)	Metrics: Max Intensity [°C (Date)]	Metrics: Max Area [Mkm^2 (Date)]
EBC	Benguela	1972/73 (62)				
		1982/83 (60)	22 Dec 1982	02 Feb 1983	4.8 (23 Jan 1983)	1.80 (26 Jan 1983)
		1984 (60,62)	08 Sep 1984	20 Nov 1984	4.8 (23 Aug 1984)	3.40 (29 Sep 1984)
		1985 (60,62)	24 Nov 1985	06 Dec 1985	***5.6*** (01 Dec 1985)	0.60 (01 Dec 1985)
		1995 (62,65)	18 Mar 1995	16 Apr 1995	3.6 (20 Mar 1995)	1.70 (08 Apr 1995)
		2001 (64)	No major event			
	Leeuwin	1950 (Feng et al 2015)				
		1961				
		1962				
		1967				
		1989	22 Jan 1989	25 Jan 1989	3.2 (24 Jan 1989)	0.23 (24 Jan 1989)
		2000				
		2011 (9,66,67,81)	04 Jan 2011	20 Mar 2011	***6.9*** (26 Feb 2011)	1.10 (03 Mar 2011)
		2012 (Feng et al 2015)	14 Jan 2012	30 Jan 2012	***5.1*** (29 Jan 2012)	1.00 (26 Jan 2012)
		2012/13 (Feng et al 2015)	30 Dec 2012	11 Jan 2013	4.4 (01 Jan 2012)	0.85 (08 Jan 2013)
	California	1957/58				
		1972/73				
		1976/77				
		1981 (58)				
		1982/83	22 Feb 1983	02 Mar 1983	3.9 (23 Feb 1983)	0.45 (24 Feb 1983)
		1984 (58)				
		1997/98 (74)	17 Oct 1997	21 Oct 1997	4.8 (19 Oct 1997)	0.62 (19 Oct 1997)
		1997 (Blob)	21 Apr 1997	23 Jun 1997	***5.7*** (30 May 1997)	3.40 (31 May 1997)

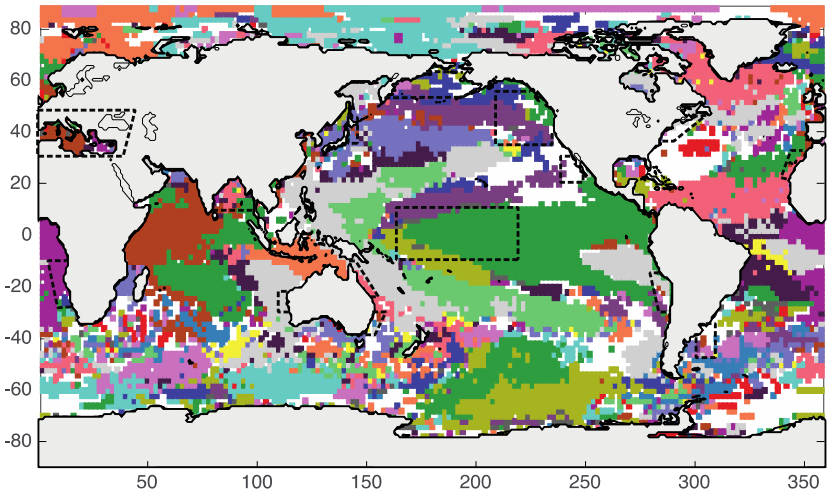




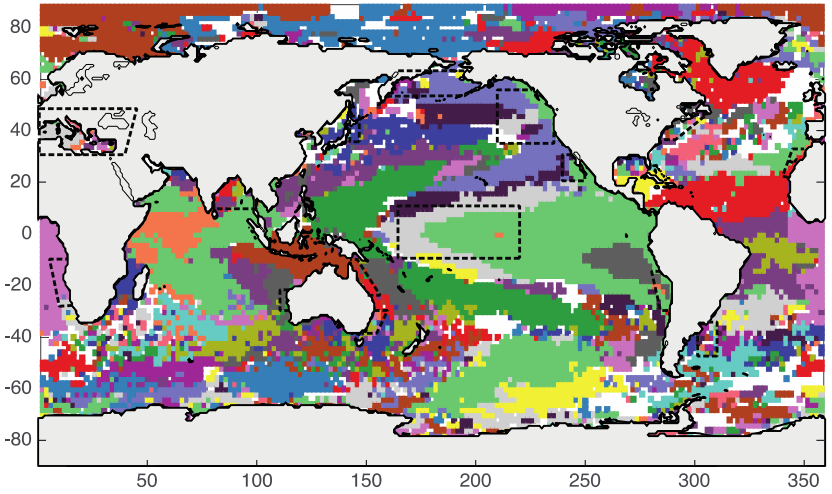


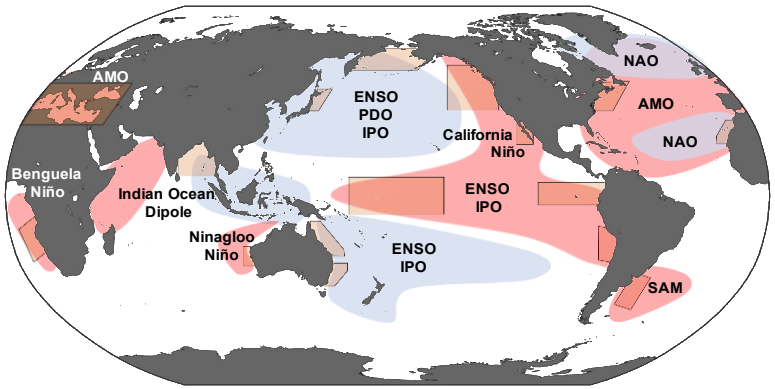
2.4 Unified MHW analysis: (suppression or enhancement?)

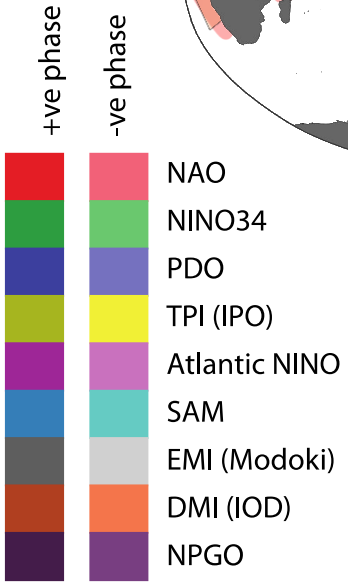
Primary drivers of increased MHW



Primary drivers of decreased MHW

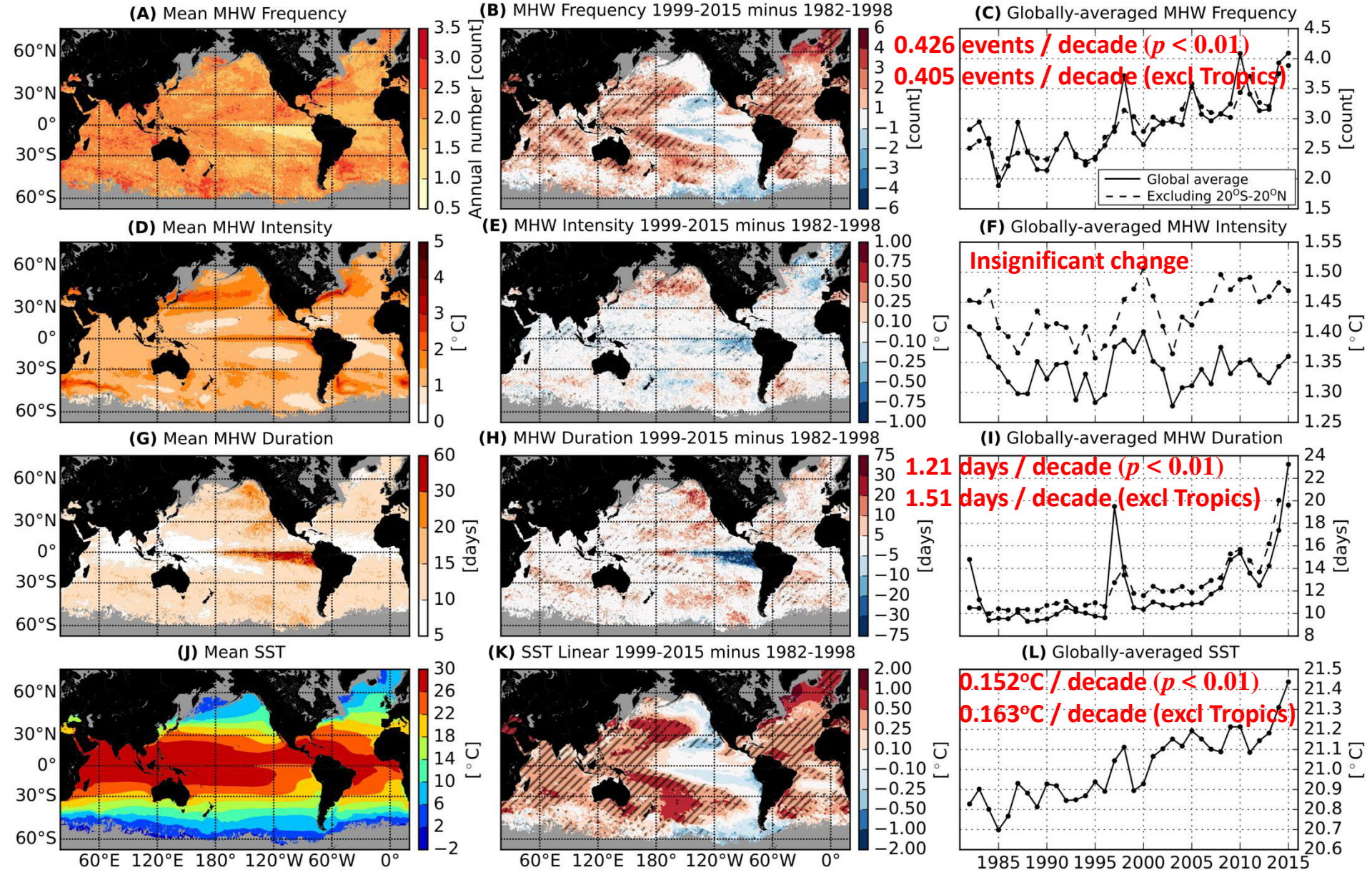






3. Global trends in MHWs?

Mean **1999-2015 minus 1982-1998** **Trend**



Long station records

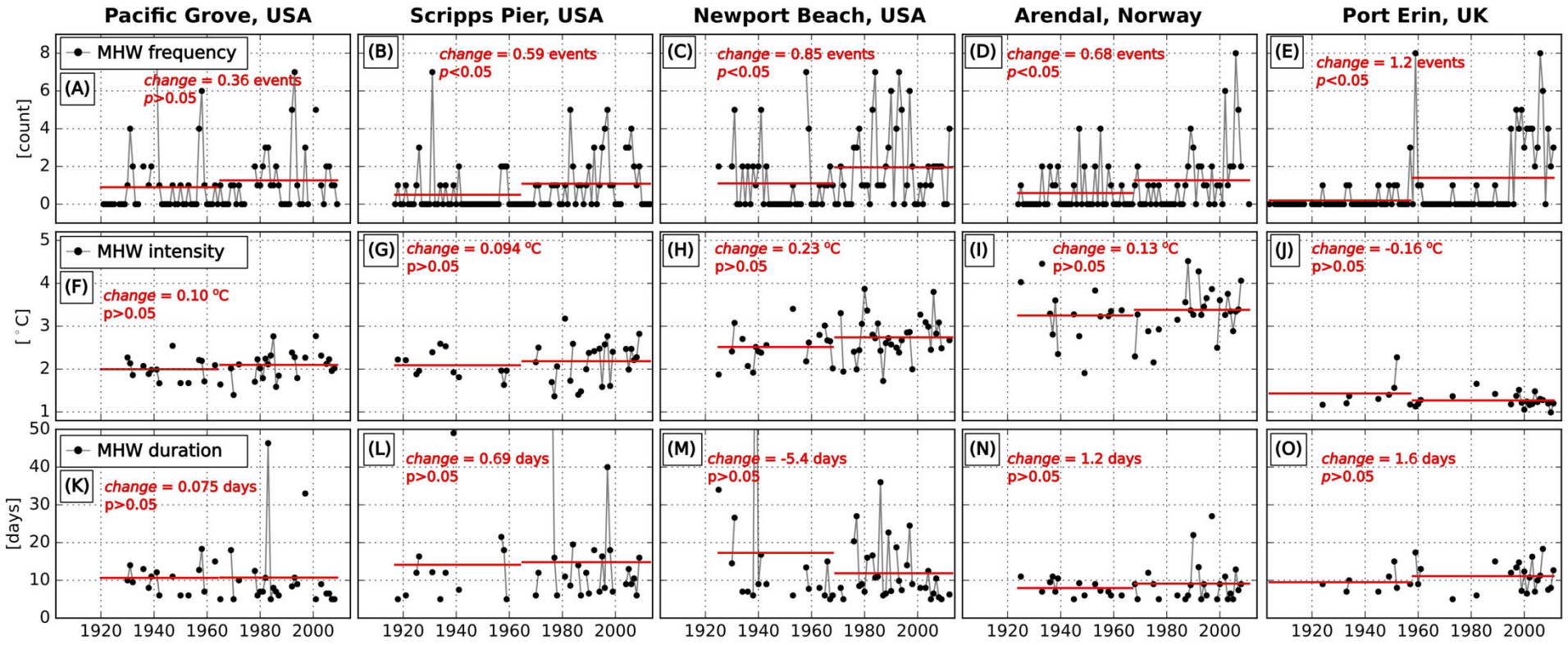
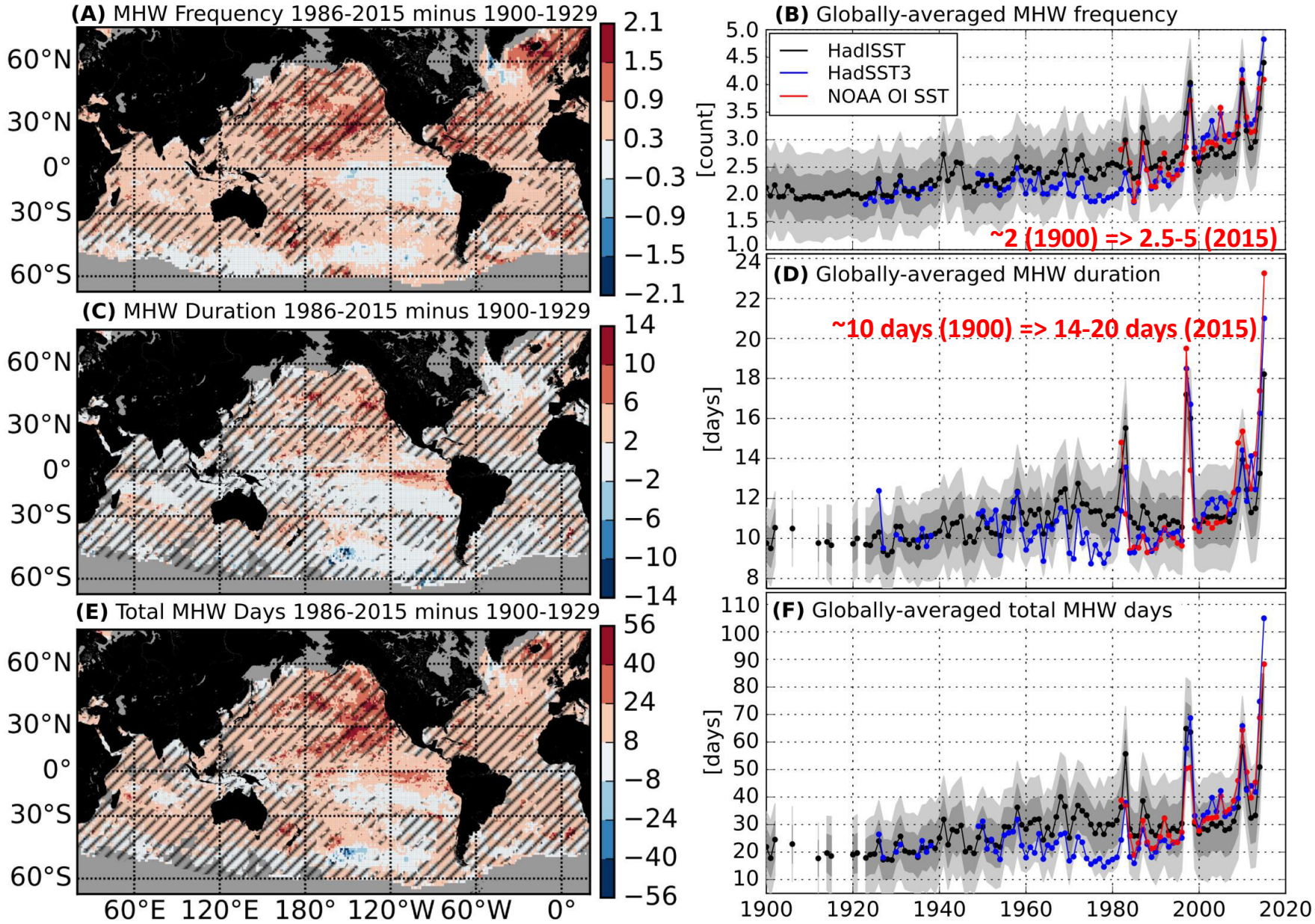


Figure: Marine heatwave properties at five sites with long-term daily in situ temperature records. Shown are (top row) the number of marine heatwaves in each year, (middle row) the average annual marine heatwave intensity, (bottom row) the average annual marine heatwave duration at Pacific Grove, Scripps Pier, Newport Beach (USA), Arendal (Norway) and Port Erin (UK). Red lines show means over the first and second halves of the time series and red text indicate differences (statistical significance given by two-sample Kolmogorov-Smirnov (KS) test).

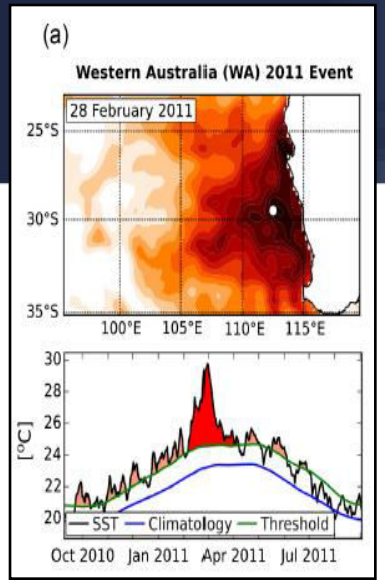
3. Global trends in MHWs?

Long-term changes in MHW proxies derived rom monthly gridded Hadley Centre SST data

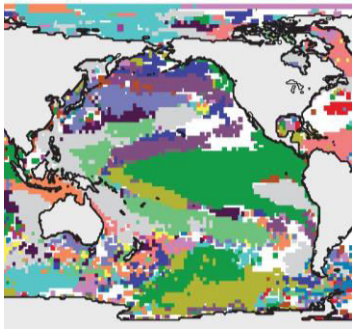


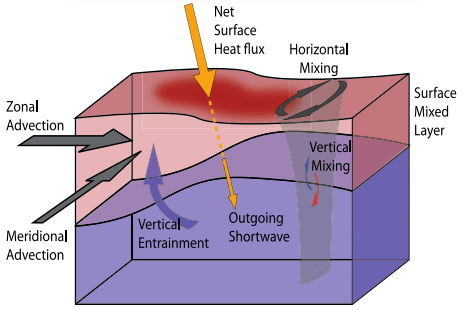
Conclusions

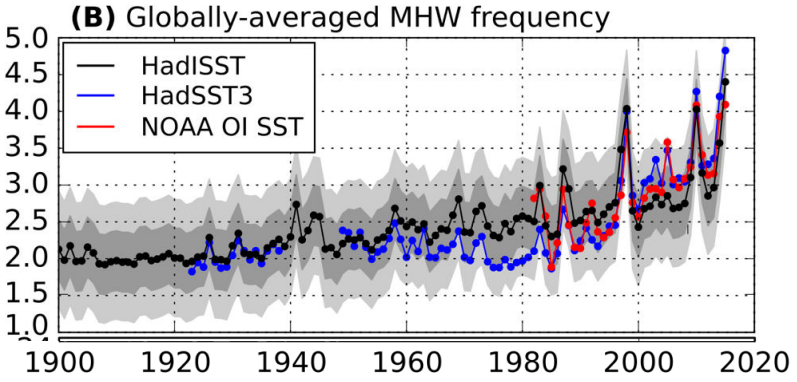
- **Marine heatwaves**: an exciting new field, developing rapidly in the **physical** and **ecological** fields
- Developed a **consistent definition**
- Distribution and variability linked to **drivers and processes**
- **Long-term trends**:
  - MHW **frequency** and **duration** **increased by 1.5-2x** (esp. since 1982, satellite period)
  - **Increase in mean SST** main reason for global increase in MHW freq. and duration
  - **Climate change** helps **increase risk** of MHWs => recent 2015/16 Tasman Sea event
- **Ongoing MHW research by the team**











Long station records

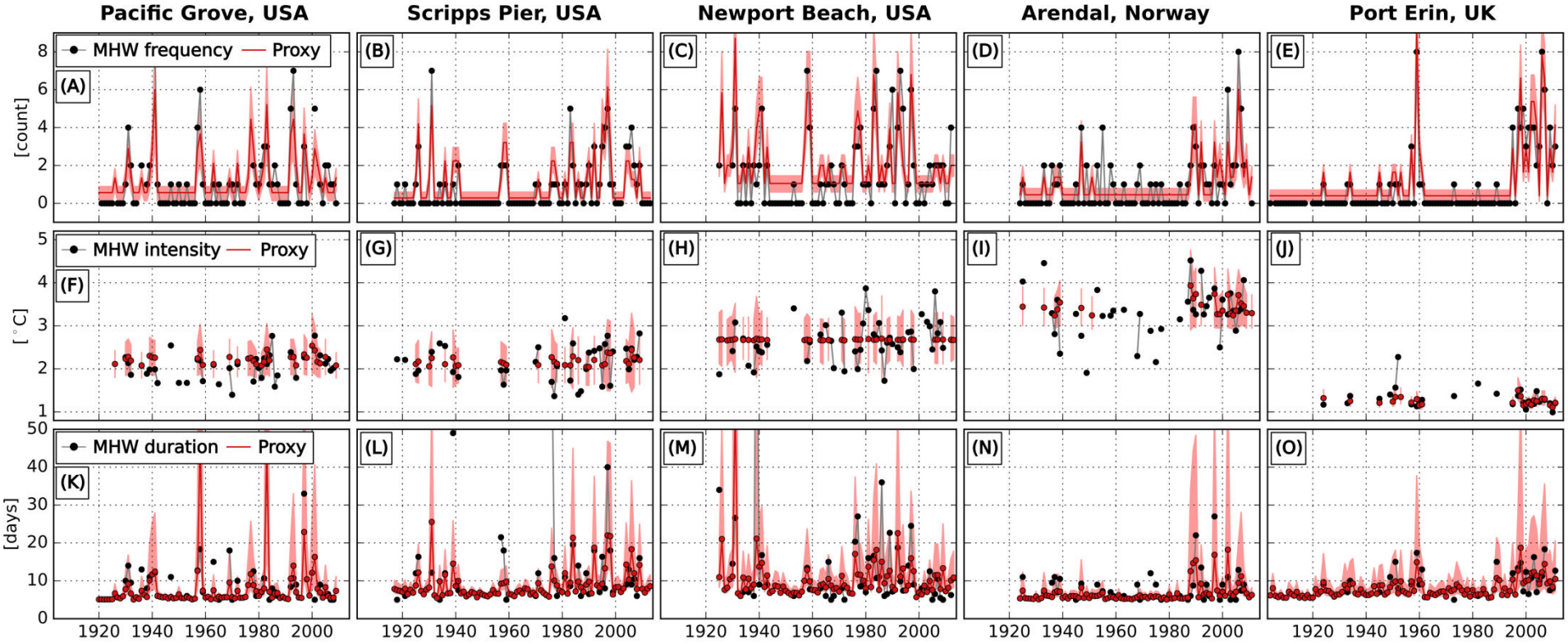


Figure: Marine heatwave properties and their proxies at five sites with long-term daily in situ temperature records. Shown as black lines are (top row) the number of marine heatwaves in each year, (middle row) the average annual marine heatwave intensity, (bottom row) the average annual marine heatwave duration at Pacific Grove, Scripps Pier, Newport Beach (USA), Arendal (Norway) and Port Erin (UK). Also shown in each panel is the corresponding proxy (red line) and 95% confidence interval (red shading) derived using monthly temperature data.

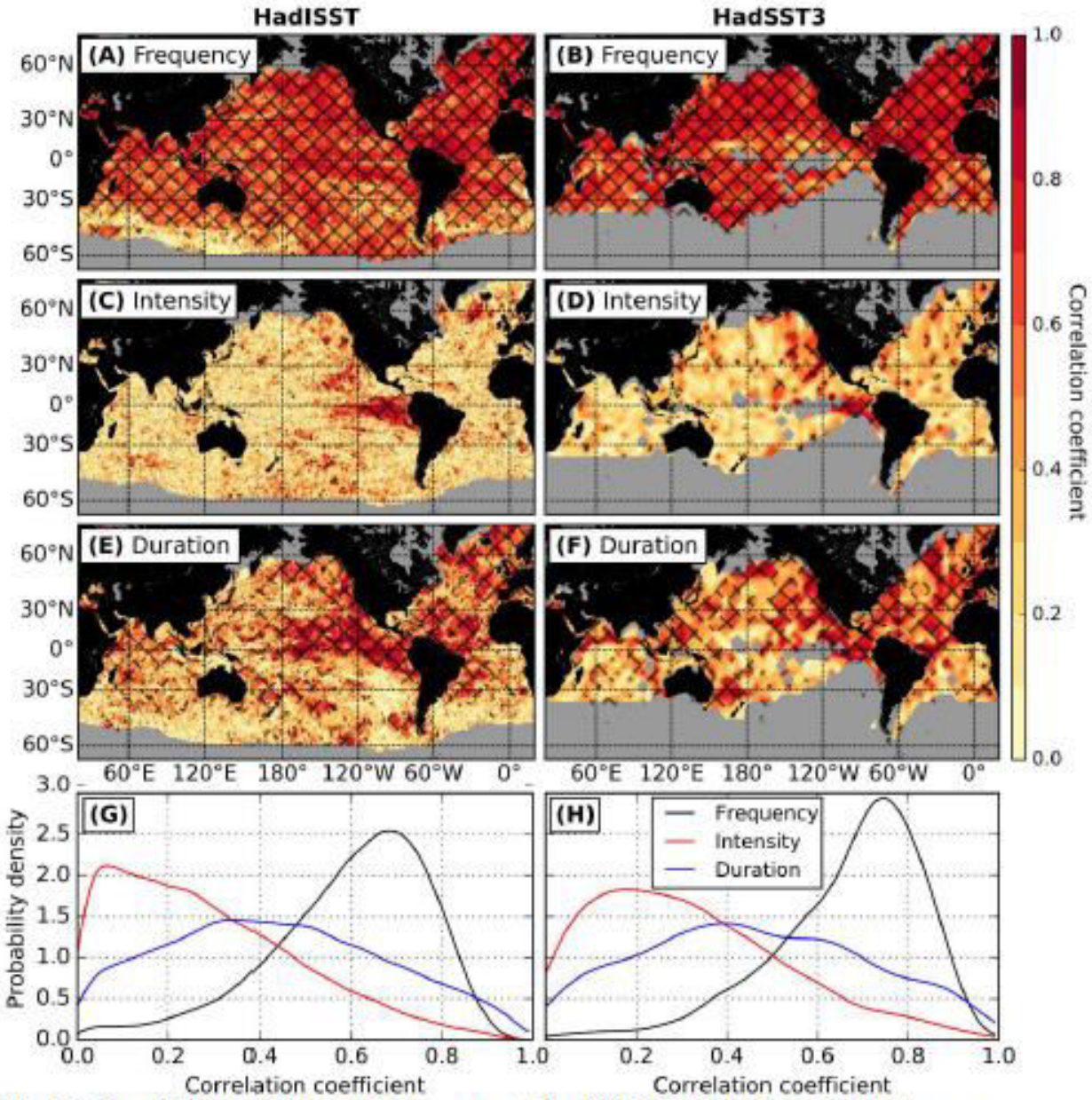


Fig. S3. Correlation coefficients for proxy models of NOAA OI SST marine heatwave properties based on (left) HadISST and (right) HadSST3 data over 1982-2015. Shown (A-F) are spatial maps of the correlation coefficients and (G-H) probability distributions of correlation values for all grid cells. Hatching indicates correlation coefficient is statistically significant at the 5% level; grey indicates missing or insufficient data.

Enhance or suppress MHWs?

	NAO		*NINO34*		*PDO*		*TPI/IPO*		*Atl. Nino*		*SAM*		*EMI*		*DMI*		*NPGO*	
	+ve	-ve	+ve	-ve	+ve	-ve	+ve	-ve	+ve	-ve	+ve	-ve	+ve	-ve	+ve	-ve	+ve	-ve
BENG	7	11	-	-	-	-	-	-	16	2	-	-	-	12	-	-	-	-
BERING	-	-	-	-	16	4	15	6	7	-	-	-	-	-	-	-	-	-
BRZ	-	-	-	-	-	-	-	-	7	14	-	-	-	-	-	-	-	-
Blob	-	-	19	6	20	5	20	6	6	-	-	-	18	5	-	-	5	20
BofB	6	12	-	-	-	-	6	-	-	-	11	7	-	-	12	7	13	6
CP	-	-	21	0	-	-	14	7	-	-	-	12	16	2	15	6	-	-
Cal	-	-	18	5	-	-	-	-	-	-	-	-	-	-	-	-	6	17
Can	6	14	13	7	-	-	-	-	-	-	-	-	-	-	13	8	-	-
EAC	8	12	-	-	-	15	-	-	13	7	-	-	-	-	-	-	-	-
GBR	6	13	-	-	-	-	-	-	-	-	-	-	-	13	7	-	-	-
GS	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Humb	-	-	14	5	-	-	-	-	-	-	-	-	-	-	13	-	-	-
KC	-	-	-	-	3	14	-	-	12	5	-	-	-	-	12	-	-	-
LEEU	-	-	4	16	6	14	4	15	-	7	-	-	3	18	-	-	14	5
MED	-	-	-	-	-	-	-	-	-	-	-	-	-	-	11	6	-	-
EP	-	-	20	2	-	-	-	-	-	-	-	-	-	-	17	6	-	-

Percentage of days that the region is in a MHW during a positive (+ve) or negative (-ve) phase of a given climate mode. **Red** (**blue**) numbers indicate when the phase of a particular mode is **enhancing** (**suppressing**) **the likelihood of a MHW**.

Guiding analysis

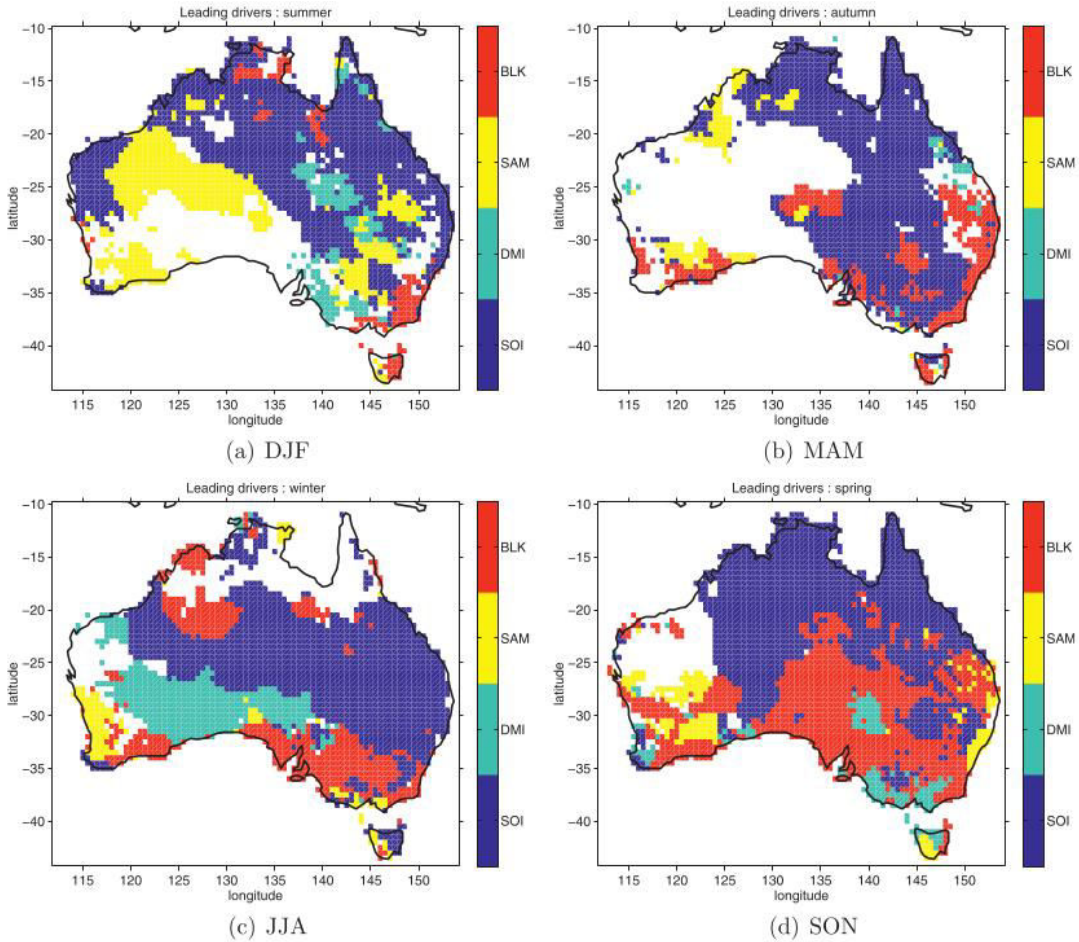
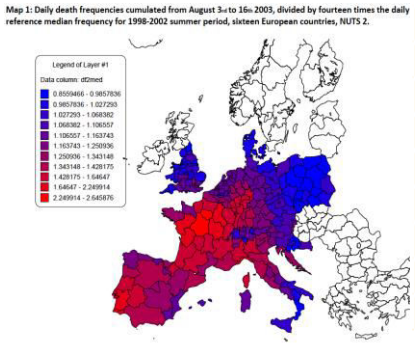


FIG. 15. Each map shows the climate driver with the highest correlation to monthly rainfall at each grid cell across the continent for each season (a) DJF, (b) MAM, (c) JJA, and (d) SON. The drivers included are blocking (BLK), SAM (SAM), IOD (DMI), and ENSO (SOI). Only correlations significant at the 95% level were included in selecting the driver with the highest correlation. In the blank areas none of the drivers has a significant correlation with rainfall. The data span the period 1957–2006.

Risbey et al, 2009: *Monthly Weather Review*, **137,** 3233-3253

Introduction

- Extreme warm events that persist for extended periods of time, also known as ***heatwaves***, can have disastrous consequences for life on Earth, e.g. 2003 in Europe!
  - UNEP 2004; Kovats et al. 2004 (*~30,000 deaths*)
- However, unlike their atmospheric counterparts over land, ***marine heatwaves (MHWs)*** are largely unstudied – although a limited number of individual events are identifiable in the literature
  - 2003 Mediterranean event (Garrabou et al 2009)
  - 2011 WA event (Smale & Wernberg 2013;Wernberg et al 2013)
  - 2012 NW Atlantic event (Mills et al 2013)
- More specifically, we have no comprehensive global understanding about the distribution, frequency, duration or intensity of MHWs, or the underlying **physical causes**



Country	Casualties
France	14 082
Germany	7 000
Spain	4 200
Italy	4 000
UK	2 045
Netherlands	1 400
Portugal	1 300
Belgium	150

