Historical and Future Projected Changes in Global Marine Heatwaves

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12 Marine Biological Association of the United Kingdom, The Laboratory, Citadel Hill, Plymouth UK
13 UWA Oceans Institute and School of Plant Biology, The University of Western Australia, Western Australia
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UNSW
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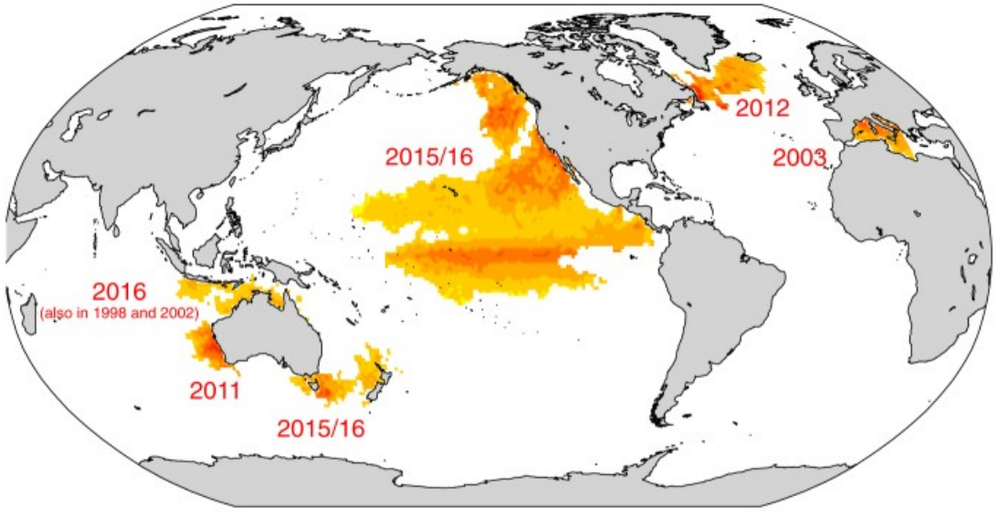
Global Context



Froelicher and Laufkoetter (2018), Nature Communications

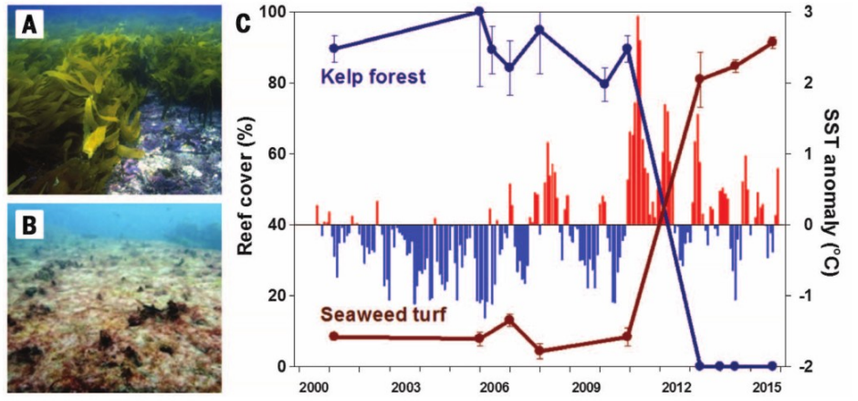
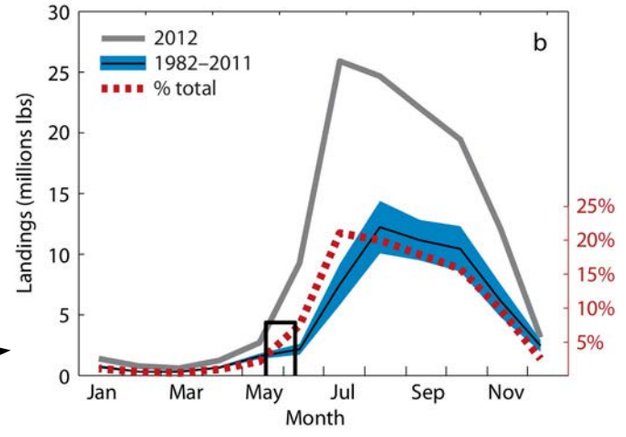


Fig. 2. Regime shift from kelp forests to seaweed turfs after the 2011 marine heat wave. Kelp

Wernberg et al. 2016 *Science*

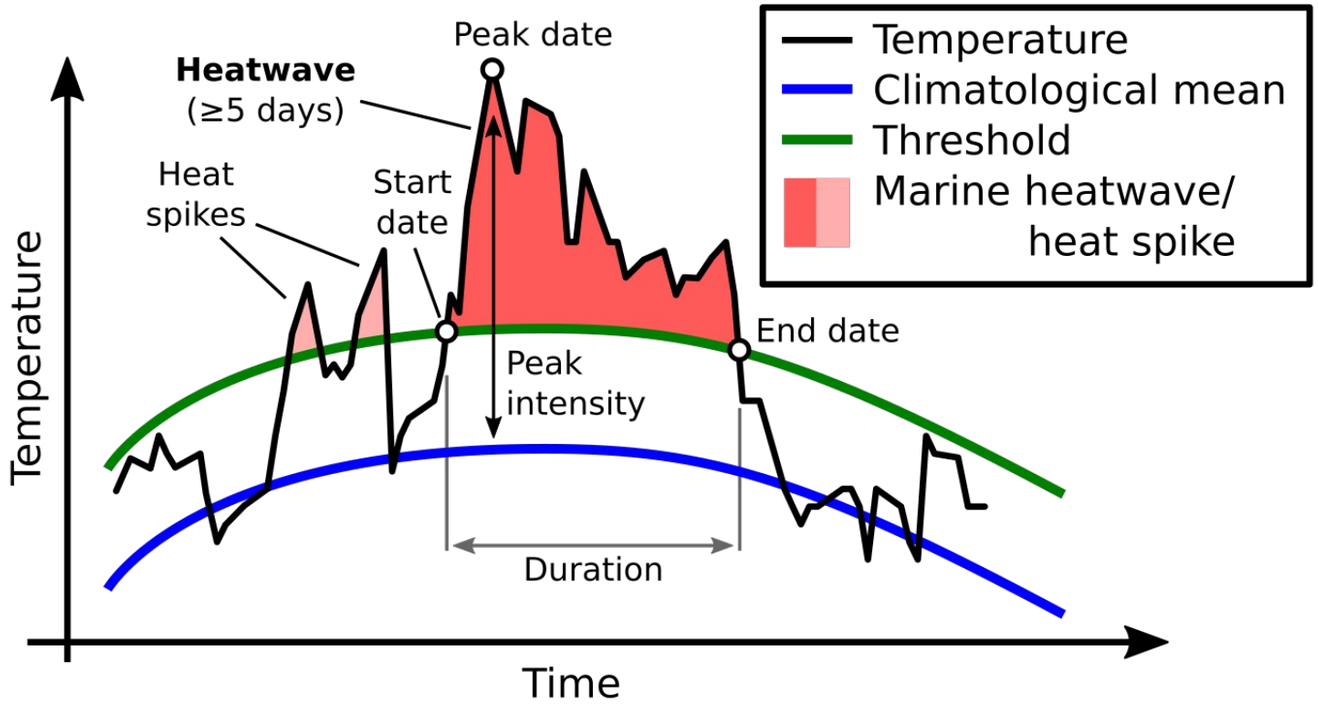


Mills et al. 2013 *Oceanography*

- A number of **major events** have occurred in **recent years**
- Each event brings **significant impacts**, e.g.,
  - Important for determining marine ecosystem structure (2011 WA event)
  - Can impact fisheries (2012 NW Atlantic event)
- Some indications that impacts of MHWs are **becoming more severe** in the context of warming climate, and that events are **more frequent**
- **How to define MHWs? Physical drivers and processes? Global trends in MHWs? Role of climate 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



Definition includes a set of metrics, including:

- **Intensity** [°C]
  - Maximum SST anomaly
- **Duration** [days]
  - Time from start to end dates

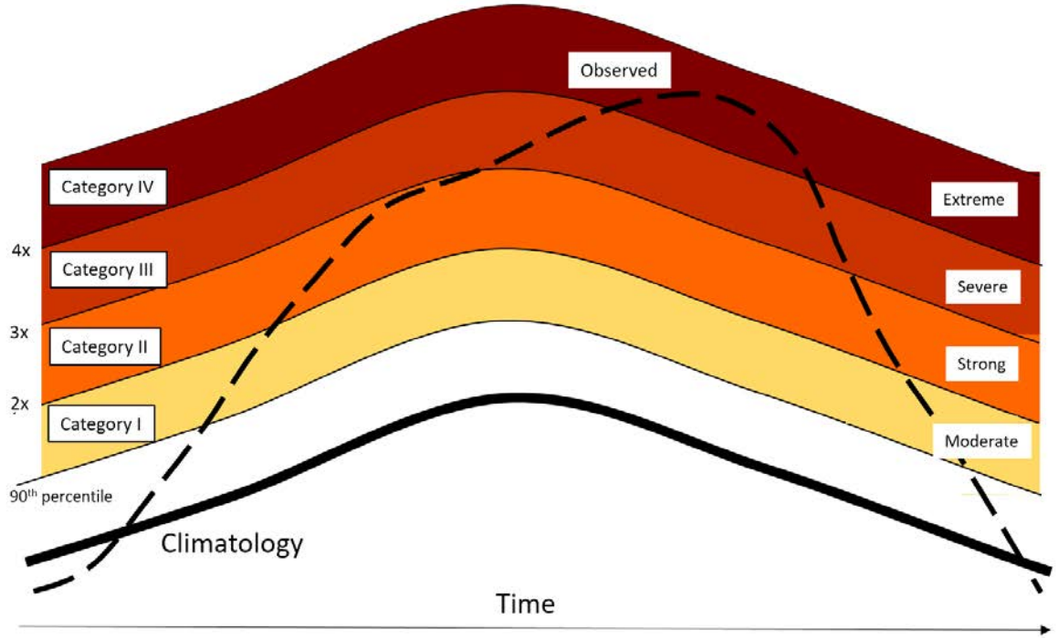
Software implementations available:

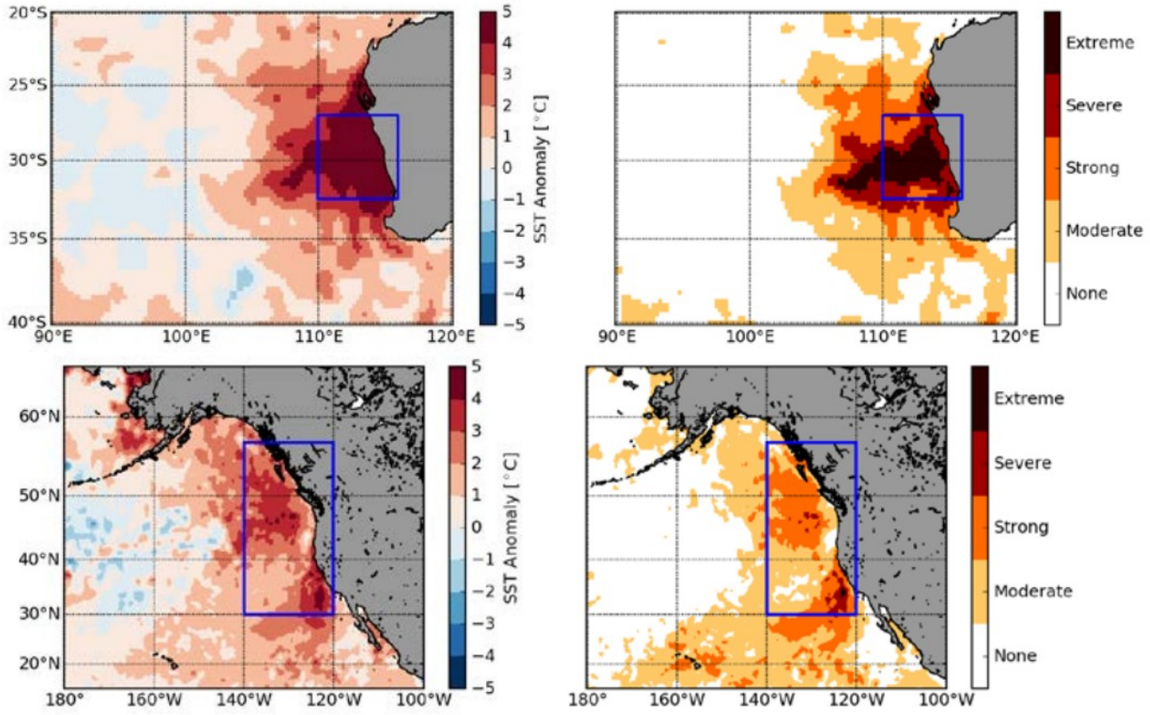
```
Python: github.com/ecjoliver/marineHeatWaves
R:      robwschlegel.github.io/heatwaveR/
MATLAB: github.com/ZijieZhao/m_mhw1.0
```

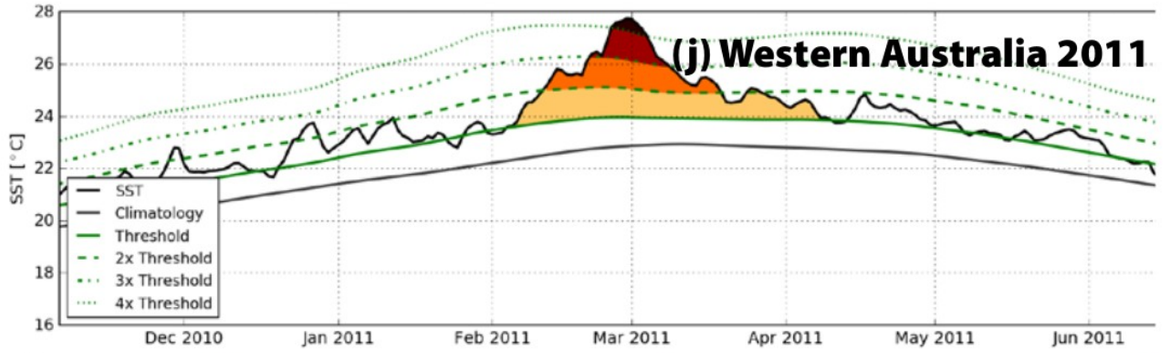
Hobday et al. (2016). A hierarchical approach to defining marine heatwaves. *Prog. Ocean.* 141: 227-238.

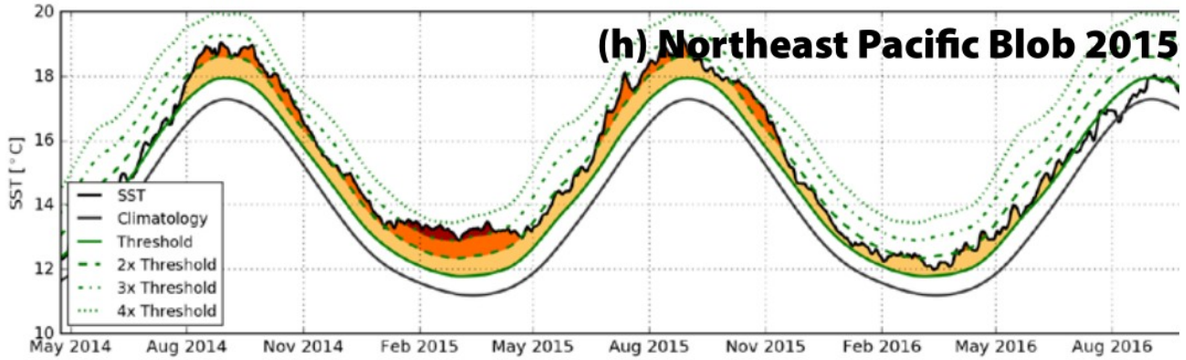
Marine Heatwave Categories

- A **marine heatwave (MHW) categorisation** has also been proposed (Hobday et al., 2018)
- Categories based on intensity (temperature anomaly) of the event
- I (Moderate) and II (Strong) events tend to have little to no lasting impacts, while III (Severe) and IV (Extreme) events have had significant published effects





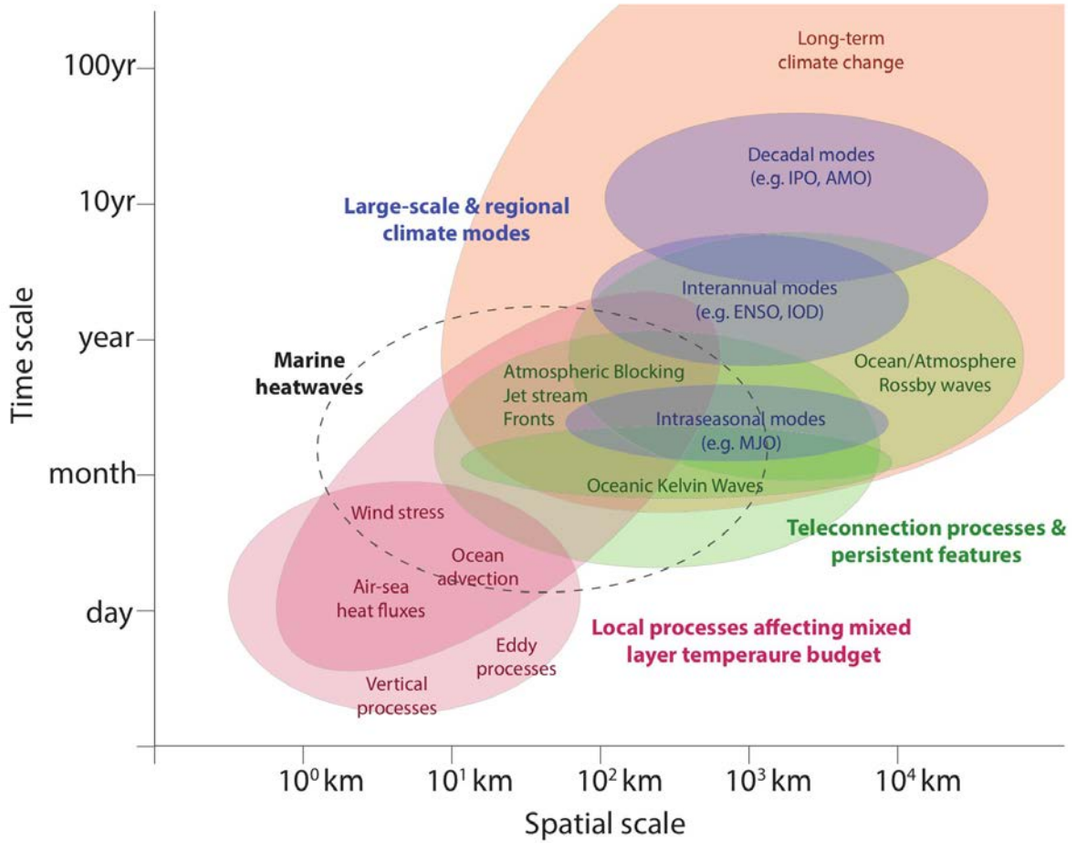




Hobday et al. (2018). Categorizing and naming marine heatwaves. *Oceanography.* 31(2)

What drives marine heatwaves?

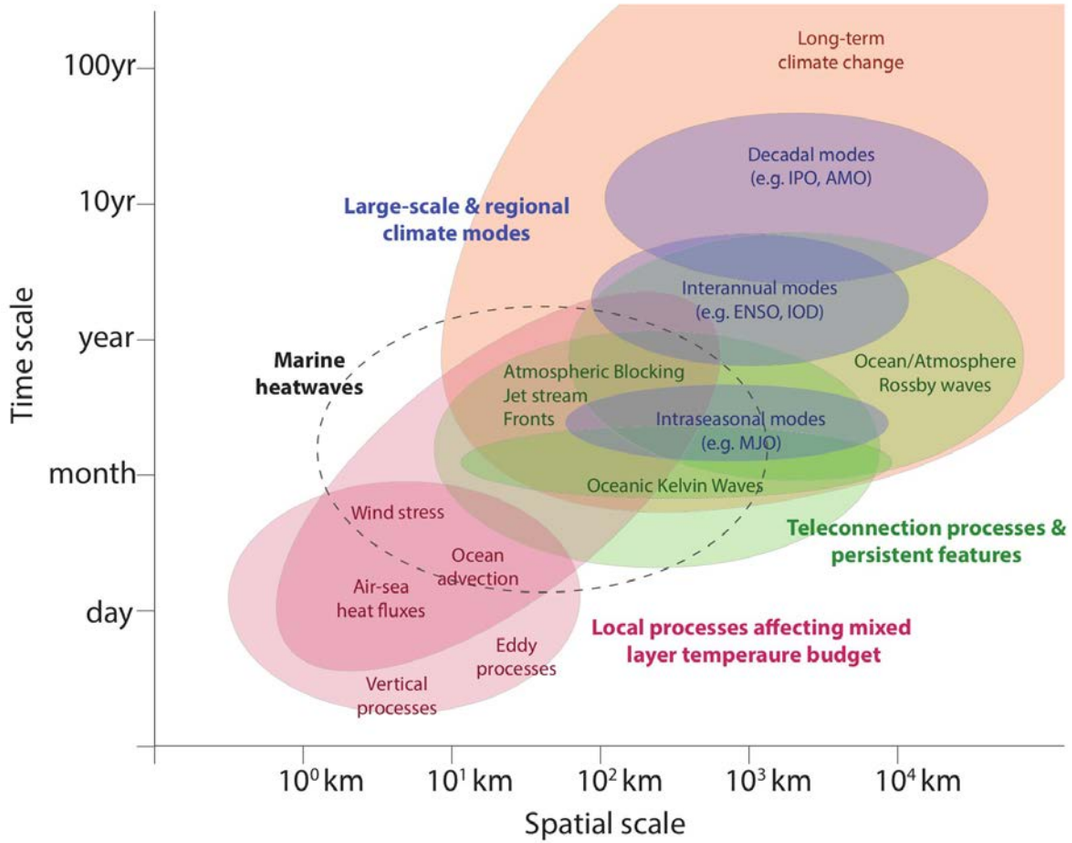
Temporal and spatial scales, and drivers



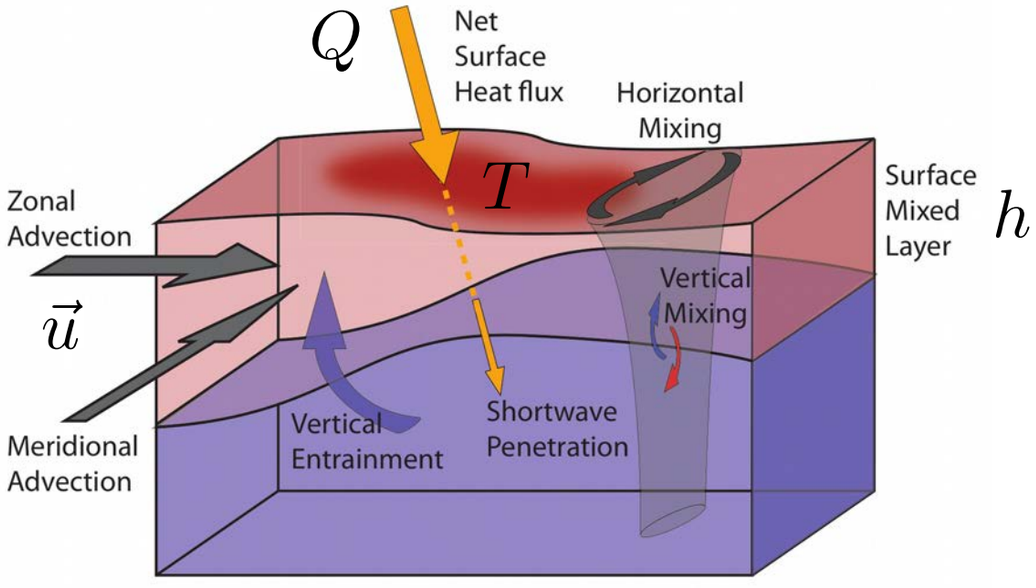
Holbrook et al. (2019). A global assessment of marine heatwaves and their drivers. *Nature Communications.* 10:2624

What drives marine heatwaves?

Temporal and spatial scales, and drivers



Physical processes



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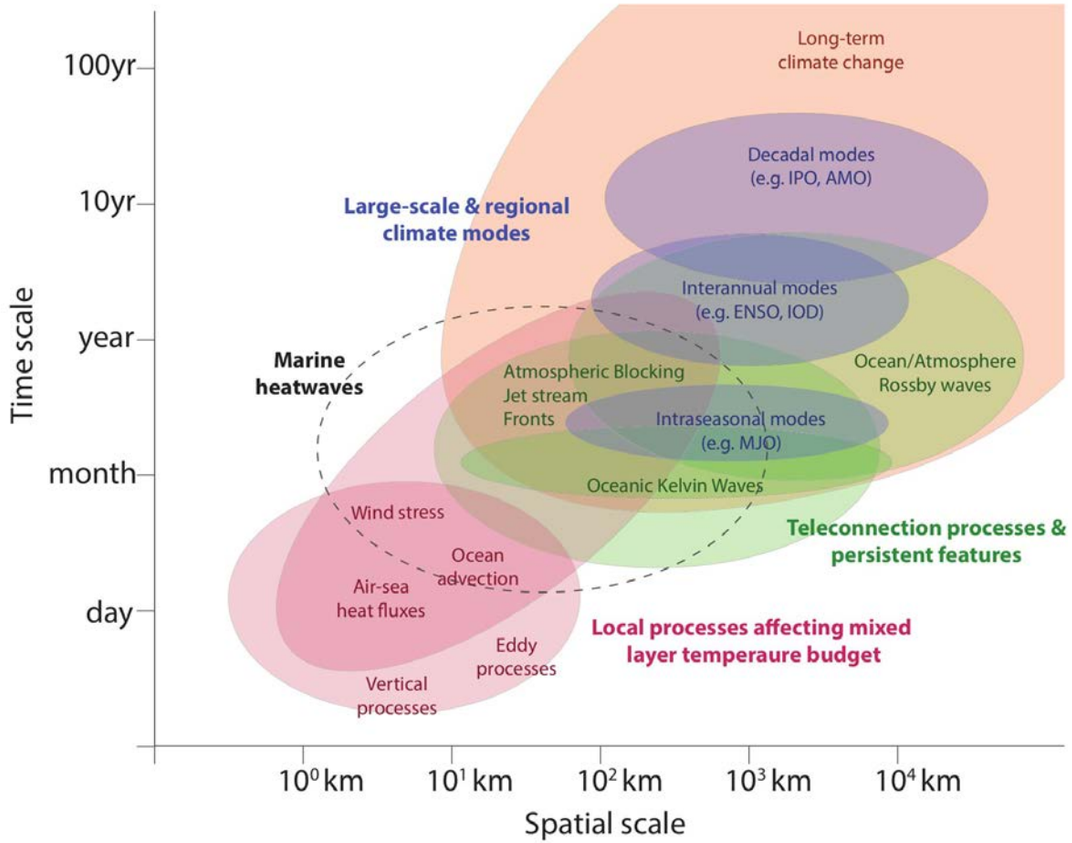

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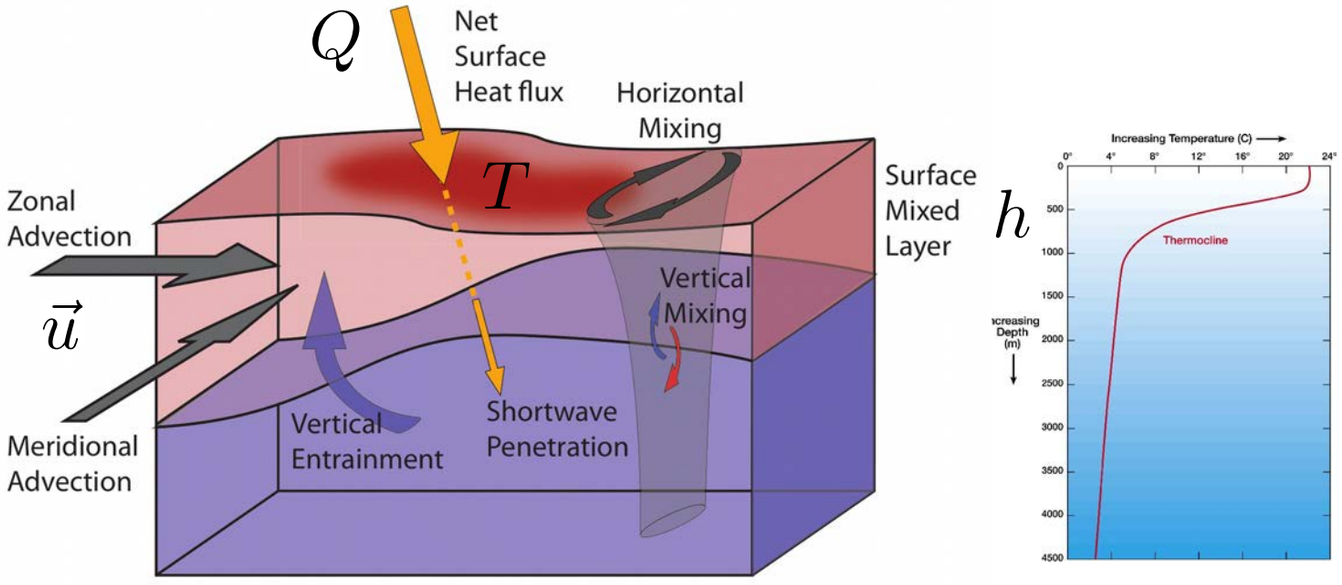

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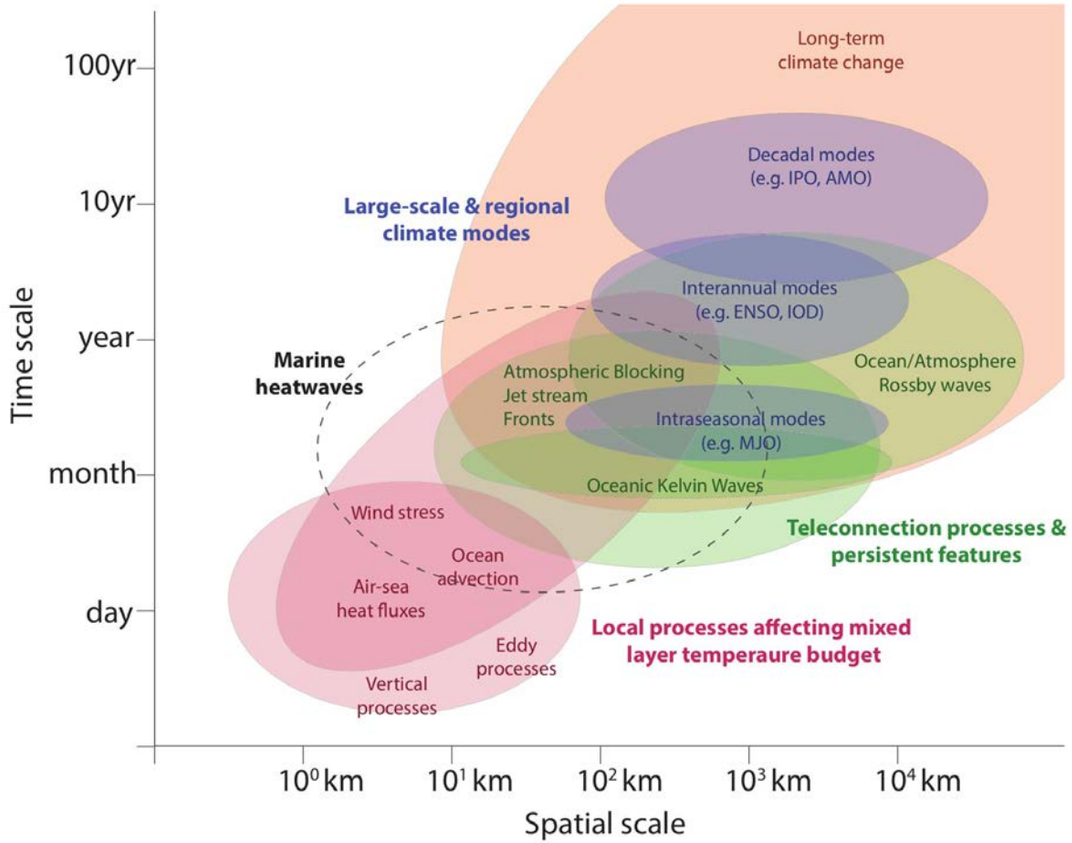

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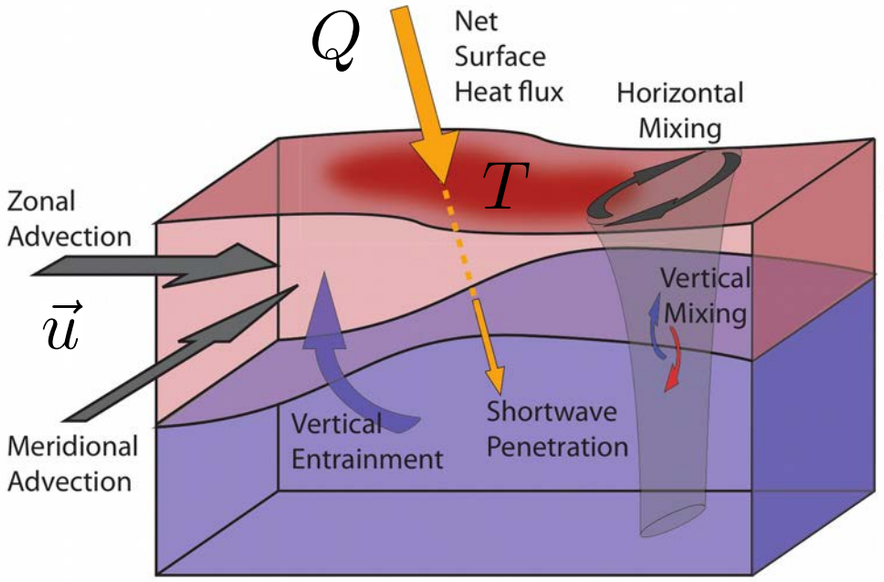
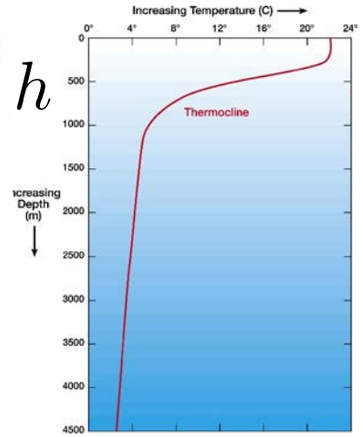




$$\frac{\partial T}{\partial t} = -\vec{u} \cdot \nabla T + \frac{Q}{\rho c_p h} + Residual$$

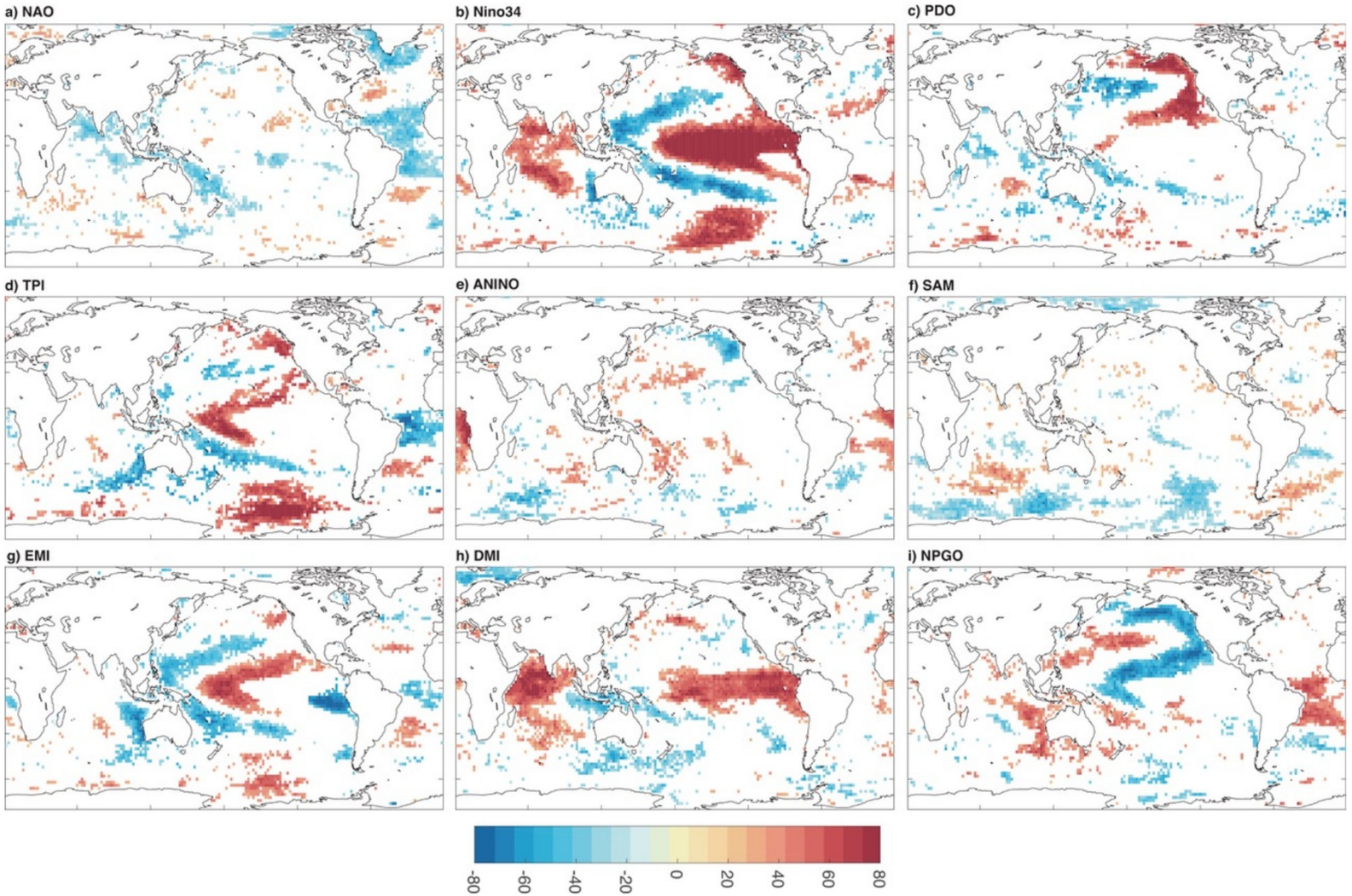
Horizontal temperature advection

Air-sea Heat flux

Includes horizontal and vertical diffusion, vertical advection

Holbrook et al. (2019). A global assessment of marine heatwaves and their drivers. *Nature Communications.* 10:2624

The role of climate modes

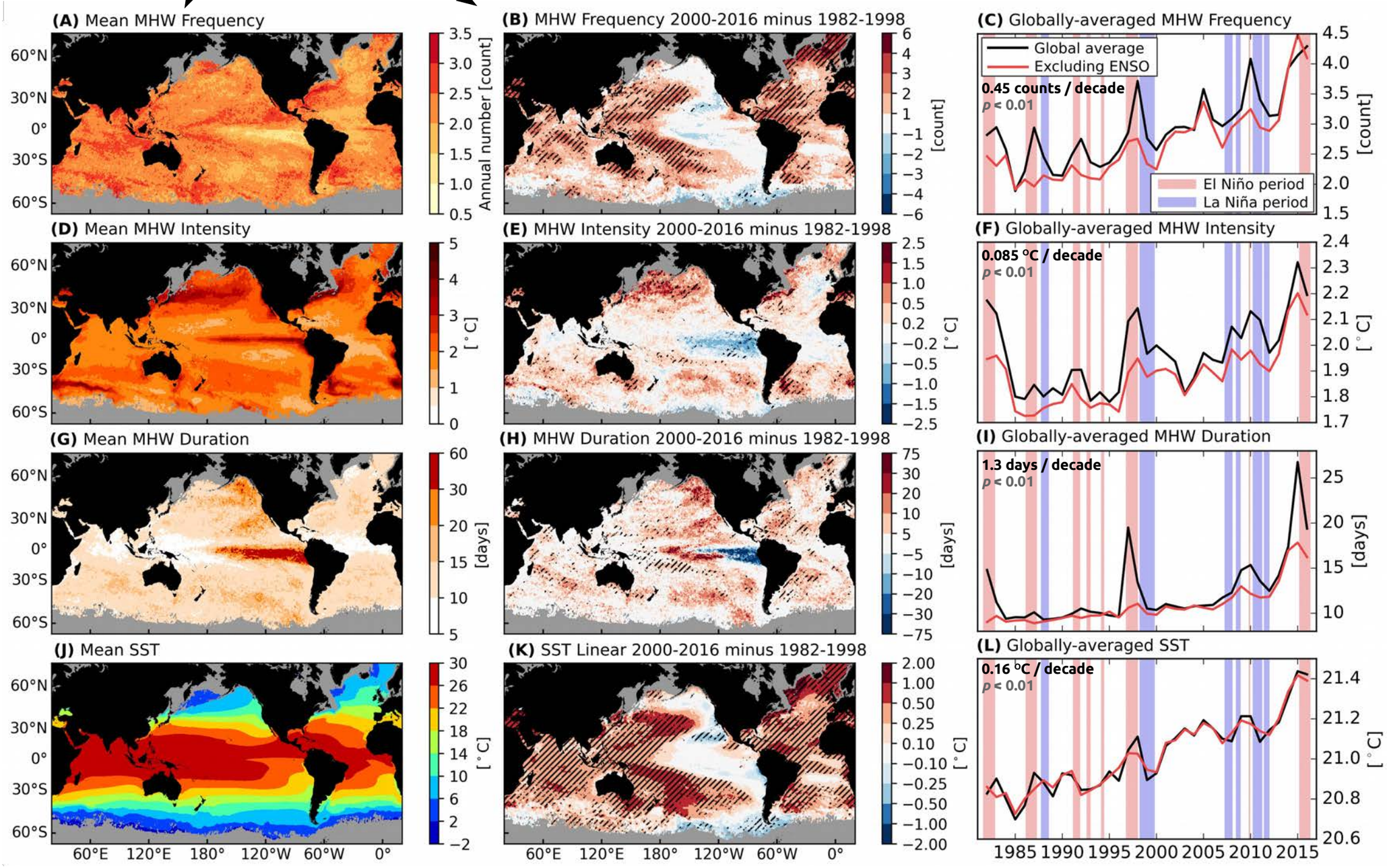


Percentage change in MHW days during positive phase of climate modes

Holbrook et al. (2019). A global assessment of marine heatwaves and their drivers. *Nature Communications.* 10:2624

Mean, **multi-decadal change**, and **globally-averaged time series** based on satellite SSTs

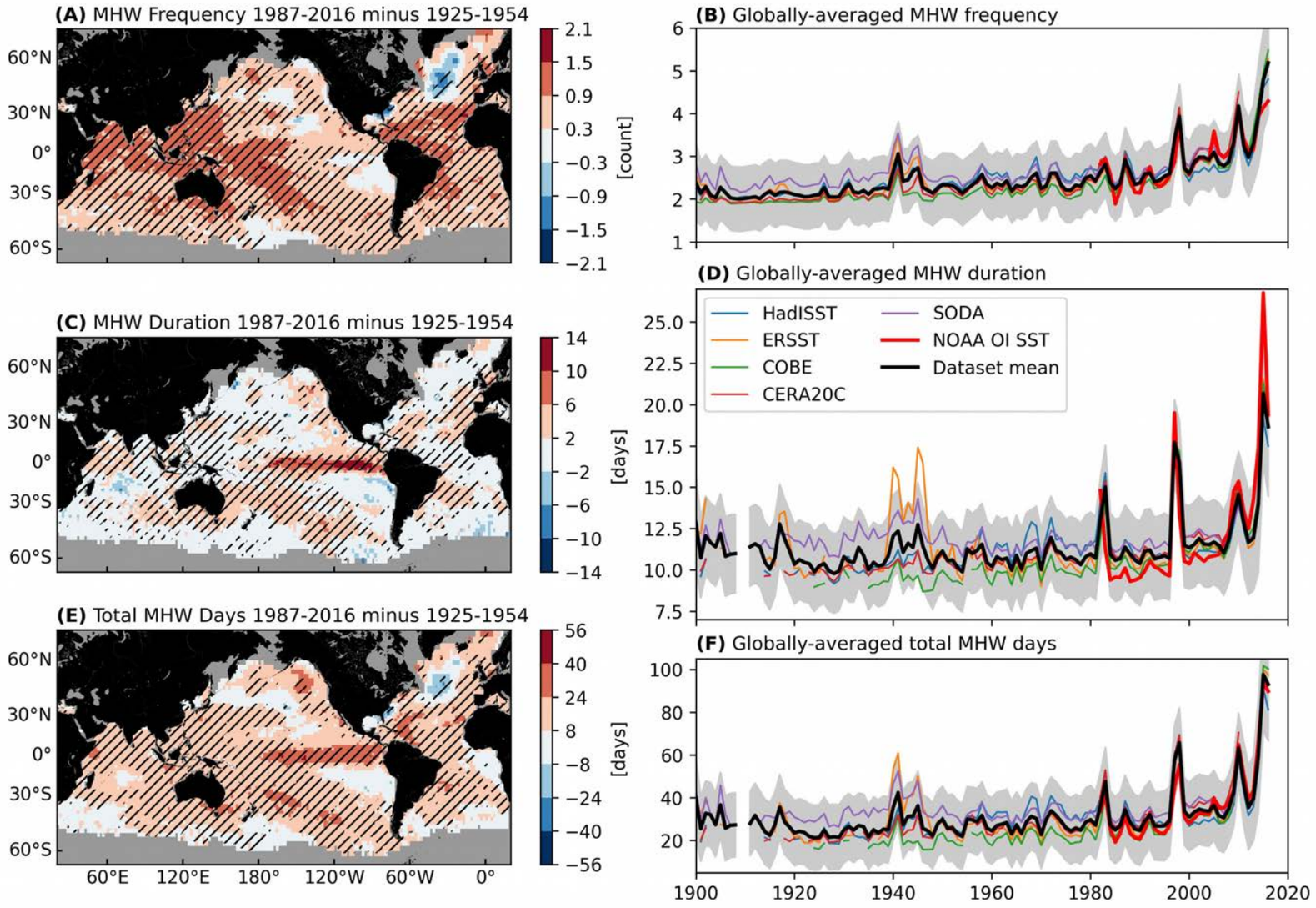
(NOAA OI SST, 1982-2016)



Oliver et al. (2018) Longer and more frequent marine heatwaves over the past century. *Nature Communications*. 9, 1324

Global Centennial Trends

- Annual MHW metrics have been calculated globally from **daily satellite** and **five long-term monthly** datasets



Changes between 1925-1954 and 1987-2016:

- **Frequency**: +0.78 annual events (p<0.01)

  → **34% increase**

- **Duration**: +1.8 days (p<0.01)

  → **17% incease**

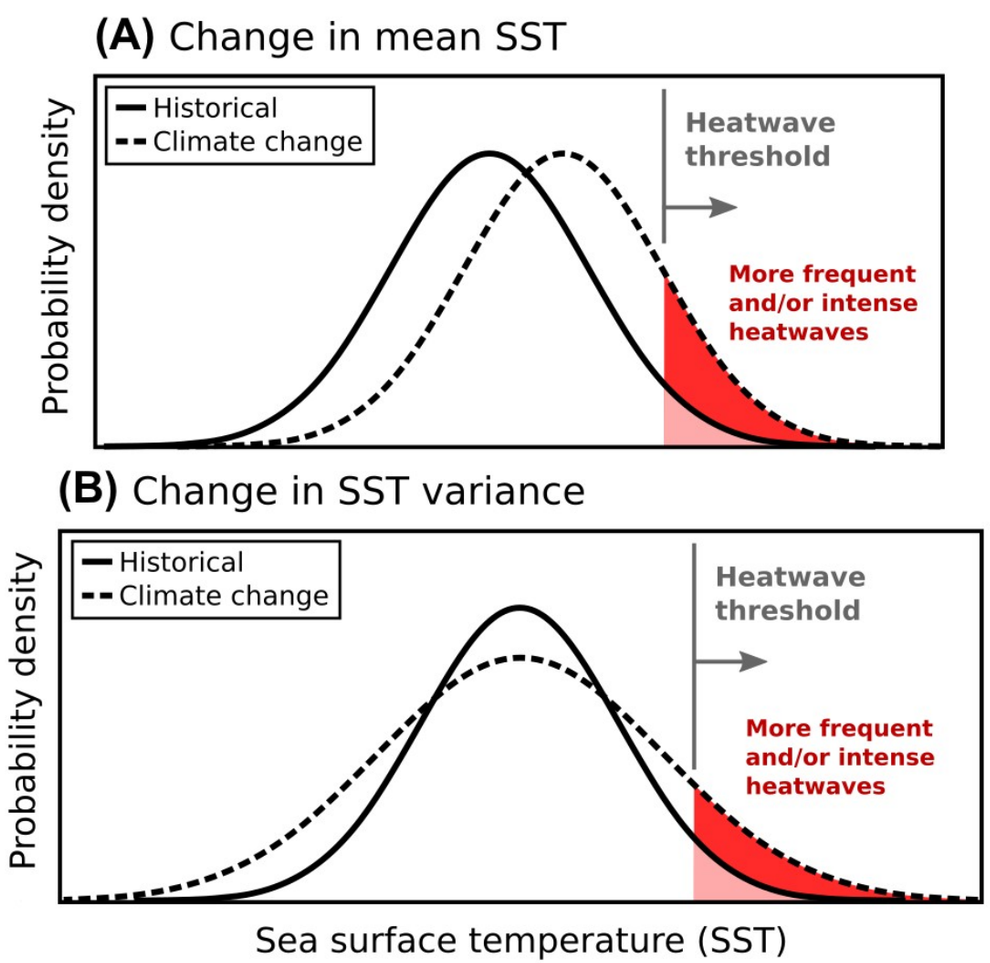
- **Combined!** → +14 annual MHW days (p<0.01)

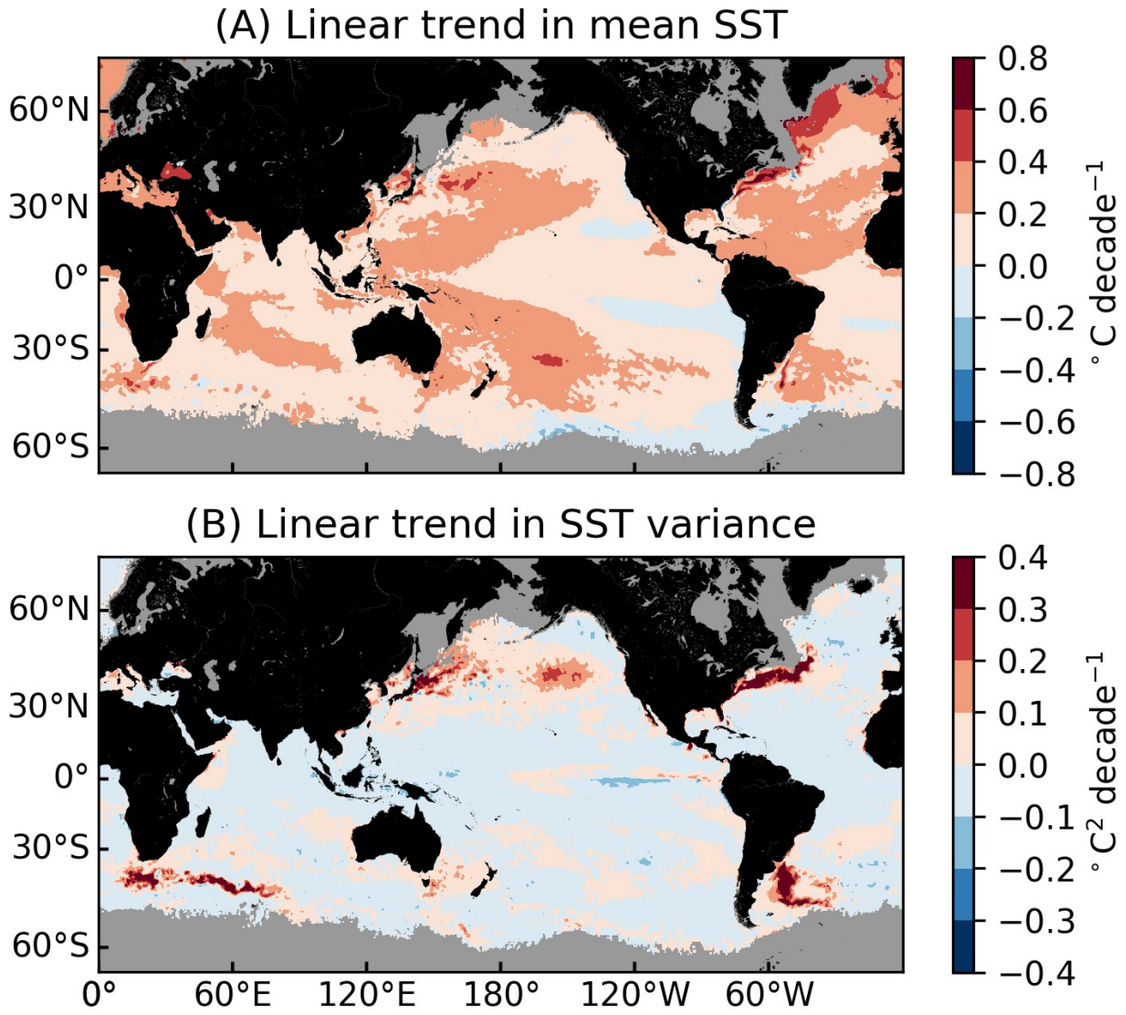
  → **54% increase**

Oliver et al. (2018) Longer and more frequent marine heatwaves over the past century. *Nature Communications.* 9, 1324

Mean or variability?

- Is it the mean warming or the change in SST variability that drives MHW trends?





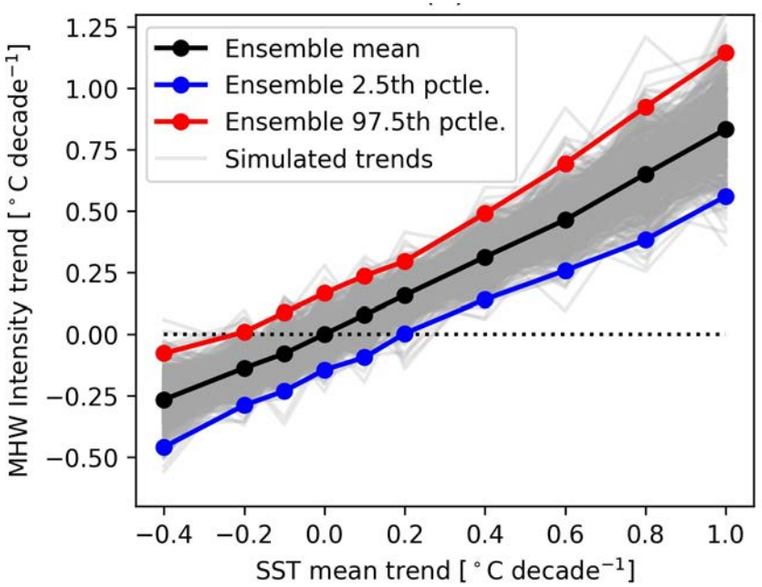
Oliver (2019) Mean warming not variability drives marine heatwave trends. *Climate Dynamics*

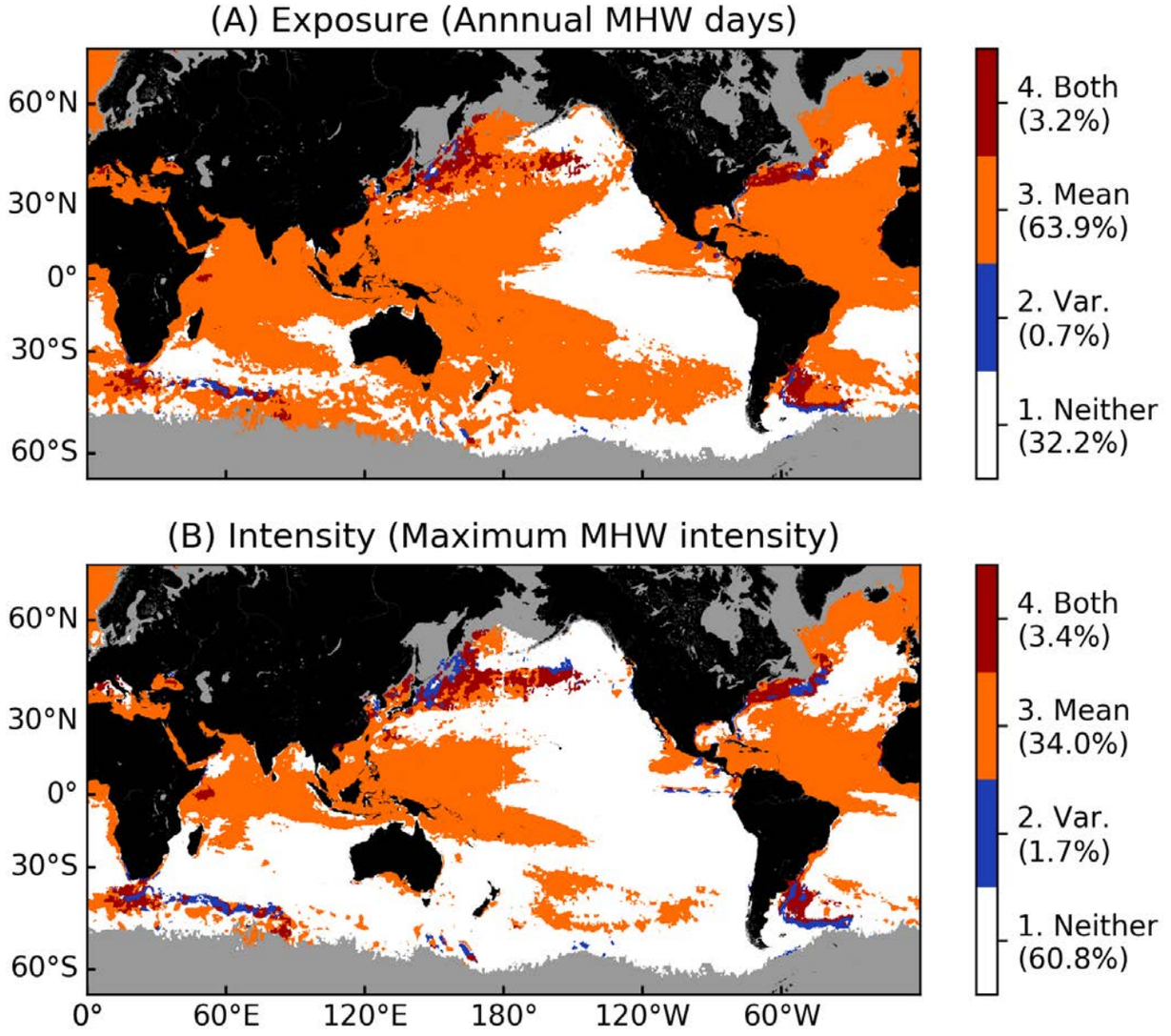
Mean or variability?

- Can test it using a statistical model.
- An autoregressive (AR1) model was fit to each location to know how the SST typically varies there:

$$T(t + \Delta t) = aT(t) + \epsilon(t)$$

- Then the SST was simulated *many times* with a range of trends in mean SST and SST variance
- If the observed trends fall within a confidence interval, the the trend in mean and/or variance alone can explain them





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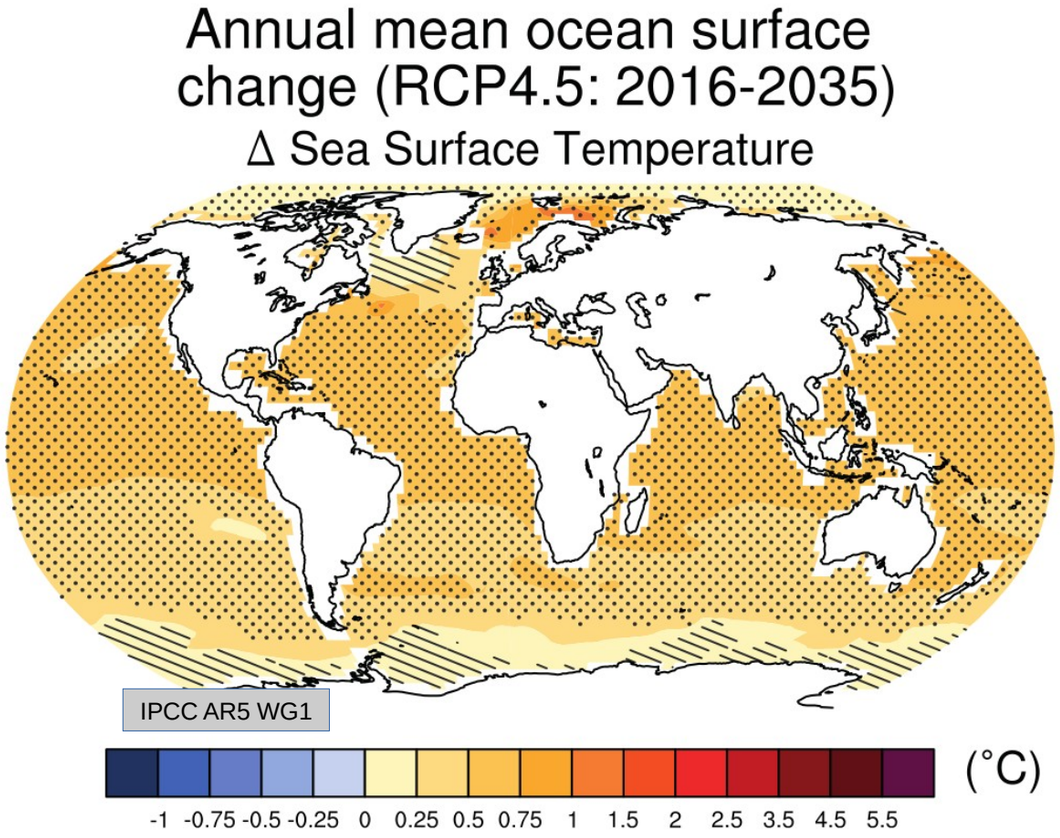
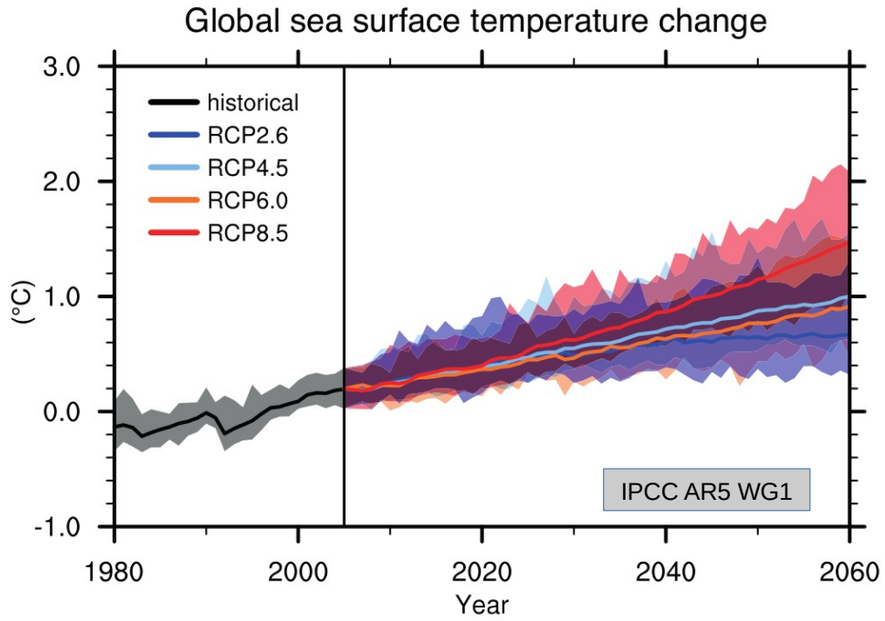
Future projections

- **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)**

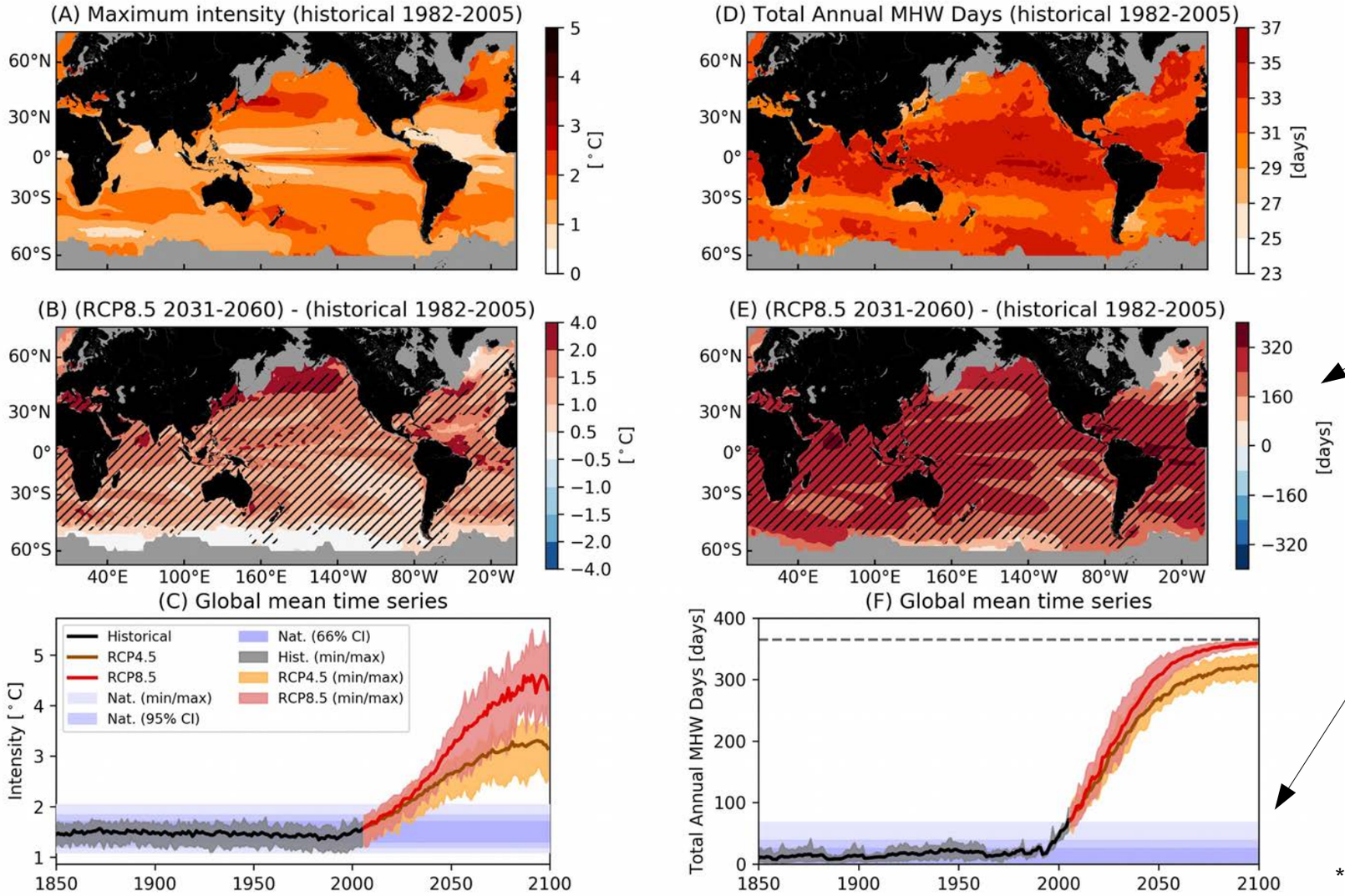




- We can expect **historical trends** in marine heatwaves to **continue into the future**
- Will they accelerate?
- What will be the impacts on marine ecosystems and fisheries?

Future projections

- Six CMIP5 models* were available with daily SSTs
- Calculated MHWs form the **historicalNat** (1850-2005), **historical** (1850-2005), **RCP4.5** (2006-2100) and **RCP8.5** (2006-2100) simulations
- Referenced relative to 1982-2005 base period from **historical** simulation



6 out of 6 models agree → $p < 0.02$ based on a binomial distribution

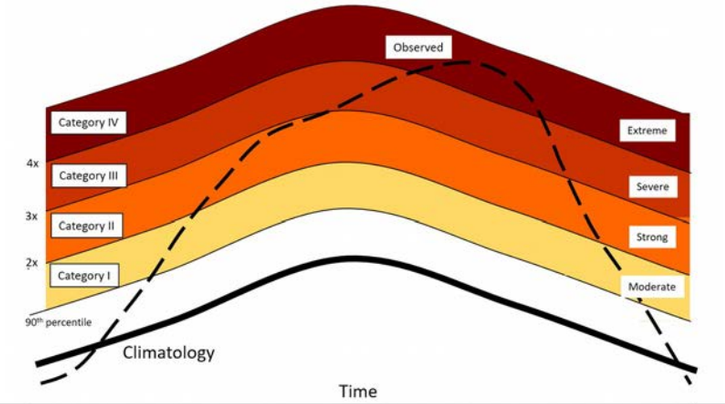
- **All models agree** (hatching): **increases** in maximum MHW intensity and total annual MHW days nearly everywhere
- Inter-model ensemble exceeds range of **natural variability** by
  - **Maximum MHW intensity:**
    - **RCP4.5**: 2044
    - **RCP8.5**: 2033
  - **Total annual MHW days:**
    - **RCP4.5**: 2009
    - **RCP8.5**: 2010

* ACCESS1-3, CSIRO-Mk3-6-0, HadGEM2-ES, IPSL-CM5A-LR, IPSL-CM5A-MR, CanESM2

Difference between RCPs

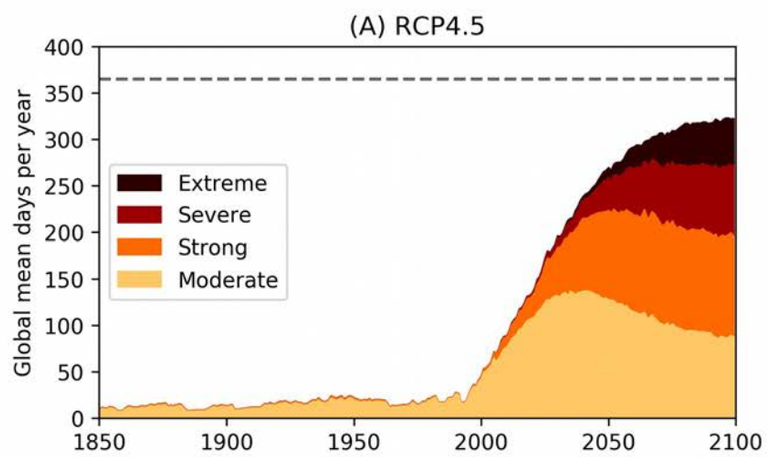
- **Both RCP4.5 and RCP8.5** lead to >300 MHWs days (global average) by late 21st century
- However, distribution of **MHW categories** differs greatly

Four categories of MHWs, increasing in intensity

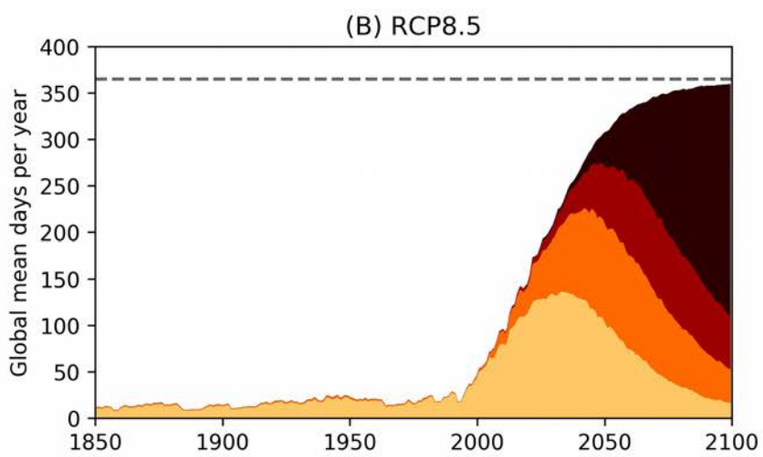


Hobday et al. (2018), Categorizing and Naming Marine Heatwaves, *Oceanography*, 31 (2)

RCP4.5: still mostly moderate or strong events



RCP8.5 mostly extreme!!!



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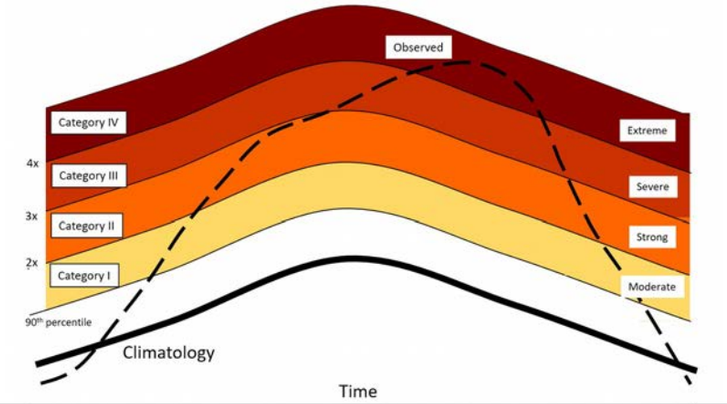

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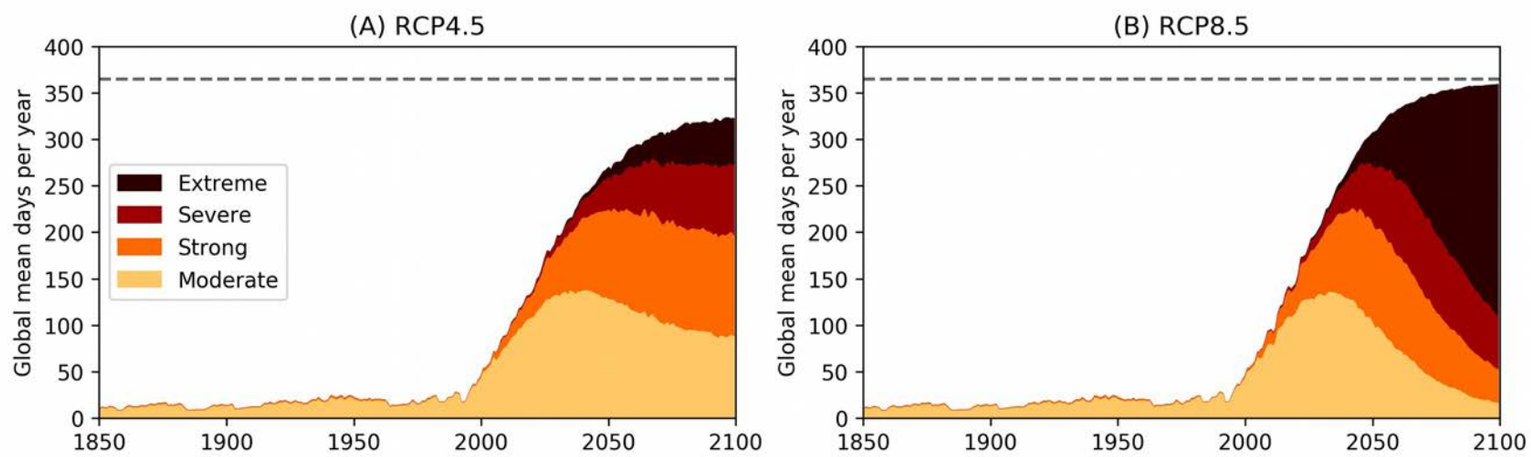
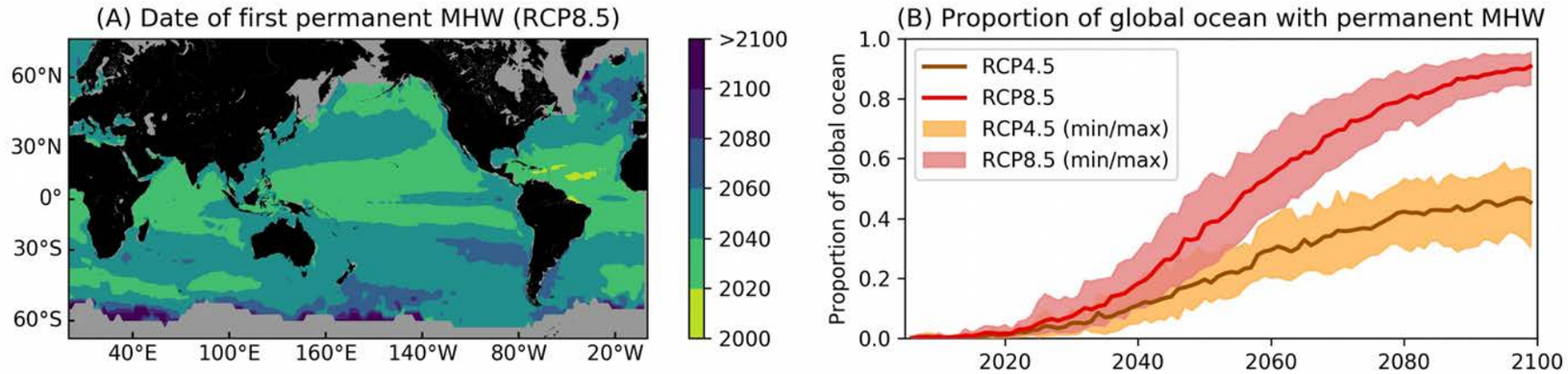
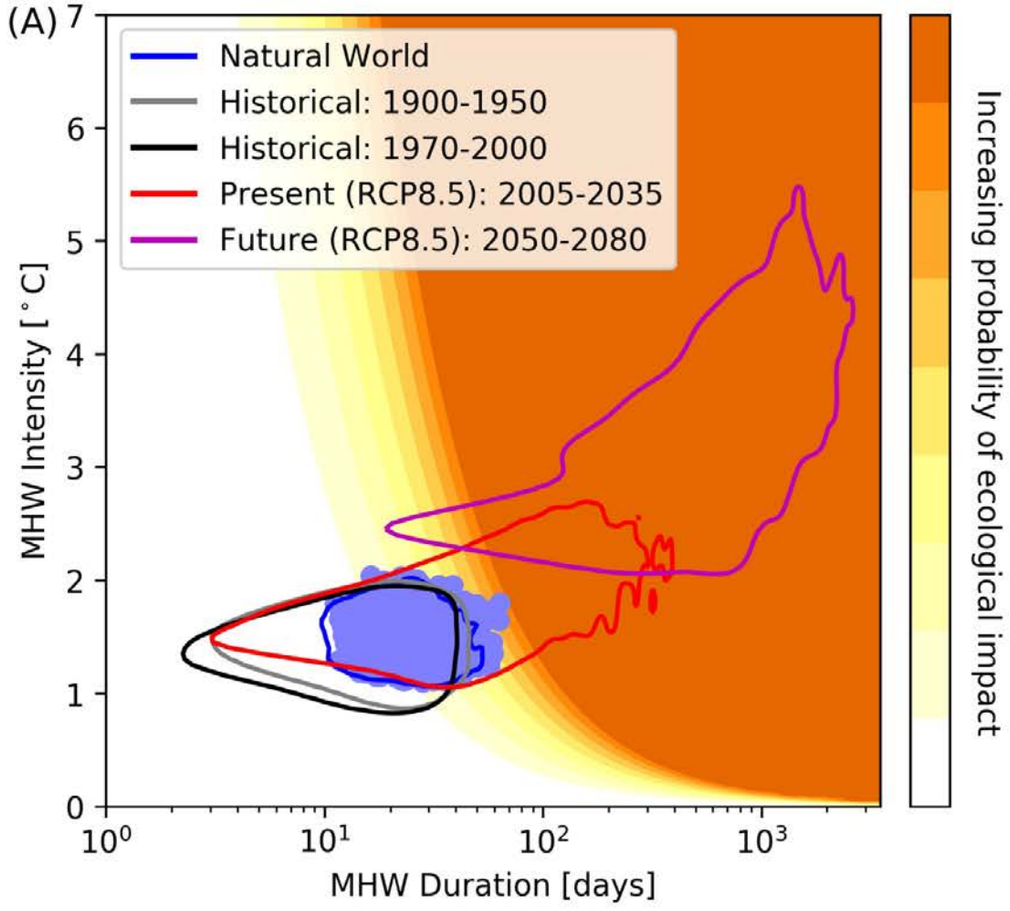


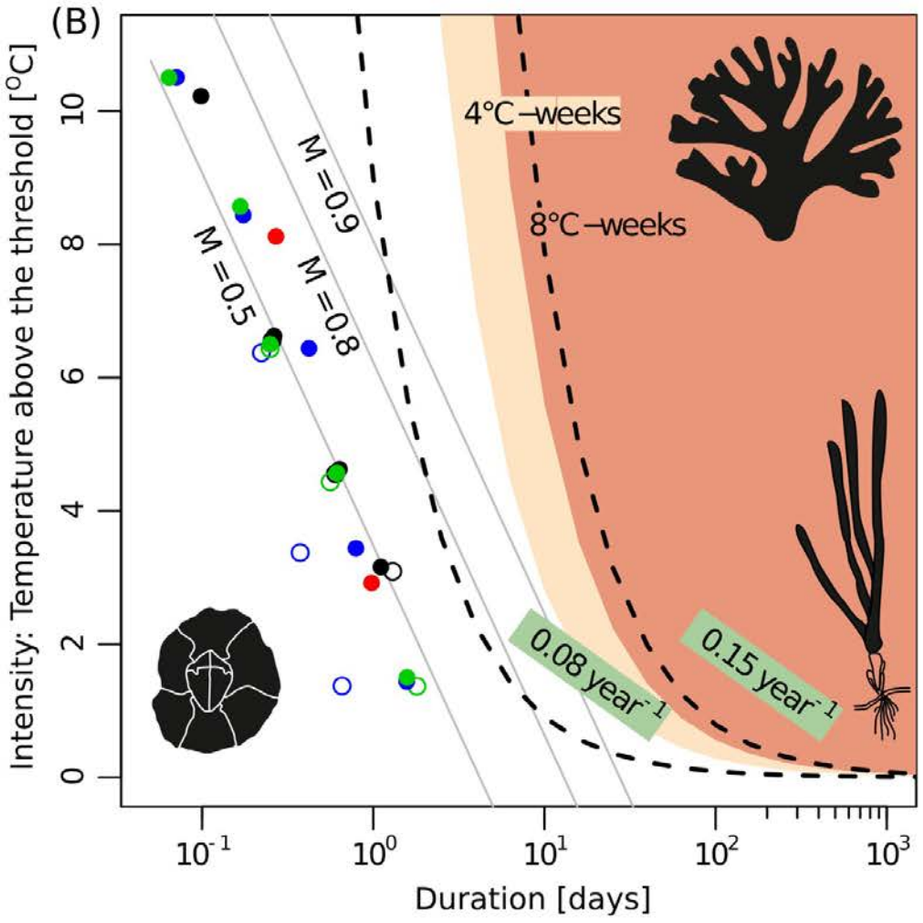
- **Definition:** *"Permanent MHW" = Full year (365 days) of MHW state*
- **Permanent MHW** first reached in tropics by 2040, later at higher latitudes *(both RCP4.5 and RCP8.5)*
- **Proportion** of globe in Permanent MHW state **varies greatly by emissions scenario**



Future projections and ecosystem impacts

- Plotting MHWs in **Intensity-Duration phase space** allows us to map out trajectories in time
- Presently and in the future we are moving towards a portion of phase space where we may expect **significant impacts**, as supported by studies on *coral reefs, seagrass and barnacles*





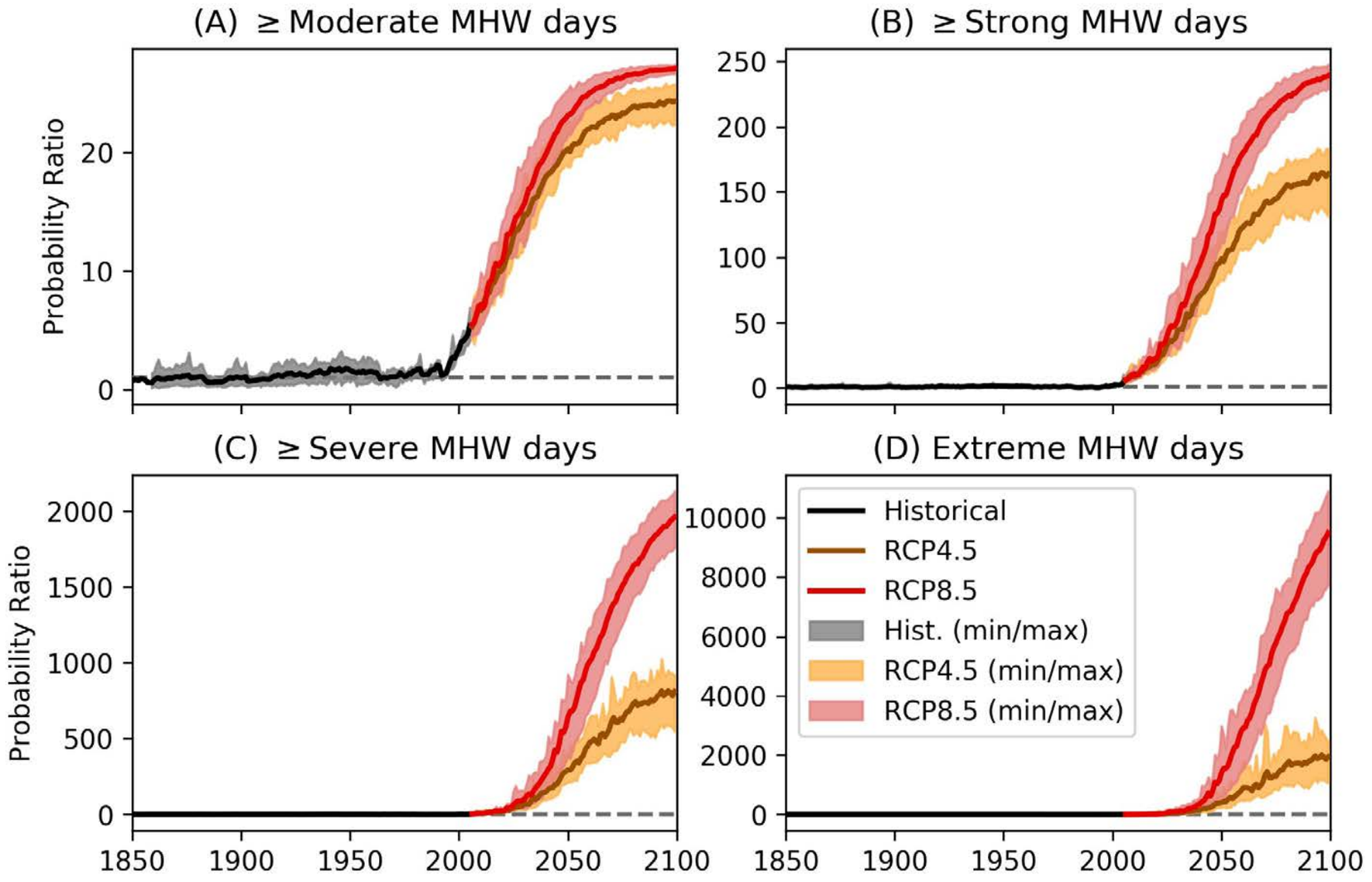
Was climate change responsible for that event?

- We can't answer that, but re-phrase as ***how would climate change modify the likelihood of that event?***

Probability Ratio (PR):

$$\mathrm{PR} = \frac{P_{\mathrm{hist/RCP}}}{P_{\mathrm{histNat}}}$$

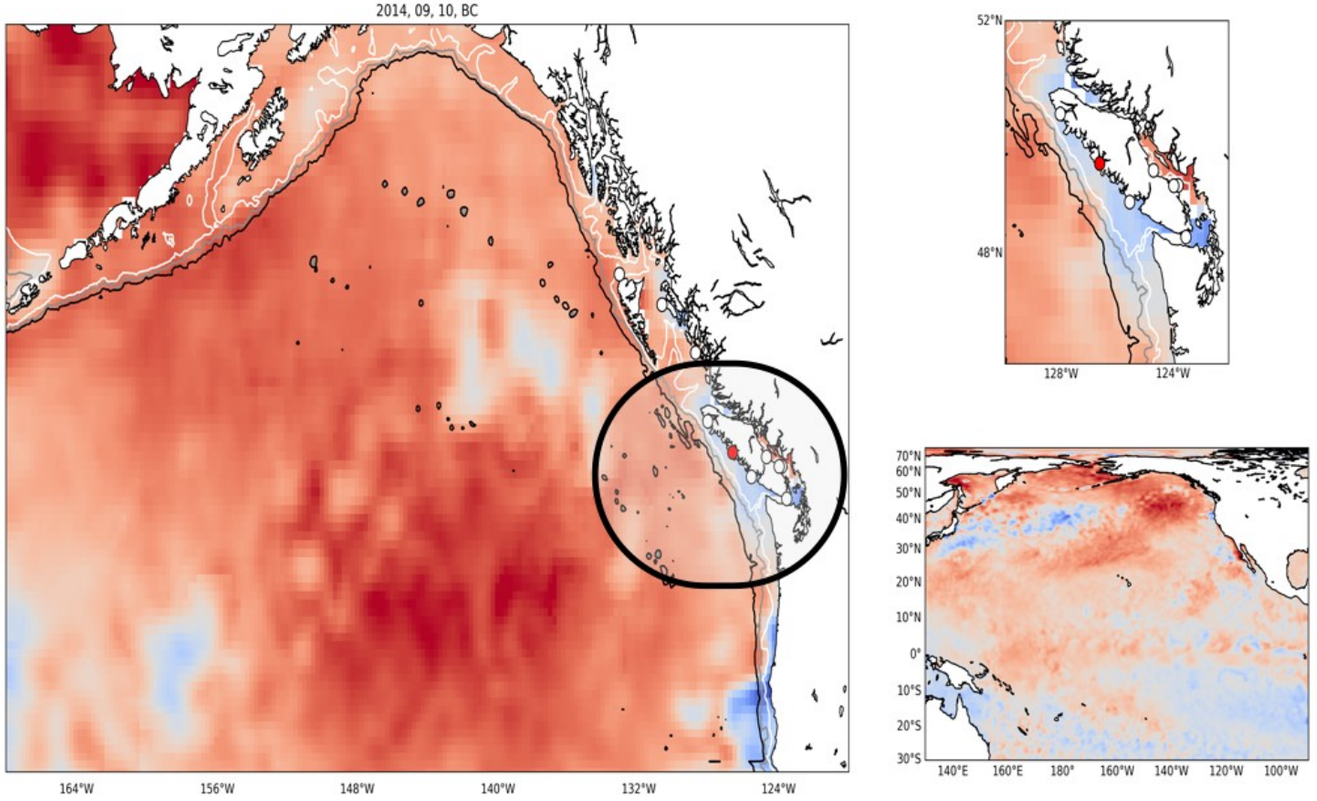
where P_X is the probability of an the event ocurring based on the modelled climate *X*.

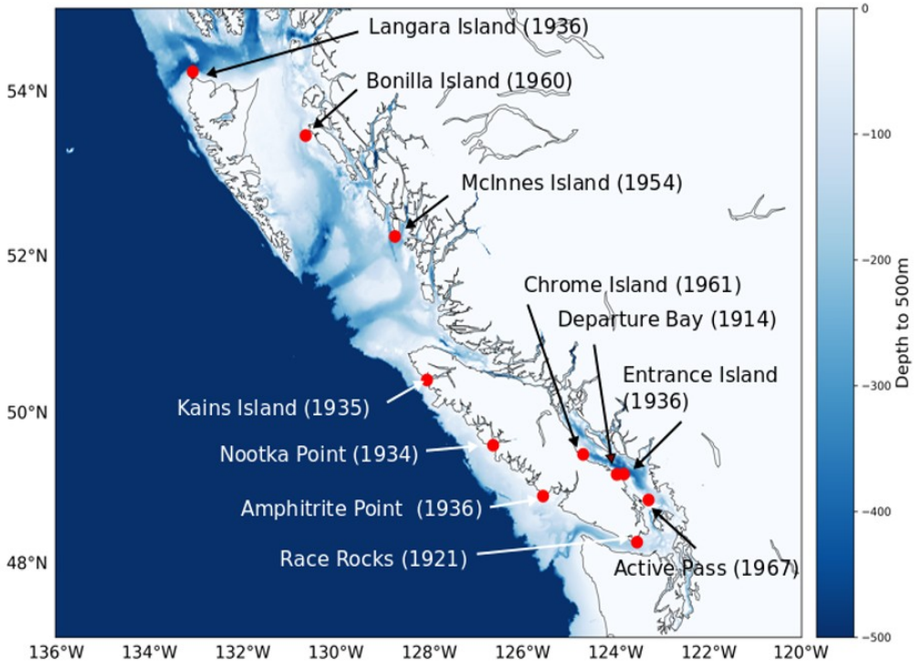


Ongoing and future research

- Long records of daily SSTs from BC lighthouses + satellite data
- Looking at how coastal upwelling may act to isolate some regions from large-scale marine heatwaves – e.g. “the Blob”

Jonathan Coyne
Honours student

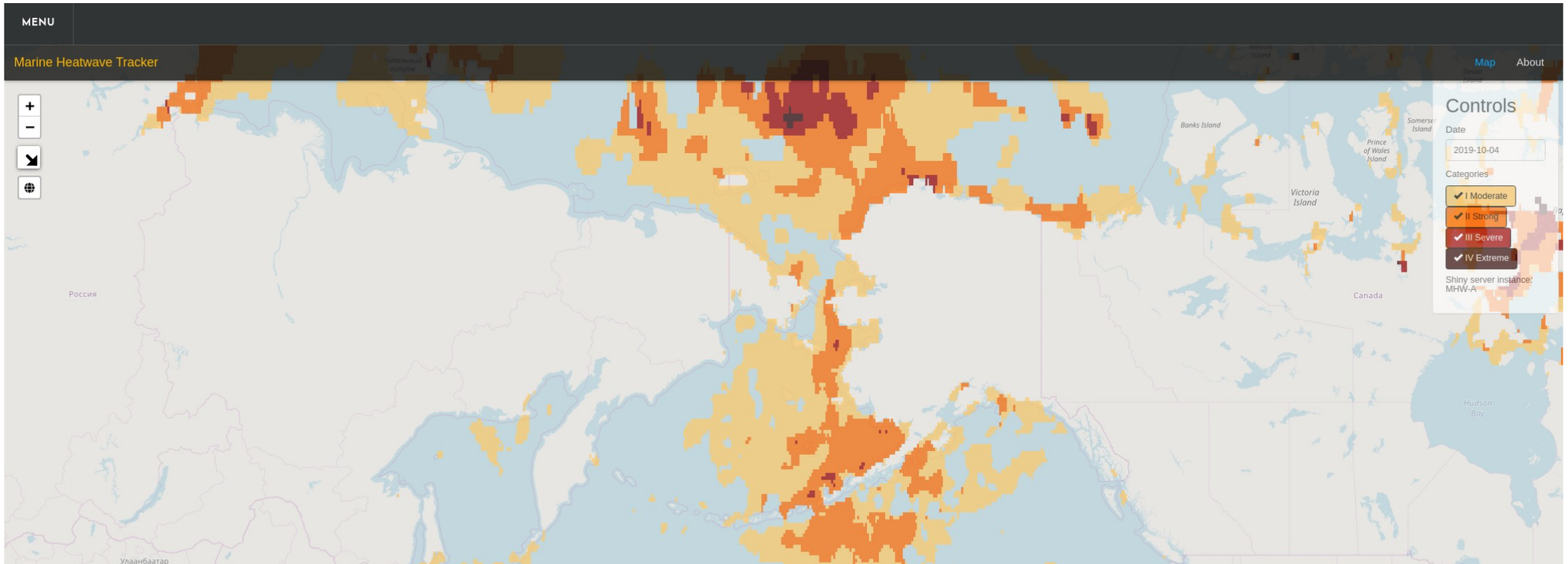




Ongoing and future research

- Maintains the R package for MHW detection
- Strong background in computing, interests in machine learning
- Projects:
  - Drivers of MHWs in the NW Atlantic using ocean model output
  - How can we detect MHWs with sub-optimal data e.g. missing, short, etc.
  - Global real-time MHW tracker! Live, interactive: **www.marineheatwaves.org/tracker**

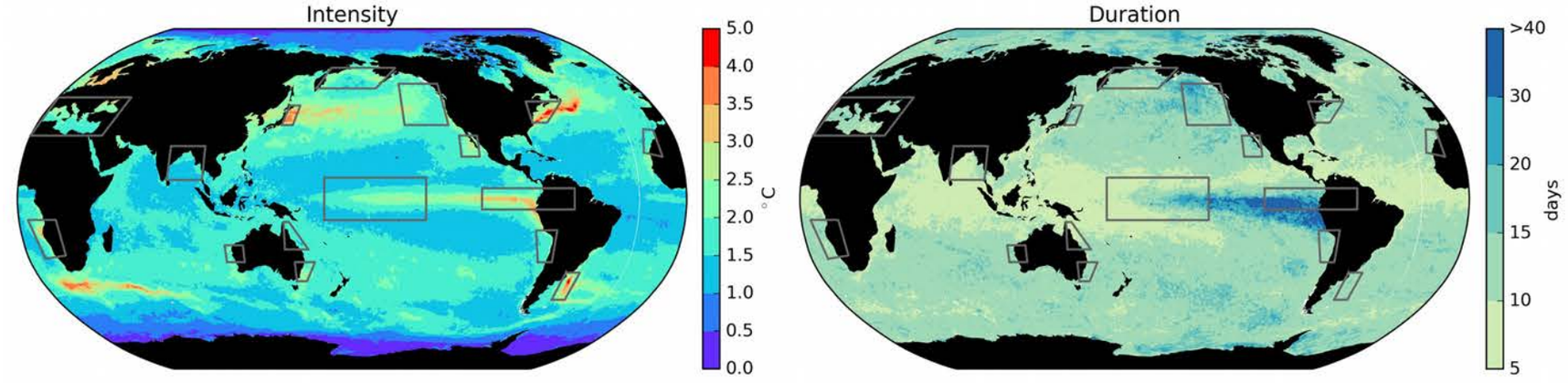
Robert Schlegel
OFI Postdoc



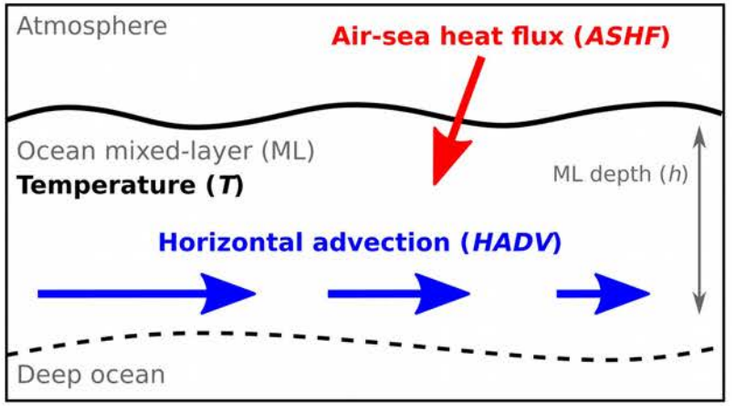
Ongoing and future research

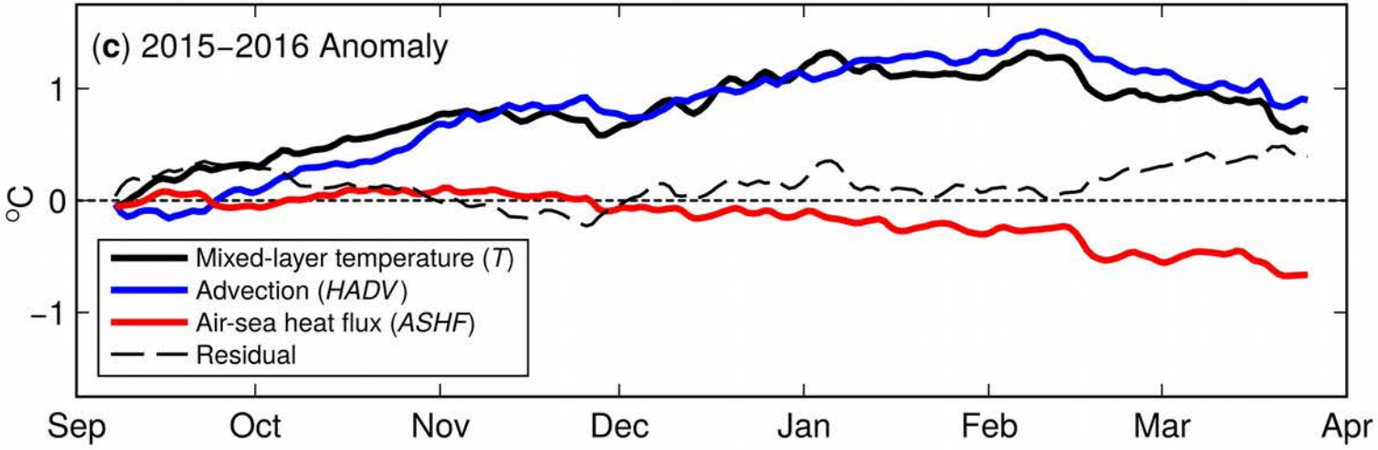
Sofia Darmaraki
MEOPAR Postdoc

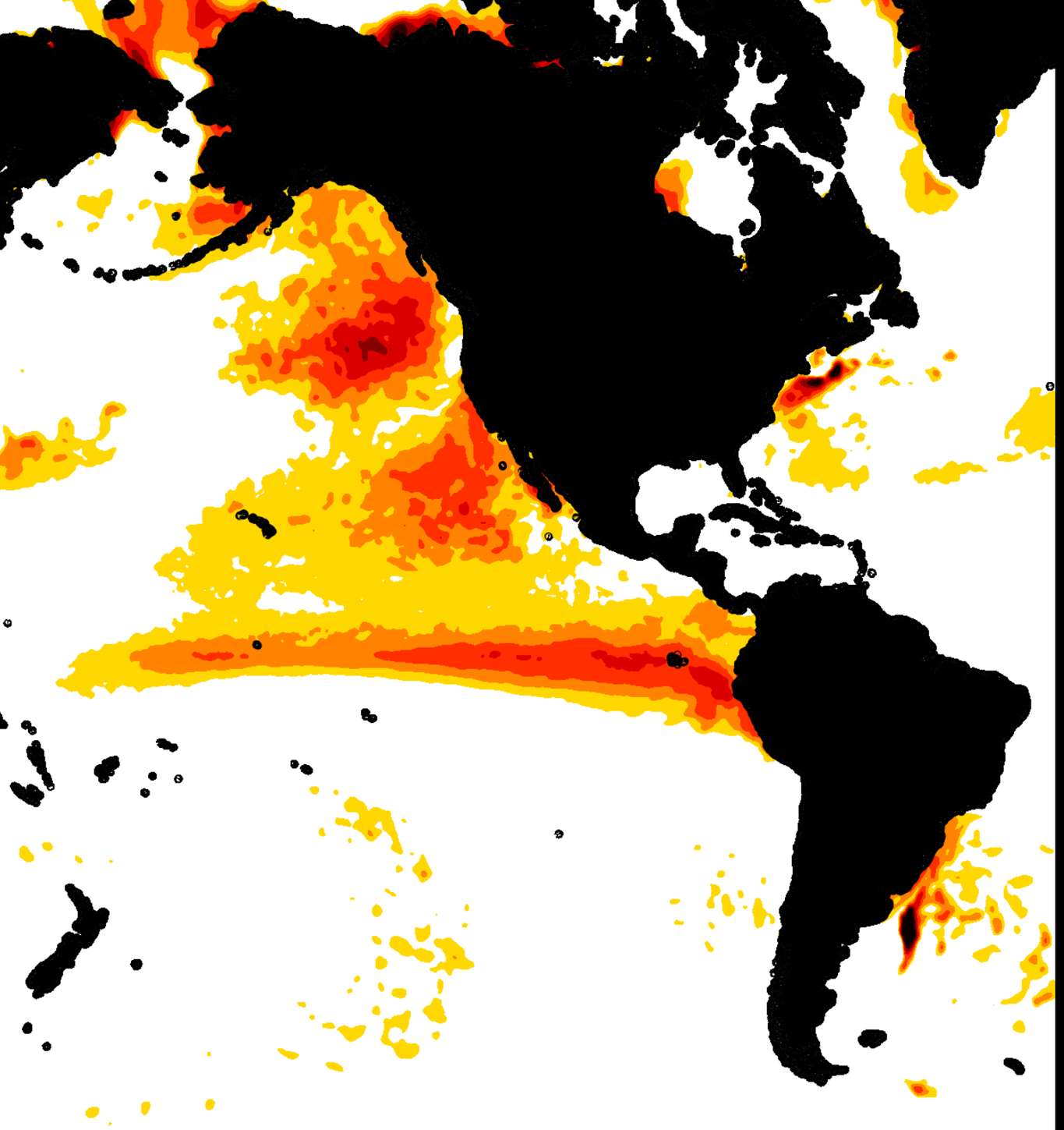
- Physical oceanographer, with past experience looking at physics of Mediterranean MHWs and the role of climate change – ***has a poster at this meeting on Med'2003 event***
- Will look at global distribution of MHWs:



- And ask what are typical drivers/processes, in typical regions? How might this change in the future?







Questions?

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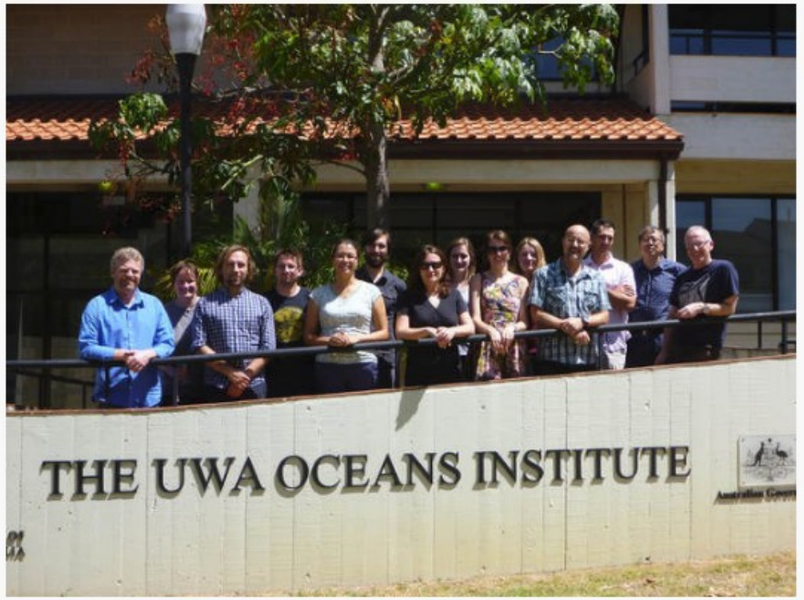


WORKSHOP #1

Theme: Physical drivers and properties of marine heatwaves

When & where: 19-21 January 2015, University of Western Australia Oceans Institute, Perth, Australia

WORKSHOP #2

Theme: Ecosystem impacts of marine heatwaves

When & where: The Marine Biological Association of the UK, Plymouth, UK

WORKSHOP #3

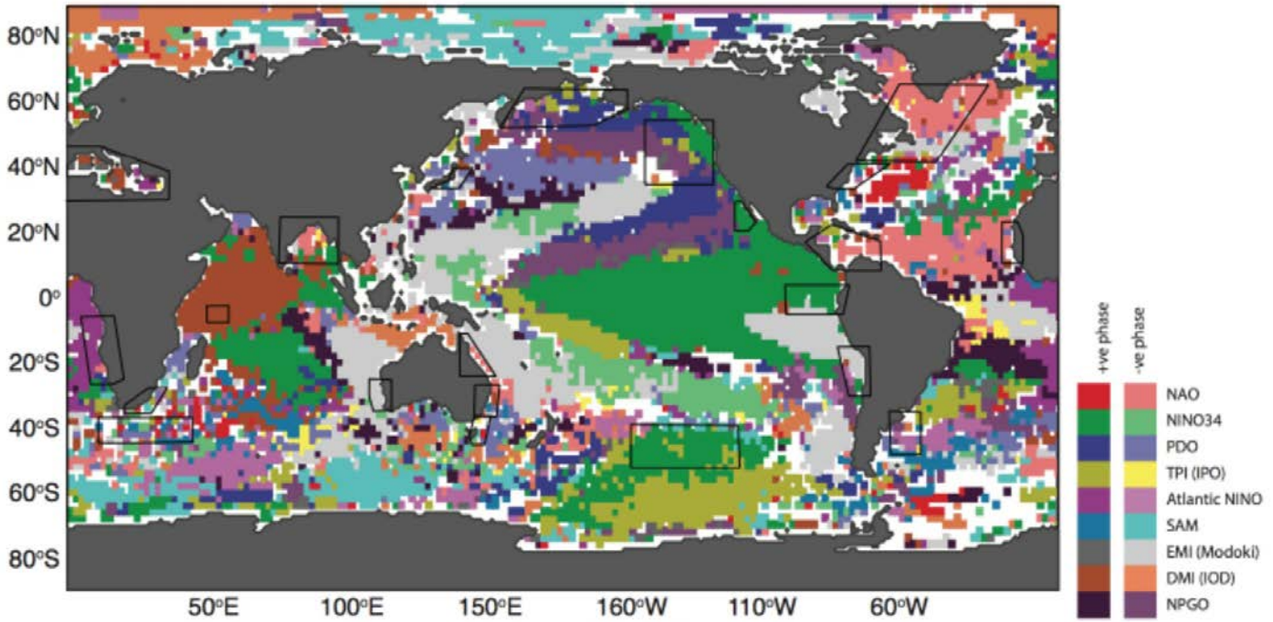
Theme: Global patterns and impacts of risk

When & where: 21-23 February 2017 Ao Nang Beach, Krabi, Thailand

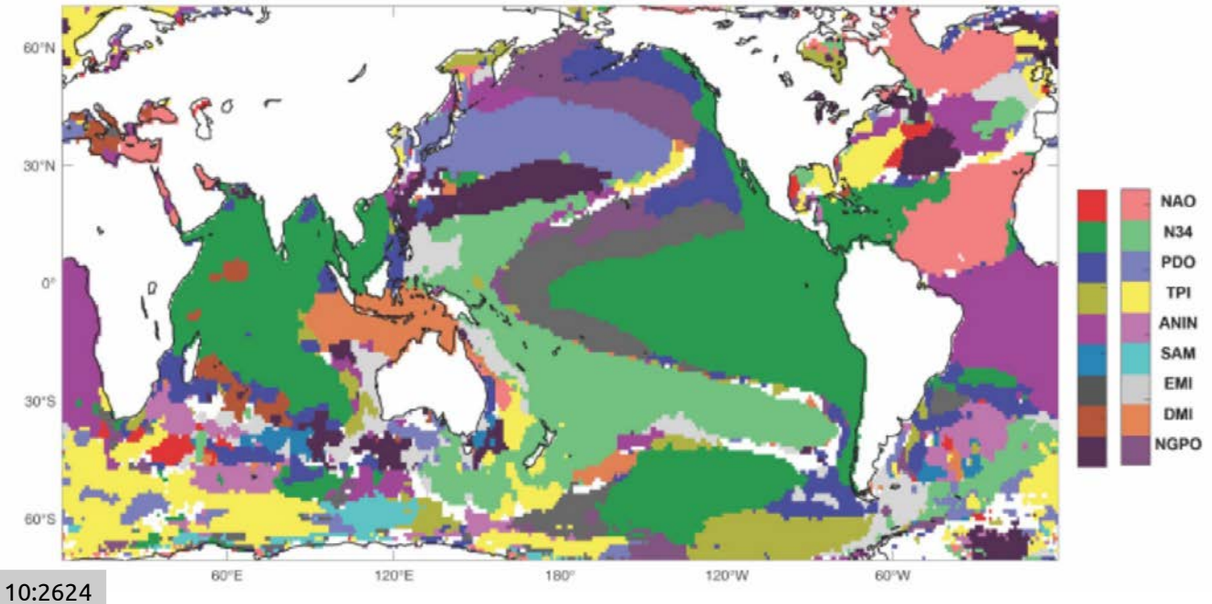
The role of climate modes

Interestingly…

the dominant mode driving changes in MHWs at each location



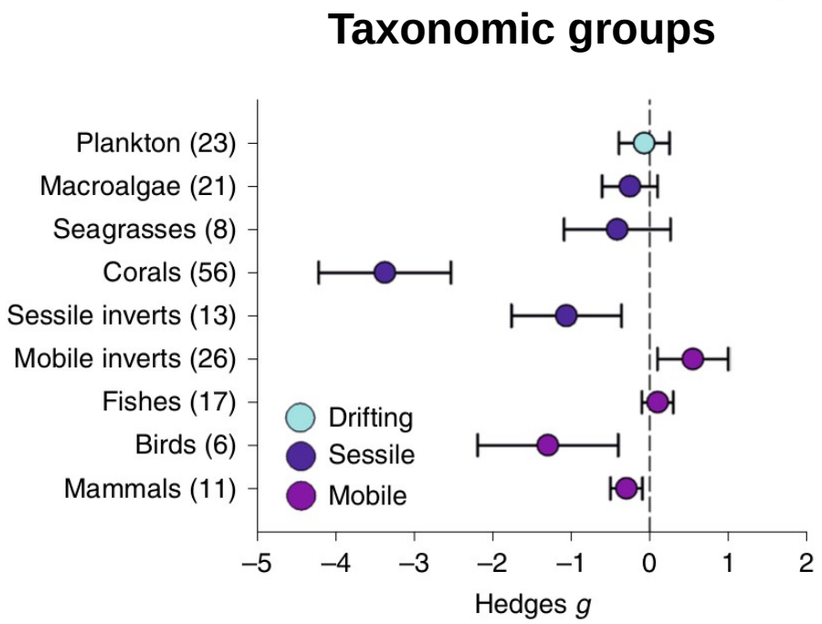
is not 1:1 with the dominant mode driving changes in SST.

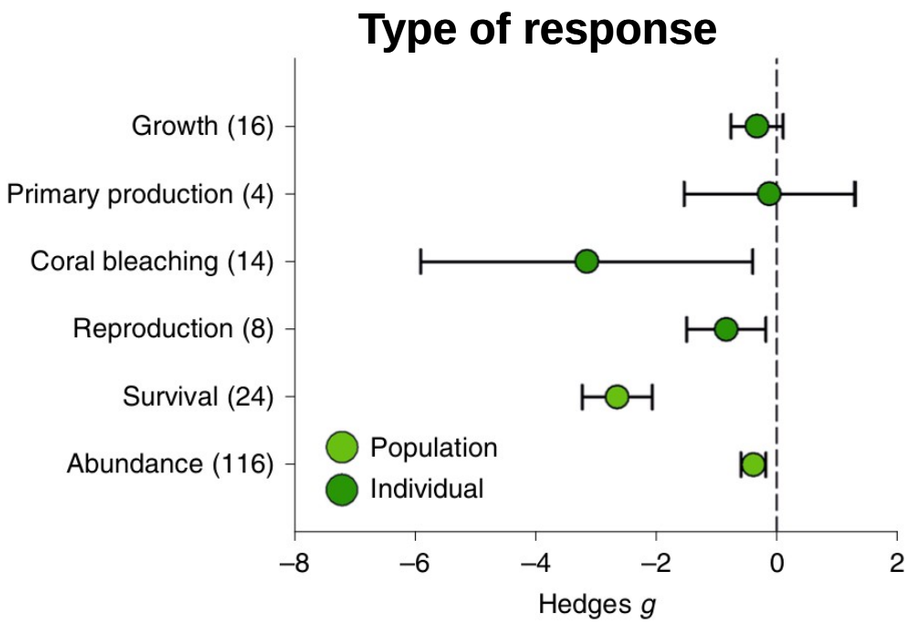


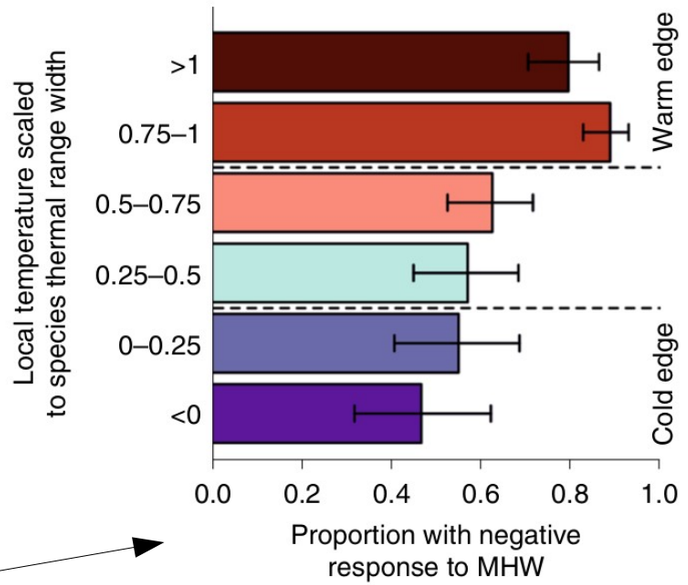
Holbrook et al. (2019). A global assessment of marine heatwaves and their drivers. *Nature Communications.* 10:2624

Impacts

- The recorded, published impacts of MHWs vary across taxonomic groups and type of response







- Species close to the warm edge of their **thermal niche** show the greatest likelihood of a negative response

Smale et al. (2019) Marine heatwaves threaten global biodiversity and the provision of ecosystem services. *Nature Climate Change*