Marine heatwaves: Global distribution, long-term trends, and case studies off southeast Australia

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[6] *Australian Institute of Marine Science, Townsville, Queensland, Australia*
[7] *Oceans and Atmosphere Flagship, CSIRO, Perth, Western Australia, Australia*
[8] *Oceans and Atmosphere Flagship, CSIRO, Hobart, Tasmania, Australia*
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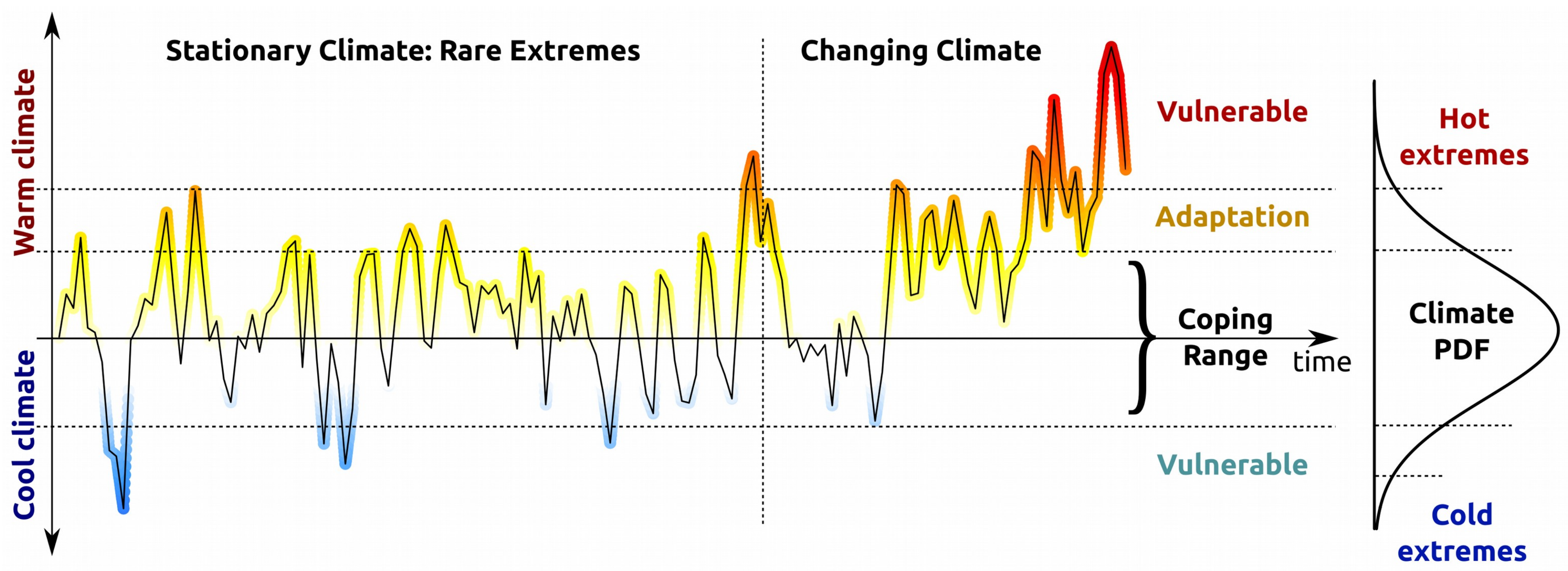
Marine Heatwaves

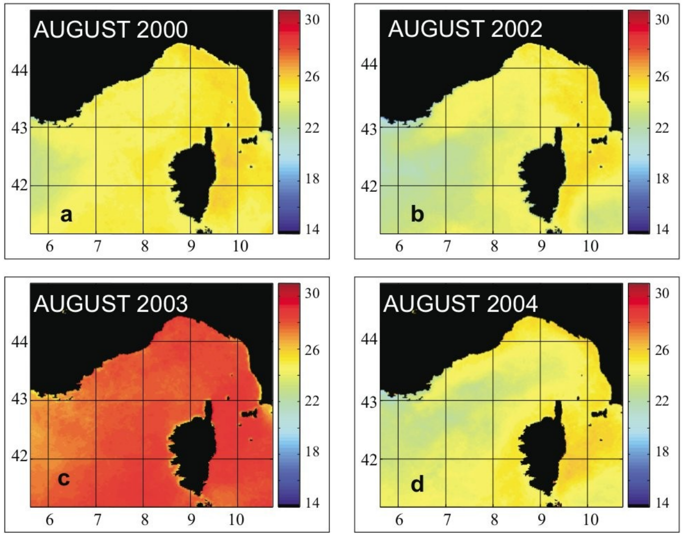
- **Marine extremes** have been studied for decades, but research has focussed on a few physical variables (**sea levels**, **wave heights** and **current speeds**), less attention on **temperature** until recently
- **Extreme events** in seawater temperature important for determining marine **ecosystem structure** (e.g., *2011 WA event*) and can **impact fisheries** (e.g., *2012 NW Atlantic event*)
- Some indications that impacts of MHWs are **becoming more severe** in the context of warming climate, and that they are becoming **more frequent**
- **How to define MHWs? What drives them? Global trends in MHWs?**



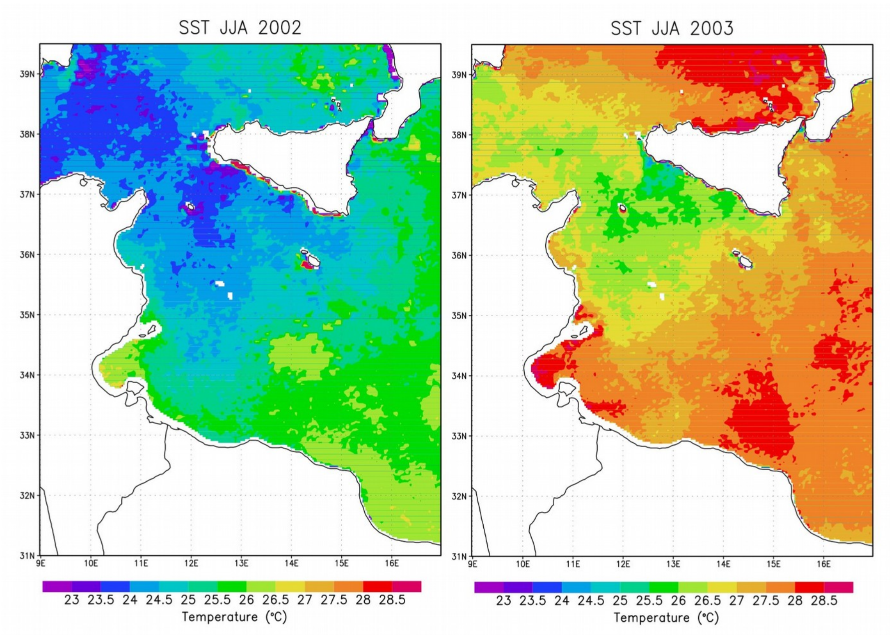
Mediterranean 2003

- In **summer 2003 a record heatwave** was experienced in Europe (particularly in France)
- August surface temperatures (SSTs) in the Ligurian Sea were as high as 28-28.5°C in 2003, **2-3°C higher than previous summers** (Sparnocchia et al., 2006)
- SSTs in the Tyrrhenian Sea were over 29.5°C, **anomalous June SSTs of up to 2.5°C** (Olita et al., 2007)
- Warming confined to the upper layers (<20 m depth), anomalously cold below this depth.
- Caused by anomalous air-sea heat flux: high air temperatures (the atmospheric heatwave) and low wind speeds.
- This marine heat wave as likely linked to the mass mortality in local **rocky reef communities** at that time (Garrabou et al., 2009).

SSTs in the Ligurian Sea



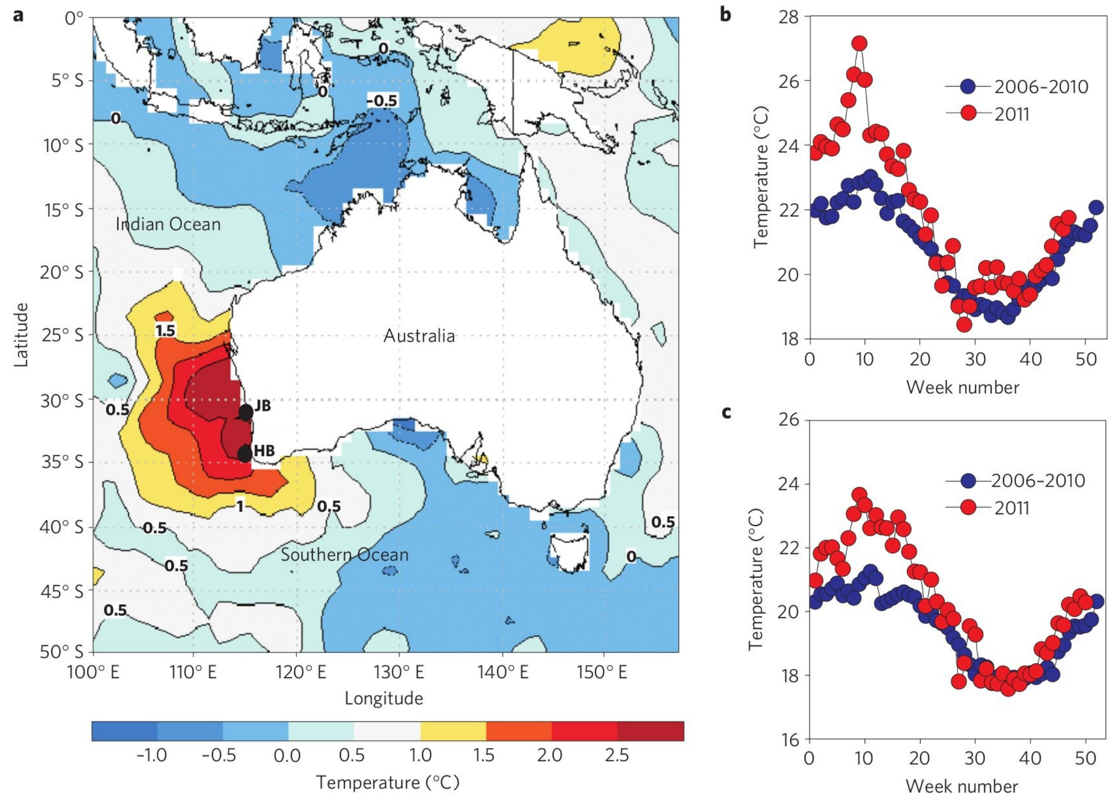
SSTs in the Tyrrhenian Sea

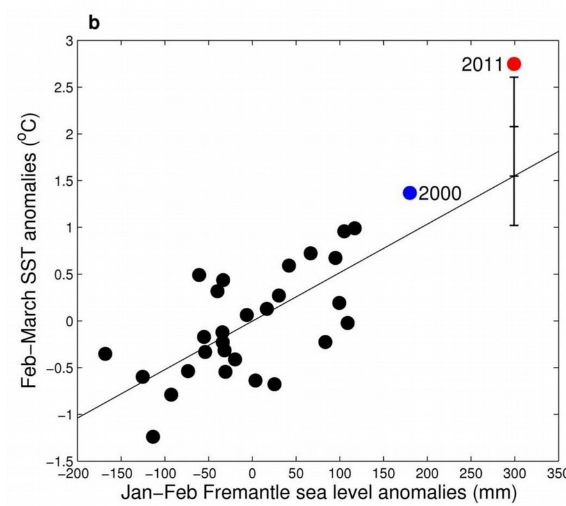


Sparnocchia, S. et al. (2006), *Annalles Geophysicae*, 24, 443-452
Olita, A. et al. (2007), *Ocean Science*, 3, 273-289
Garrabou, J. et al. (2009), *Global Change Biology*, 15, 1090-1103

Western Australia 2011

- In **summer 2010/2011 an unprecedented “marine heat wave” was documented off Western Australia**
- SST anomalies peaked at **3°C above the expected value** along a stretch of WA coast (from Ningaloo at 22°S to Cape Leeuwin at 34°S) and over 200 km offshore (Pearce and Feng, 2013)
- Feng et al. (2013) dubbed this type of event **“Ningaloo Niño”** and noted the warming was primarily due to a surge of warm water south along the coast due to the Leeuwin current.
- This was forced remotely, associated with the near-record 2010-2011 La Nina.





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

IMAS INSTITUTE FOR MARINE AND ANTARCTIC STUDIES

Western Australia 2011

UTAS

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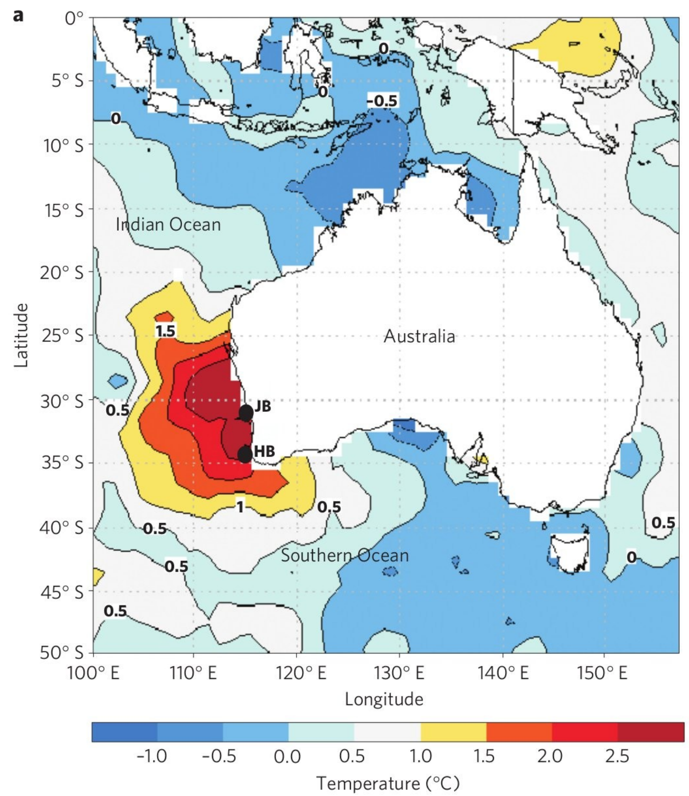
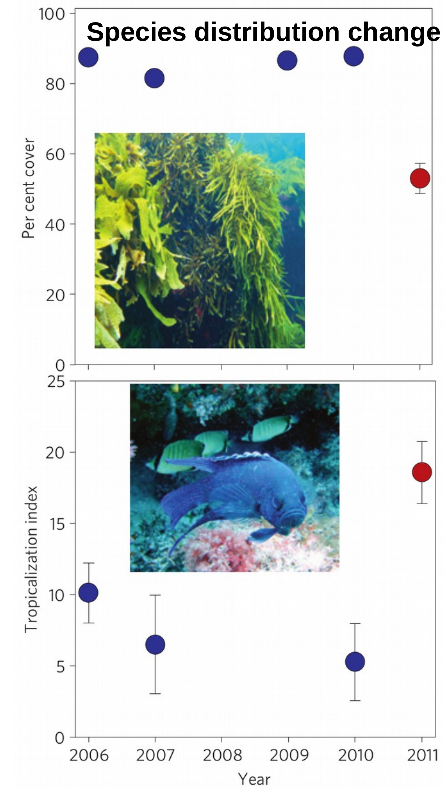
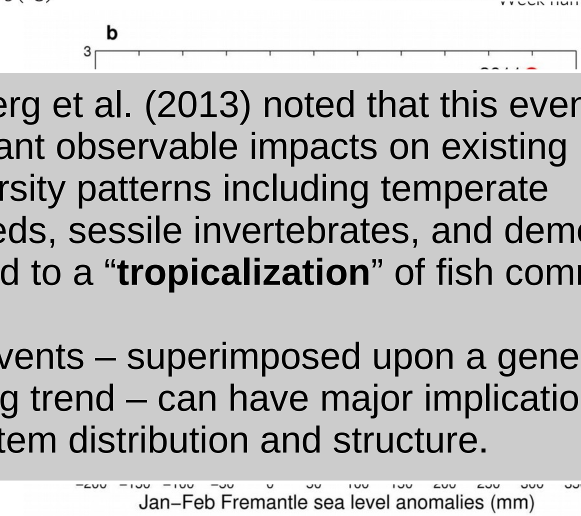






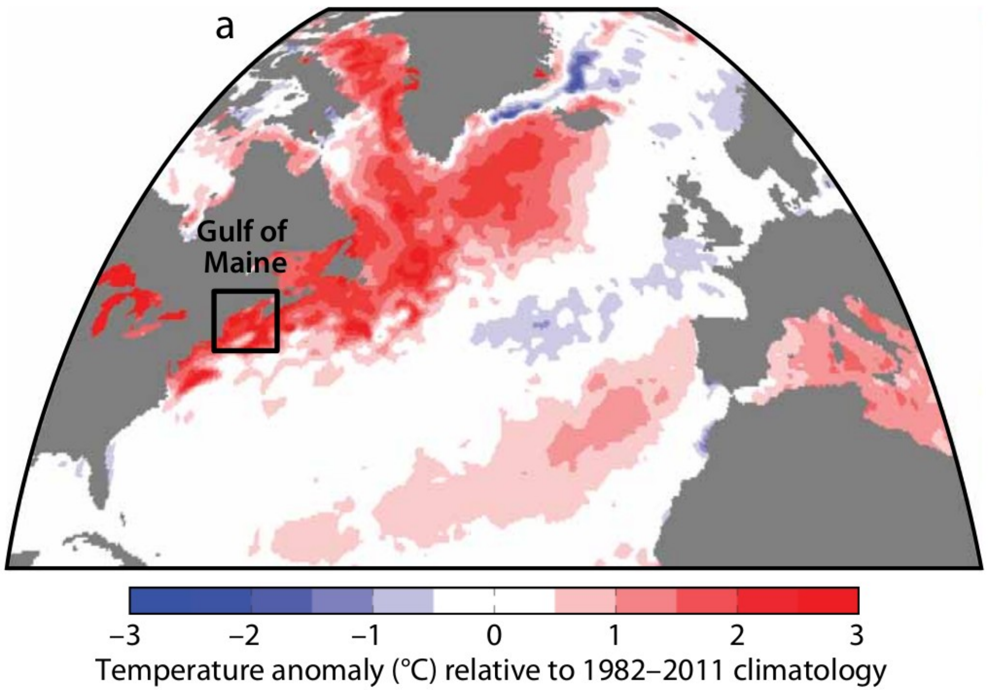
Wernberg et al. (2013) noted that this event had significant observable impacts on existing biodiversity patterns including temperate seaweeds, sessile invertebrates, and demersal fish. Led to a “**tropicalization**” of fish communities.

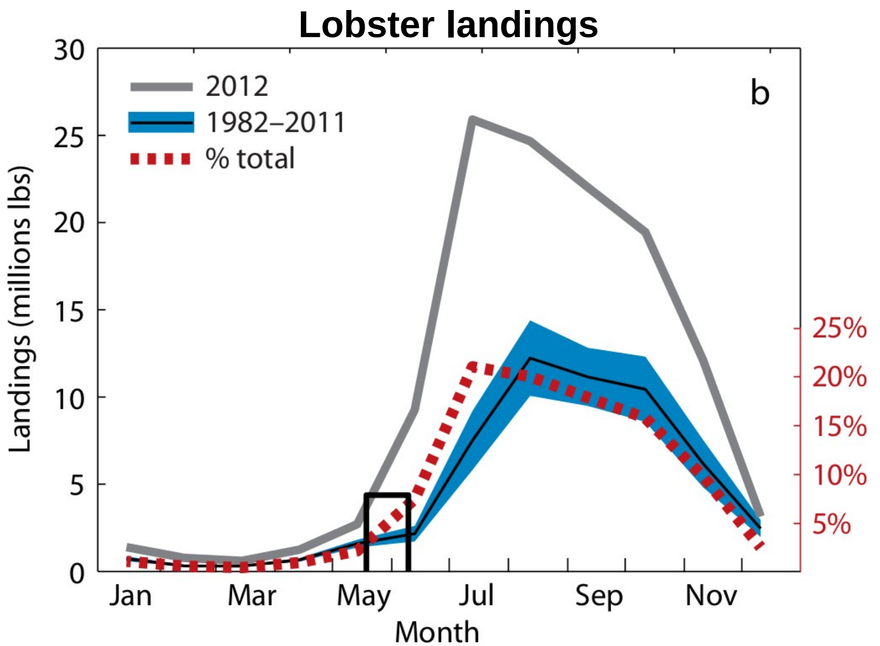
Such events – superimposed upon a general warming trend – can have major implications for ecosystem distribution and structure.

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

NW Atlantic 2012

- In **Boreal summer 2012 another dramatic heat wave occurred, in the northwest Atlantic**
- SST anomalies peaked at 3^{O}C above the expected value along a stretch of Eastern Canada and USA (Mills et al., 2013)
- Linked to **atmospheric warming** and anomalous positions of the **Gulf Stream** and the **jet 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

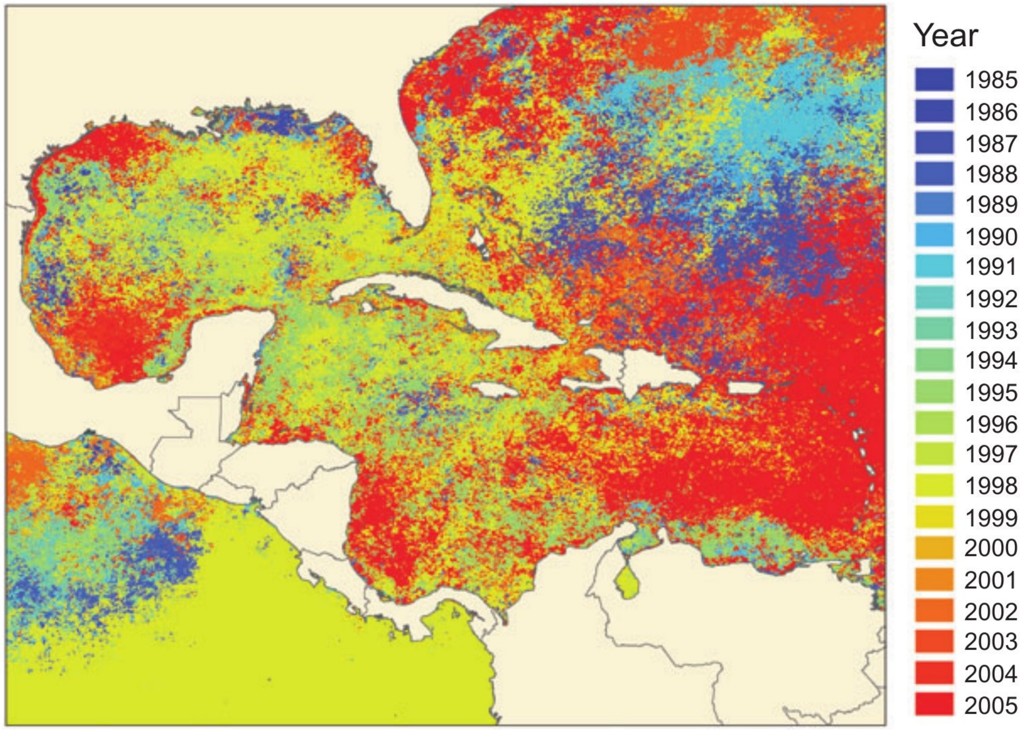




Mills, K.E. et al. (2013), *Oceanography*, 26(2), 60-64
Chen K.. et al. (2014), *JGR Oceans*, 119, 1-10
Chen K.. et al. (2015), *JGR Oceans*, 120, 4324-4339

Global Context

- Selig et al. (2010) examined global SST anomalies over a 21-year period and represented the data as the magnitude, timing, and frequency of **thermal stress anomalies (TSAs)**.
- TSAs are defined for each grid cell as temperatures that **exceed the climatological warmest week** of the year (in that grid cell).
- They showed significant **regional variation** in extreme ocean temperatures (as characterised by the TSAs)



Selig, E. R. et al. (2010), *Global Ecology and Biogeography*, 19, 397-411

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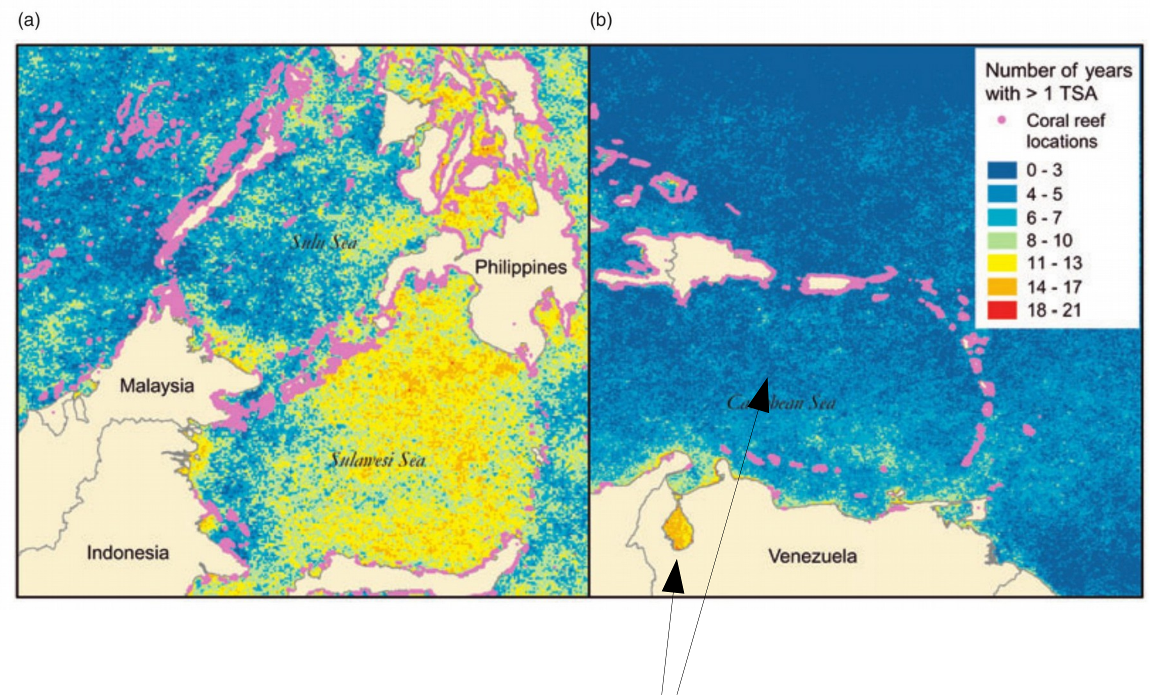


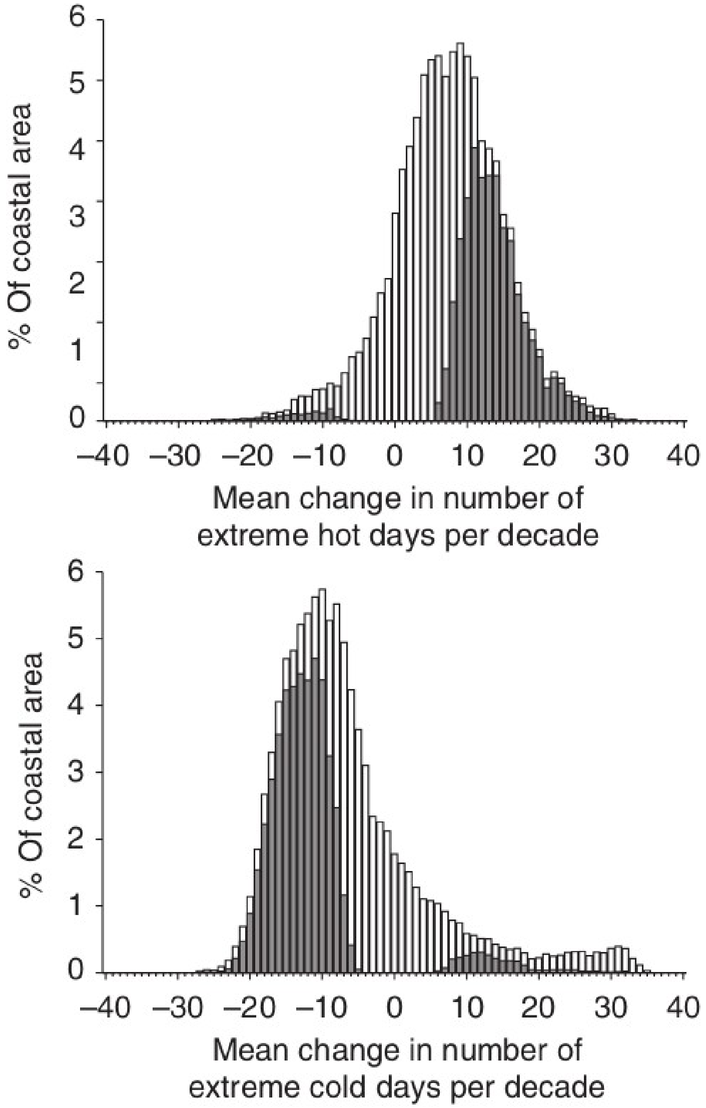
Non-homogeneous response (coastal vs. offshore)

Selig, E. R. et al. (2010), *Global Ecology and Biogeography*, 19, 397-411

Global Context

Lima and Wethey (2012) performed an analysis of **coastal marine temperatures** around the globe noted that

- linear trends vary regionally and seasonally,
- However, globally frequencies of
  - **extremely warm days** are generally **increasing**, and
  - **extremely cold days** are generally **decreasing**



Lima, F. P. and D. S. Wethey (2012), *Nature Communications*, 3, 704

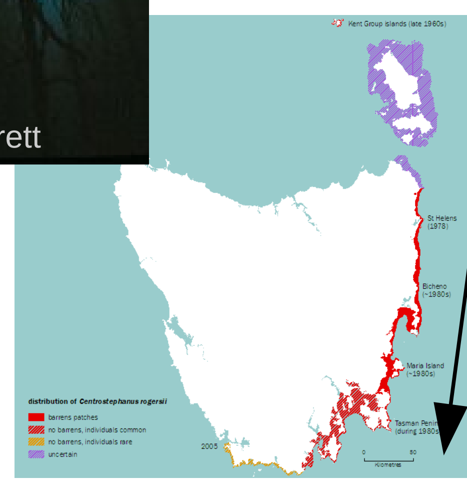
Temperate Impacts

- Spiny sea urchins are **displacing giant kelp** along Tasmania's coastline

Spiny sea urchin
(C. rodgersii)

Kelp forests (Macrocystis pyrifera) off Tasmania

kelp become → urchin barrens

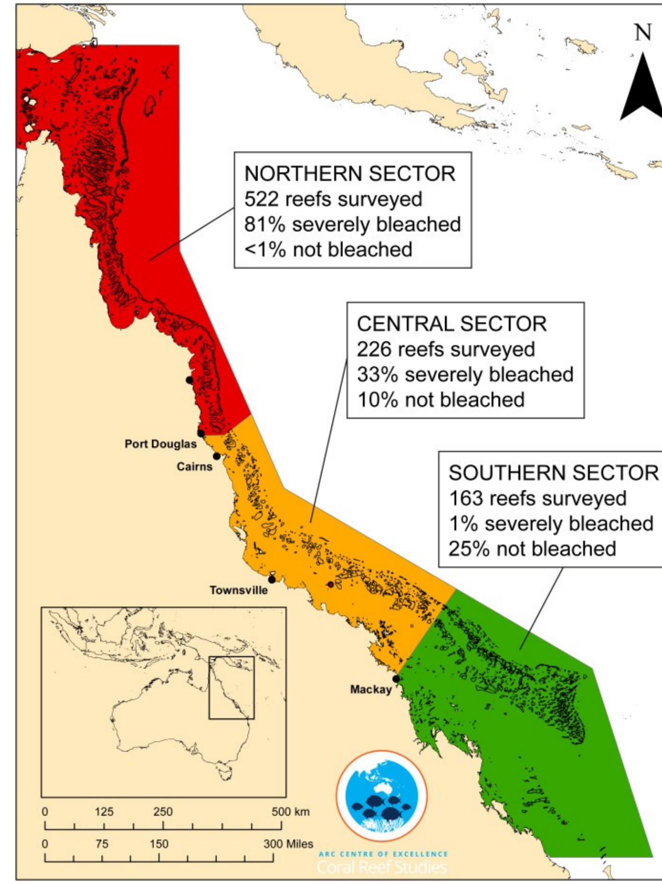


Range extension

e.g. Johnson et al. (2011), JEMBE, 400, 17-32

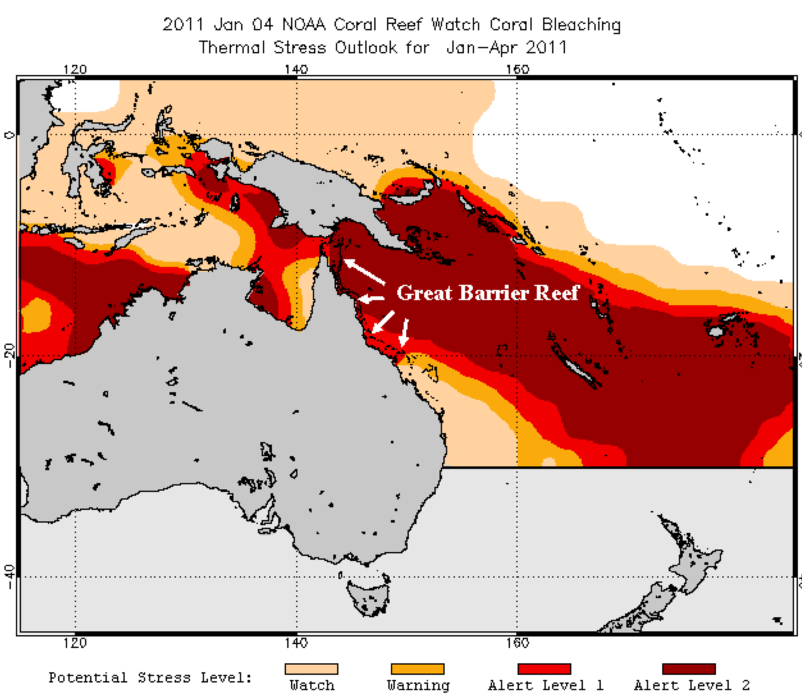
Tropical impacts

- **Coral bleaching** is caused by exposure of coral reefs to elevated ocean temperatures and/or light levels
- Can be harmful to the coral reef **ecosystem**
- Reefs increasingly sensitive to bleaching in a **warming ocean…**

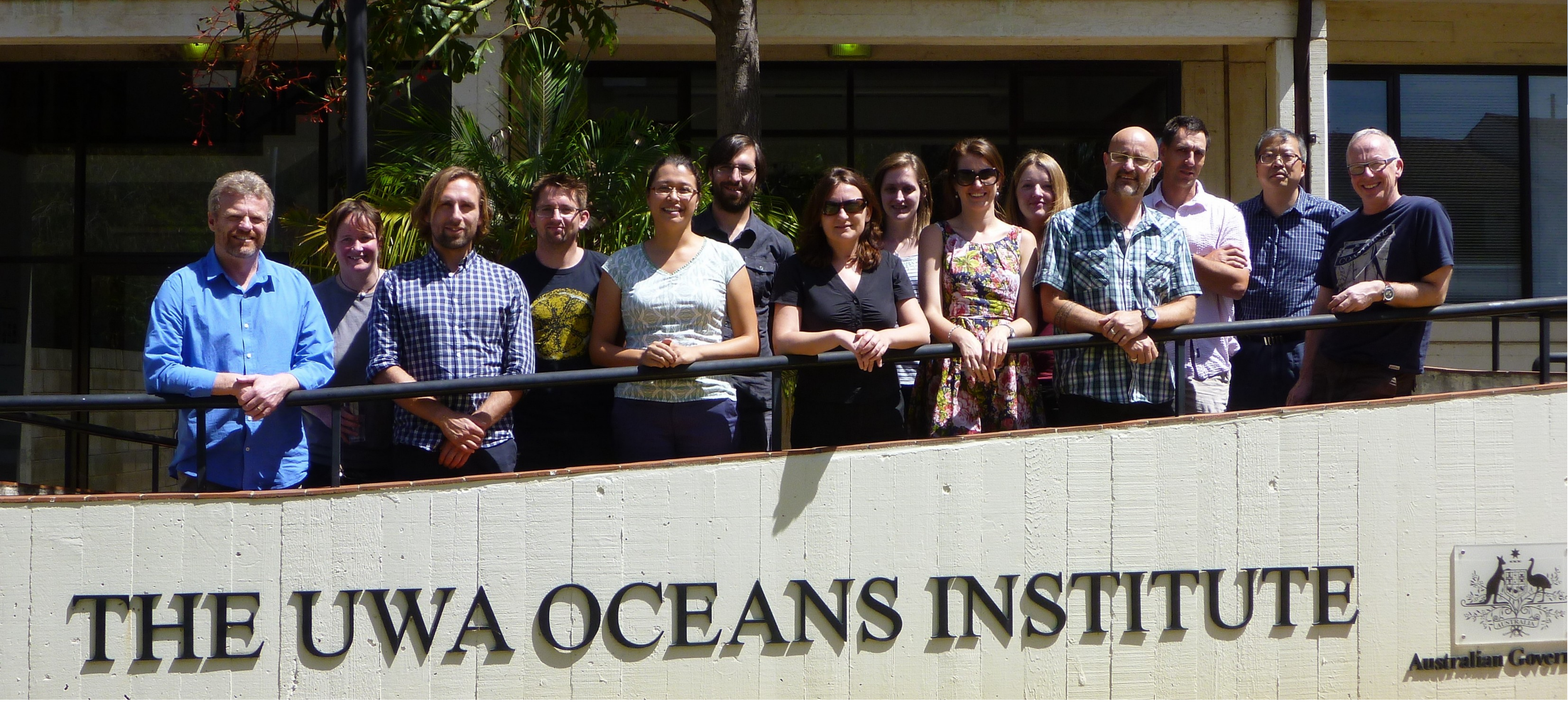


ARC COE Coral Reef Studies

2016 Great Barrier Reef Bleaching Event



NOAA Coral Reef Watch



- Cross-disciplinary **“Marine Heatwaves – Physical drivers and properties Workshop”** held in Perth in January 2015 led to three main research themes
  - “A hierarchical approach to defining marine heatwaves” (Hobday, Oliver et al., 2016, *Prog. Ocean.*)
  - “Global drivers of marine heatwaves” (Holbrook, Oliver et al., *in prep.*)
  - “Long-term trends in global marine heatwaves” (Oliver et al., *in review*, *Science*)

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ELSEVIER

A hierarchical approach to defining marine heatwaves

CrossMark

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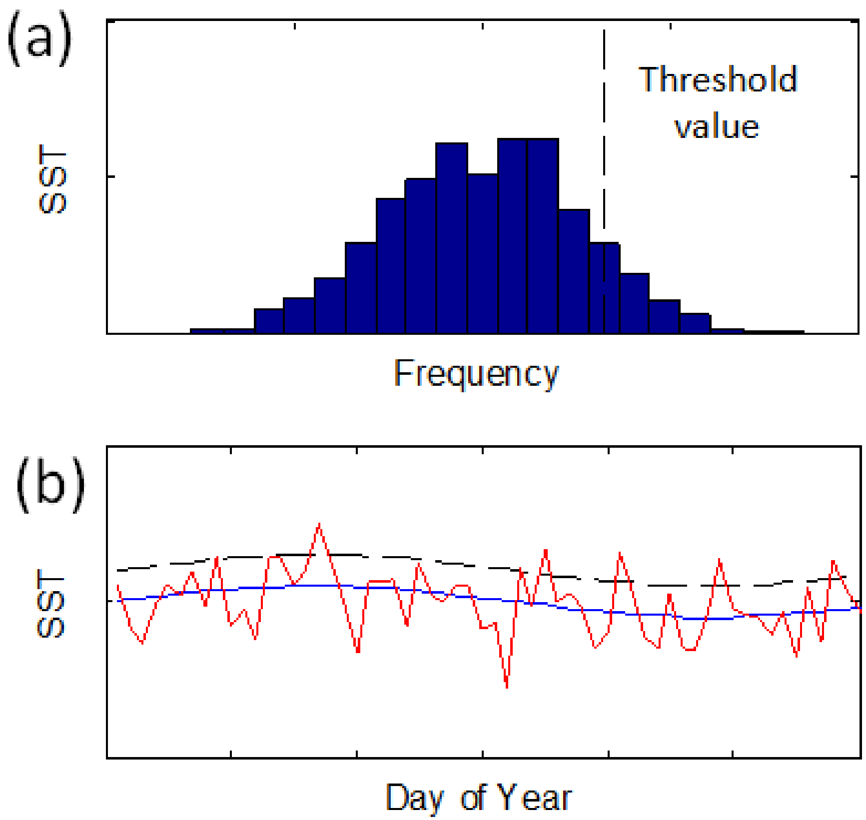
- “Marine heatwave” (MHW) **terminology** very new, first use appears to be Pearce and Feng (2013)
- Many **MHW “definitions”** have been used:
  - Maximum temperature [$^{\circ}$C], Temperature anomaly [$^{\circ}$C], Degree heating weeks [$^{\circ}$C x weeks] or days [$^{\circ}$C x days], Heating rate [$^{\circ}$C/day], Thermal stress anomalies [$^{\circ}$C]
  - “a period of at least three to five days during which mean or maximum temperature anomalies were at least 3–5°C above normal”
  - Coral bleaching metrics generally include the effect of extreme event duration and magnitude of temperature anomalies
- **Limited consistency** (outside coral bleaching research) regarding how MHW metrics are applied or how useful they are in ecological applications
- The atmospheric community has recently sought to define standard metrics (e.g., the ETCCDI) and the proposed MHW **definition has leveraged off of these efforts**

Proposed MHW definition

Hobday et al. (2016, *Prog. Ocean.*) MHW definition:

- Qualitative: **a discrete prolonged anomalously warm water event at a particular location**
  - Does not assume any particular driver or any specific impact
  - Flexible definition, can be specifically targeted towards applications e.g. coral reef monitoring, fisheries management

- Quantitative:
  - **'anomalously warm'**: a MHW must lie above a high percentile and referenced to a baseline climatology
    - Recommend 90^{th} percentile
    - Climatology and percentile both vary with time of year
  - **'prolonged'**: a MHW must persist for ≥ 5 days
    - Sensitivity tests show spatial uniformity at this threshold
  - **'discrete'**: a MHW event has well-defined start and end times
    - Subsequent events with gaps of ≤ 2 days considered as one event

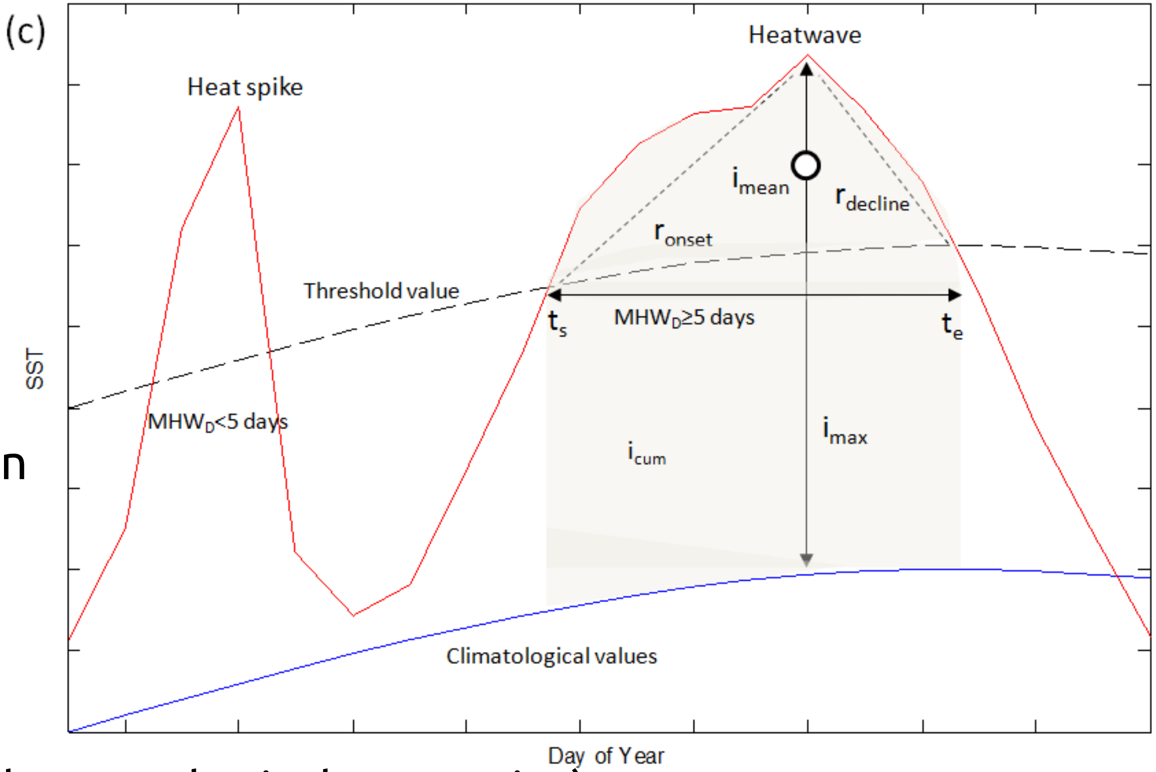


Hobday, Oliver et al. (*Prog Ocean, 2016*)

Metrics

- For each MHW event, a set of metrics include measures of intensity, duration, frequency and spatial extent
- **A hierarchical set of such metrics is proposed:**
- **Primary metrics** (most general; duration and intensity)
  - Intensity (mean, maximum) [deg C]
  - Duration [days]

(c)

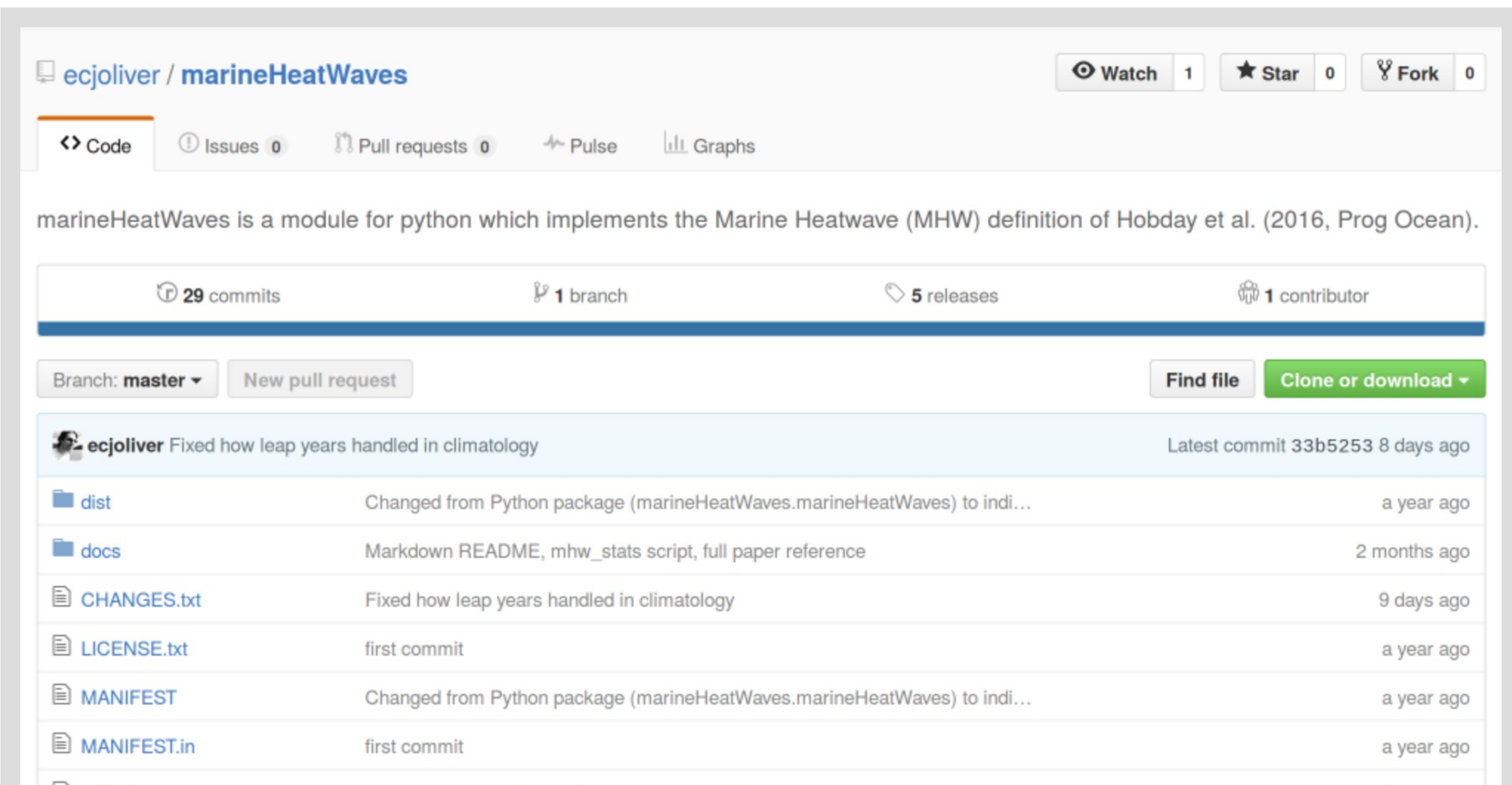


- **Secondary metrics** (less general; still inherent physical properties)
  - Cumulative intensity (~DHDs/DHWs) [deg C x days]
  - Rate of onset/decline [deg C/day]
  - Spatial extent (linear or areal) [km or km^2]
- **Tertiary metrics** (specific to the system under investigation)
  - Preconditioning factors (e.g., drivers, processes, states)
  - Ecological impacts (e.g., stress in a biological sense)
  - ..etc...

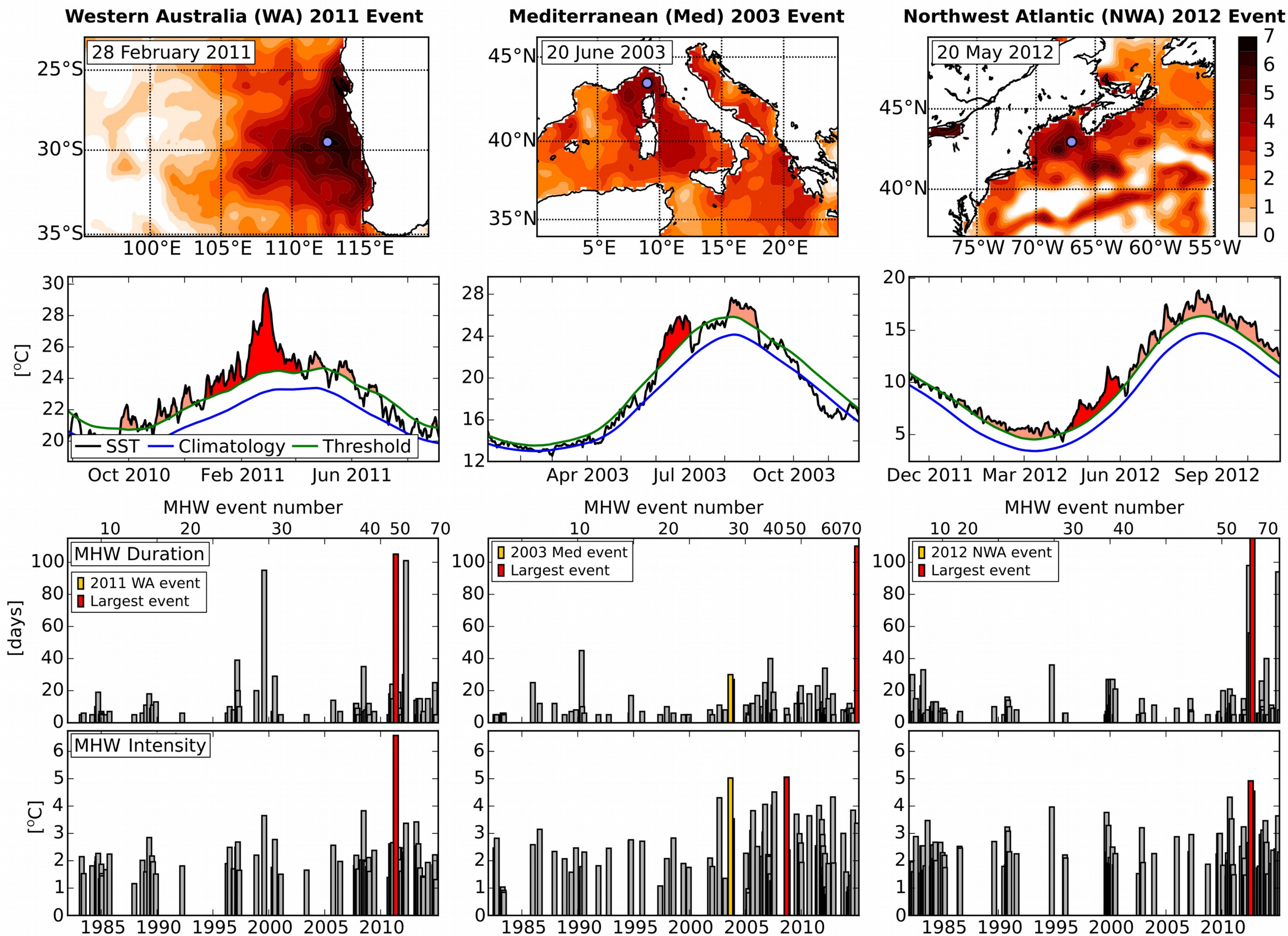
Hobday, Oliver et al. (*Prog Ocean, 2016*)

Software

- MHW definition has been implemented as a **software package**
- Written in **Python**, freely available, open-source
- Available here: `http://github.com/ecjoliver/marineHeatWaves`
- Requires daily data (for now), allows for missing values, **feedback requested**
- Nothing ocean-specific about code: default parameters (e.g. 5-day minimum duration, 2-day gap duration) can be modified to suit atmospheric (or other) data



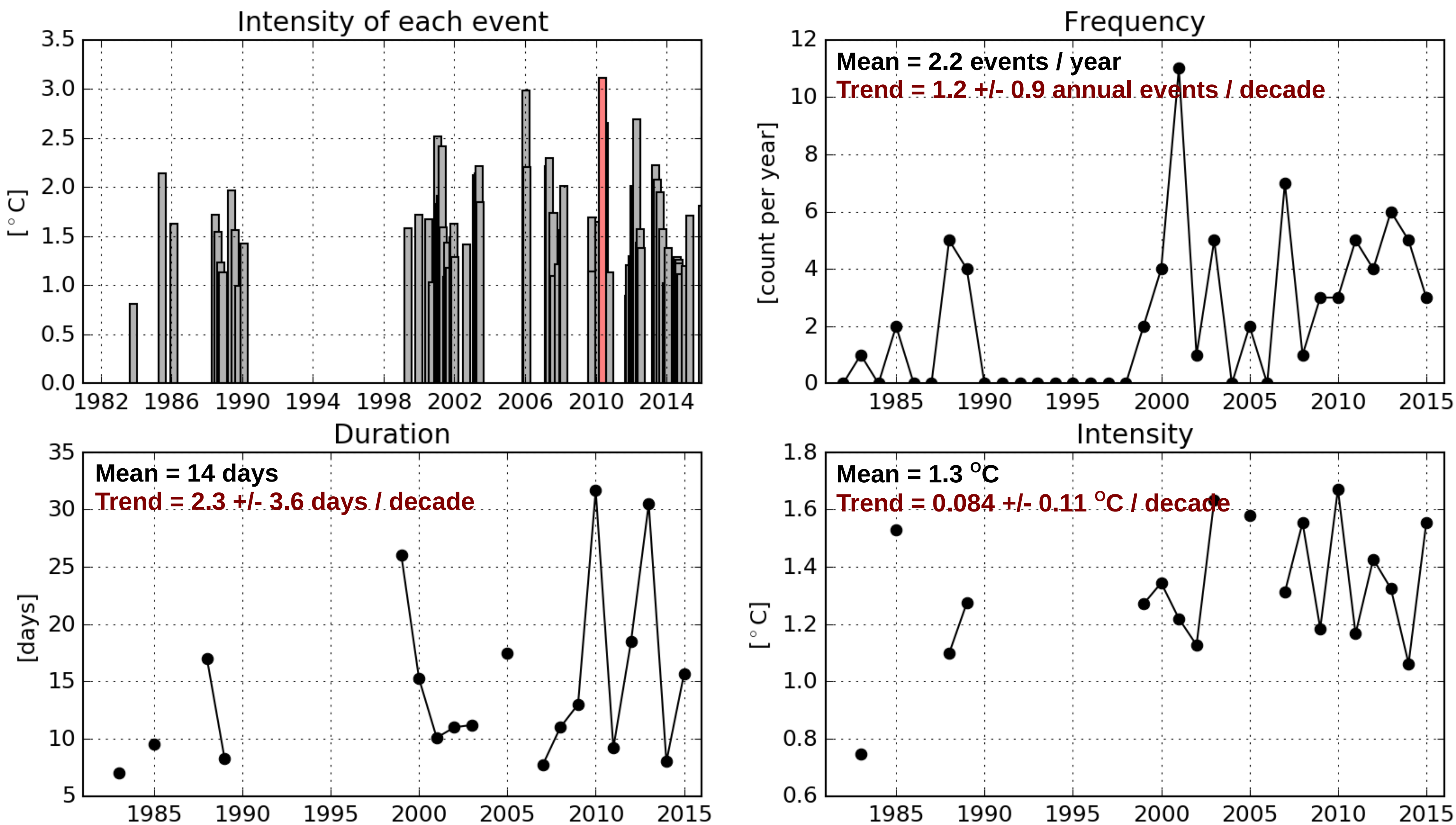
Can **identify historical events** from the observational record (satellite SST measurements: NOAA OI SST)



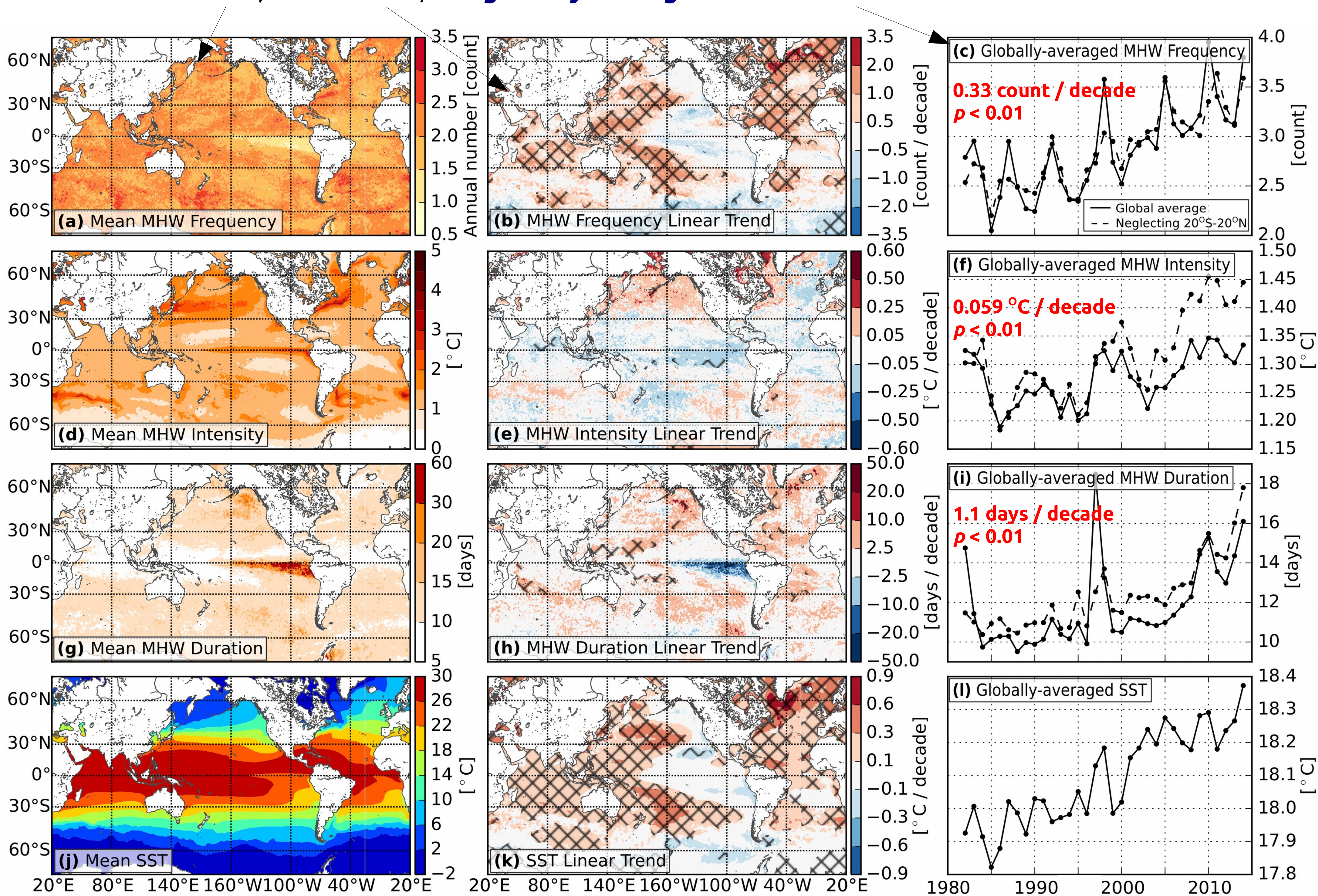
Hobday, Oliver et al. (*Prog Ocean*, 2016)

Annual Time Series

- Can calculate a **time series** of **annual-average MHW properties** at any location
- We can then calculate long-term **means** and **linear trends**
- For example, off eastern Tasmania (43.7^{O}S,147.2^{O}E) based on satellite SST:

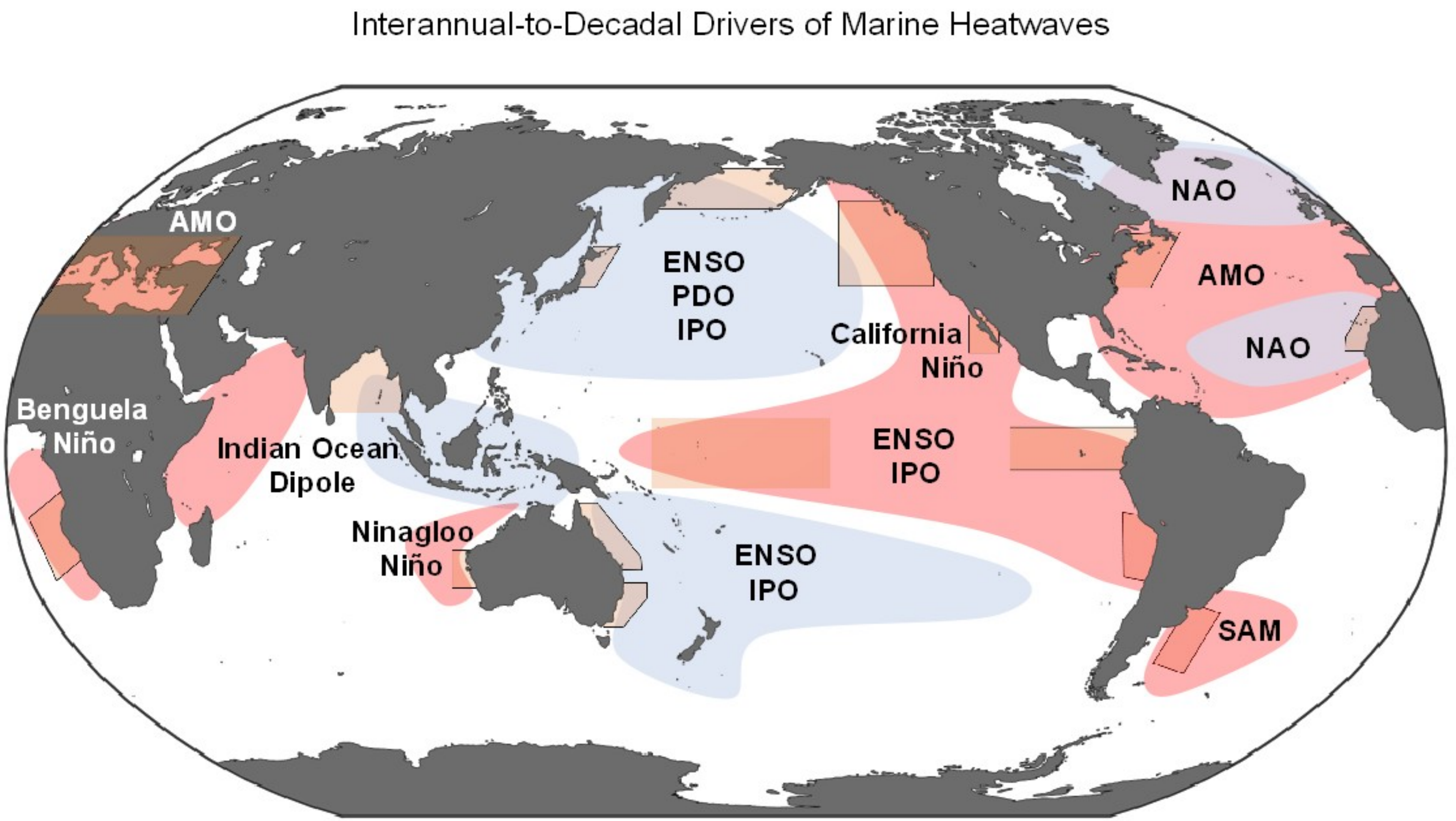


Mean, **linear trend**, and **globally-averaged time series** based on satellite SSTs



Oliver et al. (*Science, under review*)

a priori understanding

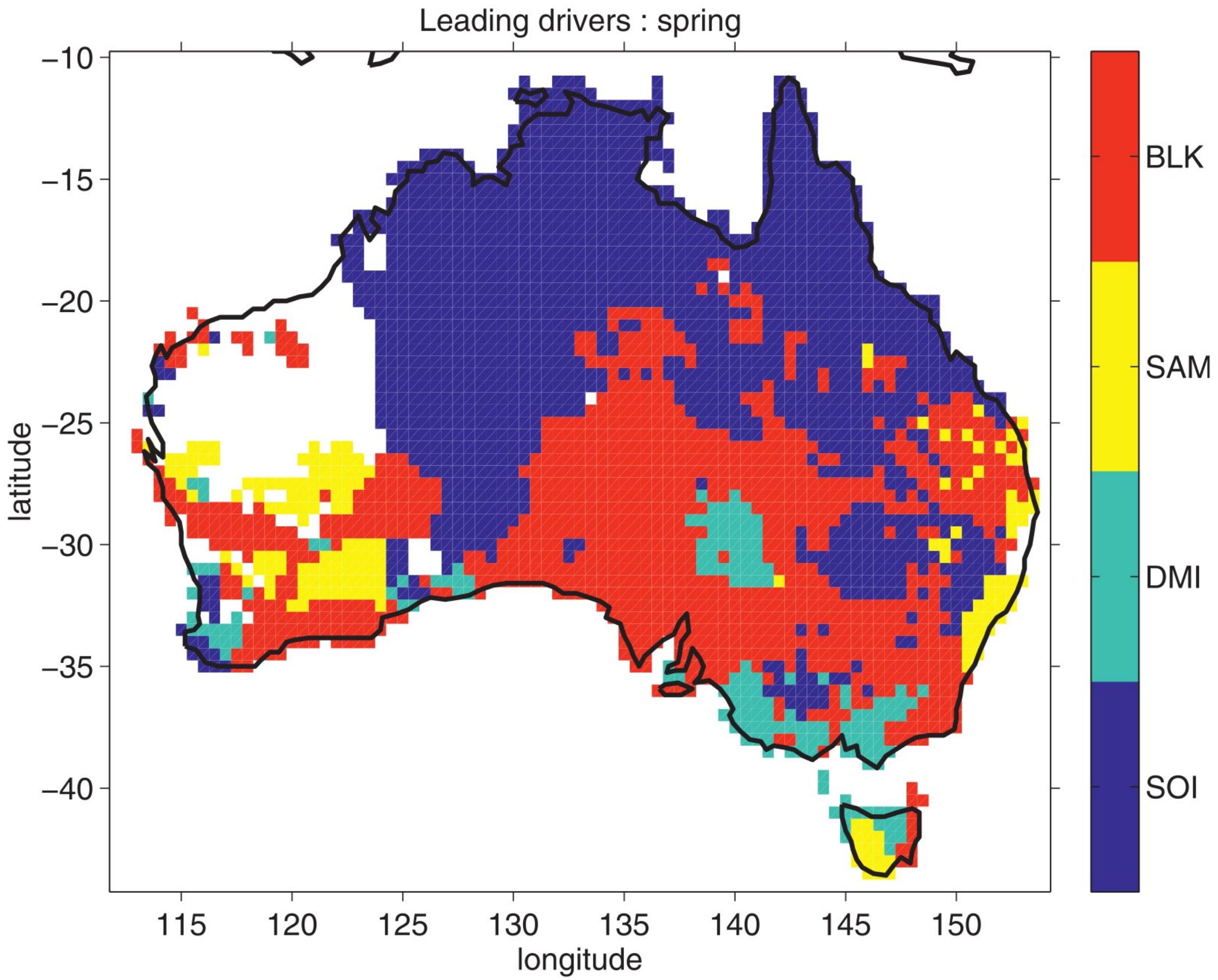


A priori sketch of global connections between large-scale climate drivers and **marine heatwave** events in case study regions, based on confidence assessment of literature and knowledge of climate mode patterns

Holbrook, Oliver et al. (*in prep*)

Guiding Analysis

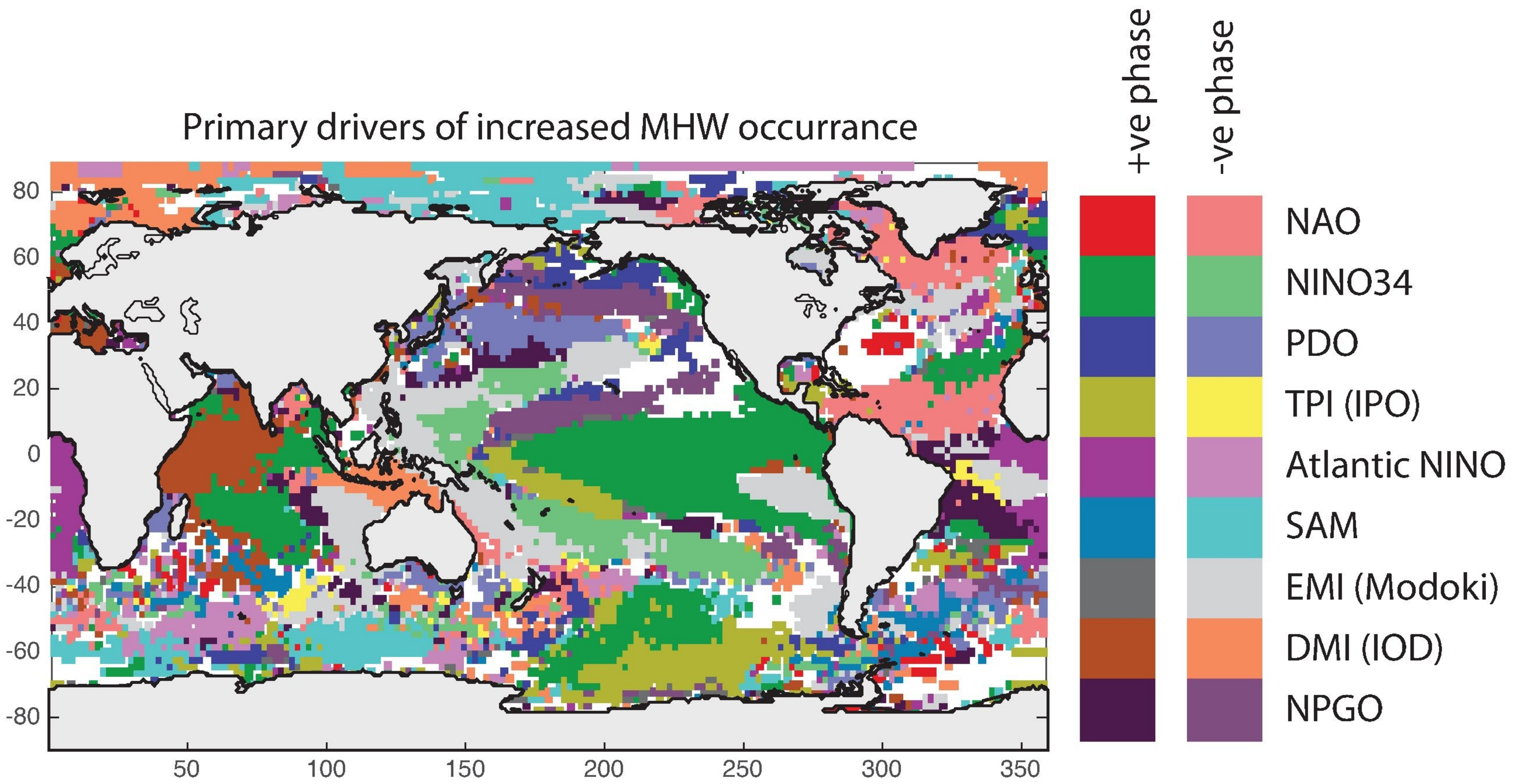
Leading drivers of Australian precipitation



SON

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

a posteriori understanding



A posteriori sketch determined by quantitative analysis of historical MHWs (1982-2014) and climate mode indices

Holbrook, Oliver et al. (*in prep*)

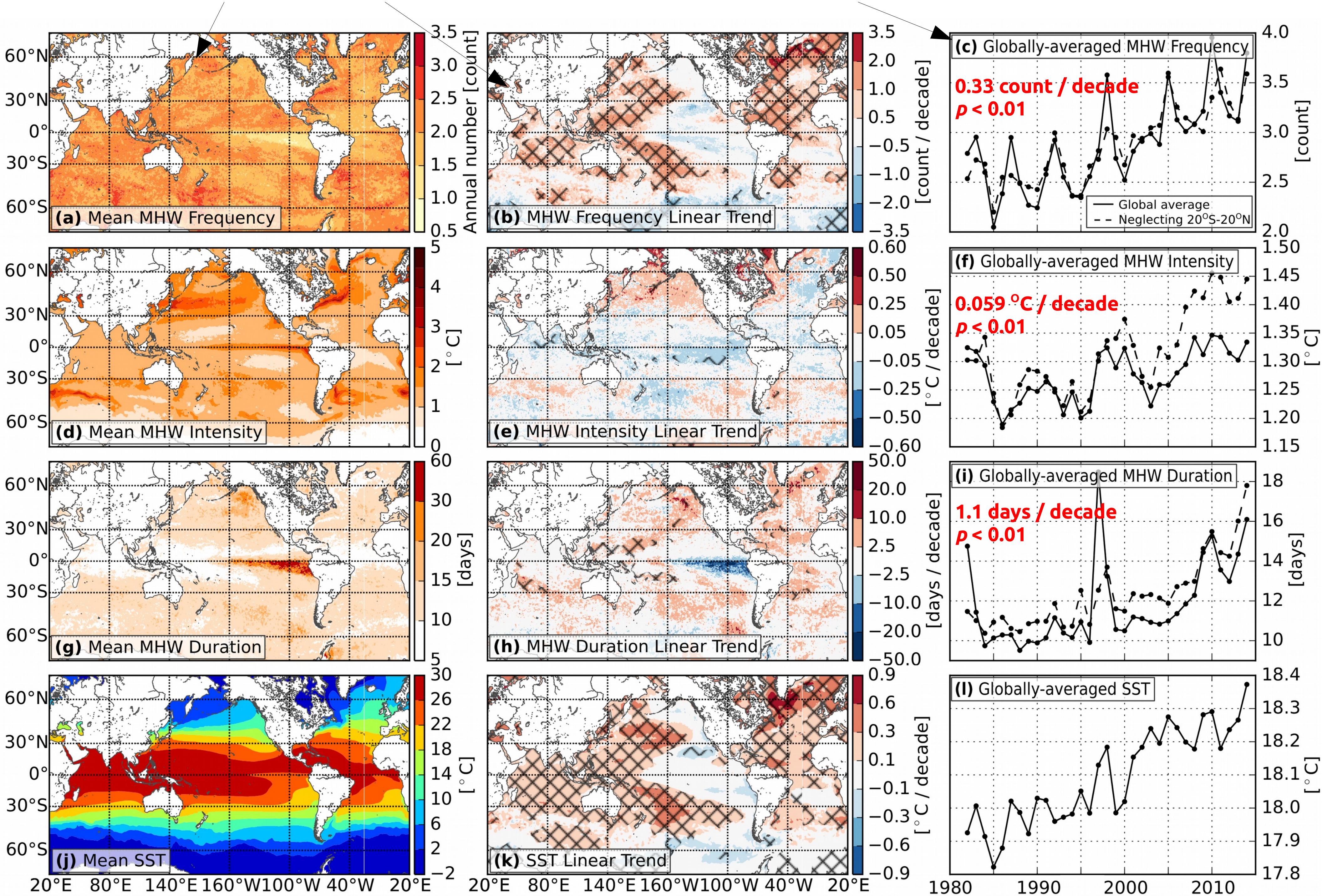
Enhance or suppress MHWs

	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	-	-	-	-	-	-	-	-	15	1	-	-	-	11	11	-	-	-
BERING	-	-	-	-	-	3	18	4	-	-	-	-	-	-	-	-	-	-
BRZ	-	-	-	-	-	-	-	-	8	-	-	-	-	-	-	-	-	-
Blob	-	-	20	6	19	5	20	6	5	-	-	-	-	6	-	-	7	19
BofB	6	14	-	-	-	-	6	-	-	-	-	-	-	-	13	-	-	-
CP	-	-	22	0	-	-	-	-	-	-	-	-	16	3	16	6	-	-
Cal	-	-	18	5	17	4	-	-	-	-	-	-	-	-	-	-	5	18
Can	5	15	14	7	-	-	-	-	-	-	-	-	-	-	14	7	-	-
EAC	7	14	-	-	-	-	-	-	-	6	-	-	-	-	-	-	-	-
GBR	6	13	-	-	-	-	-	-	-	-	-	-	-	13	-	-	13	6
GS	-	-	-	-	-	-	-	-	-	-	15	8	-	-	-	-	-	-
Humb	-	-	16	5	-	-	-	-	-	13	-	-	-	-	-	-	-	-
KC	-	-	-	-	2	16	-	-	11	5	-	-	-	-	12	6	-	-
LEEU	-	-	4	16	-	-	5	-	-	7	13	7	4	19	-	-	15	5
MED	-	-	-	-	-	-	-	-	-	6	-	-	-	-	14	6	-	-
NINO	-	-	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**.

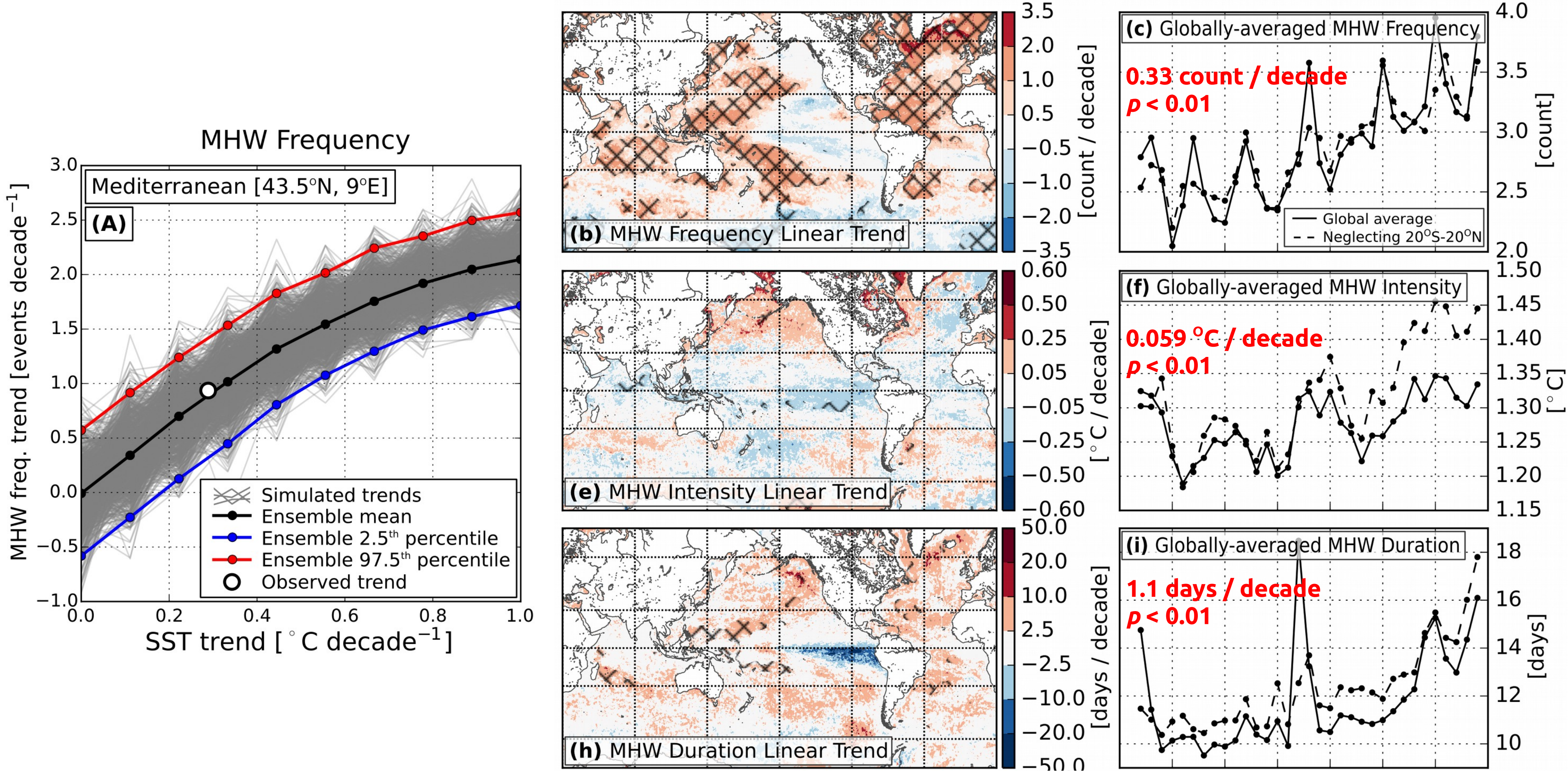
Holbrook, Oliver et al. (*in prep*)

Mean, **linear trend**, and **globally-averaged time series** based on satellite SSTs



Oliver et al. (*Science, under review*)

Can relate the trend in MHW properties to the expected trend due to rising SSTs alone

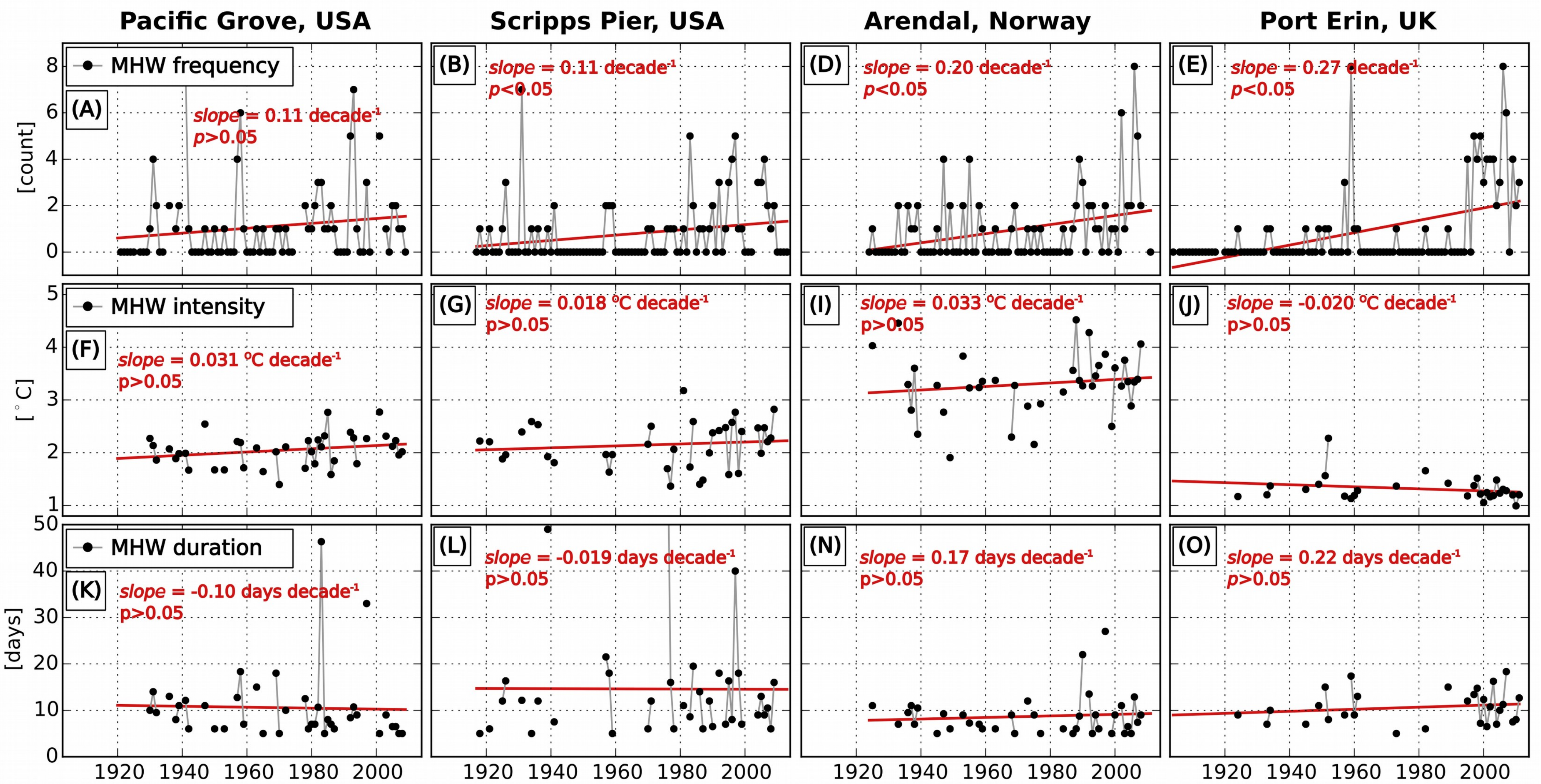


- Trends in MHW frequency and duration **explained by trend in mean SST** over more than 83% and 73% of ocean surface respectively (p<0.05).
- Mean SST trend only explains 47% of trend in MHW intensity.
- This is reflected in **pattern correlation** of SST trend and MHW trends (freq: 0.85, dur: 0.35, int: 0.10)

Oliver et al. (*Science, under review*)

Long Station Records

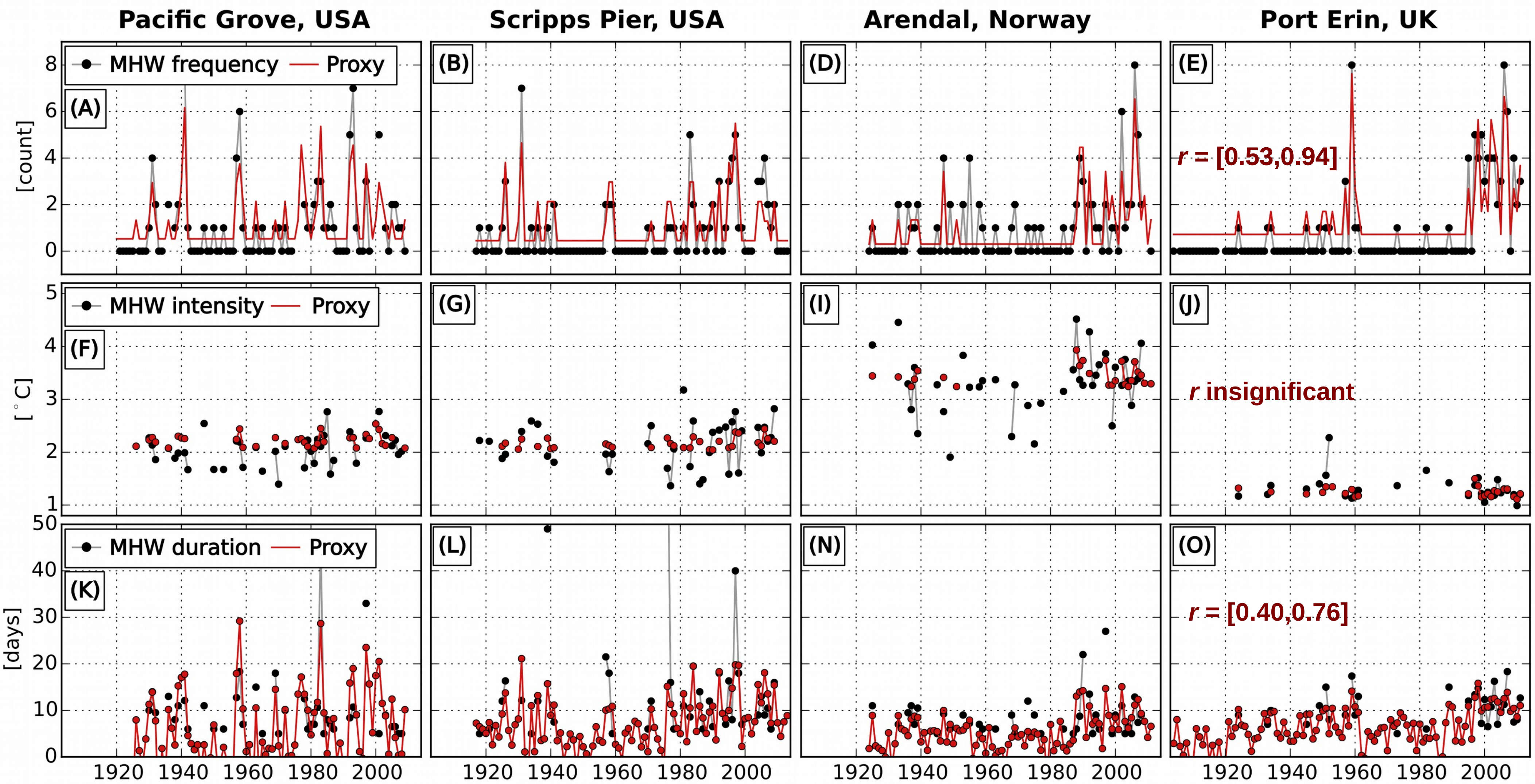
- Centennial-scale scale trends from the few long daily time series stations
- Weaker, but still we see **more** and possibly **longer** and **more intense** MHWs



Oliver et al. (*Science, under review*)

Monthly MHW proxies?

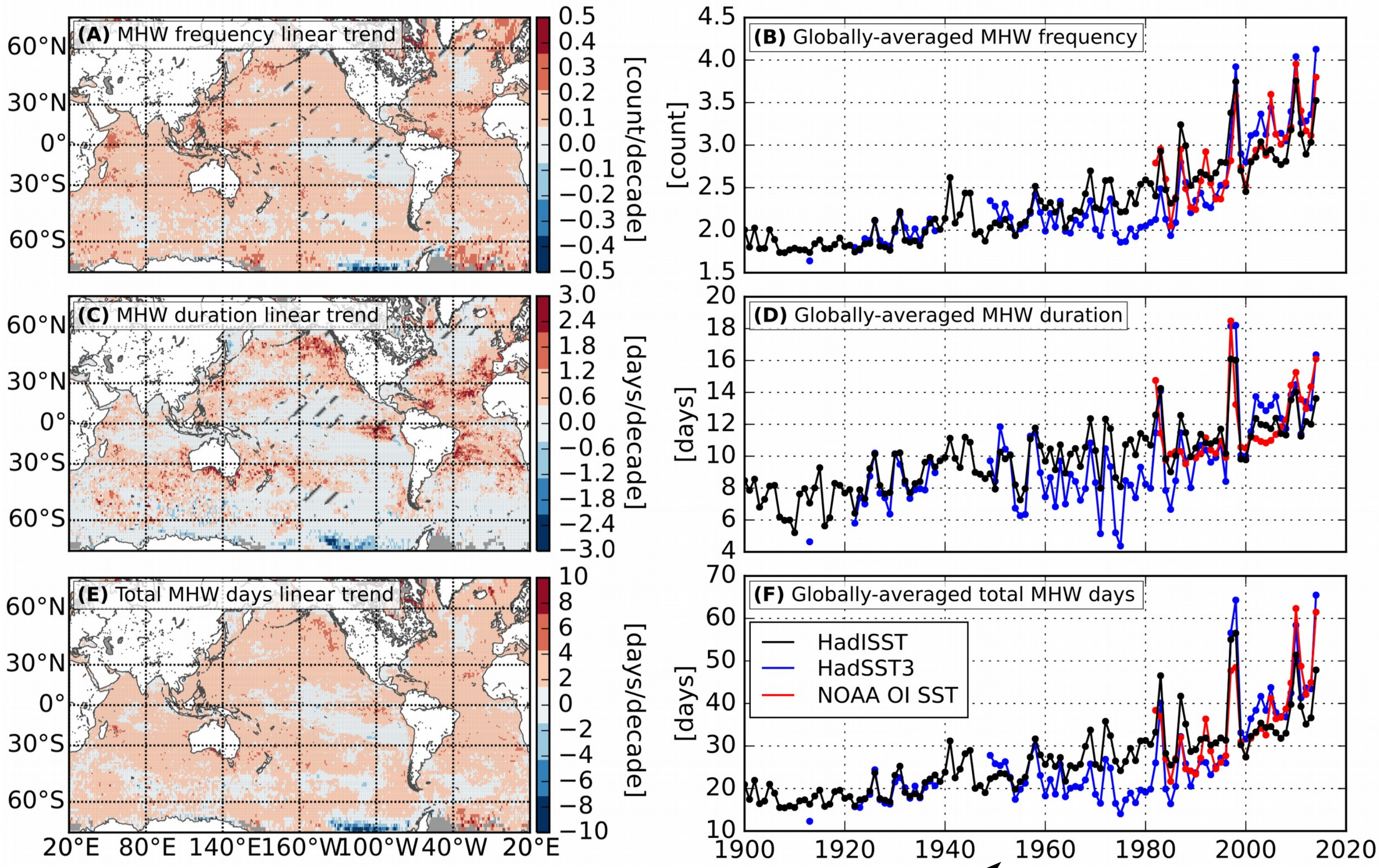
- Can we **predict** annual-average **MHW properties** **from monthly SSTs**?
- **Yes**, using a set of proxies:
  - frequency ~ threshold counts, duration ~ maximum anomaly, can't predict intensity



Oliver et al. (*Science, under review*)

Global Centennial Trends

- These proxies were used with monthly HadISST and HadSST3 datasets

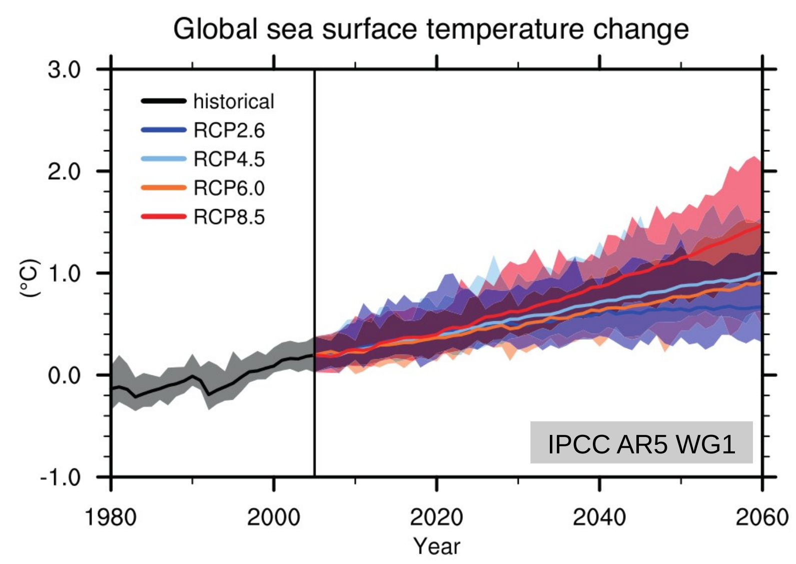


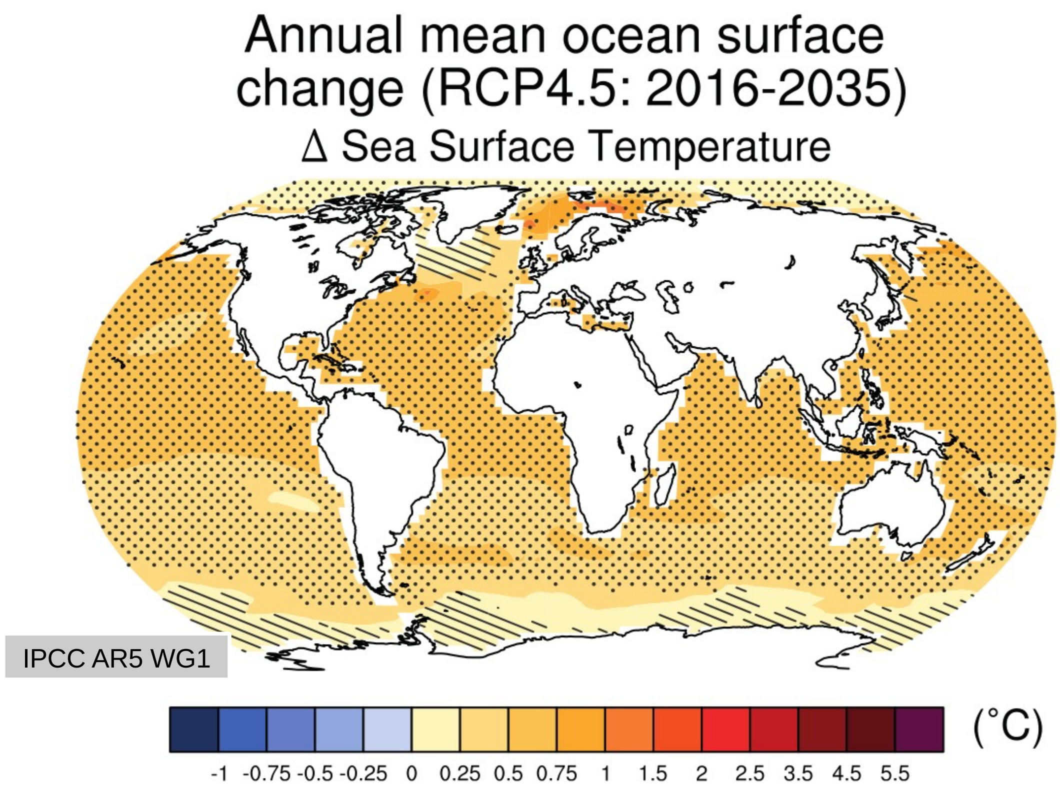
Oliver et al. (*Science, under review*)

- Trends over 1900-2014:
  - **Frequency**: 0.12 events / decade ($p<0.01$) → **1x - 2x increase**
  - **Duration**: 0.50 days / decade ($p<0.01$) → **2x increase**
  - **Combined!** → 2.0 MHW days / decade ($p<0.01$) → **2x - 3x increase**

Future projections…

- **IPCC AR5** projects that the global ocean will **continue to warm** during the 21st century
  - Warming in the top hundred metres projected to be **0.6°C (RCP2.6)** to **2.0°C (RCP8.5)**





- We can expect **historical trends** in marine heatwaves to **continue into the future**
- <u>Will they accelerate?</u>
- <u>What will be the impacts on marine ecosystems and fisheries?</u>

Southeast Australia

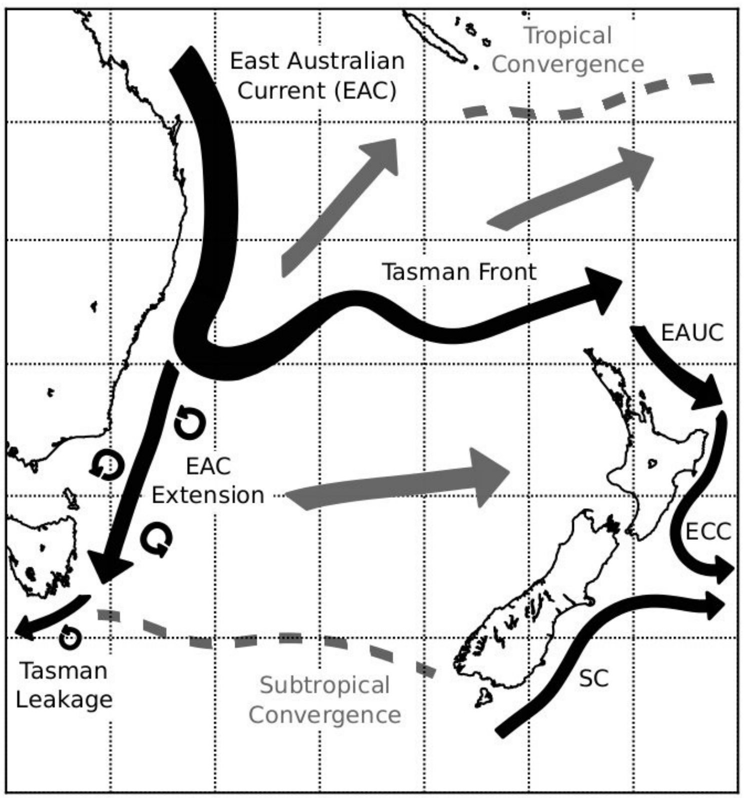
- Southeast Australia is a hotspot for global warming: **surface waters warming nearly 4 times the global average rate**)
- Associated risks for fragile regional **marine ecosystems**
- **Highly variable due to large eddies** being spun off from the East Australian Current
- Future projections indicate an enhancement of the EAC Extension and an increase in eddy activity (Oliver and Holbrook, 2014; Oliver et al., 2015)

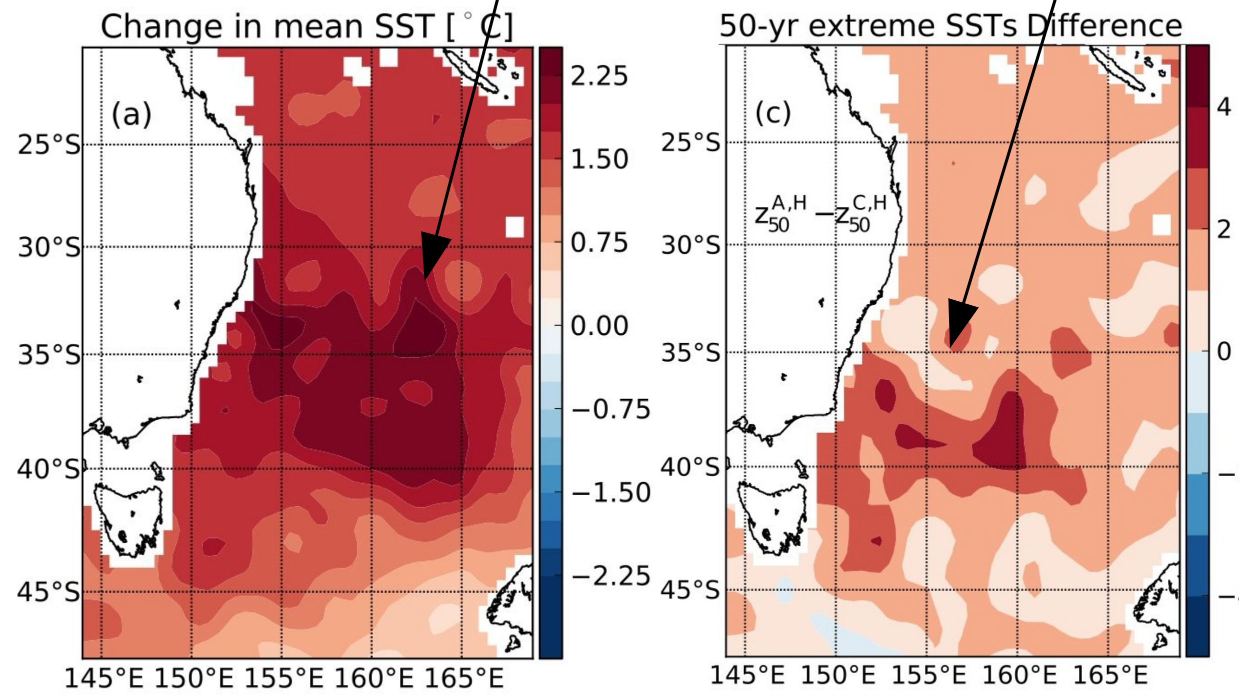
Hotspot of increasing mean SST in the Tasman Sea

Projected change leads to a **"hotspot"** of enhanced extremes located in the **southwestern Tasman Sea**

This **hotspot** not colocated with the hotspot in mean SST change

Due to a combined effect of the **change in mean and variance of SSTs**

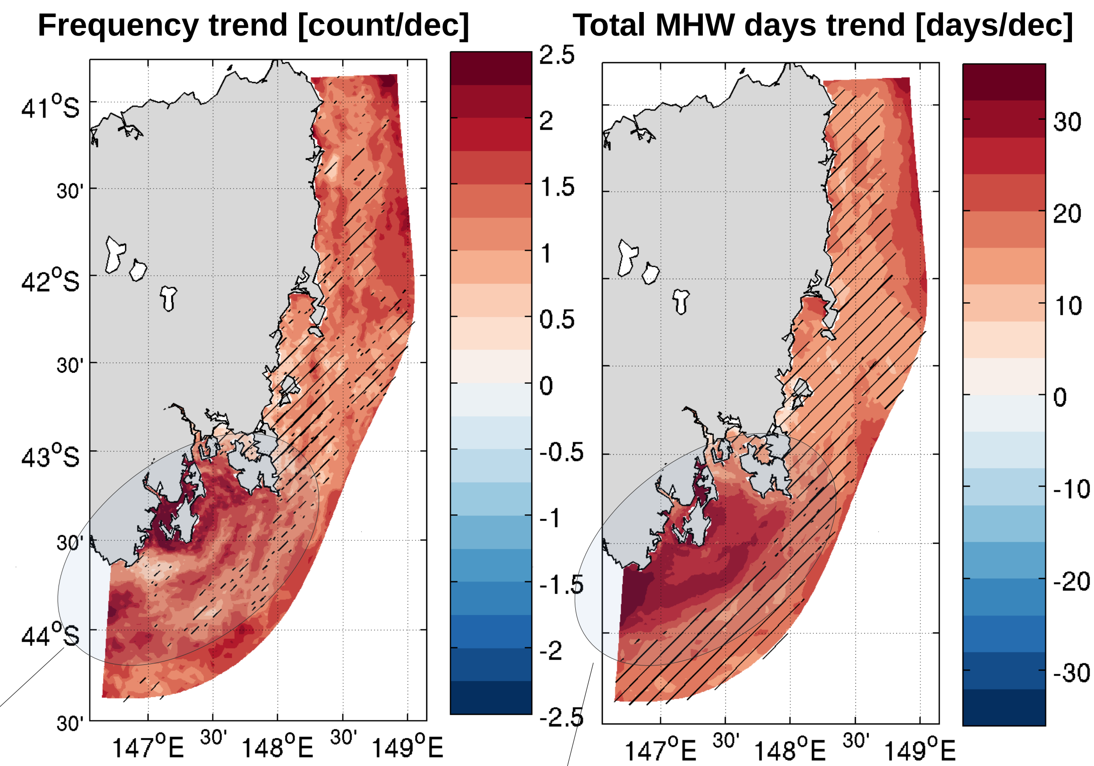


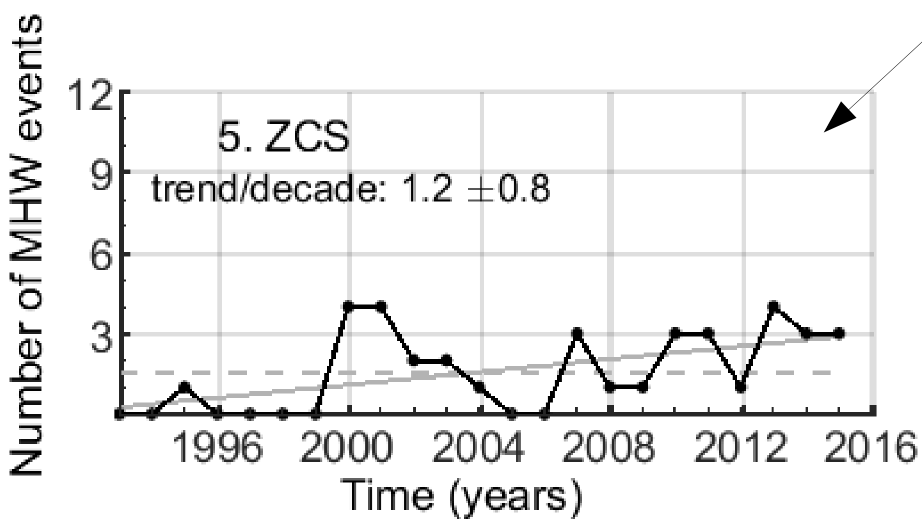


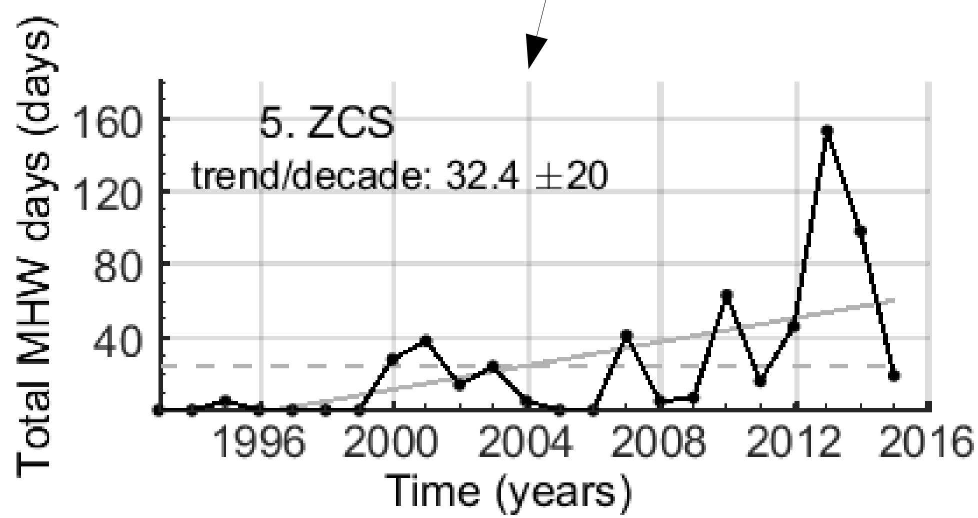
Oliver, Wotherspoon, Chamberlain, Holbrook (*J Clim*, 2014)
Oliver, Wotherspoon, Holbrook (*Prog Ocean*, 2014)
Oliver, Holbrook (*JGR*, 2014); Oliver, O'Kane, Holbrook (*JGR*, 2015)

Trends off Tasmania

- The **ETAS model** (Oliver et al., *in revision*) allows us to examine MHWs off **eastern Tasmania** over **1993-2015** at high resolution (**~2km**)
- Strong positive trends
- **Particularly off the southeast!**



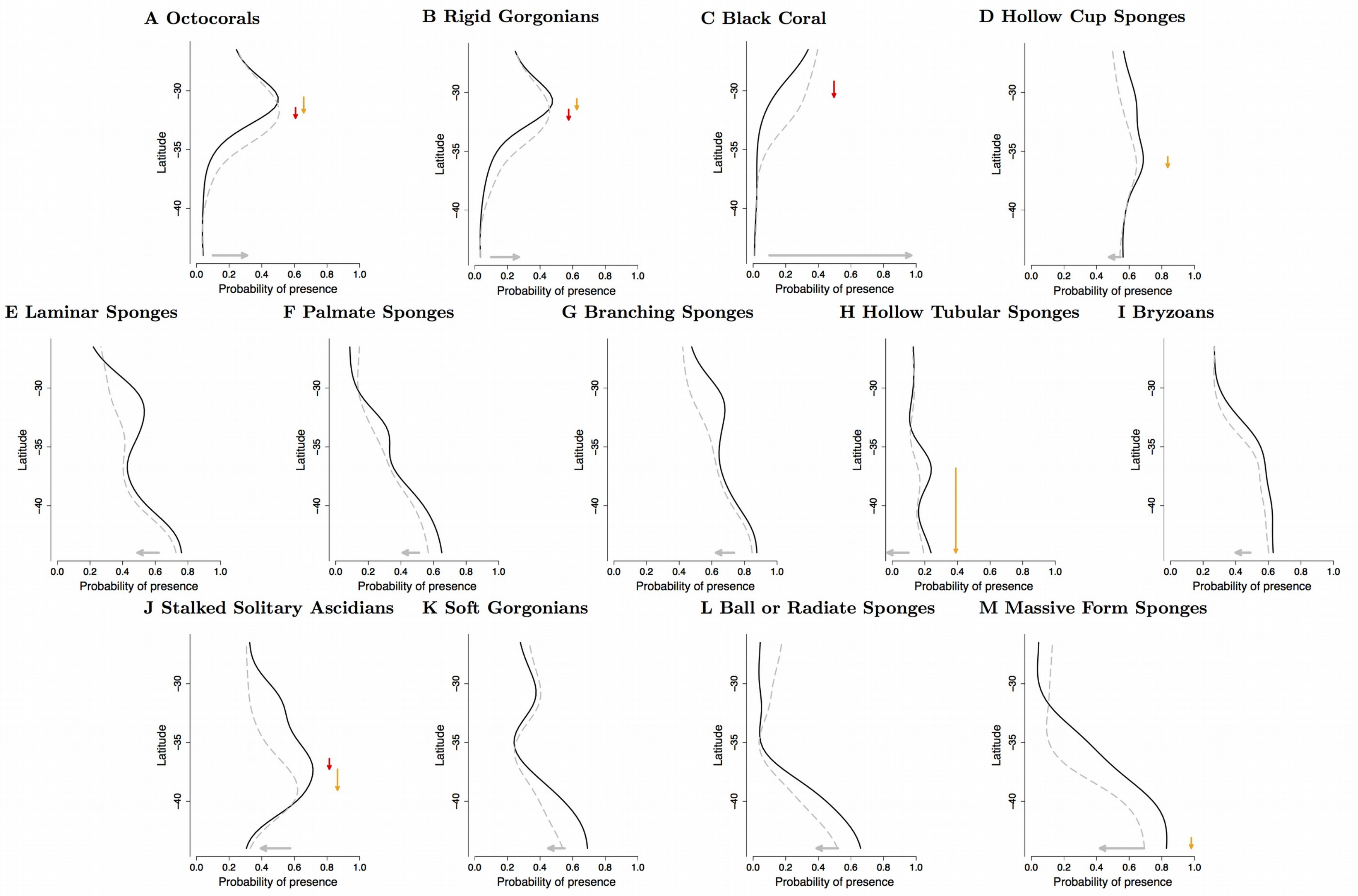




Acknowledgement: Véronique Lago (UTAS/REGS)

Ecological Impacts

- Projections of change to SST mean, variance, etc used to project **ecosystem changes**



Marzloff, Oliver et al. (*in prep.*)

Was Tasmania's summer of fires and floods a glimpse of its climate future?

April 19, 2016 4.26pm AEST

Tasmania's bushfires damaged pristine bushland and stretched emergency services to the limit. AAP Image/Patrick Caruana

Drought, fires, floods, marine heatwaves – Tasmania has had a tough time this summer. These events damaged its natural environment, including world heritage forests and alpine areas, and affected homes, businesses and energy security.

In past decades, climate-related warming of Tasmania's land and ocean environments has seen dozens of marine species moving south, contributed to dieback in several tree species, and encouraged businesses and people from mainland Australia to relocate. These slow changes don't generate a lot of attention, but this summer's events have made people sit up and take notice.

If climate change will produce conditions that we have never seen before, did Tasmania just get a glimpse of this future?

Hot summer

After the coldest winter in half a century, Tasmania experienced a warm and very dry spring in 2015, including a record dry October. During this time there was a strong El Niño event in the Pacific Ocean and a positive Indian Ocean Dipole event, both of which influence Tasmania's climate.

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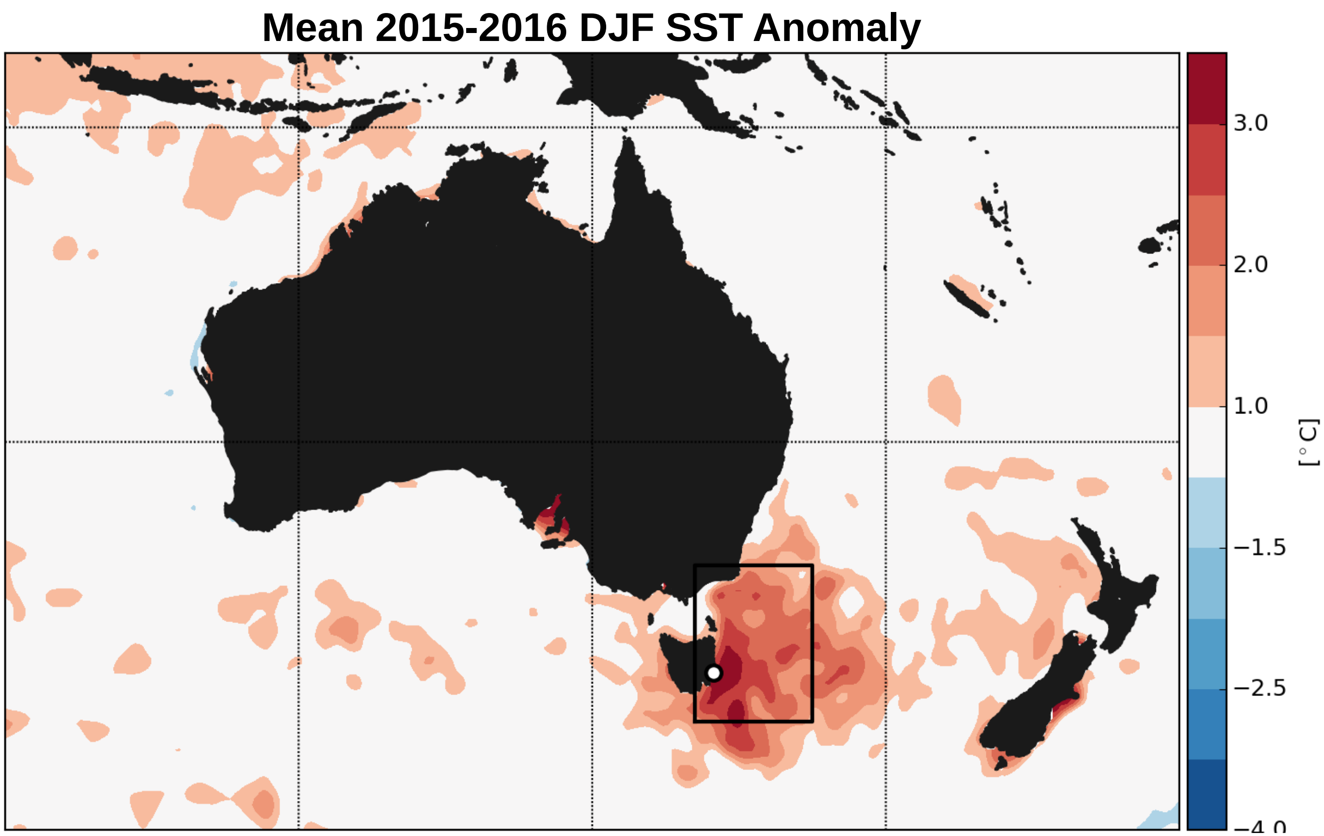
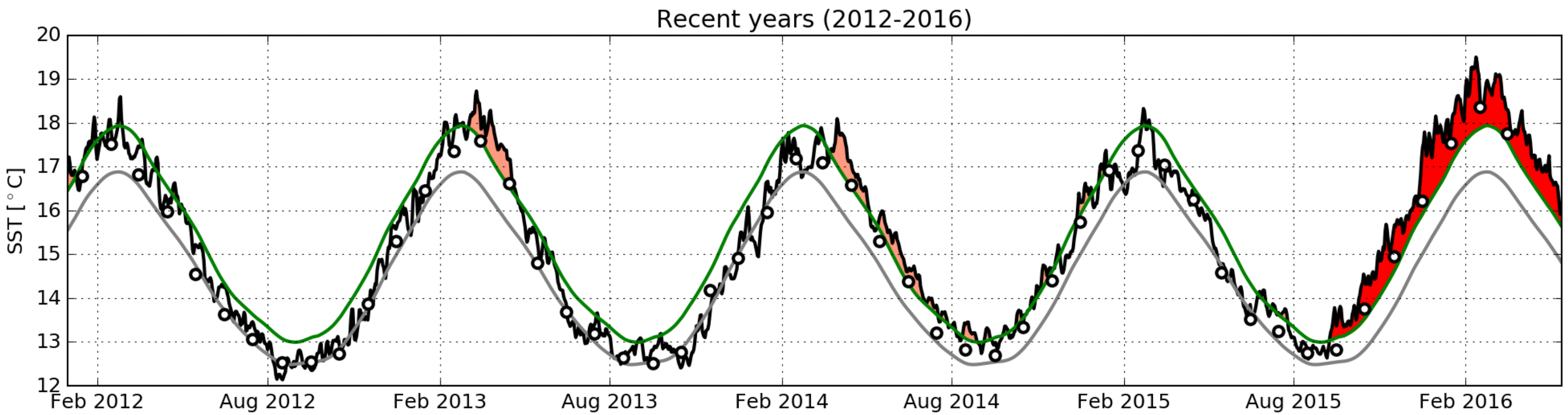
Eric Oliver and Jan McDonald do not work for, consult,

Hobday, Oliver, McDonald, Grose, *The Conversation*, https://theconversation.com/was-tasmanias-summer-of-fires-and-floods-a-glimpse-of-its-climate-future-58055

2015-2016 SE Australia MHW

- There was a **marine heatwave** that occurred this **past summer (Austral)** off southeastern Australia (9 Sep 2015 – 15 May 2016)
- It is unprecedented in
  - **Duration (250 days)**
  - **Intensity (2.7°C max)**
- **Impacts**: POMS (Oysters), dead abalone, poor salmon farm performace, strange fish intrusions, kelp thinning…
- Currently developing framework to **report and understand** these events in **near-real time**.

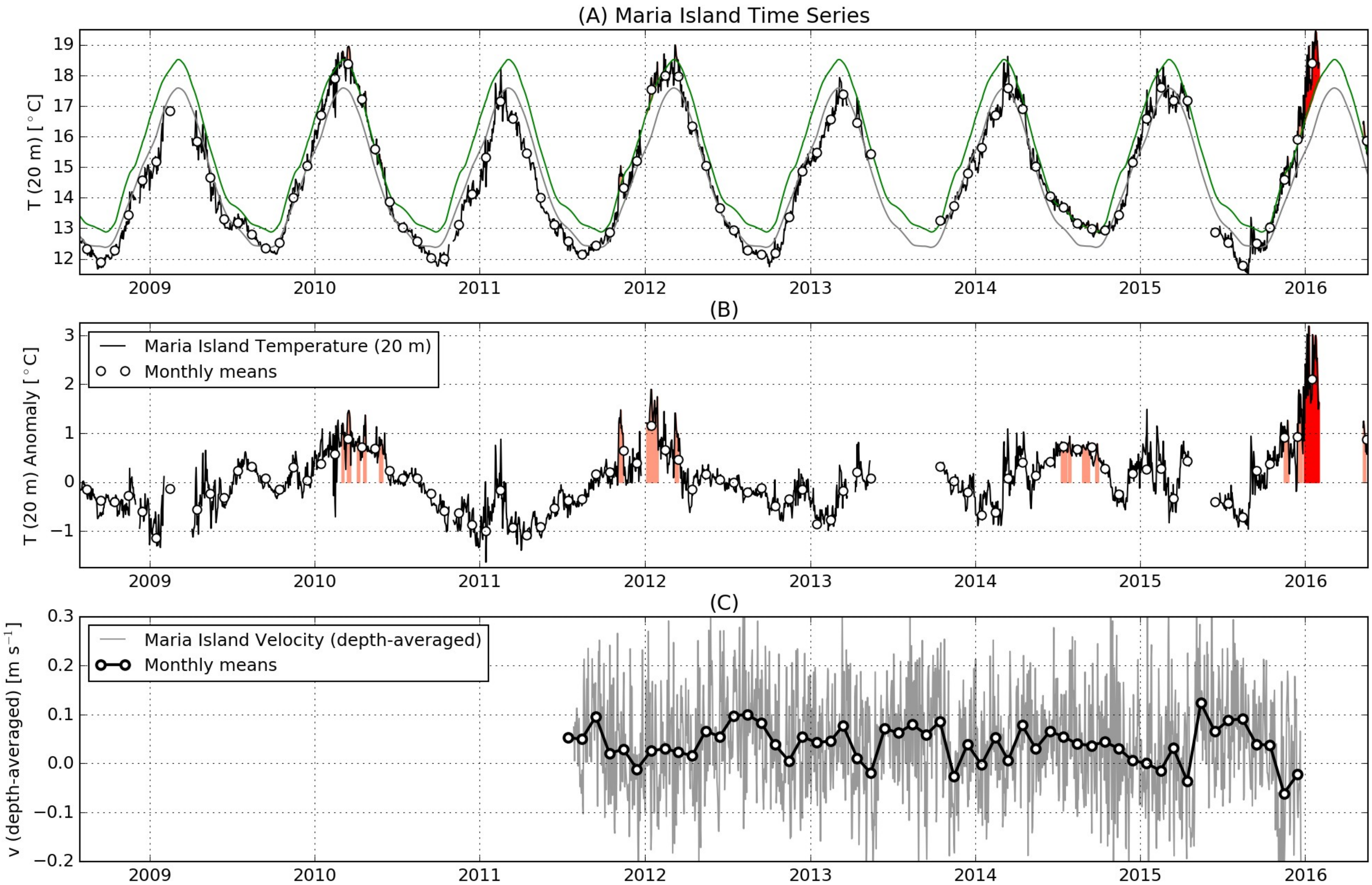




Oliver et al. (*in prep*)

Nearshore Record

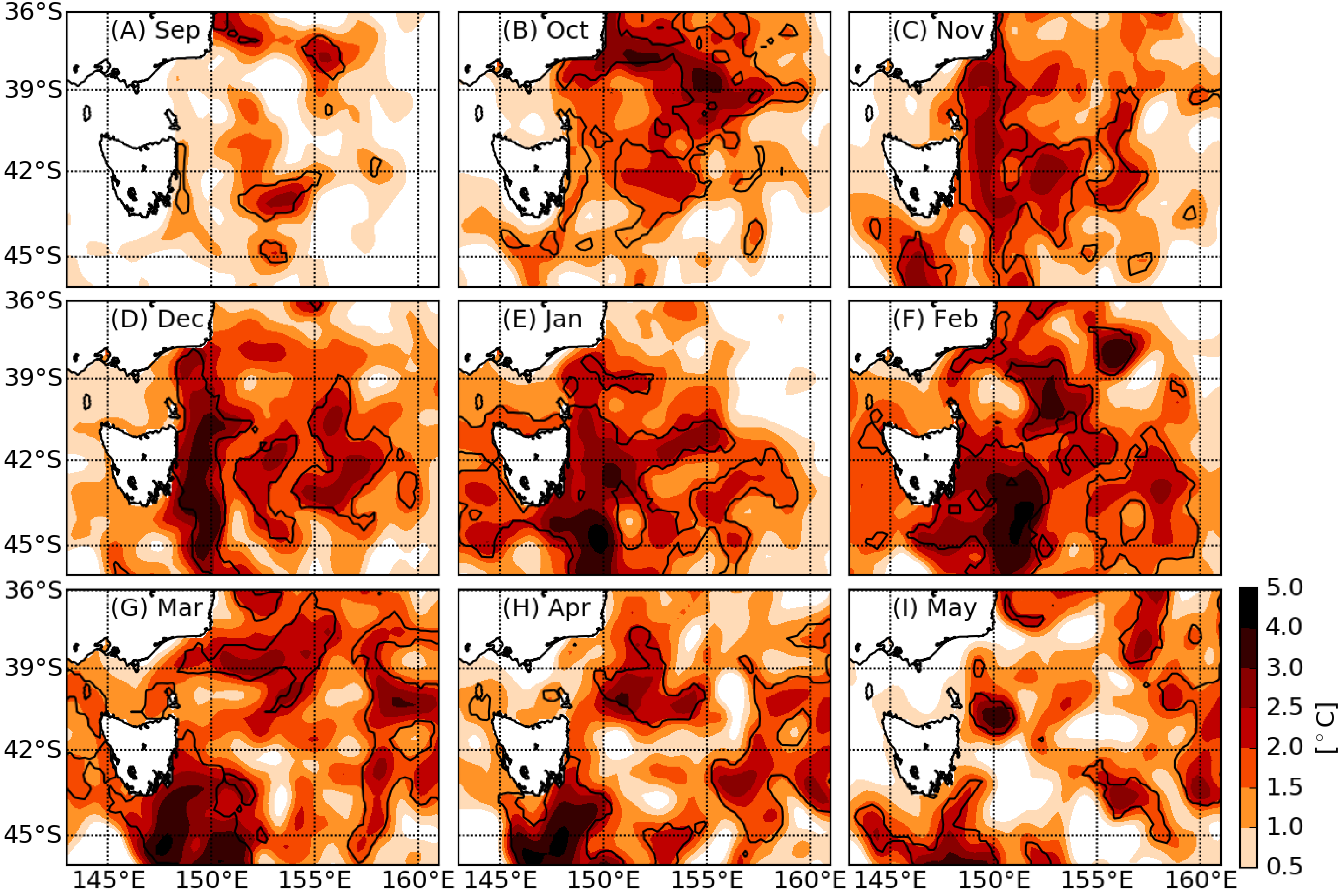
- This event was record strength, since 2008, in the **coastal zone @ 20 m depth**
- Record **southward flows**, possible indication of **forcing mechanism**



Oliver et al. (*in prep*)

Evolution of the event

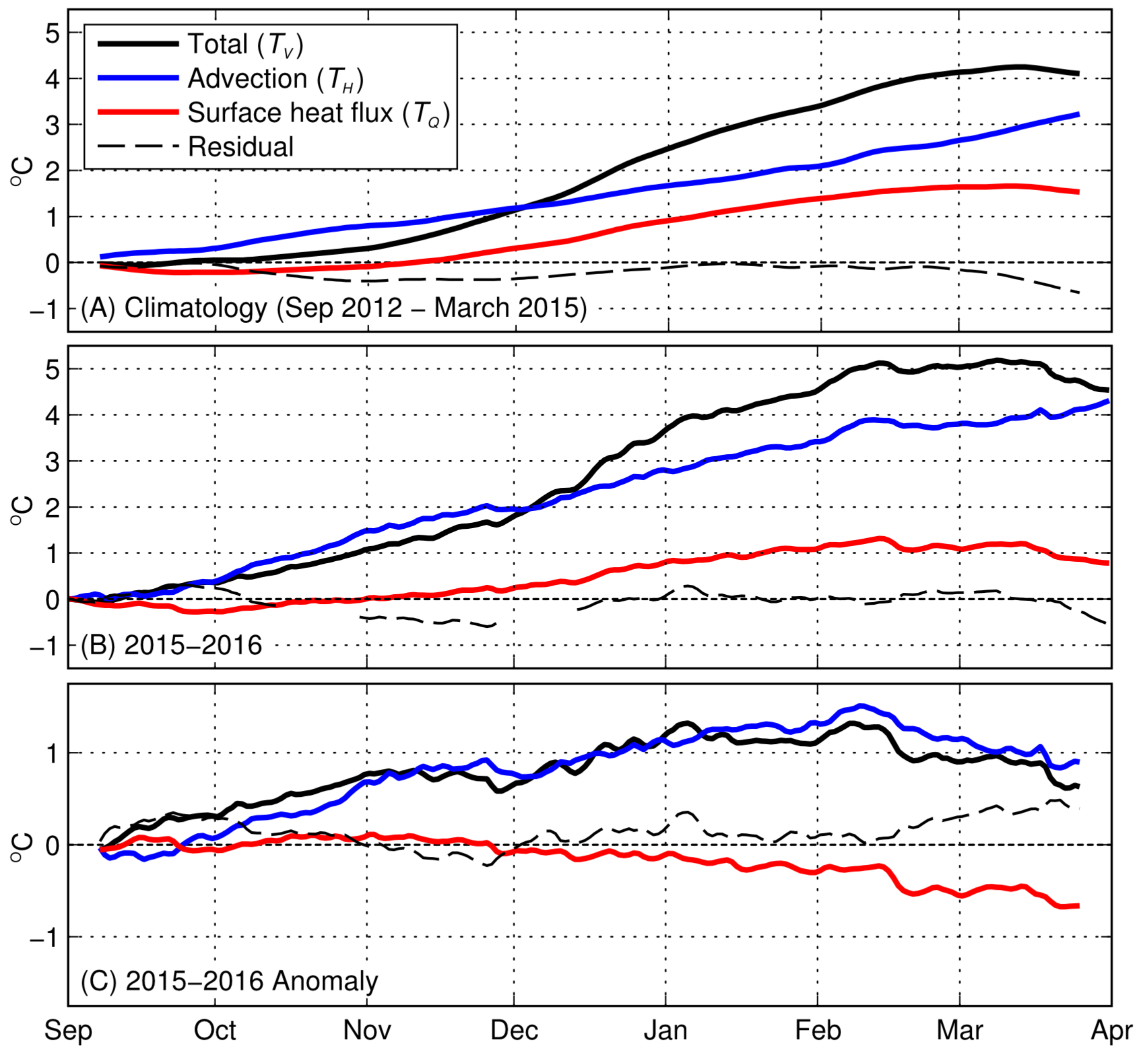
Monthly SST anomalies: contour encloses areas that were detected as MHWs for >90% of that month



Oliver et al. (*in prep*)

Physical drivers

- **<u>Temperature budget</u>**
- Volume averaged (0-100 m) temperature since Sep 1
- Consider:
  - Temperature avection (T_H)
  - Air-sea heat flux (T_Q)
- <u>Climatology</u>: by mid-February T_H contributes ~3/5 of the warming while T_Q contributes ~2/5
- <u>2015-2016</u>: by mid-February T_H contributes ~4/5 of the warming while T_Q contributes ~1/5
- Marine heatwave primarily driven by **anomalous temperature advection**



Oliver et al. (*in prep*)

Role of climate change

- **Role of climate change** investigated using Fraction of Attributable Risk (FAR):

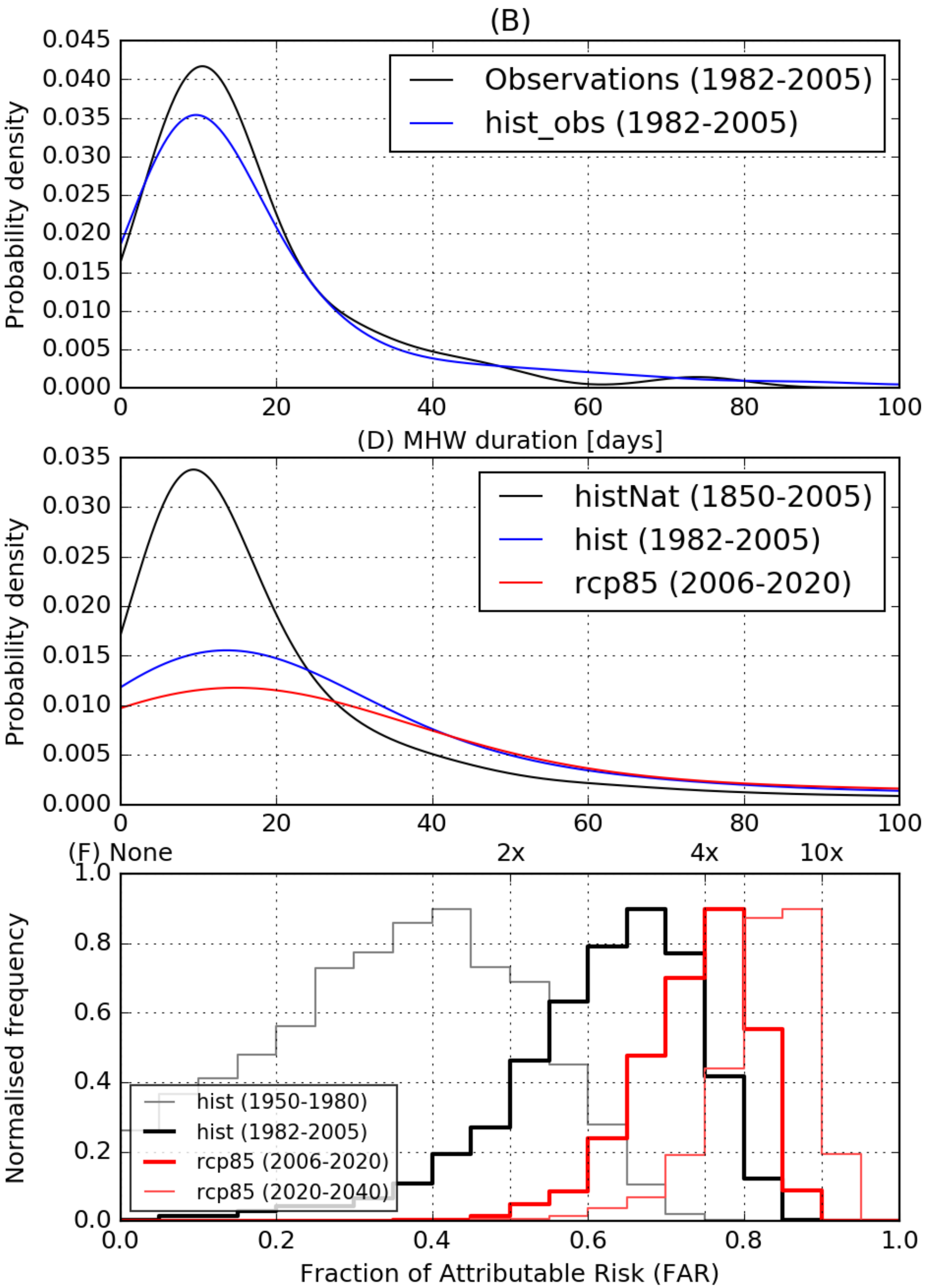
  $$FAR = 1 - P_{histNat} / P_{hist}$$

  Historical and natural distributions determined from CMIP5 global climate models

- **Duration**: An event of this duration was
  - **4x as likely** in 2005-2020 (RCP8.5 simulations) compared to the “natural world” (historicalNat 1850-2005 simulations)

- **Intensity**: An event of this intensity was
  - **2.5x as likely** in 2005-2020 compared to the “natural world”

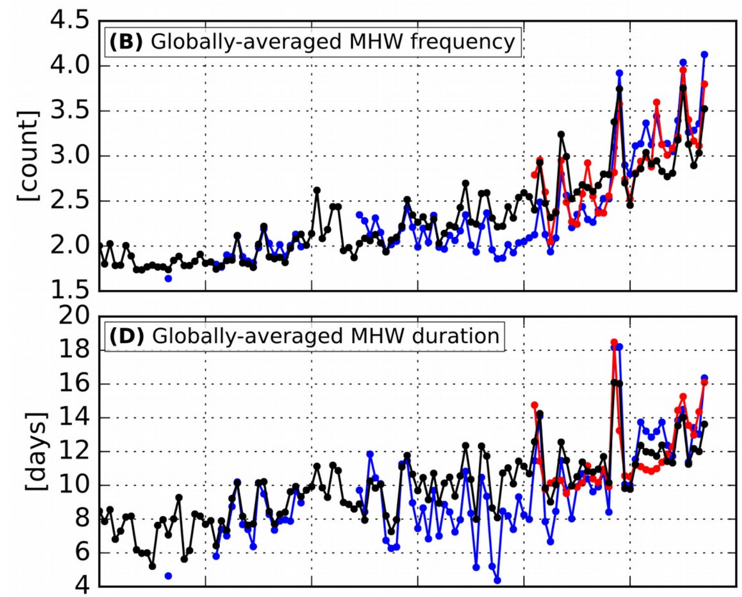
- → Virtually certain (>99%) that anthropogenic climate change increased the likelihood of an event of this duration and intensity by 2005-2020

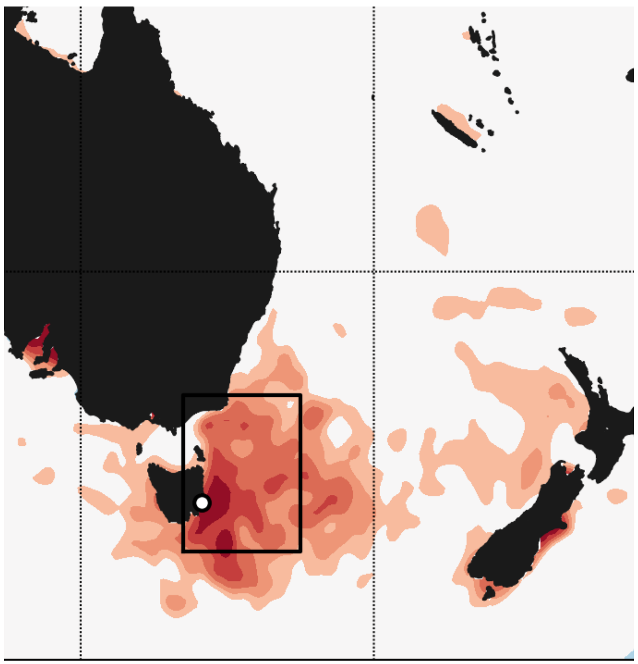


Oliver et al. (*in prep*)

Summary

- **“Marine heatwaves”** is an exciting new field, developing rapidly in both physical and biological fields
- Developed a **consistent definition**, beginning to understand **physical drivers and processes**
- **Long-term trends** on decadal and centennial scales, from satellite and in-situ observation data:
  - MHW **frequency** and **duration** have **nearly doubled** over the 1900-2014 period
  - Together led to a **2-3x increase** in the total number of annual MHW days from 15-25 days to 30-60 days.
  - Global increases in MHW frequency and duration can be **primarily explained by rise in background SST**
- **Climate change** plays a role in **increasing risk** of MHWs off southeast Australia, including recent 2015-2016 event
- **Part of large and ongoing group of work:**
  MHW definition
  MHW drivers and processes
  Case studies (eastern Tasmania, GBR, South Africa, etc...)





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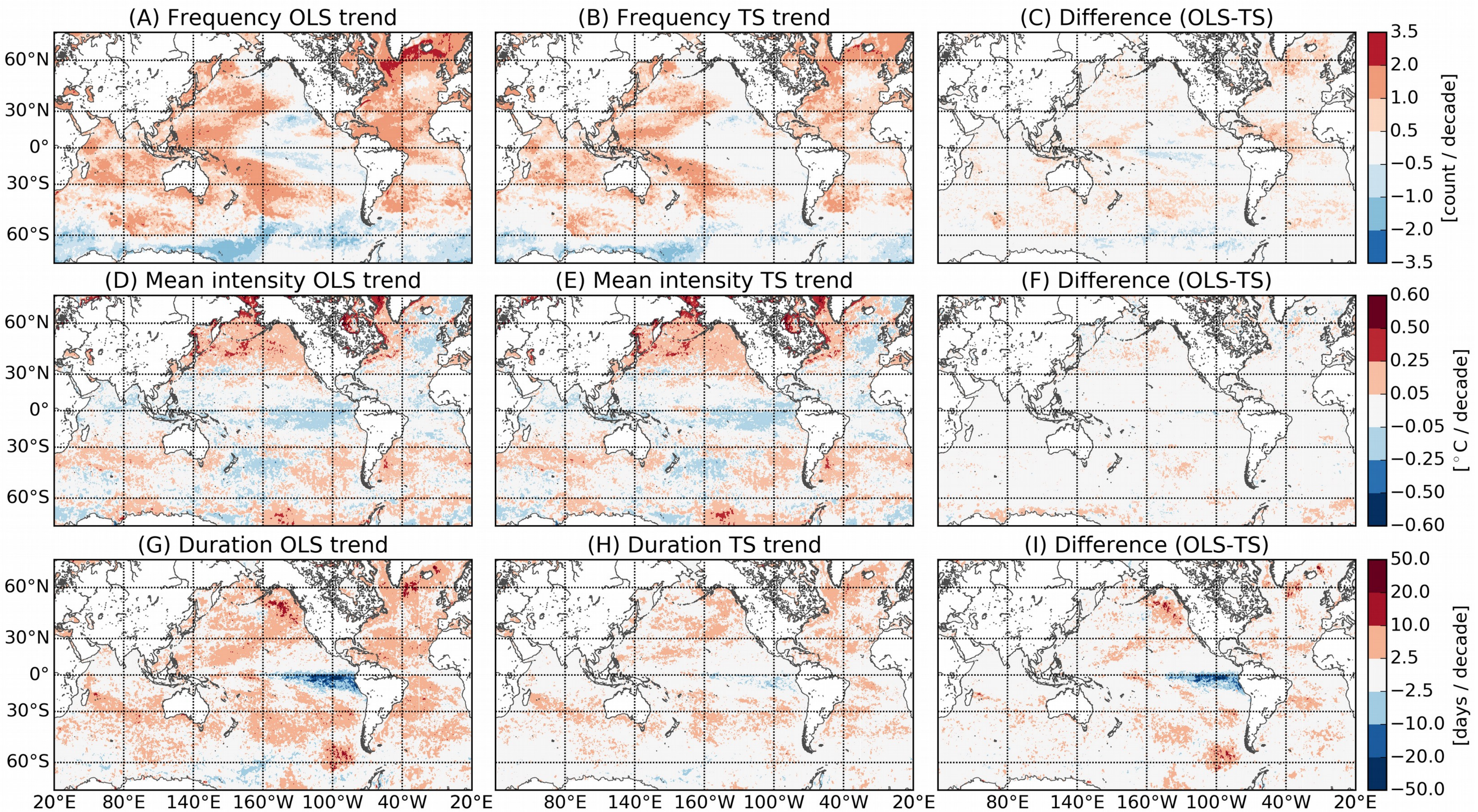
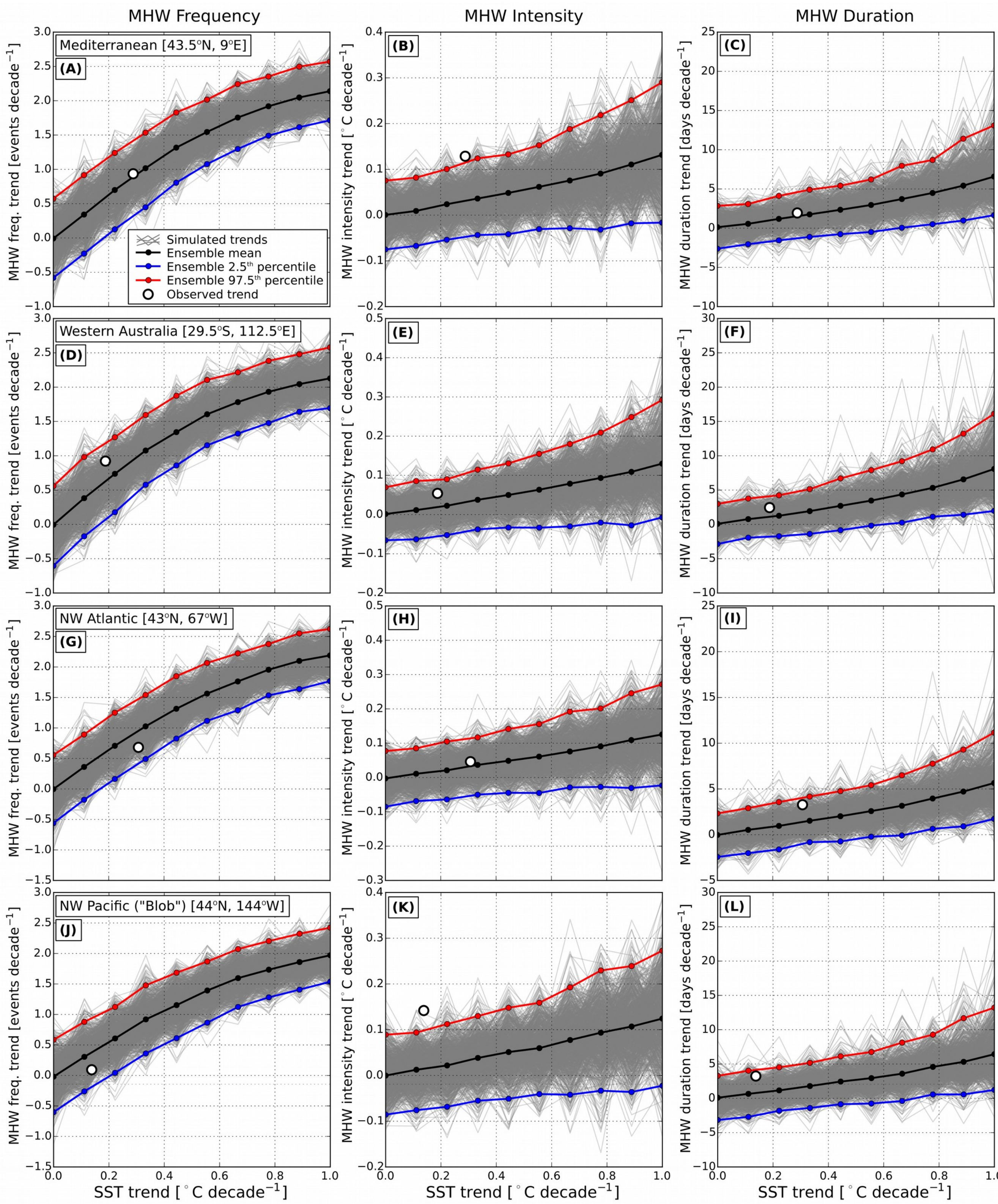
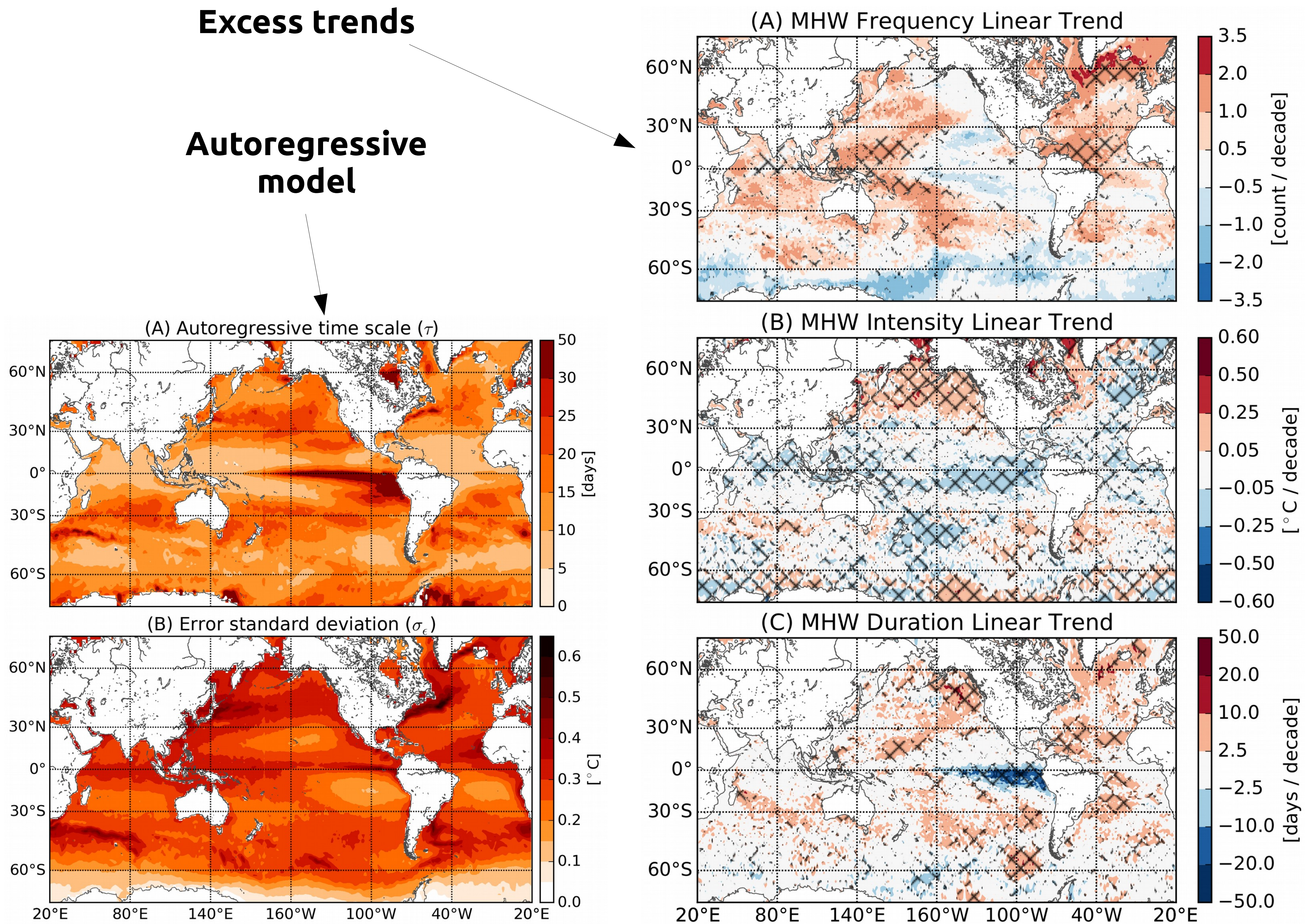
EXTRA SLIDES

Comparison of linear trends estimated by Ordinary Least Squares (OLS) and Theil-Sen (TS)





Can relate the trend in MHW properties to the expected trend due to rising SSTs alone


Excess trends
Autoregressive model
(A) Autoregressive time scale (τ)
[days]
(B) Error standard deviation (σ_ϵ)
[°C]
(A) MHW Frequency Linear Trend
[count / decade]
(B) MHW Intensity Linear Trend
[°C / decade]
(C) MHW Duration Linear Trend
[days / decade]
60°N
30°N
0°
30°S
60°S
20°E
80°E
140°E
160°W
100°W
40°W
20°E

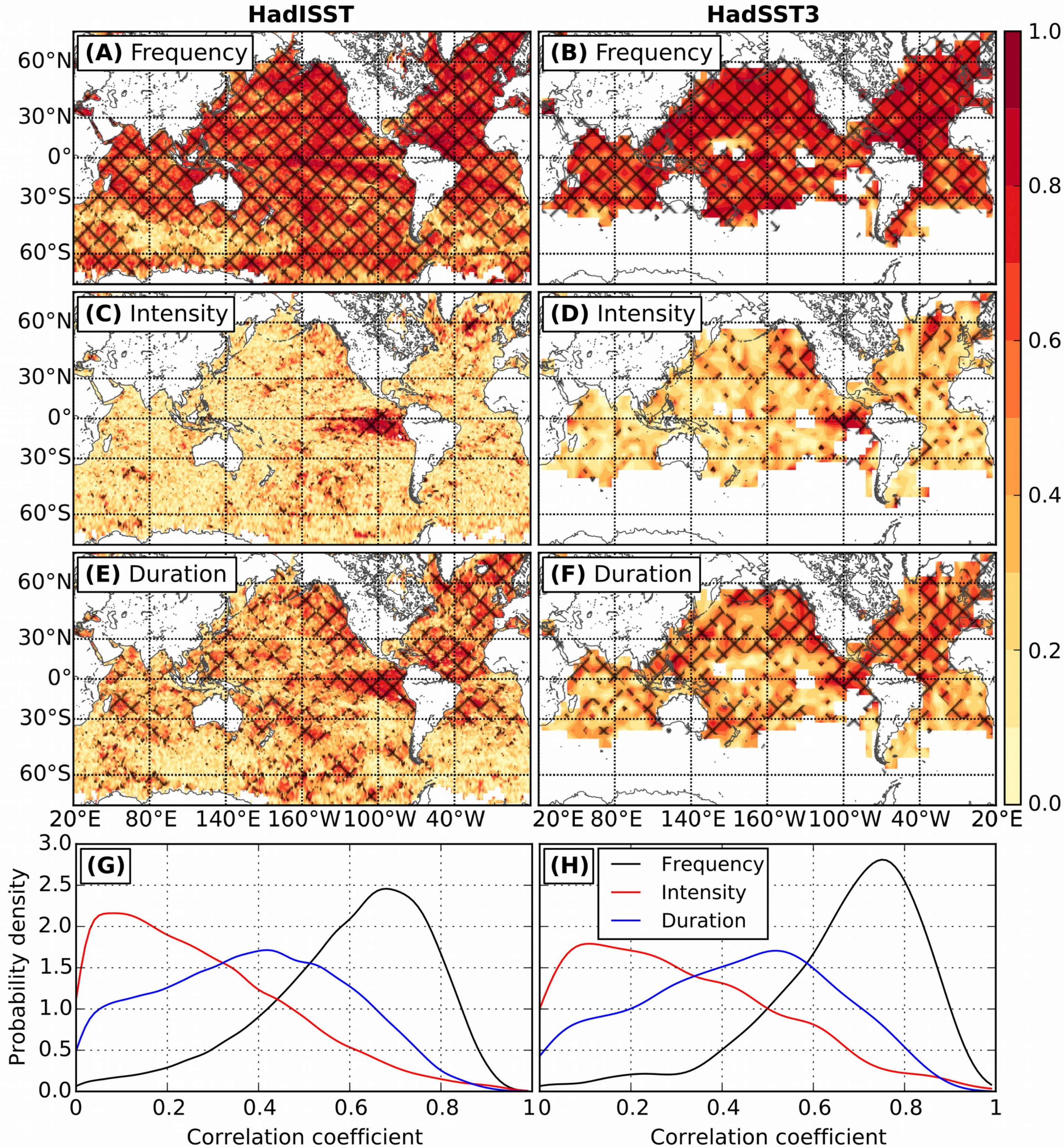
Fit of monthly proxies to long station records

Table S2. Performance of marine heatwave proxies from long-term *in situ* records of ocean temperatures. Shown are the correlation coefficient between annually-averaged marine heatwave properties and their prediction using proxies derived from monthly-mean temperatures (see Eq. 1). Correlations are shown for the model training period (1982 to the end of time series) and for the model validation period (beginning of time series to 1981). Roman, bold roman and bold italics indicate a value is significantly different from zero with the 90%, 95% and 99% confidence, respectively, and a "–" indicates a value not significantly different from zero with 90% confidence.

	Training correlation (1982-)			*Validation correlation (-1981)*		
Station	*Frequency*	*Intensity*	*Duration*	*Frequency*	*Intensity*	*Duration*
Pacific Grove, USA	***0.77***	-	***0.73***	***0.92***	-	***0.76***
Scripps Pier, USA	***0.83***	-	***0.62***	***0.86***	-	0.43
Newport Beach, USA	***0.71***	-	**0.48**	***0.87***	-	***0.50***
Arendal, Norway	***0.85***	-	***0.64***	***0.53***	-	0.40
Port Erin, UK	***0.82***	***0.70***	***0.67***	***0.94***	-	***0.71***

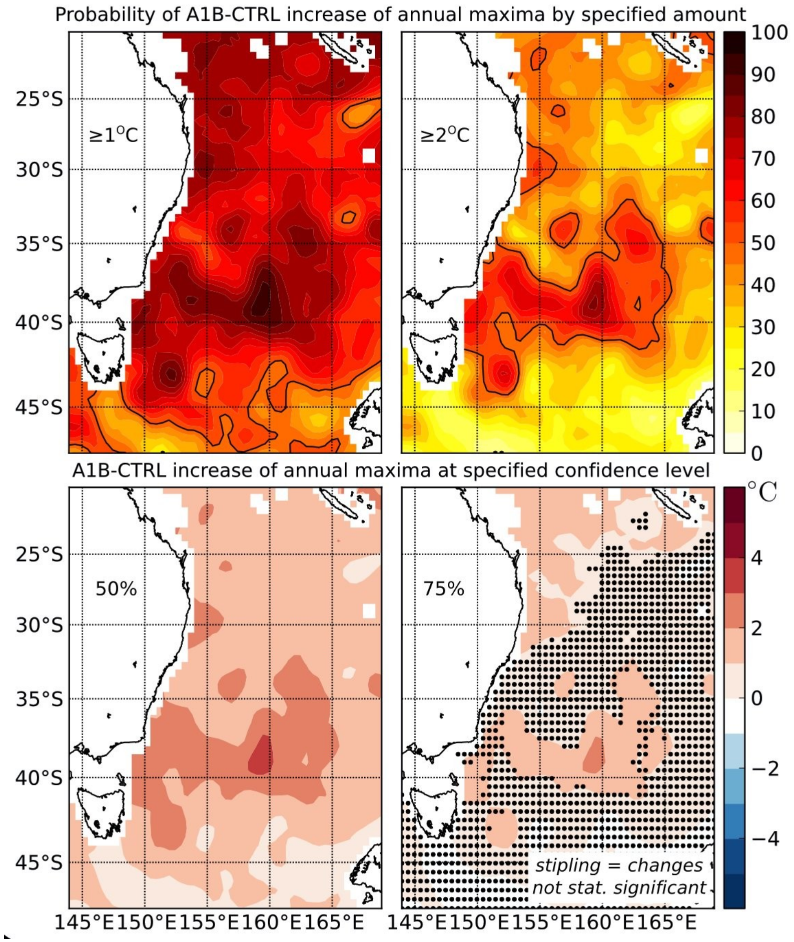
Station	*Time span*	*Number of Years*	*Latitude*	*Longitude*	*% Complete*
Pacific Grove, USA	1920-2009	90	36º 37.3' N	121º 54.2' W	94
Scripps Pier, USA	1917-2013	97	32º 52' N	117º 15.5' W	97
Newport Beach, USA	1925-2013	89	33º 36' N	117º 56' W	98
Arendal, Norway	1924-2011	88	58º 29' N	8º 47' E	96
Port Erin, UK	1904-2011	108	54º 5.1' N	4º 46.1' E	99

Hadley SST proxy fits

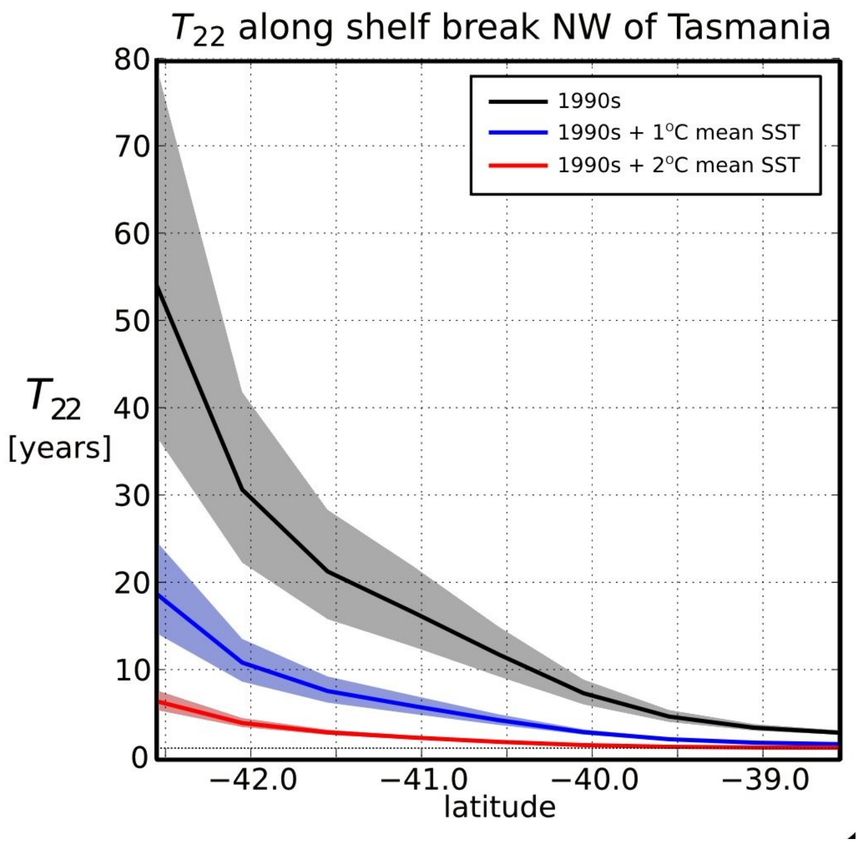


Southeast Austrlaia

- Due to the **probabilistic** (Bayesian) nature of the model we are able to assign probabilities (and **confidence**) to the model projections:



- We are not restricted to model simulated climates, and can in fact **test the response of the extremes to prescribed changes in climate**, i.e., a fixed increase in mean temperature

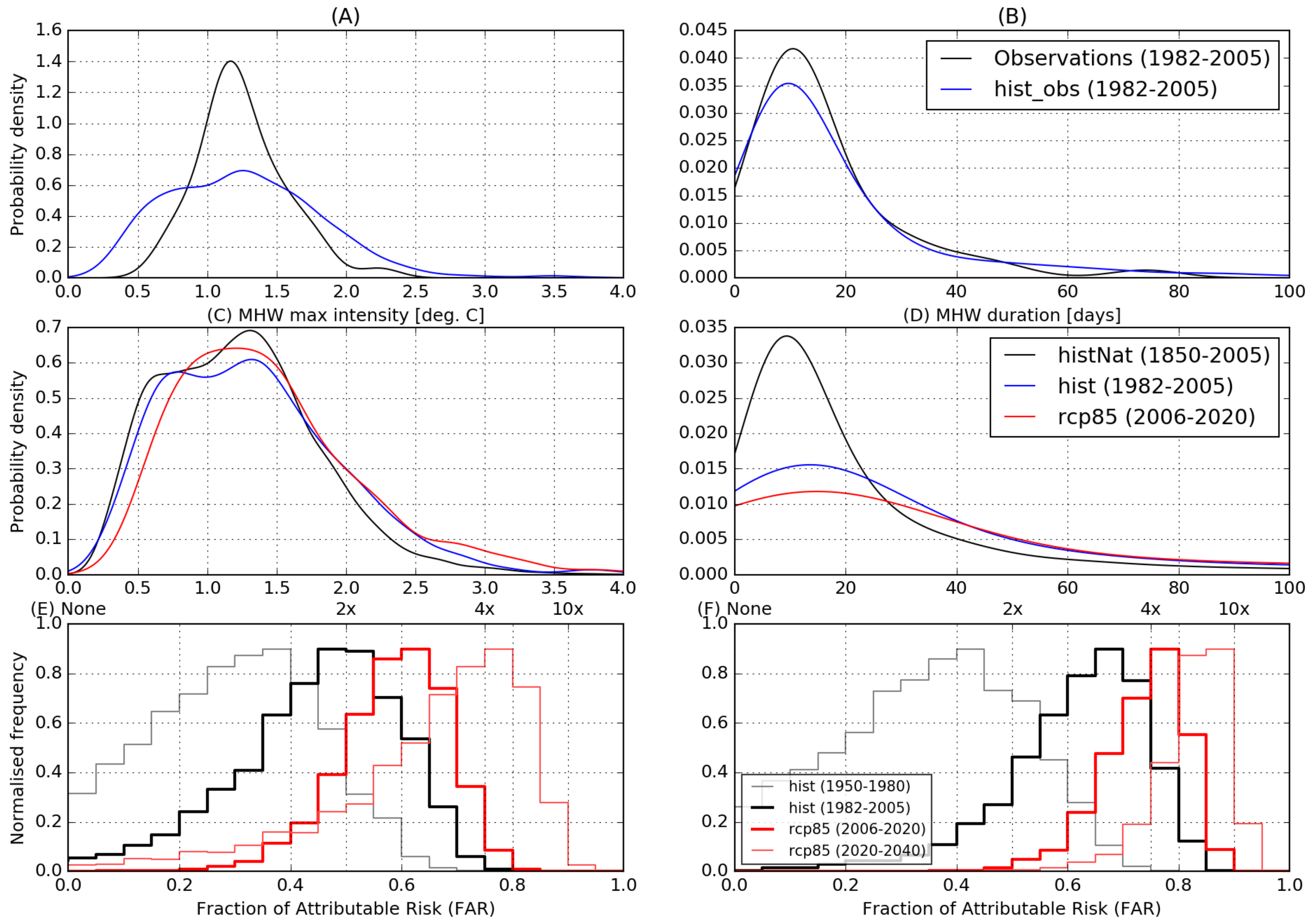


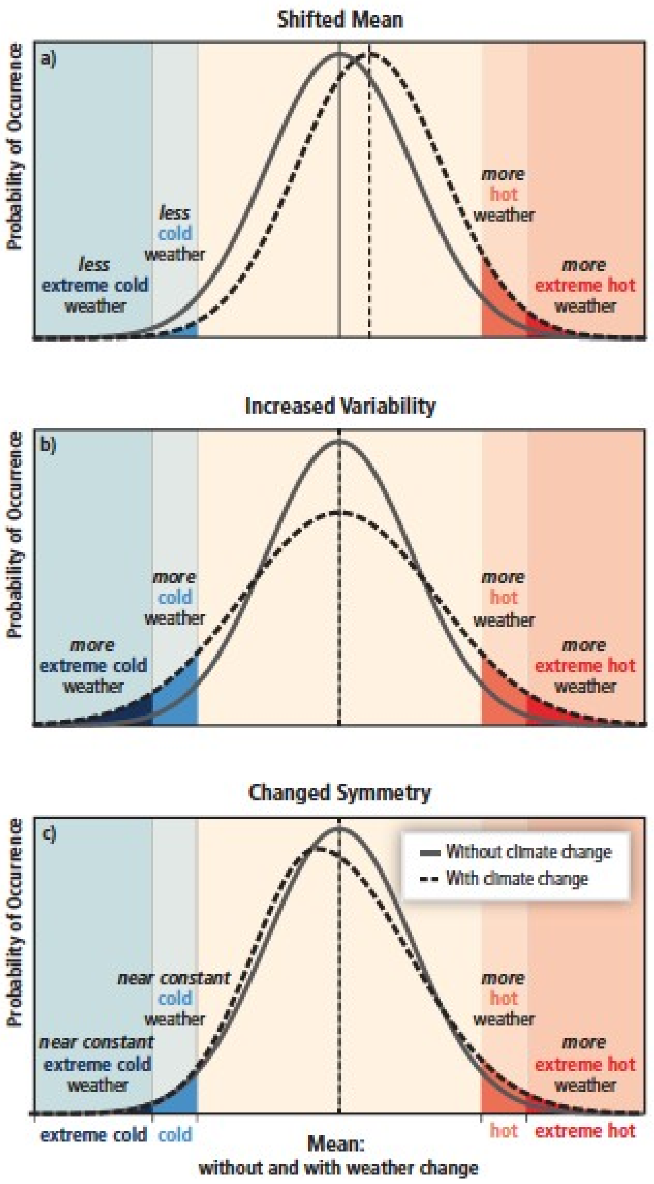
Oliver, E. C. J., S. J. Wotherspoon, M. A. Chamberlain and N. J. Holbrook (2014a), Projected Tasman Sea extremes in sea surface temperature through the 21st century, *Journal of Climate*, 27(5), 1980-1998

Oliver, E. C. J., S. J. Wotherspoon and N. J. Holbrook (2014b), Estimating extremes from global ocean and climate models: A Bayesian hierarchical model approach, *Progress in Oceanography*, 122, 77-91

Oliver, E. C. J. and N. J. Holbrook, Extending our understanding of South Pacific gyre 'spin-up': Modeling the East Australian Current in a future climate, *Journal of Geophysical Research* (available online)

Role of climate change




Shifted Mean
a)
Probability of Occurrence
less extreme cold weather
less cold weather
more hot weather
more extreme hot weather
Increased Variability
b)
Probability of Occurrence
more extreme cold weather
more cold weather
more hot weather
more extreme hot weather
Changed Symmetry
c)
Probability of Occurrence
Without climate change
With climate change
near constant extreme cold weather
near constant cold weather
more hot weather
more extreme hot weather
extreme cold
cold
hot
extreme hot
Mean:
without and with weather change

Marine Heatwave Definition

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

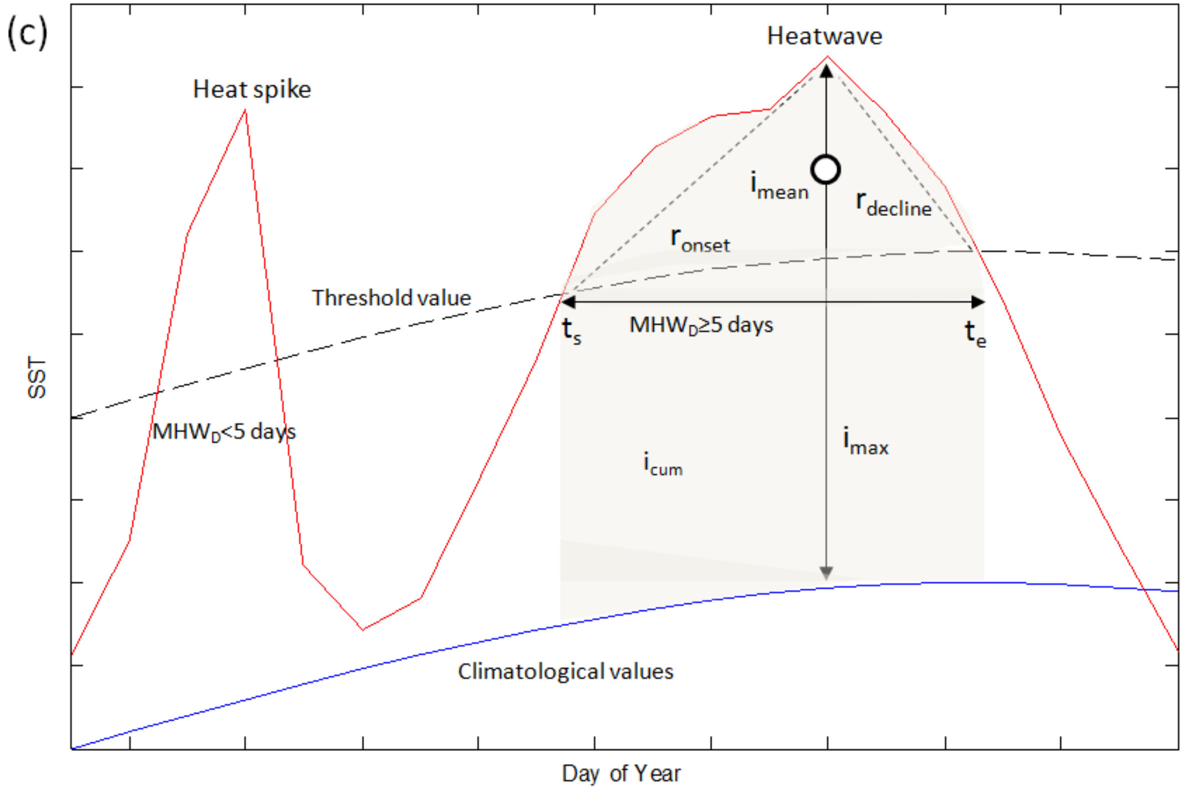


Figure from Hobday et al. (2016) *Prog. Ocean.*

Definition includes a set of metrics, including:

- **Intensity** [°C]
  - both maximum and event-mean
- **Duration** [days]
  - Time from start to end dates

Software implementation in Python freely available here:
`github.com/ecjoliver/marineHeatWaves`