climate extremes
ARC centre of excellence

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Marine heatwave drivers: a global overview

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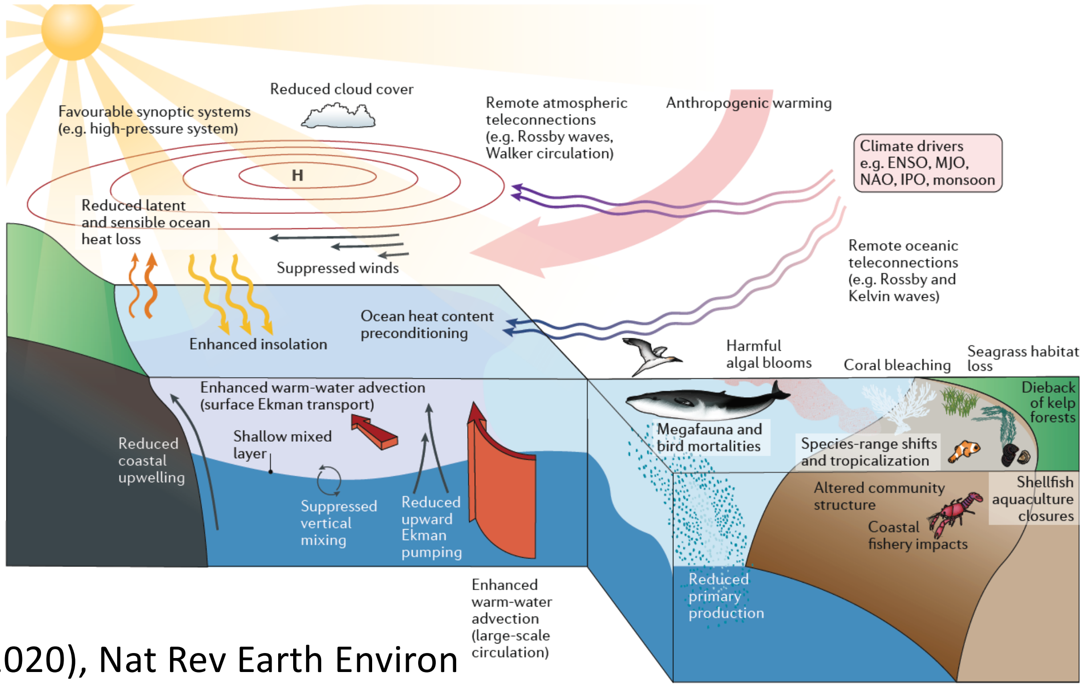
CLIVAR WCRP World Climate Research Programme ICTP

CLIVAR/ICTP Summer School in Marine Heatwaves
25 July 2023, ICTP, Trieste, Italy

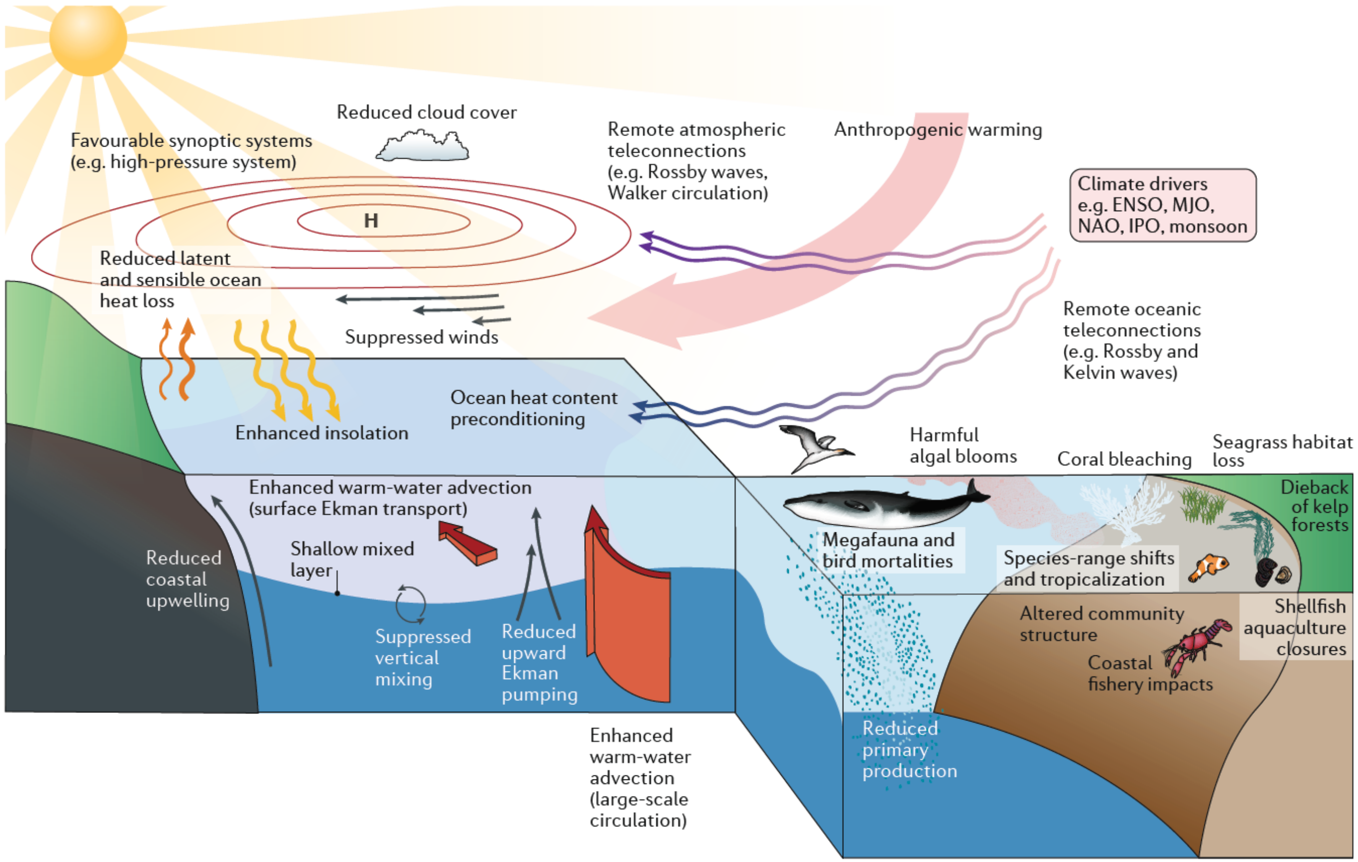


Holbrook et al. (2020), Nat Rev Earth Environ

Table of Contents

1. Introduction: processes, definitions, characteristics and scales

Introduction: Marine heatwave processes and impacts



Marine habitats and species

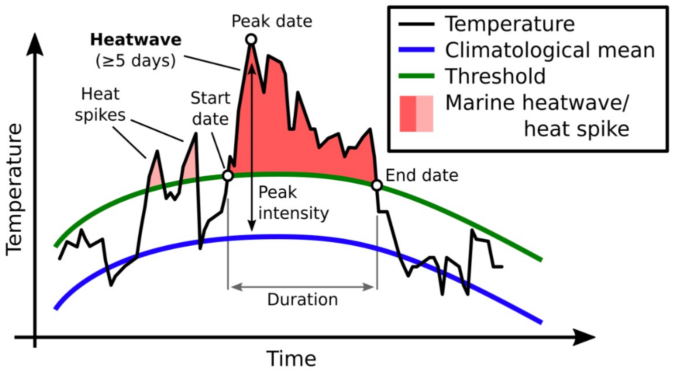
Aquaculture

Wild fish

Sea birds

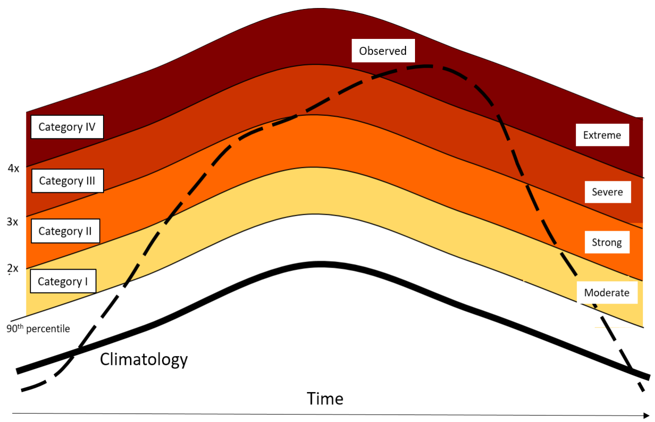
Holbrook et al (2020), Nature Rev Earth & Environment

Marine heatwave and intensity categorisation definitions
- simply about choices -



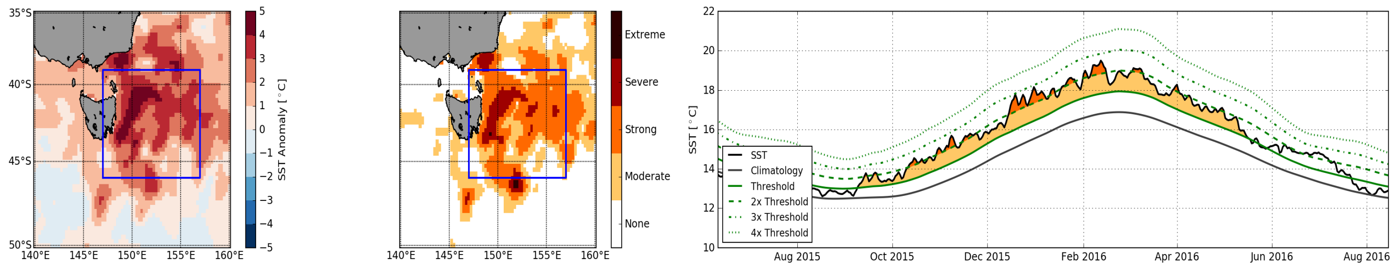
www.marineheatwaves.org/all-about-mhws.html

Hobday et al. (2016), Prog Oceanogr

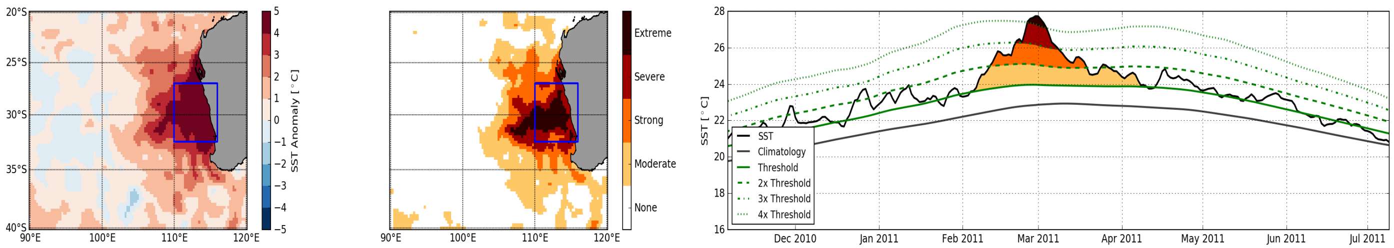


Hobday et al. (2018), Oceanography

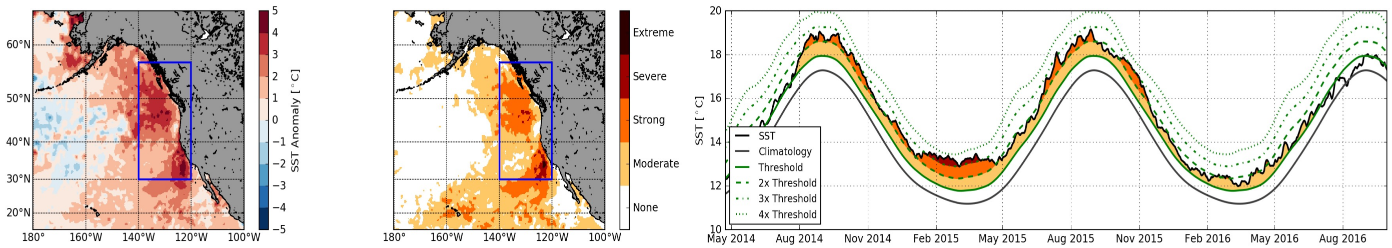
Tasman Sea 2015/16



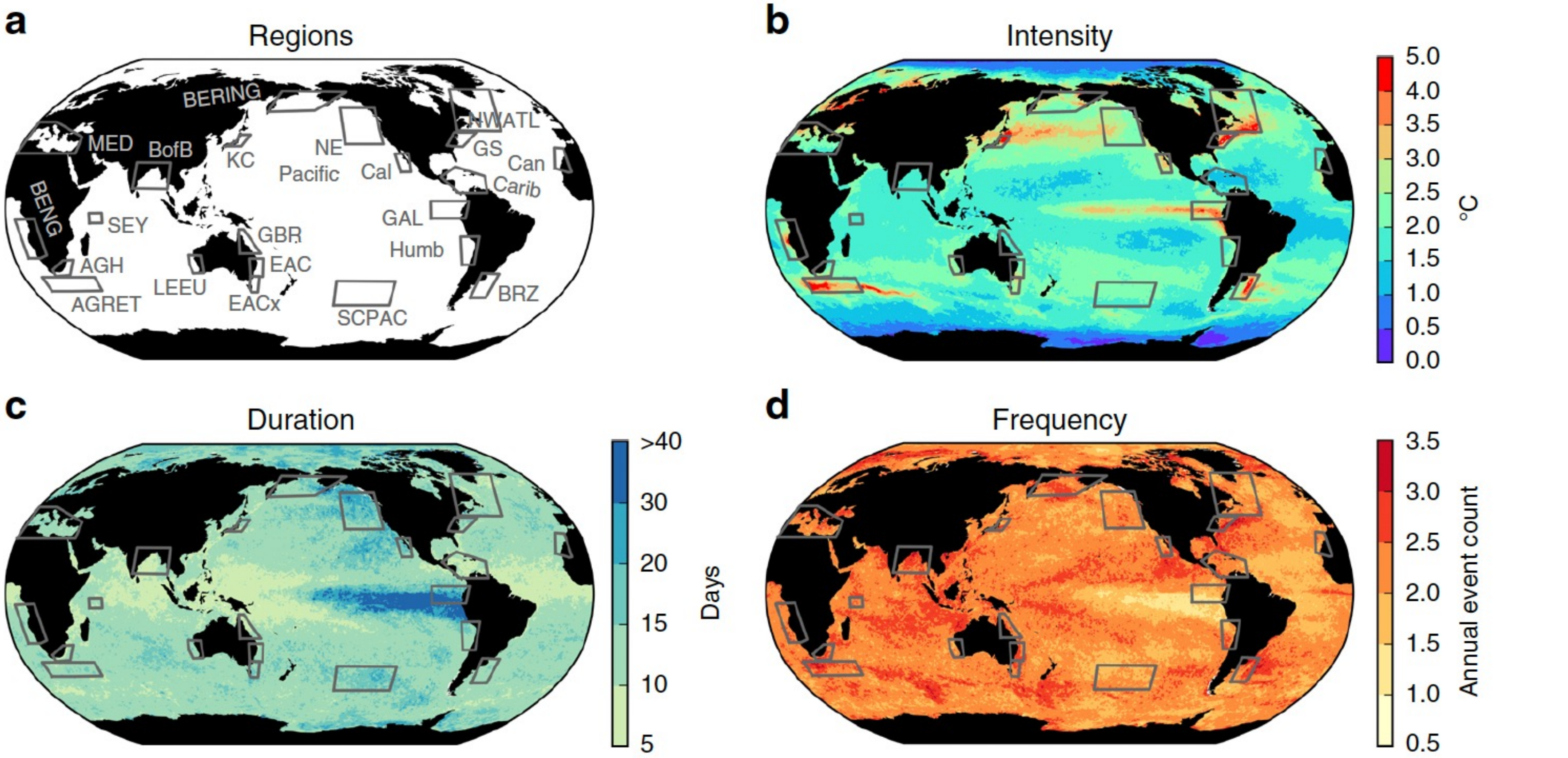
Western Australia 2011



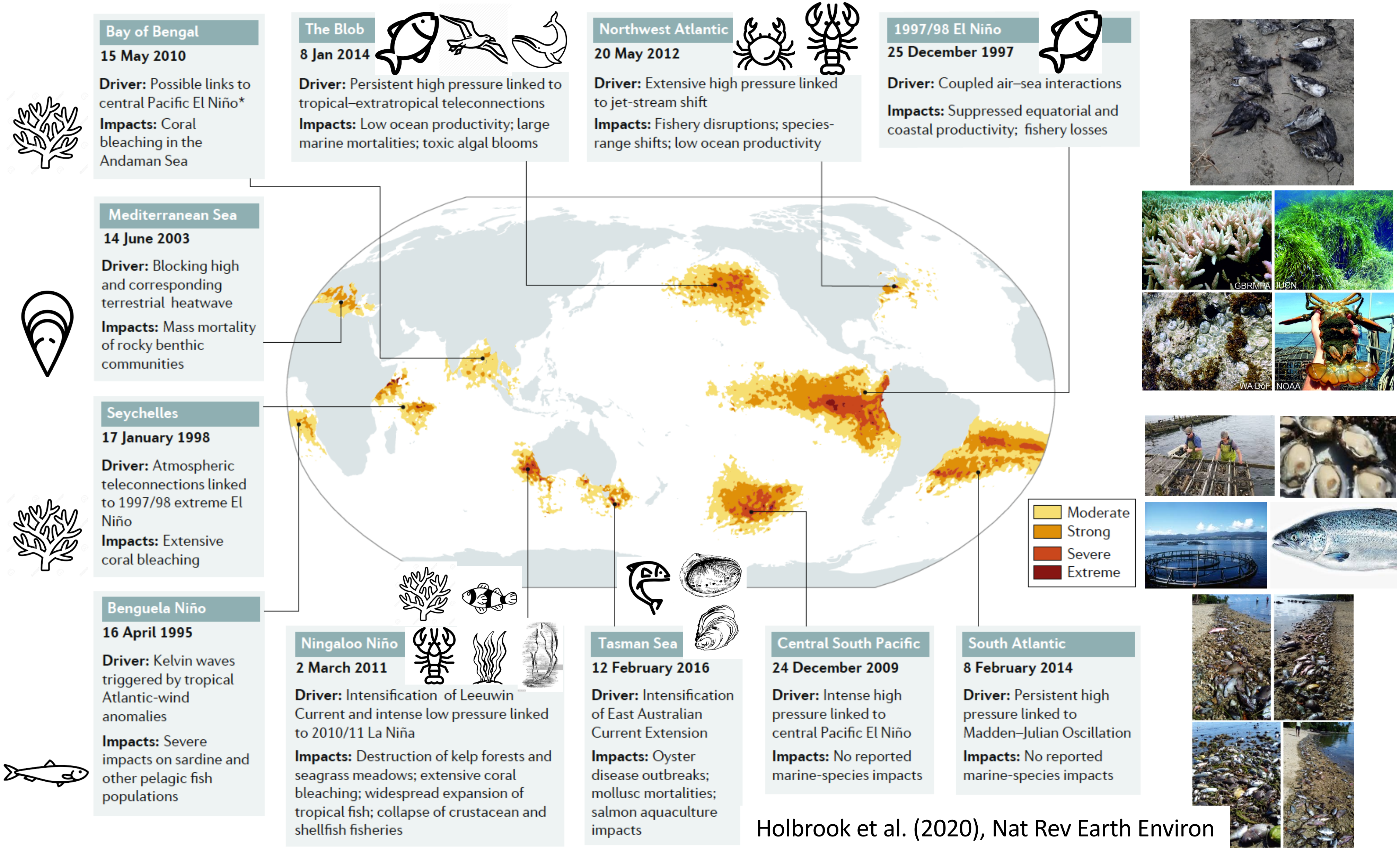
Northeast Pacific 2014-16



Global marine heatwave (MHW) characteristics

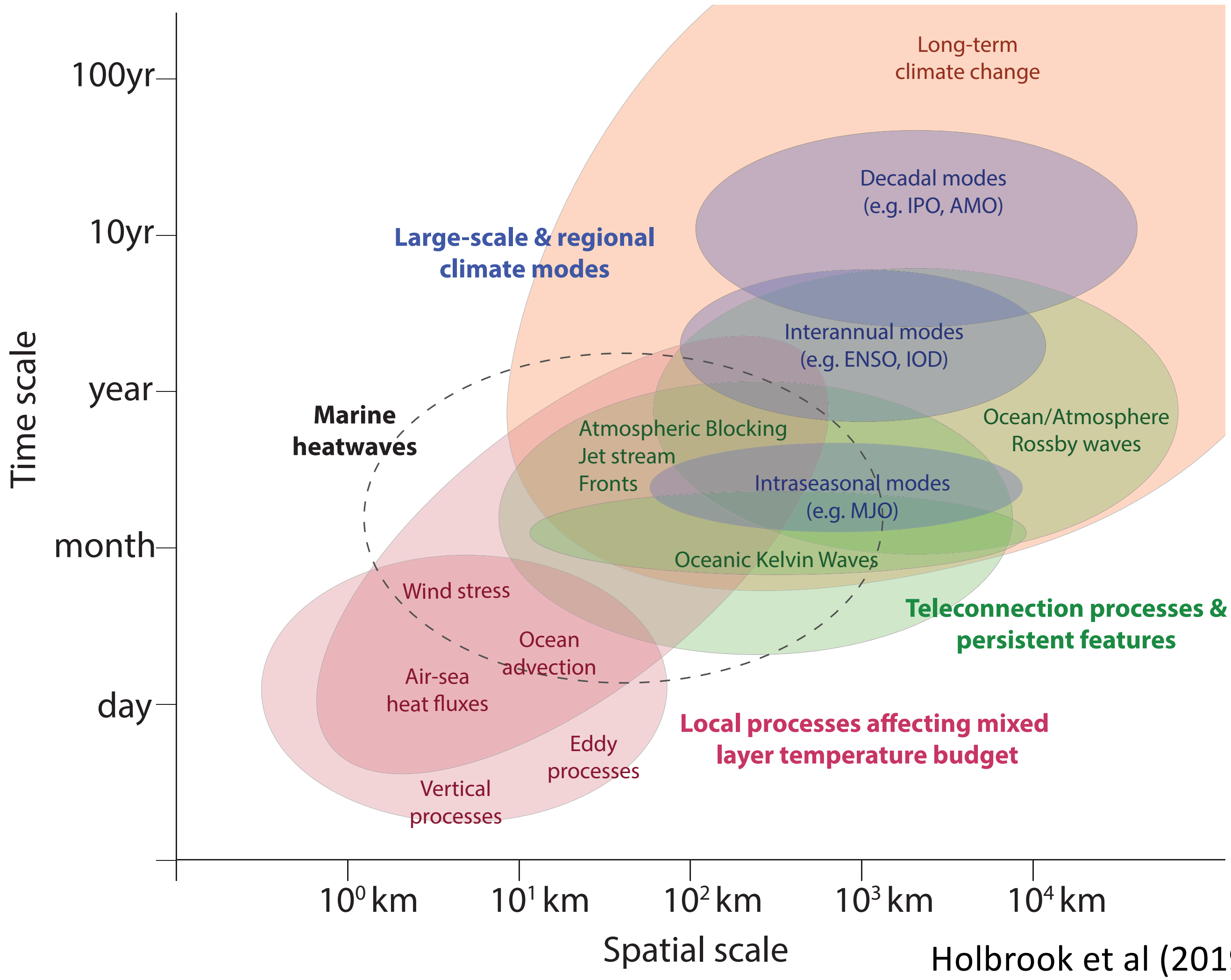


Holbrook et al. (2019), Nature Communications



Holbrook et al. (2020), Nat Rev Earth Environ

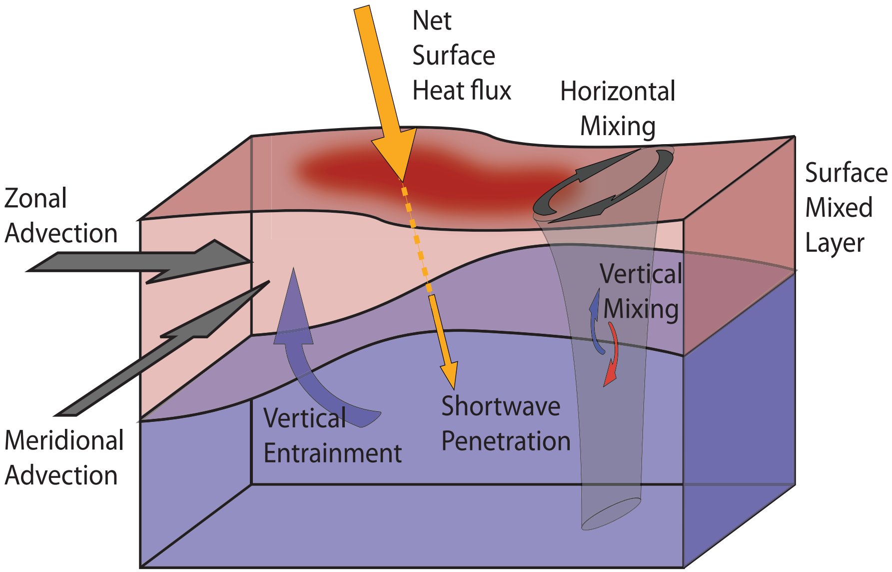
Space and time scales of MHWs and drivers



Holbrook et al (2019), Nature Communications

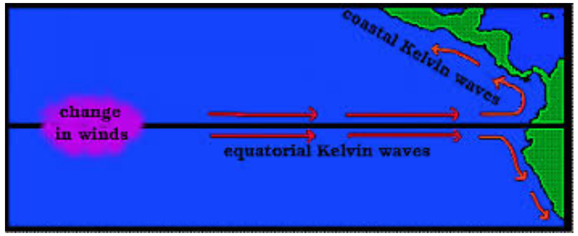
What drives [surface] marine heatwaves?

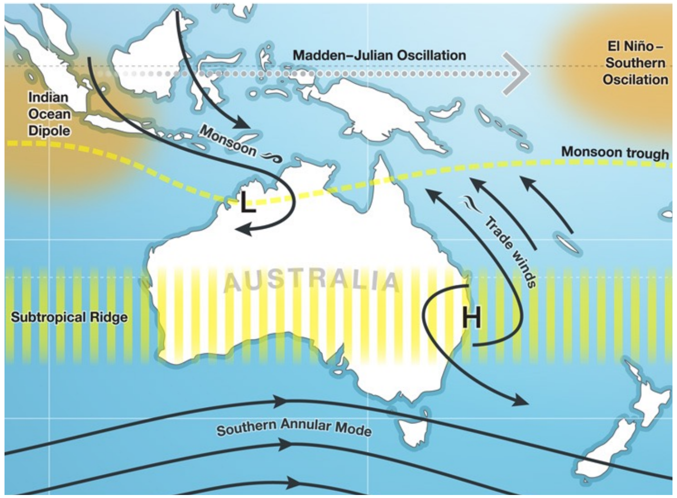
What causes MHWs locally?
=> The **local processes**

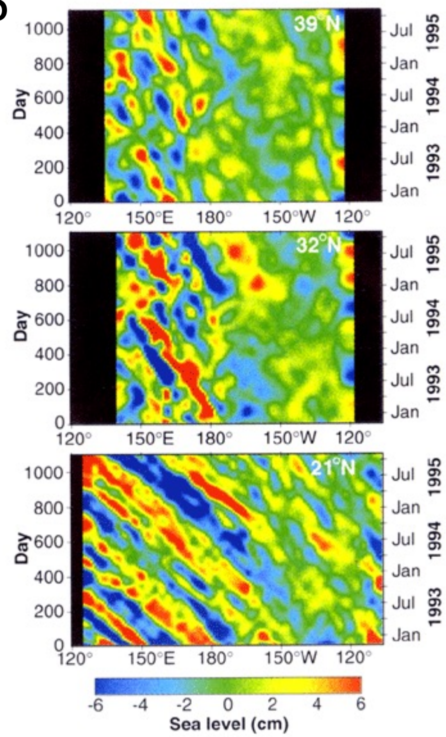


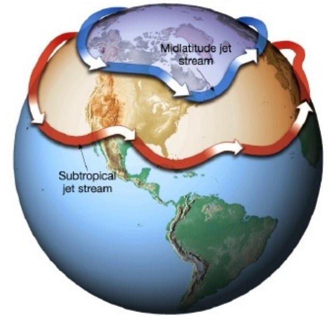
Holbrook et al. (2019), Nature Communications

What are the remote drivers?
=> **Climate modes and teleconnections**



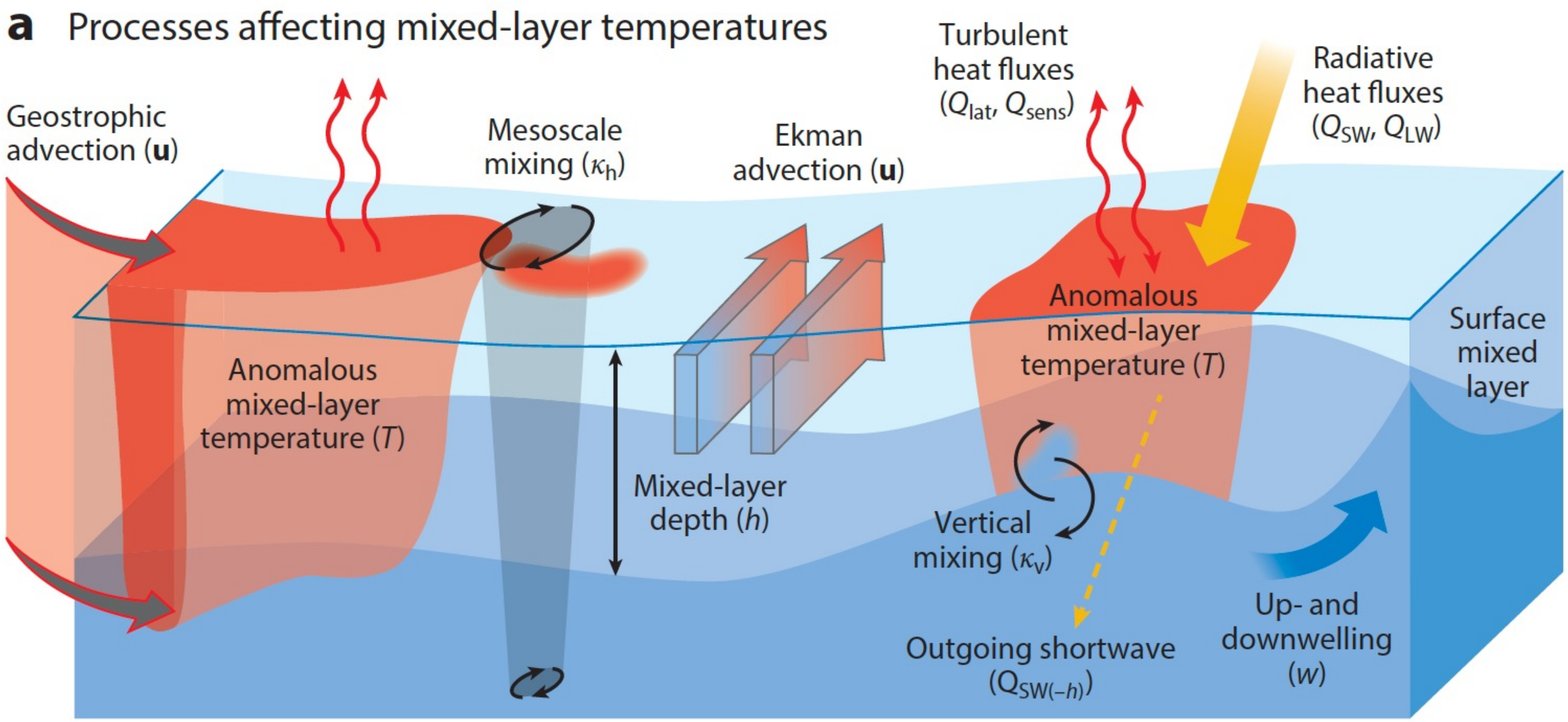






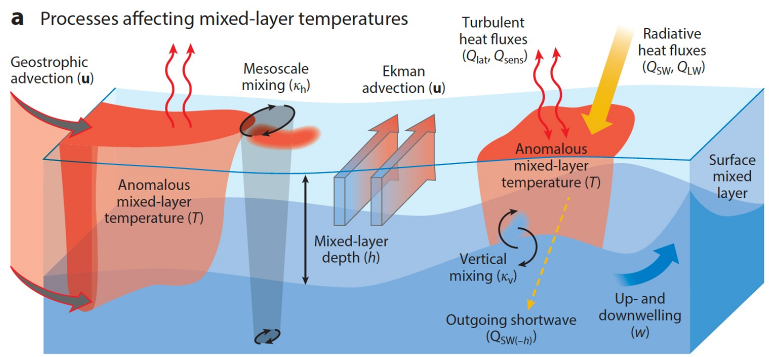
2. Local processes causing (surface mixed layer) marine heatwaves

Physical processes affecting mixed layer temperatures



Oliver et al. (2021), Ann Rev Mar Sci

Temperature tendency equation



$$\underbrace{\frac{\partial \overline{T}}{\partial t}}_{\text{Temperature tendency}} = -\underbrace{\overline{\mathbf{u}} \cdot \nabla \overline{T}}_{\text{Horizontal advection}} + \underbrace{\overline{\nabla \cdot (\kappa_{\mathrm{h}} \nabla T)}}_{\text{Horizontal mixing}} - \underbrace{\frac{1}{h}\kappa_{\mathrm{z}} \left.\frac{\partial T}{\partial z}\right|_{-h}}_{\text{Vertical mixing}}$$

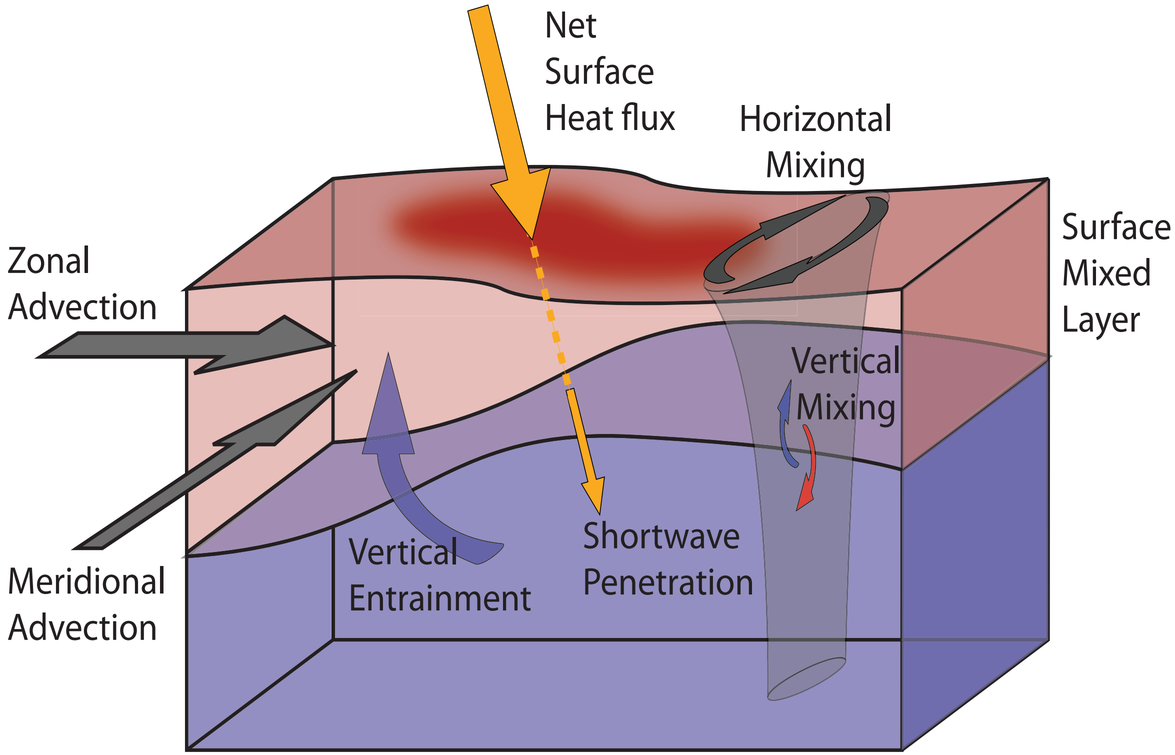
$$\underbrace{-\left(\frac{\overline{T} - T_{-h}}{h}\right)\left(\underbrace{\frac{\partial h}{\partial t}}_{\text{MLD tendency}} + \underbrace{\mathbf{u}_{-h} \cdot \nabla h}_{\text{Lateral induction}} + \underbrace{w_{-h}}_{\text{Vertical advection}}\right)}_{\text{Entrainment}}$$

$$+ \underbrace{\frac{Q_{\mathrm{SW}} - Q_{\mathrm{SW}(-h)} + Q_{\mathrm{LW}} + Q_{\mathrm{sens}} + Q_{\mathrm{lat}}}{\rho c_{\mathrm{p}} h}}_{\text{Air–sea heat flux}},$$

where T is the temperature in the surface mixed layer, t is time, $\mathbf{u} = (u, v)$ is the two-dimensional horizontal (x, y) velocity vector, w is vertical (z) velocity, ∇ is the horizontal gradient operator, Q comprises various components of the air–sea heat flux (see details below), ρ is the seawater density, c_{p} is the specific heat capacity of seawater, h is the mixed-layer depth (MLD), and κ_{h} and κ_{z} are the horizontal and vertical diffusivity coefficients. Quantities have been vertically averaged over the mixed layer, and the vertical average of any quantity x is defined to be $\overline{x} = h^{-1}\int_{-h}^{0} x\,\mathrm{d}z$; a subscript x_{-h} indicates that the quantity is evaluated at the base of the mixed layer, i.e., at $z = -h$. Note that Equation 1 neglects second-order correlation terms (for the full form of the budget, see Moisan & Niiler 1998).

Oliver et al. (2021), Ann Rev Mar Sci

Temperature tendency equation – dominant terms



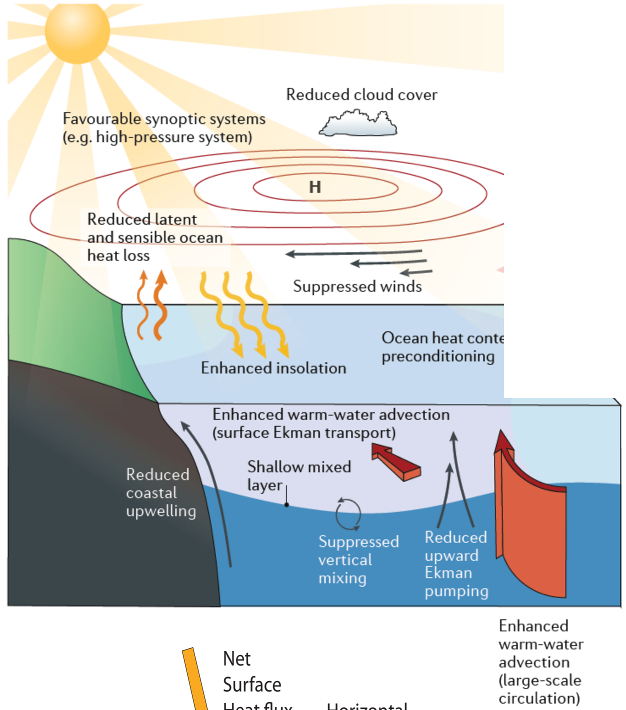
$$\frac{\partial T}{\partial t} = -\frac{1}{H}\int_{-H}^{0} (\mathbf{u} \cdot \nabla_h T)\, dz + \frac{Q}{\rho C_p H} + \text{residual}$$

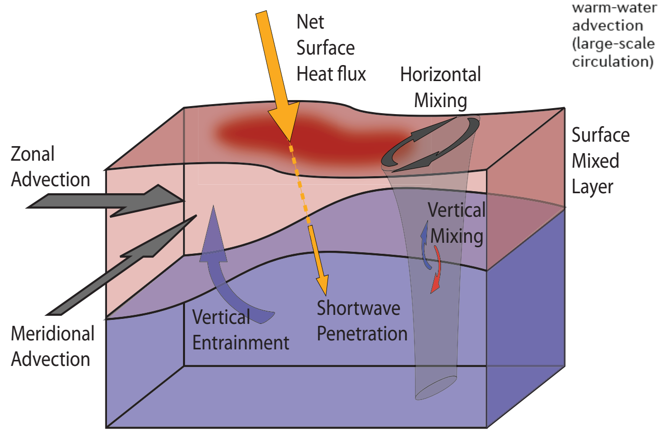
Holbrook et al (2019), Nature Communications

Local processes causing MHWs

- **solar radiation** into the ocean (e.g. from blocking highs)
- **downward longwave radiation** (greenhouse/anthropogenic warming)
- **suppressed latent and sensible heat losses** from the ocean to the atmosphere
- **increased horizontal transport** (advection) **of heat** (currents, eddies in EAC)
- **reduced vertical heat transport** associated with suppressed mixing and reduced coastal upwelling or Ekman pumping

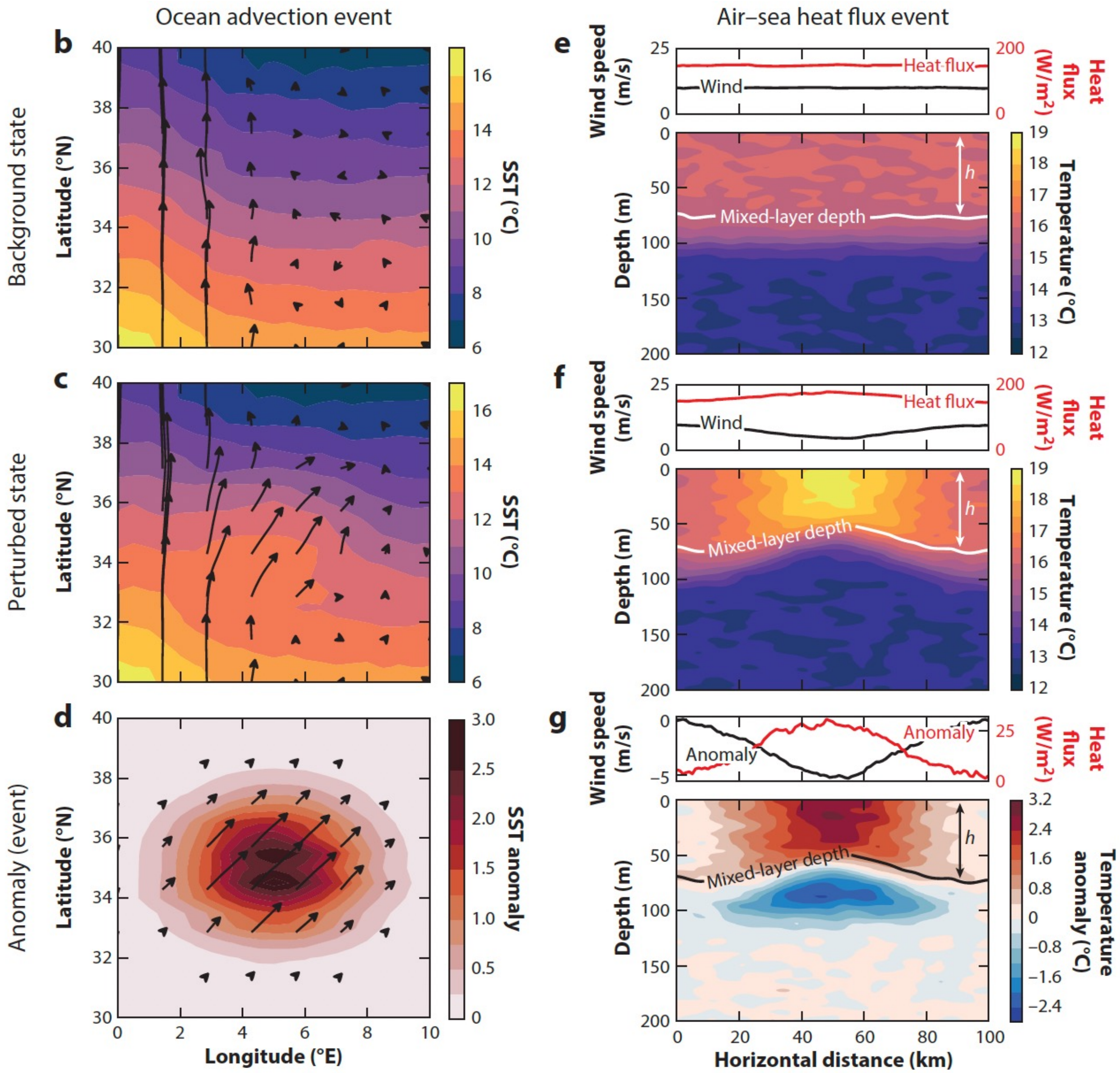
$$\frac{\partial T}{\partial t} = -\frac{1}{H}\int_{-H}^{0} (\mathbf{u} \cdot \nabla_h T)\, dz + \frac{Q}{\rho C_p H} + \text{residual}$$





Holbrook et al (2019), Nat Rev Earth Environ
Holbrook et al (2019), Nature Communications

Idealised examples of (b-d) **ocean advection** and (e-g) **air-sea heat flux** type events

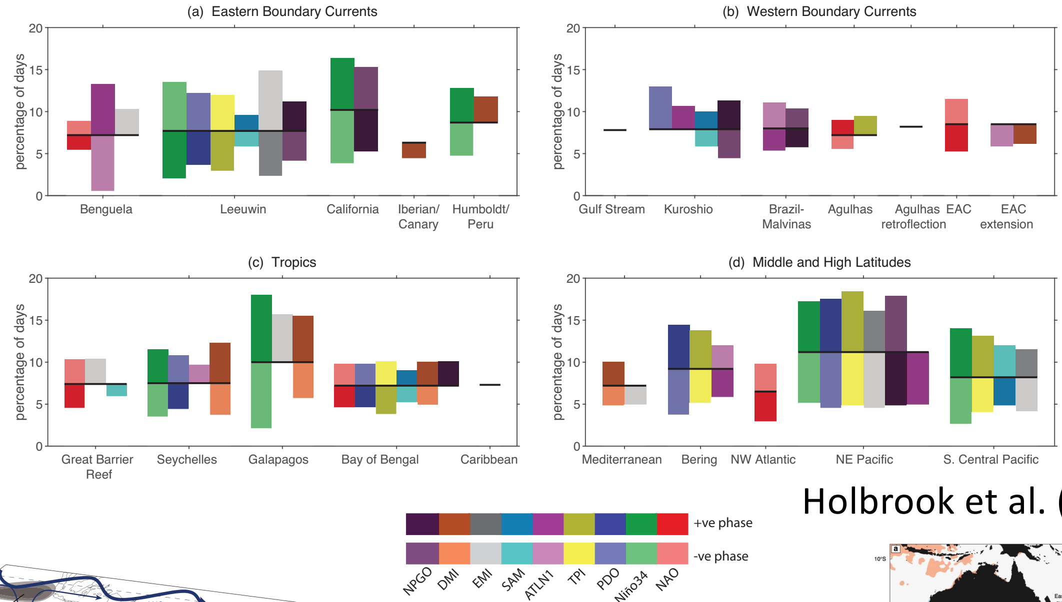


Oliver et al. (2021), Ann Rev Mar Sci

3. Remote drivers of marine heatwaves

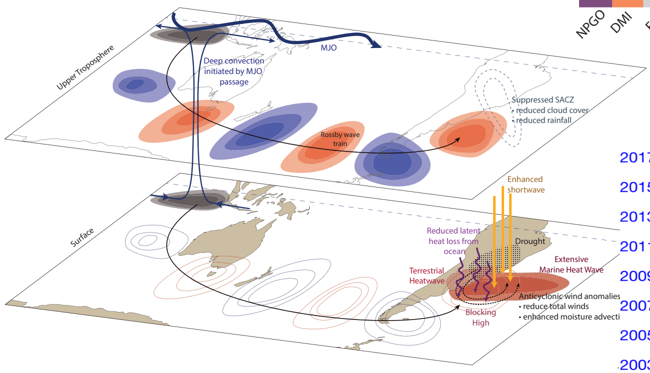
Potential predictability from **remote forcing**

- **large-scale modes of climate variability** (ENSO, IOD, SAM etc.) [e.g. Scannell et al. 2015; Oliver et al. 2018; Holbrook et al. 2019]

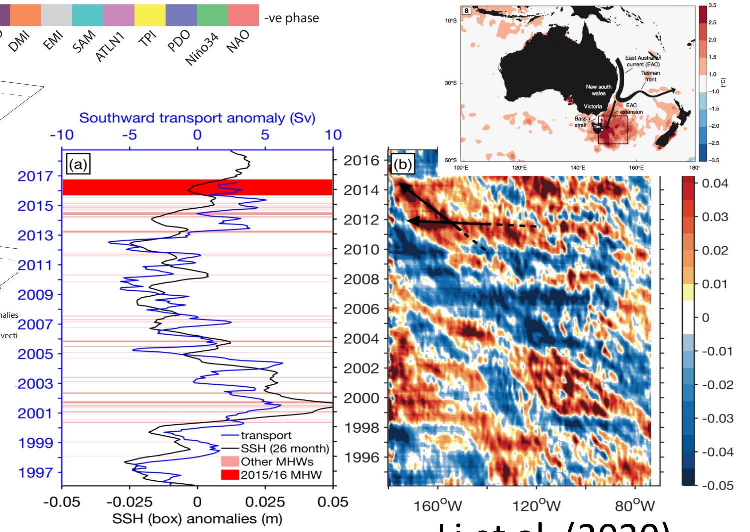


Holbrook et al. (2019)

- **teleconnections**, e.g. planetary Rossby waves, Kelvin waves (set the timing of potential predictability) [e.g. Rodrigues et al. 2019; Li et al. 2020]

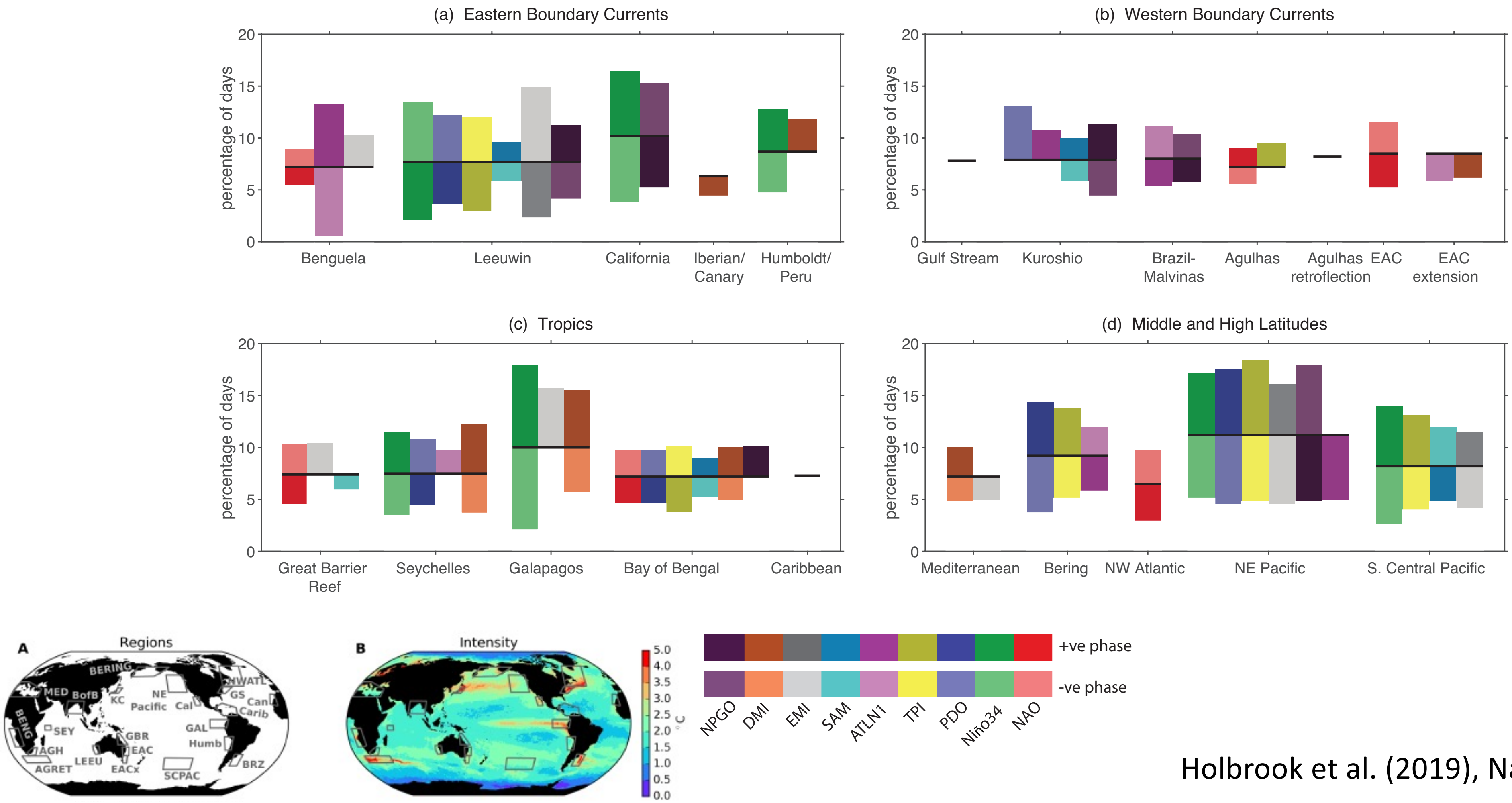


Rodrigues et al. (2019)



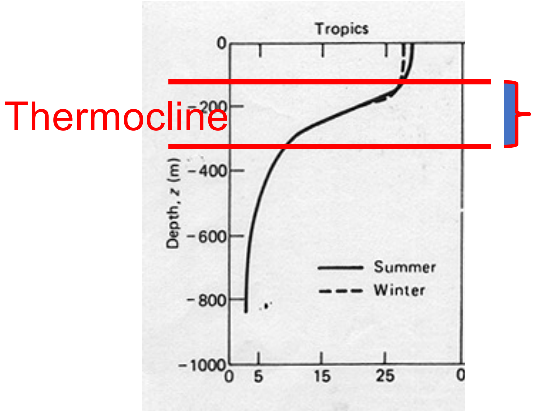
Li et al. (2020)

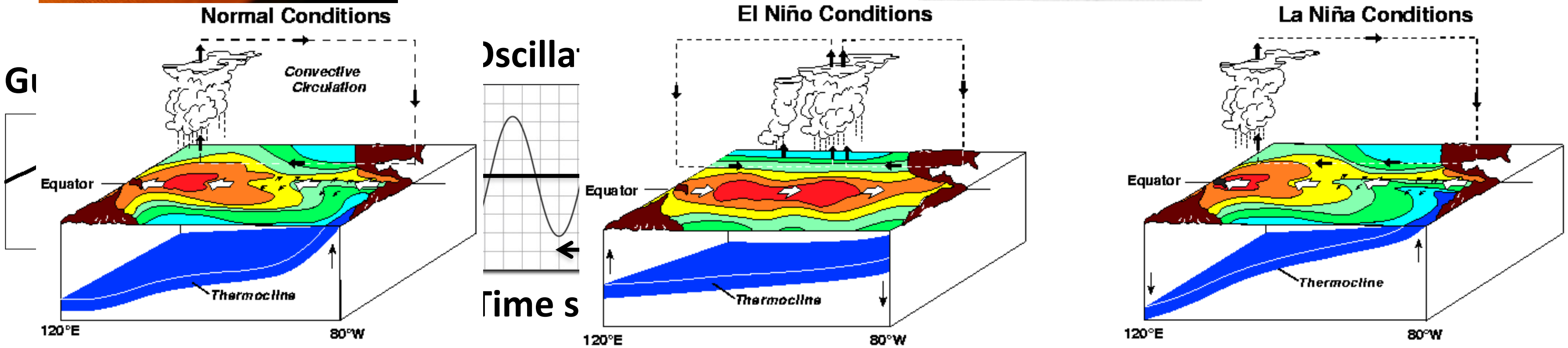
Enhanced or suppressed MHW likelihood from climate mode phase

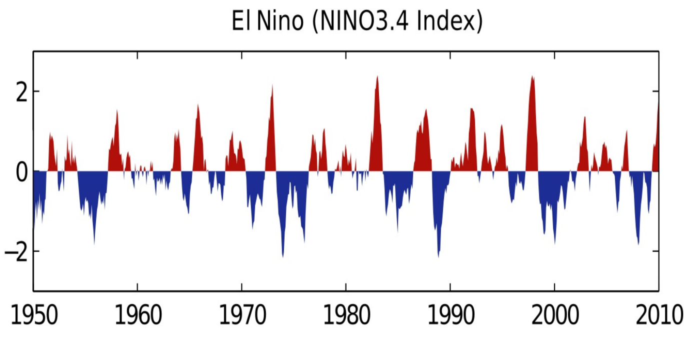


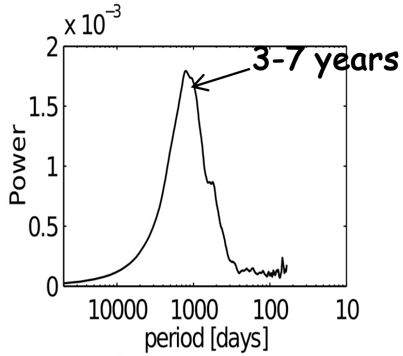
Holbrook et al. (2019), Nature Comms

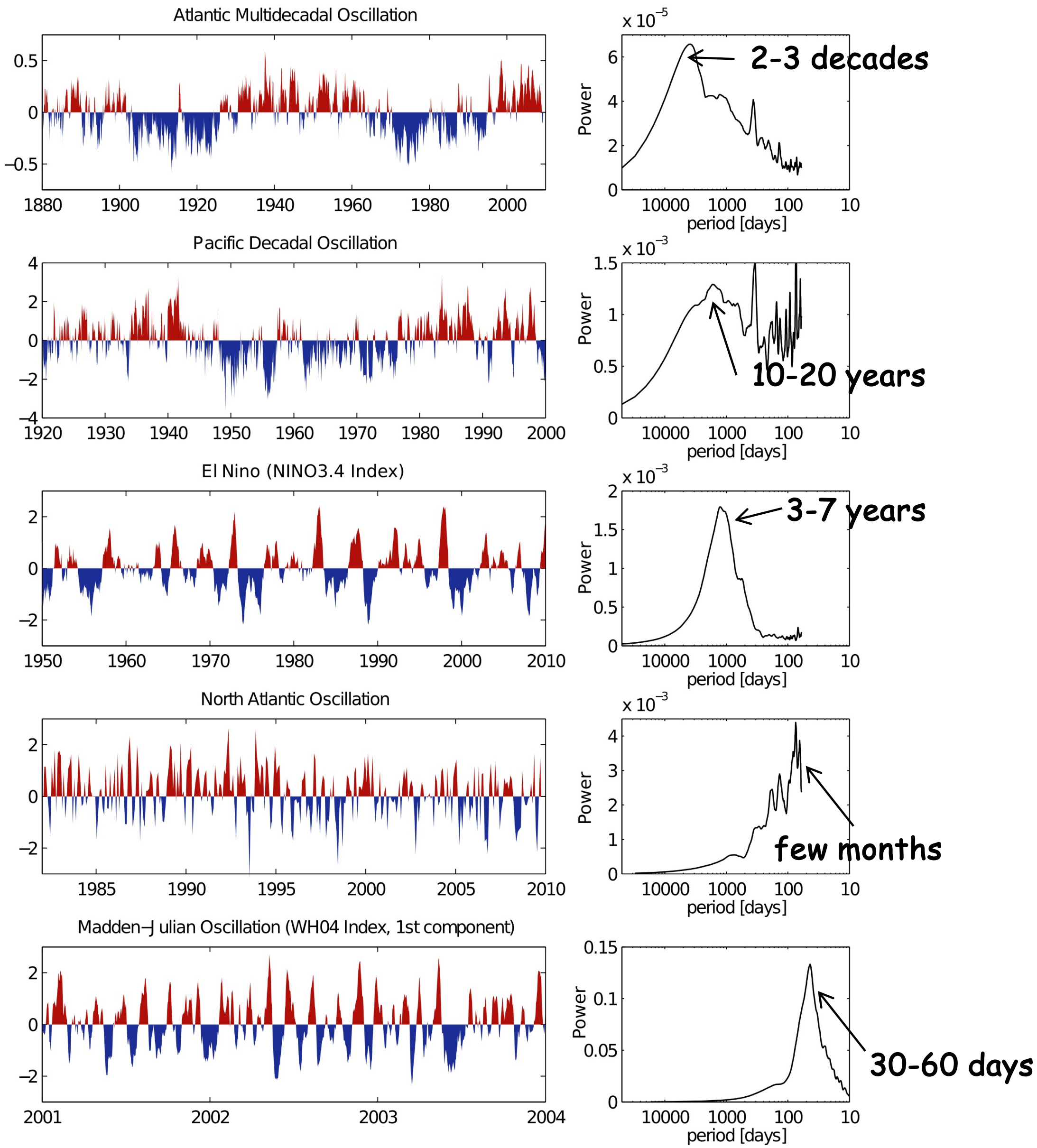
Natural oscillations/modes







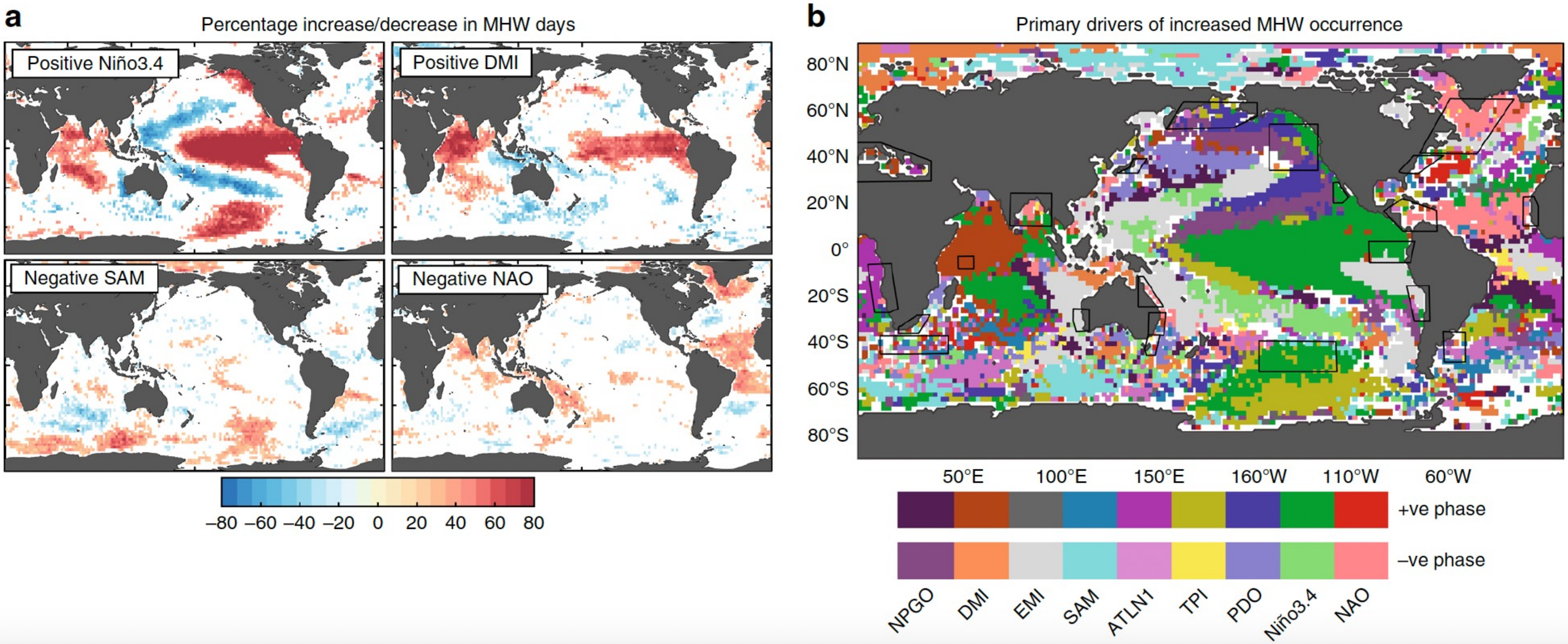




Time series of climate modes

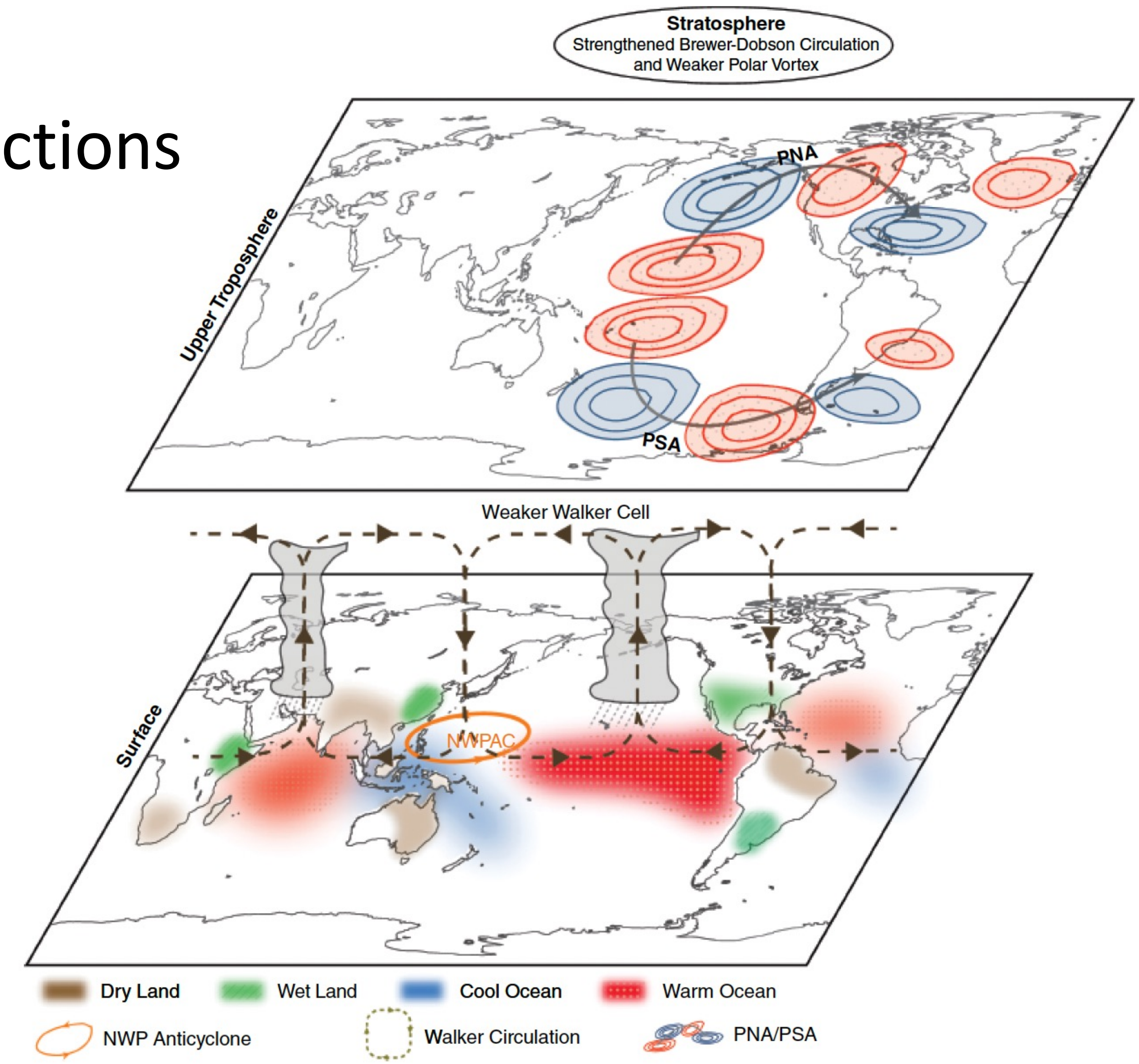
Modes of variability in the climate system occur on a range of time scales from days to weeks to years to decades to centuries…

Enhanced or suppressed MHW occurrence likelihoods according to climate mode phase



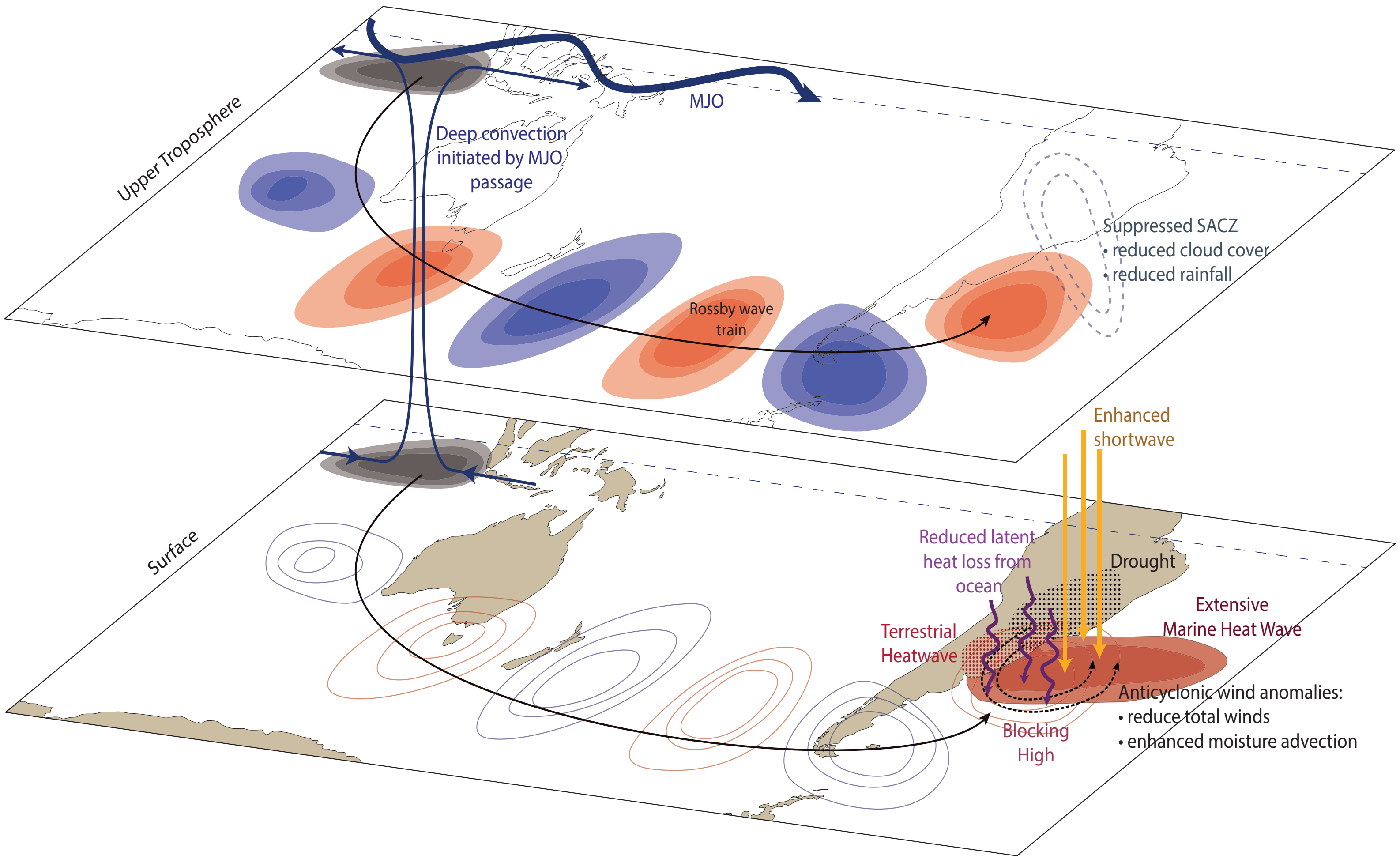
Holbrook et al. (2019), Nature Communications

ENSO
Atmospheric Teleconnections



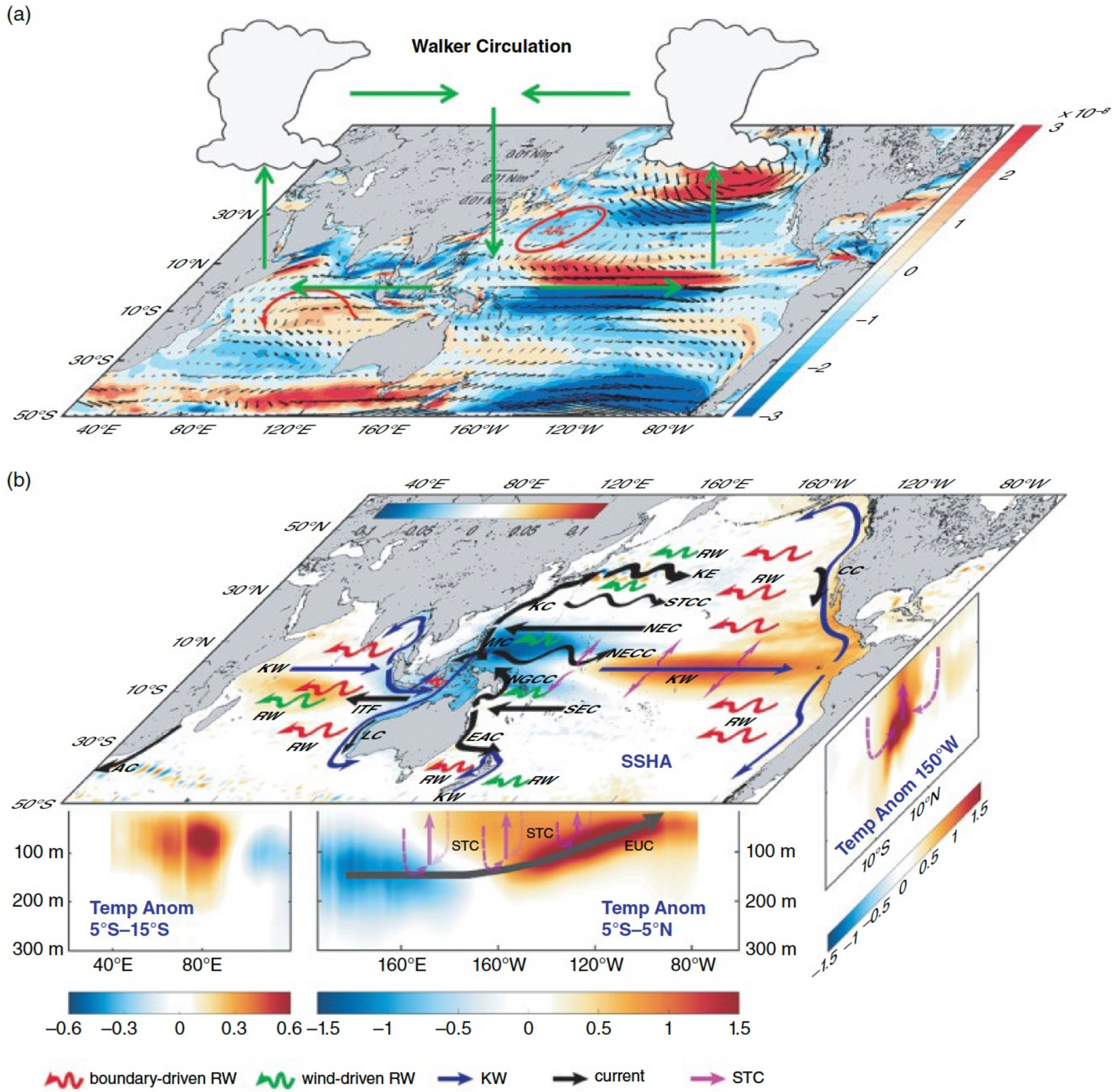
Taschetto et al. (2021), Chapter 14,
ENSO in a Changing Climate, AGU Book

Example Atmospheric Teleconnections causing MHW

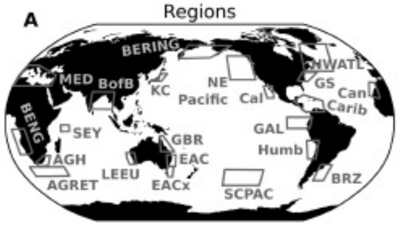


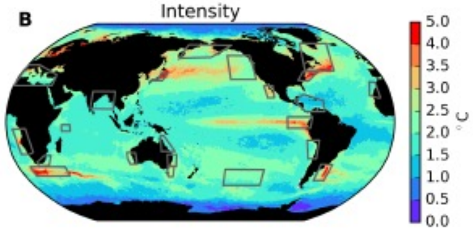
Rodrigues et al (2019), Nature Geoscience

ENSO
Oceanic Teleconnections



Sprintall et al. (2021), Chapter 15,
ENSO in a Changing Climate, AGU Book





Drivers of marine heatwaves

Timescale

Typology	Case Study	Synoptic: Mode/ Teleconnection	Synoptic: Local Process	Seasonal to Intraseasonal: Mode/ Teleconnection	Seasonal to Intraseasonal: Local Process	Interannual: Mode/ Teleconnection	Interannual: Local Process	Decadal: Mode/ Teleconnection	Decadal: Local Process
EBC	Benguela [1–3]			ABF, RWS, KWO, MJO	ADV, ASHF	RWS, KWO	ADV, VP		
	Leeuwin [4–7]			RASC, SLP(-), LWS	ADV, EHF, ASHF, VP	ENSO(-), SLP, RWS	ADV, ASHF	PDO(-), ENSO	ASHF
	California [8–12]			LWS	ADV, ASHF, VP	ENSO(+), RWS, SLP(-)	ASHF, VP, ADV		
	Iberian / Canary [8,13]	AB	ASHF	NAO(-), RASC, RWS	ADV, ASHF	JS	ASHF		
	Humboldt / Peru [14–18]			KWO, RWS	VP, ADV, ASHF	ENSO(+), RWS	ADV, ASHF		

Large-scale and regional climate modes

ENSO(+/-)	El Niño-Southern Oscillation
CPEN	Central Pacific El Niño
IPO	Interdecadal Pacific Oscillation
PDO(+/-)	Pacific Decadal Oscillation
IOD(+/-)	Indian Ocean Dipole
MJO	Madden-Julian Oscillation
NAM	Northern Annular Mode
NAO(+/-)	North Atlantic Oscillation
NPGO(+/-)	North Pacific Gyre Oscillation
NPO	North Pacific Oscillation
AMO	Atlantic Multidecadal Oscillation
SAM	Southern Annular Mode
ASM	Asian Summer Monsoon

Teleconnection processes & climatological features

AB	Atmospheric Blocking
AL	Aleutian Low
SLP(+/-)	Sea Level Pressure
JS	Jet Stream position
PNA	Pacific North American Pattern
RWA	Rossby Wave (Atmospheric)
ABF	Angola-Benguela Front
BI	Baroclinic Instability
KWO	Kelvin Wave (Oceanic)
RWO	Rossby Wave (Oceanic)
RWS	Regional wind stress change
RASC	Regional air-sea coupling
LWS	Local wind stress change

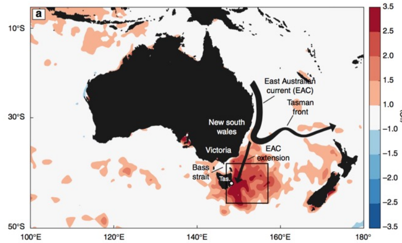
Local processes affecting the mixed layer temperature budget

ADV	Ocean Advection
EHF	Eddy heat flux
ASHF	Air-sea heat flux
VP	Vertical Processes (entrainment, turbulent mixing, thermocline deepening)

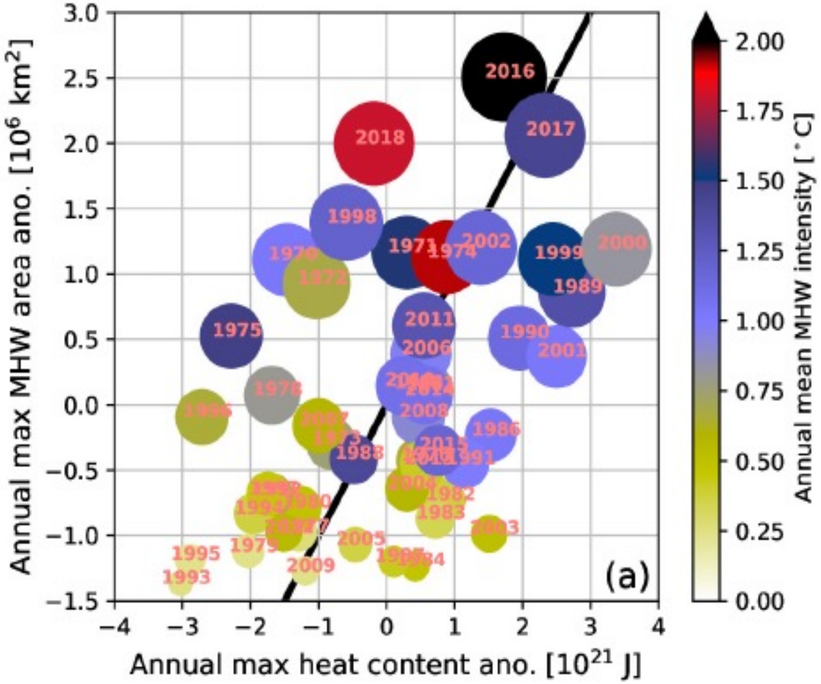
Medium *Strong agreement* *Limited evidence*	**High** *Strong agreement* *Moderate evidence*	**Very High** *Strong agreement* *Sizeable evidence*
Low *Fair agreement* *Limited evidence*	**Medium** *Fair agreement* *Moderate evidence*	**High** *Fair agreement* *Sizeable evidence*
Very Low *Weak agreement* *Limited evidence*	**Low** *Weak agreement* *Moderate evidence*	**Medium** *Weak agreement* *Sizeable evidence*

Holbrook et al (2019), Nature Communications

Preconditioning factors



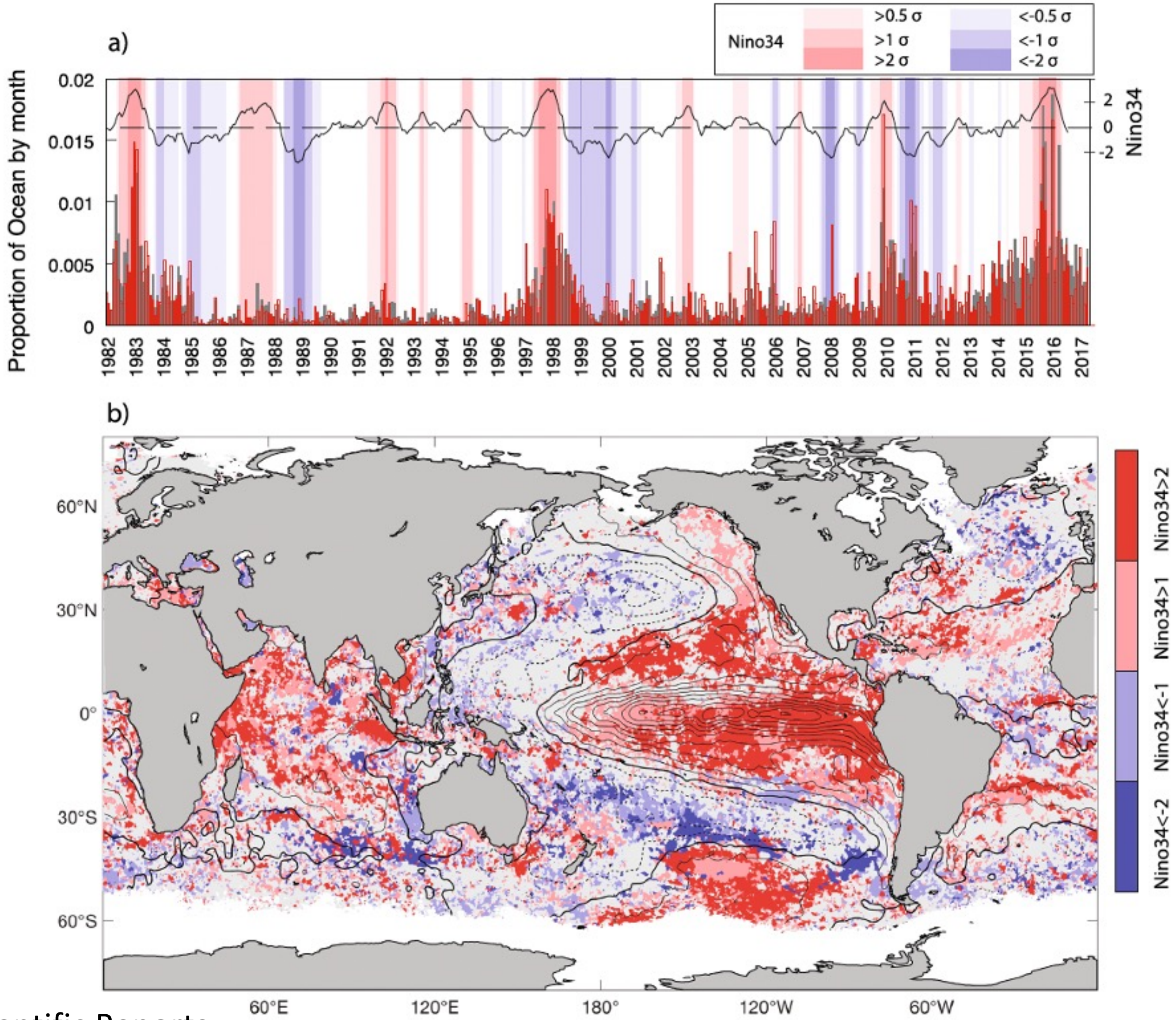
- **elevated ocean heat content** (background ocean state consideration) [e.g. Behrens et al. 2019]
- a **shallow mixed layer** from increased stratification (mixed layer can warm more easily) [e.g. Benthuysen et al. 2014; Kataoka et al. 2017]
- **persistent weather patterns** – e.g. through winter ahead of summer that reduce wintertime heat loss from the ocean to the atmosphere [e.g. Bond et al. 2015]



Behrens et al (2019), FMARS

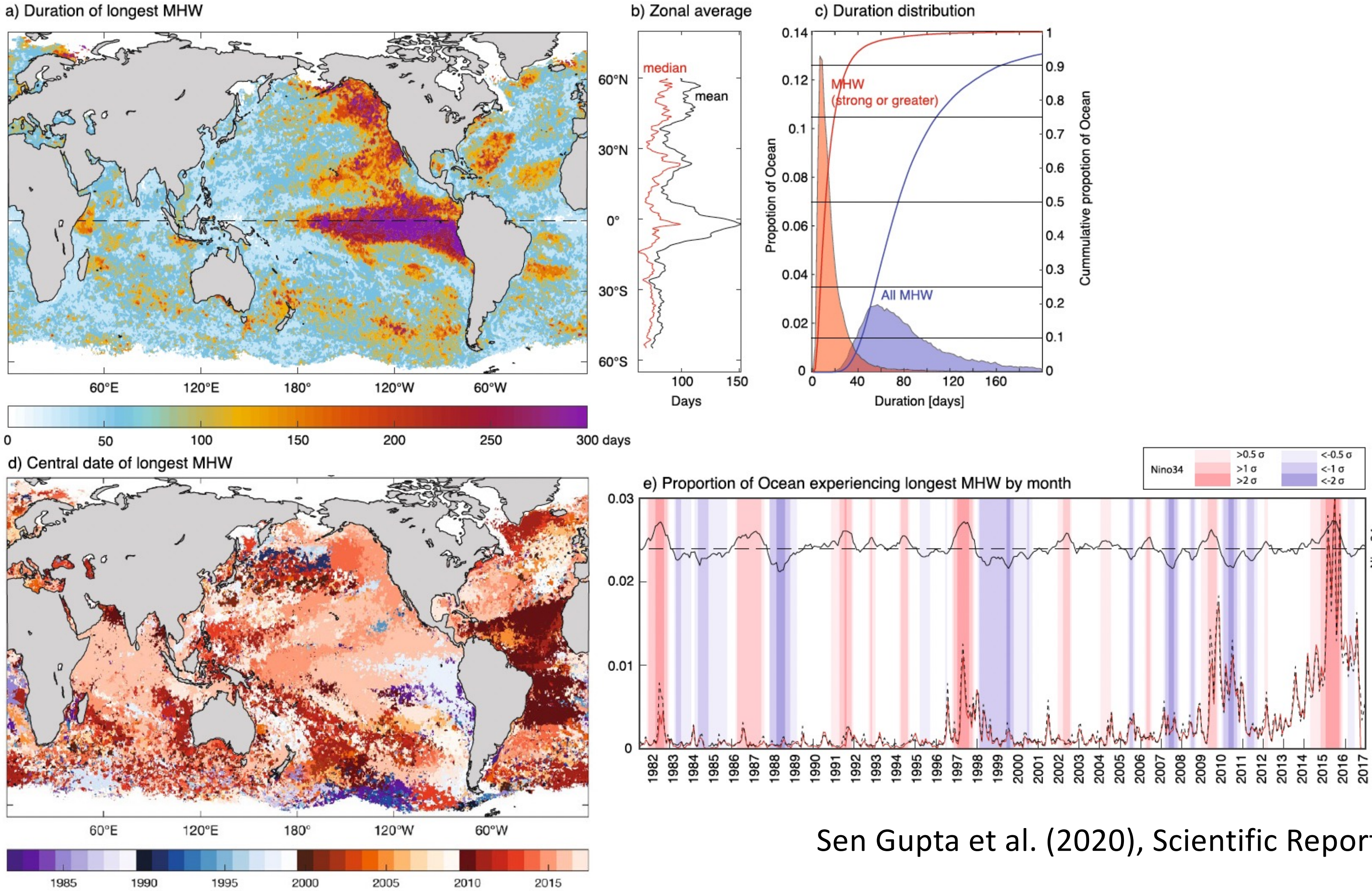
4. Drivers of the most extreme marine heatwaves

ENSO modulation of MHW severity



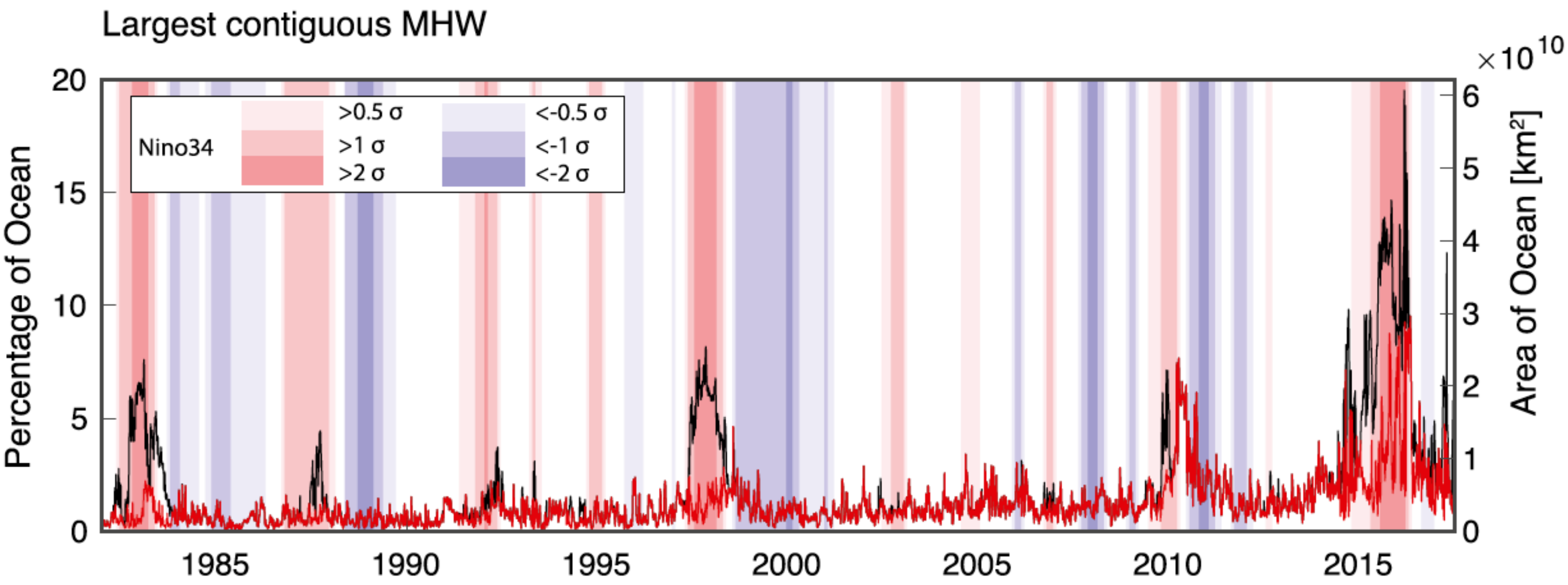
Sen Gupta et al. (2020), Scientific Reports

Characteristics of MHW duration



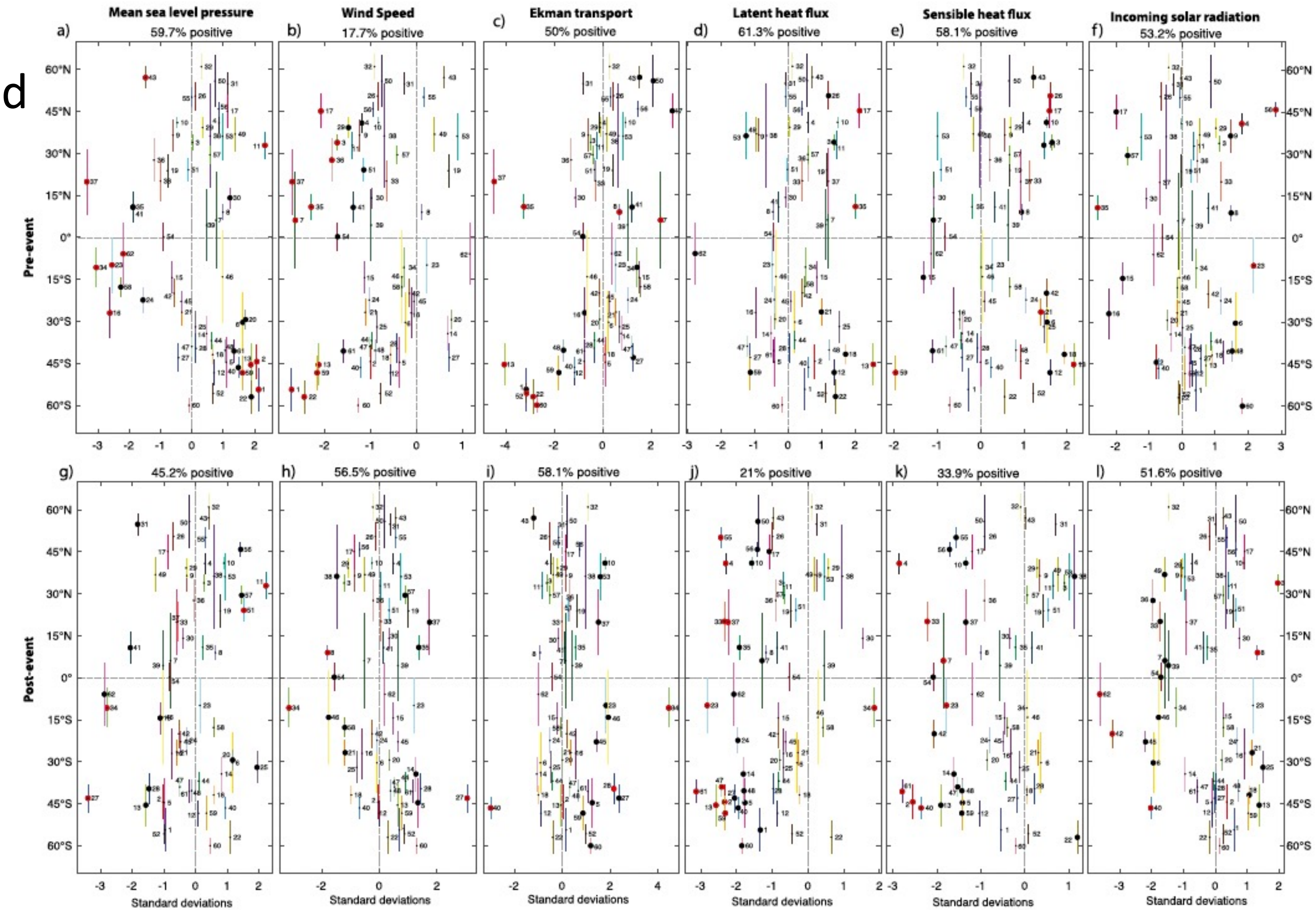
Sen Gupta et al. (2020), Scientific Reports

Largest single contiguous MHW each day



Sen Gupta et al. (2020), Scientific Reports

Normalised anomalies averaged over 62 extreme MHW regions

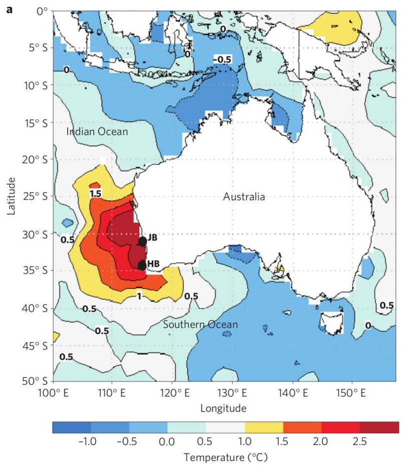


Sen Gupta et al. (2020), Scientific Reports

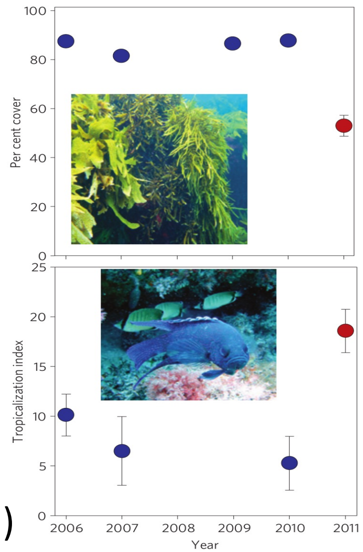
5. Oceanic teleconnections as sources of potential predictability: Australian case study examples

The 2011 Western Australia MHW

- In **summer 2010/2011** an unprecedented **"marine heatwave"** was reported off **Western Australia (WA)** (Pearce et al. 2011)
- 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)
- Remotely forced via near-record 2010/11 **La Niña** and **regional wind changes** (Feng et al. (2013), *Sci Rep*)

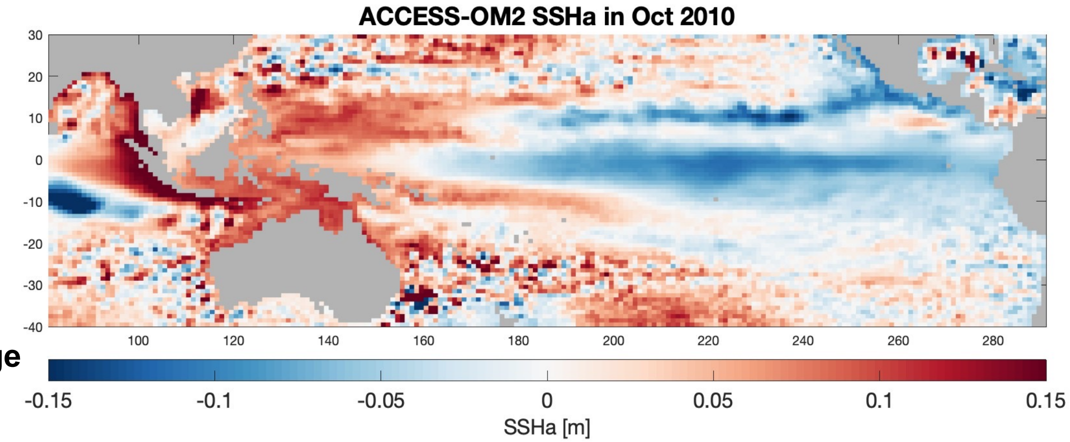


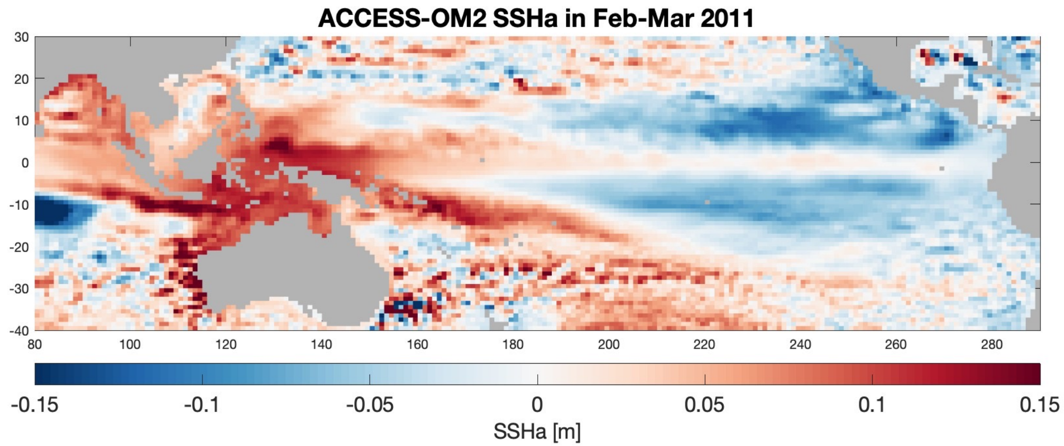
Species distribution change



Wernberg et al. (2013)

Model simulation (ACCESS-OM)

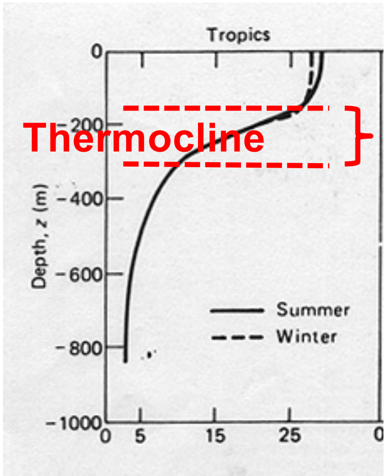


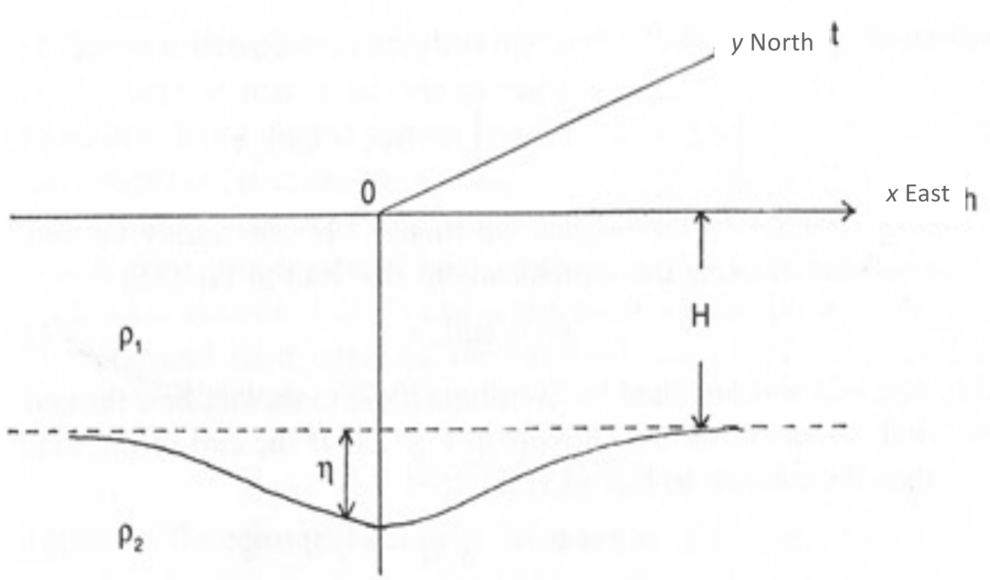


Wang et al. (in prep)

Linear shallow-water model equations

- 1 1/2-layer model of stratified ocean
- $c_1 = (g'H)^{1/2}$; $g' = (\Delta\rho/\rho_o)g$; $H = 300$m; g'=fixed (e.g., = 0.03ms^{-2}) or geographically varying
- $1^o \times 1^o$ horizontal resolution

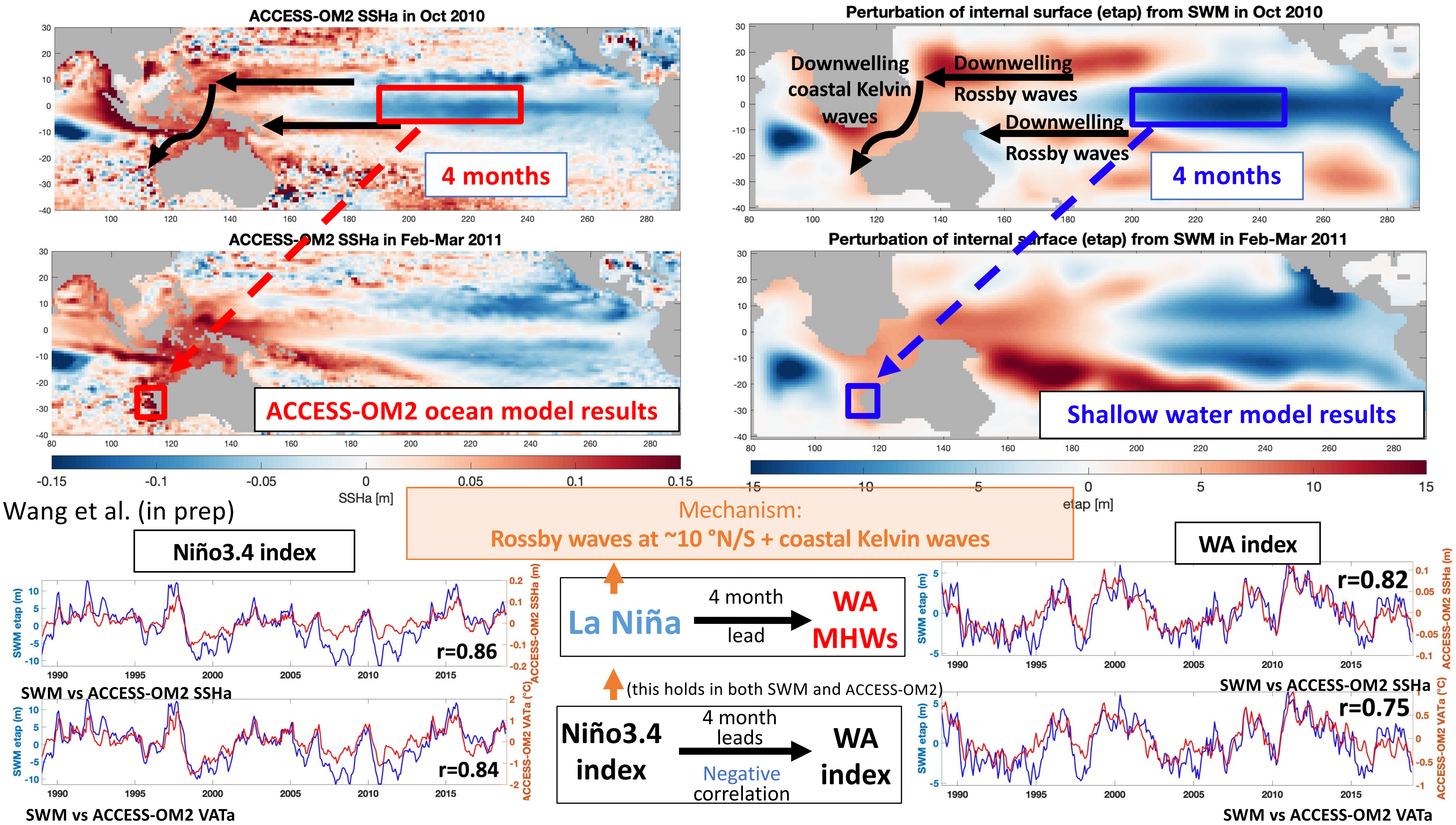




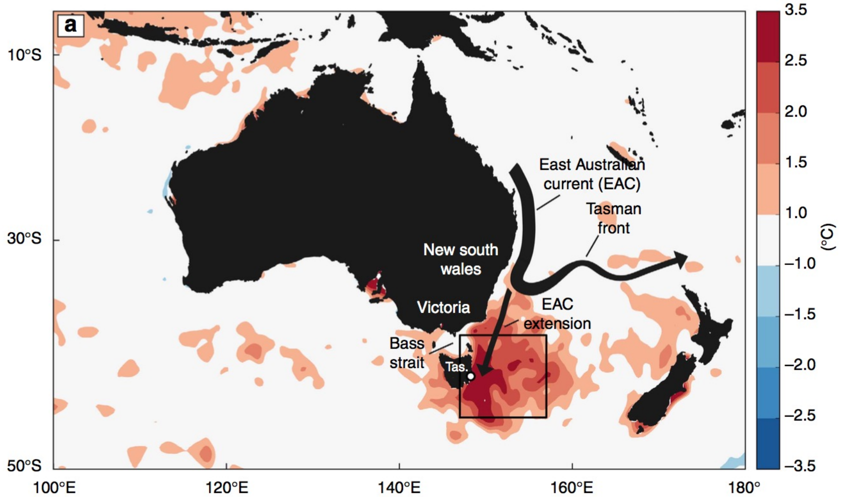
$$\frac{\partial u}{\partial t} - fv + g'\frac{\partial \eta}{\partial x} = \frac{\tau^x}{H}$$

$$\frac{\partial v}{\partial t} + fu + g'\frac{\partial \eta}{\partial y} = \frac{\tau^y}{H}$$

$$g'\frac{\partial \eta}{\partial t} + c_1^2\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right) = 0$$


ACCESS-OM2 SSHa in Oct 2010
4 months
ACCESS-OM2 SSHa in Feb-Mar 2011
ACCESS-OM2 ocean model results
SSHa [m]
Perturbation of internal surface (etap) from SWM in Oct 2010
Downwelling coastal Kelvin waves
Downwelling Rossby waves
Downwelling Rossby waves
4 months
Perturbation of internal surface (etap) from SWM in Feb-Mar 2011
Shallow water model results
etap [m]
Wang et al. (in prep)
Mechanism:
Rossby waves at ~10 °N/S + coastal Kelvin waves
Niño3.4 index
r=0.86
SWM vs ACCESS-OM2 SSHa
r=0.84
SWM vs ACCESS-OM2 VATa
La Niña
4 month lead
WA MHWs
(this holds in both SWM and ACCESS-OM2)
Niño3.4 index
4 month leads
Negative correlation
WA index
WA index
r=0.82
SWM vs ACCESS-OM2 SSHa
r=0.75
SWM vs ACCESS-OM2 VATa
SWM etap (m)
ACCESS-OM2 SSHa (m)
ACCESS-OM2 VATa (°C)

2015/16 Tasman Sea marine heatwave

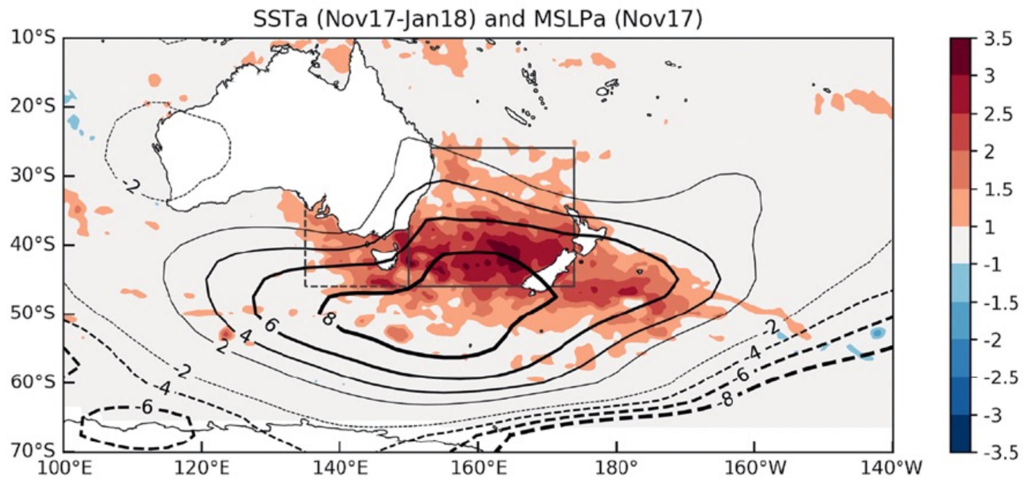


Oliver et al (2017), Nature Comms

- Narrower horizontal spatial scale
- Relatively deep to >200 m depth
- Long duration 251 days (>8 mths!)

- Dominant process => **ADVECTION**

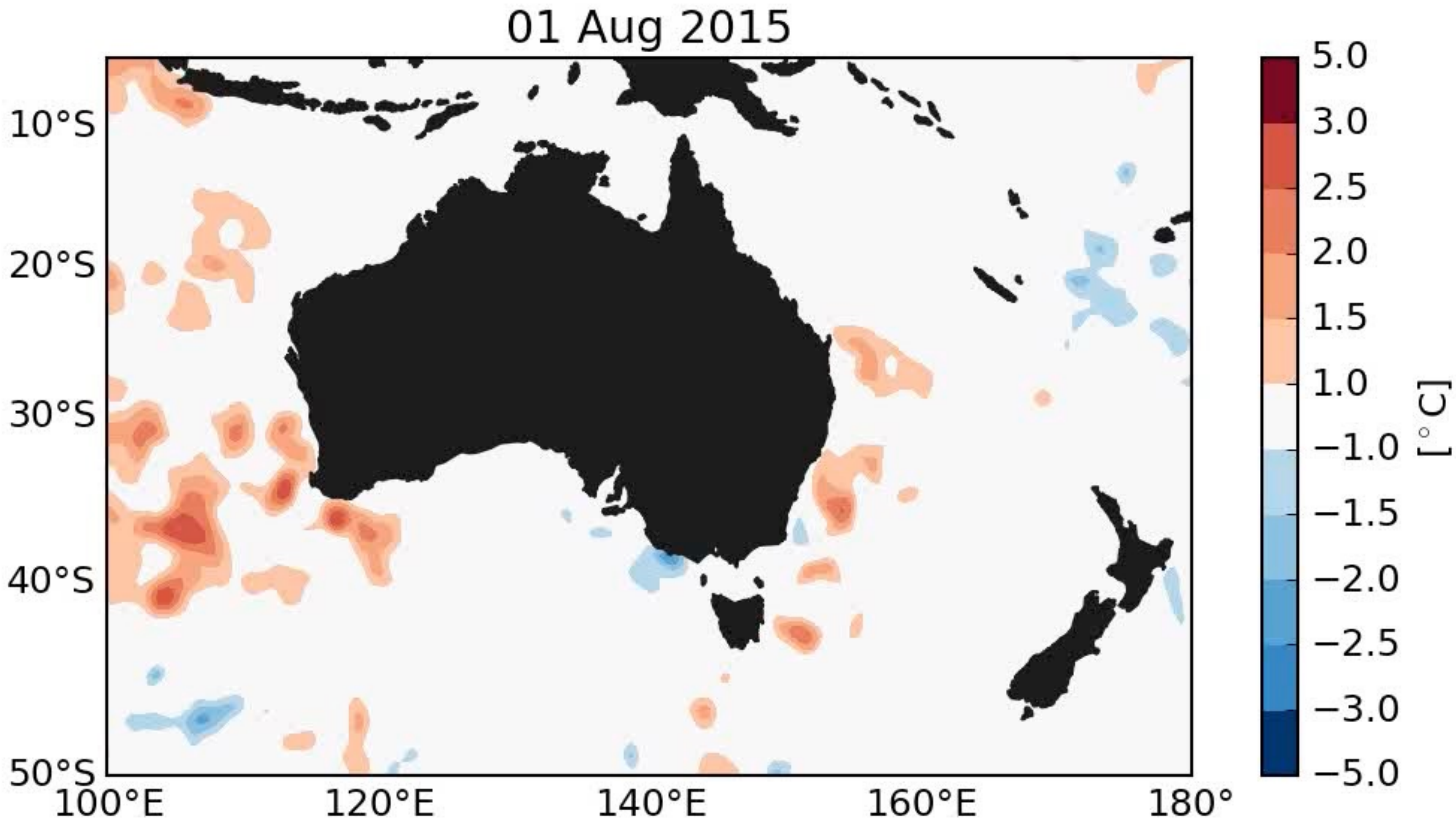
2017/18 Tasman Sea marine heatwave



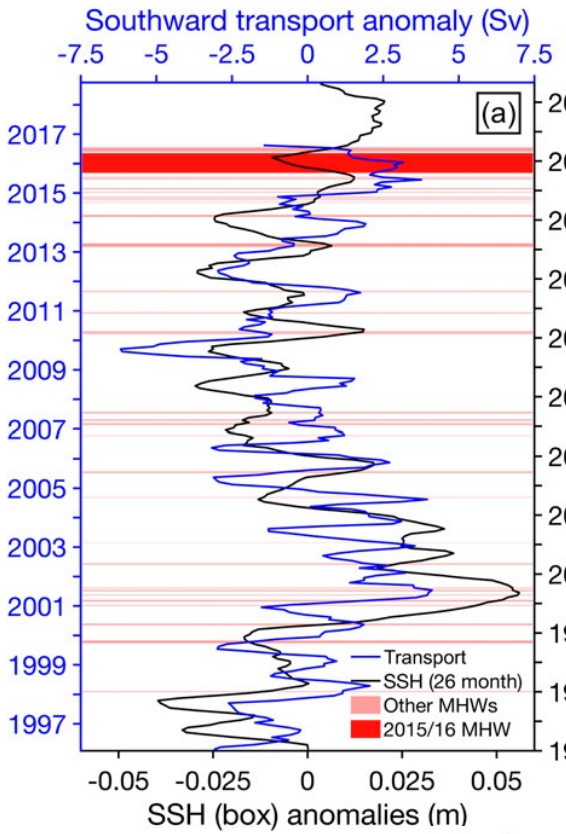
Perkins-Kirkpatrick et al (2019), BAMS

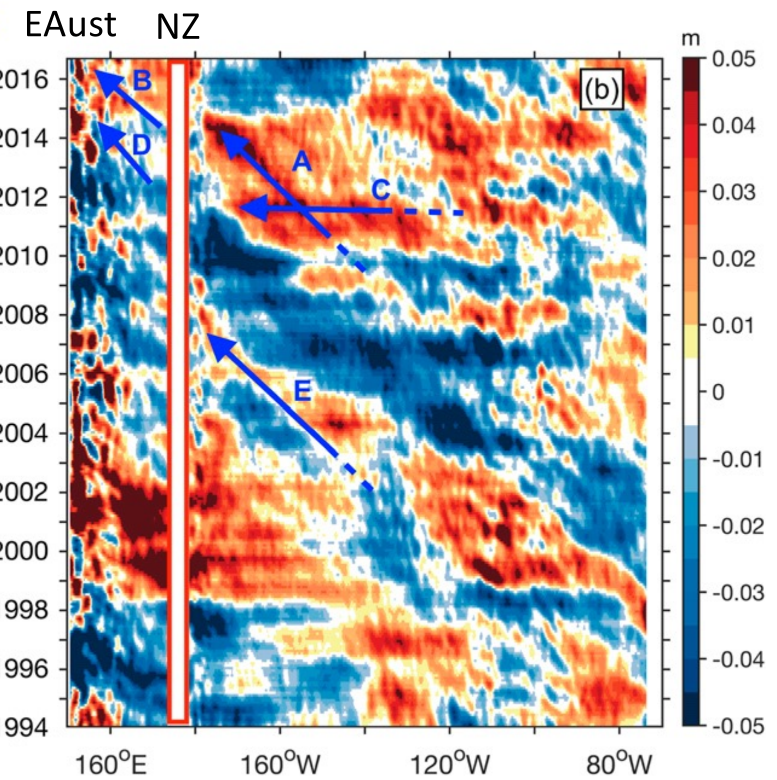
- Much broader horizontal spatial scale
- Relatively shallow to ~20 m depth
- Shorter duration (~2-3 mths)

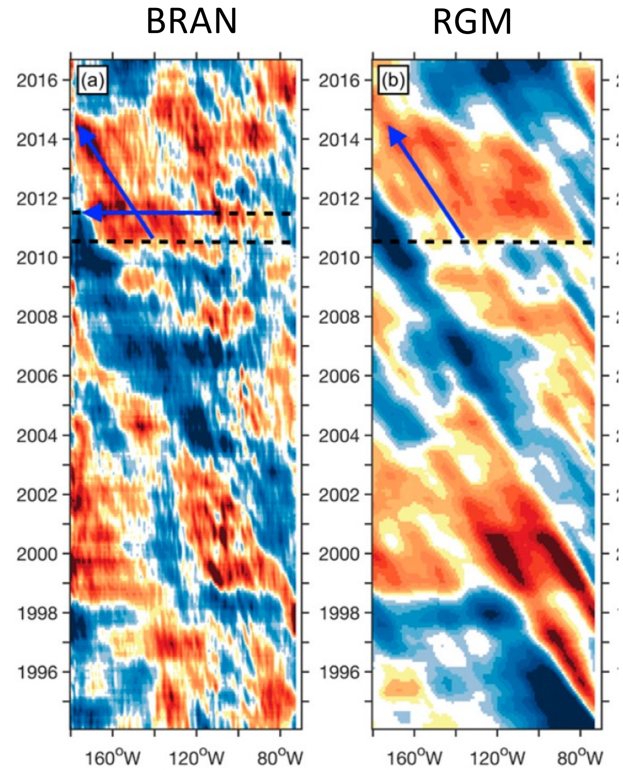
- Dominant process => **SURFACE HEAT FLUX**

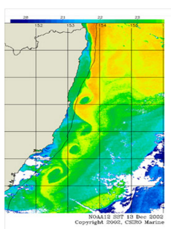

01 Aug 2015
10°S
20°S
30°S
40°S
50°S
100°E
120°E
140°E
160°E
180°
5.0
3.0
2.5
2.0
1.5
1.0
−1.0
−1.5
−2.0
−2.5
−3.0
−5.0
[°C]

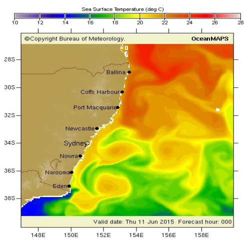
Source of potential MHW predictability months to years in advance

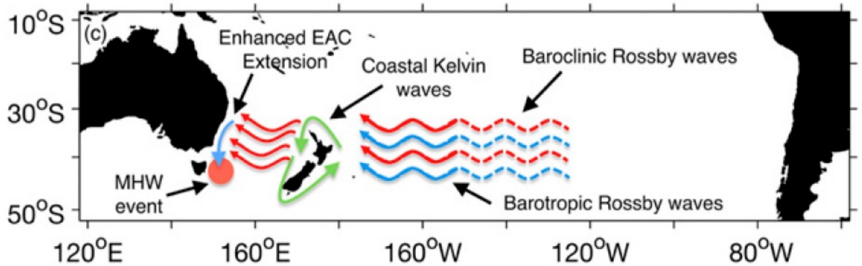








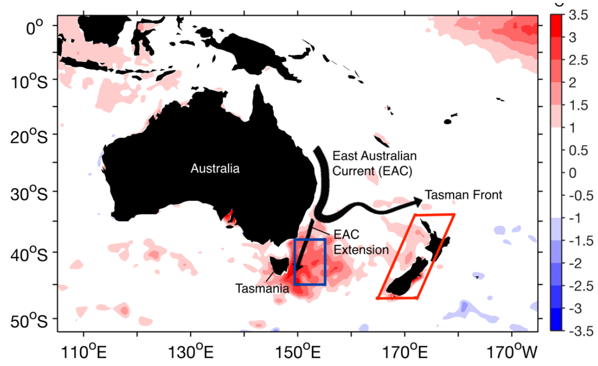


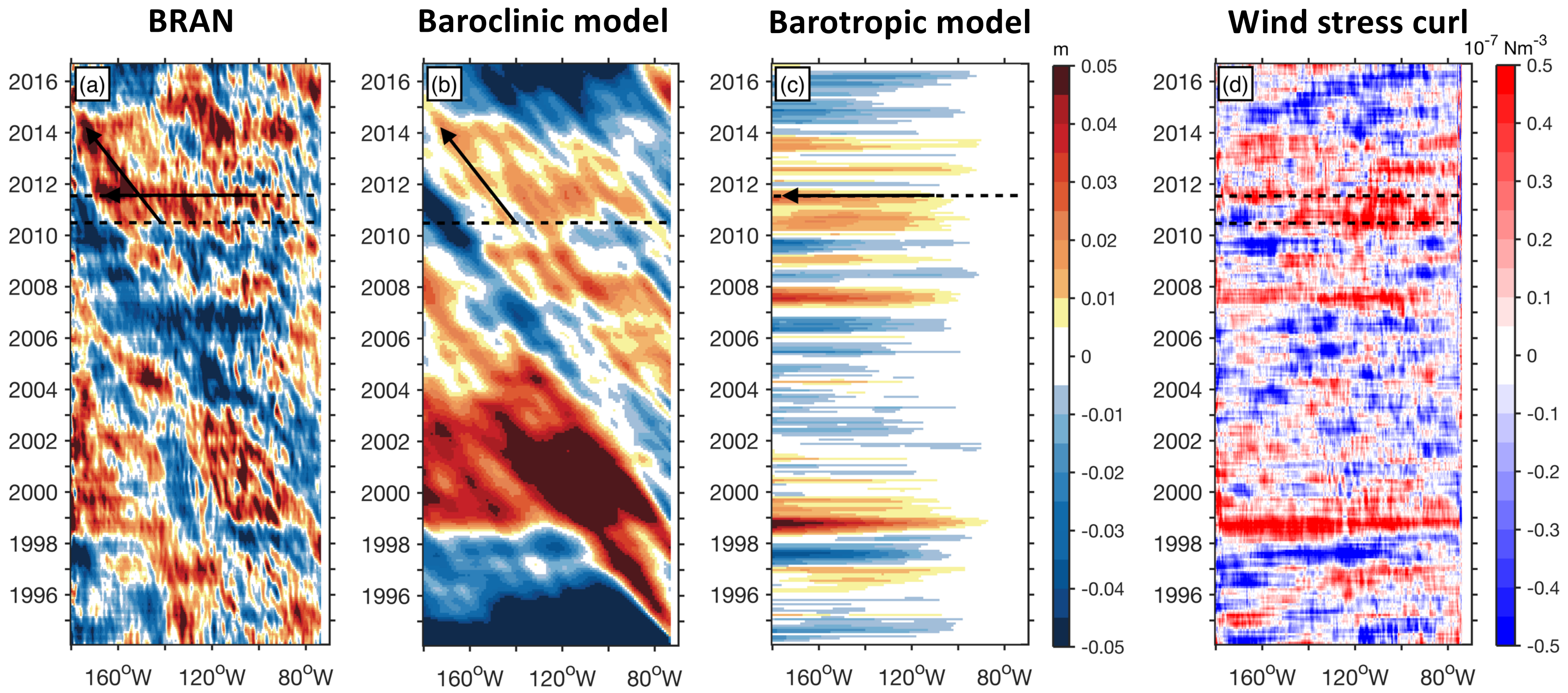


Li et al. (2020), J Climate

Remote forcing of Tasman Sea MHWs (via oceanic teleconnections)

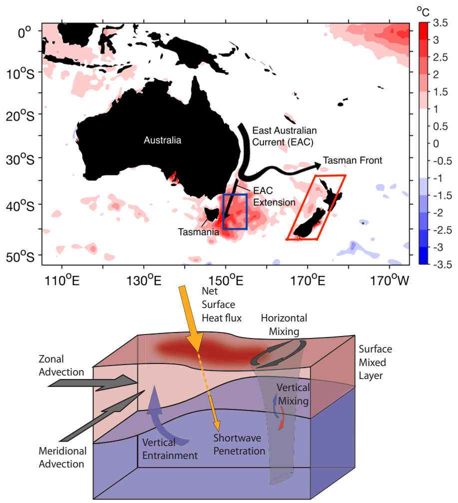
- **51% of Tasman Sea MHWs attributed to intensification of EAC Extension**





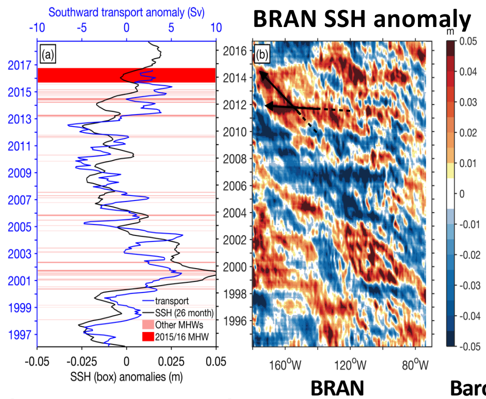
Li et al. (2020), J Climate

Eulerian versus Lagrangian approaches



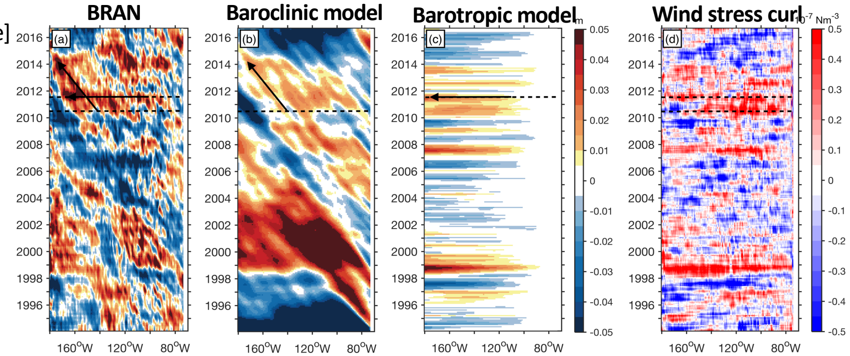
[Holbrook et al. 2019, Nat Comms]

$$\frac{\partial T}{\partial t} = -\frac{1}{H}\int_{-H}^{0} (\mathbf{u}\cdot\nabla_h T)\,dz + \frac{Q}{\rho C_p H} + \text{residual}$$



[Li et al. 2020, J Climate]

Simple process modelling



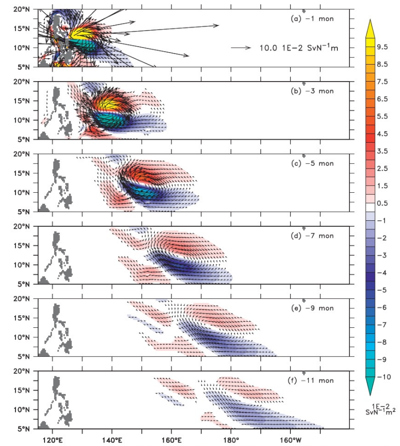


FIG. 4. Adjoint sensitivity (10^{-2} Sv N^{-1} m^2) of monthly mean meridional transport in the upper 400 m immediately east of the Philippine coast from 125.33° to 126.67°E across 12°N in December 2006 to monthly wind stress in previous months during 2006. Colors show sensitivity to zonal wind stress, while vectors show sensitivity to both zonal and meridional wind stress.

Adjoint model **sensitivity** to forcing (back trajectory)

[Zhang et al. 2012, JPO]

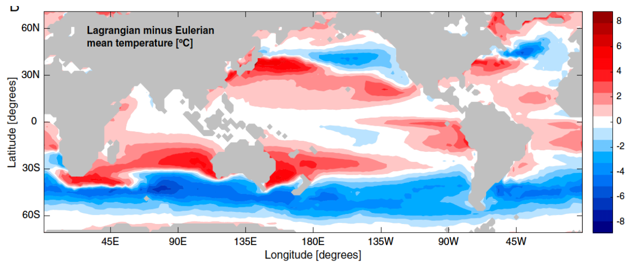
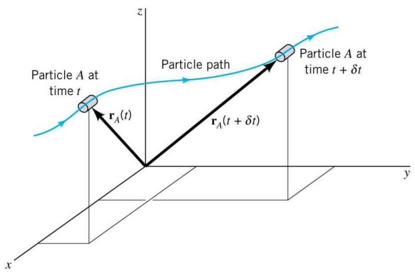


Fig. 1. Advection of microbial genotypes by ocean currents. (*A*) The average meridional (latitudinal) distance traveled by 500-d microbial genotypes. Although microbes can be advected for thousands of kilometres in the global ocean, they are most likely to experience changes in temperature through meridional rather than zonal (longitudinal) transport. (*B*) The offset between the along-trajectory average temperature experienced by the microbes as they traveled for 500 d and the local temperature at each grid location. The poleward flowing western boundary currents carry microbes that have provenances in much warmer water than where they are found. In contrast, microbes on the northern flank of the Antarctic Circumpolar Current originate from the cold water close to Antarctica and have been carried northward by the Ekman transport.

Lagrangian minus Eulerian microbial trajectory exposure to (meridional) **T(°C)** change after 500 days

[Doblin and van Sebille 2016, PNAS]



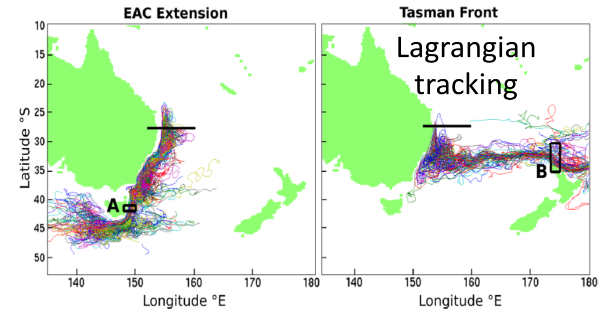
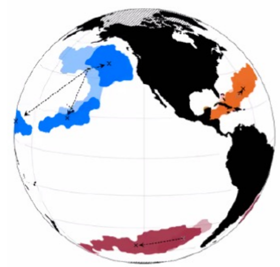


Figure 1. Random subset of 80 particles advected in the ocean model following (left) the pathway of the extension of the EAC and (right) the pathway of the Tasman Front, following their release at 27°S. Particles traveling through box A (41.5°S–42.5°S and 148°E–150°E) are selected to form the extension of the EAC. Particles traveling through box B (31°S–36°S and 173.5°E–175°E) form the pathway of the Tasman Front. The black line shows the transect at 28°S which is located upstream of the separation latitude. Coloring is random.

[Ypma et al. 2015, JGR-Oceans]



Object tracking of ~1,100 MHWs worldwide

[Scannell 2020, based on ANN?]

6. Take home messages

- P**rocess understanding of marine heatwaves** has improved substantially over the past 10 years

- **Air-sea heat flux** driven MHWs tend to occur anywhere acoss the global oceans, while **advection** driven MHWs often occur in boundary current regions

- **Marine heatwave predictability** time and space scales depend on the drivers (atmosphere, ocean and preconditioning factors) and regions

- MHW potential predictability is afforded by **modes of climate variability** and **teleconnections**, with longer time scale predictability likely from **oceanic teleconnections**