Physical Drivers of global Marine Heatwaves

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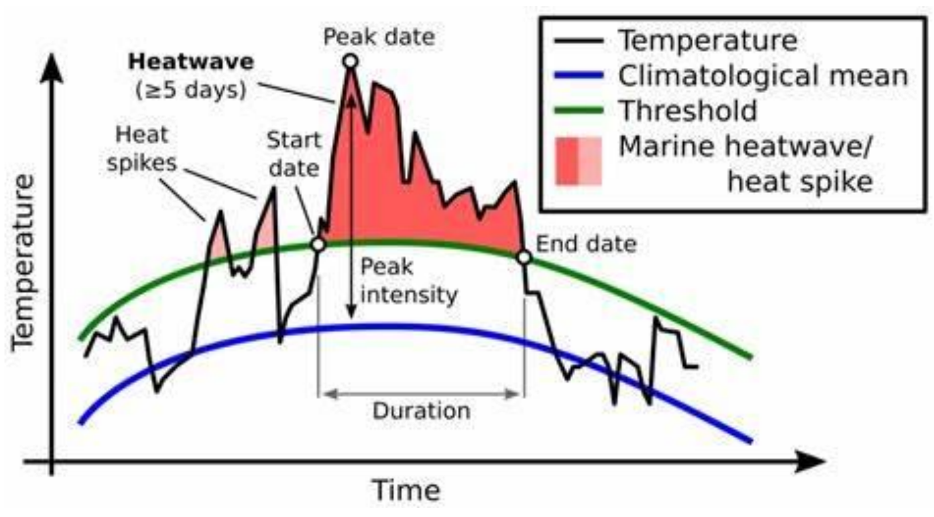
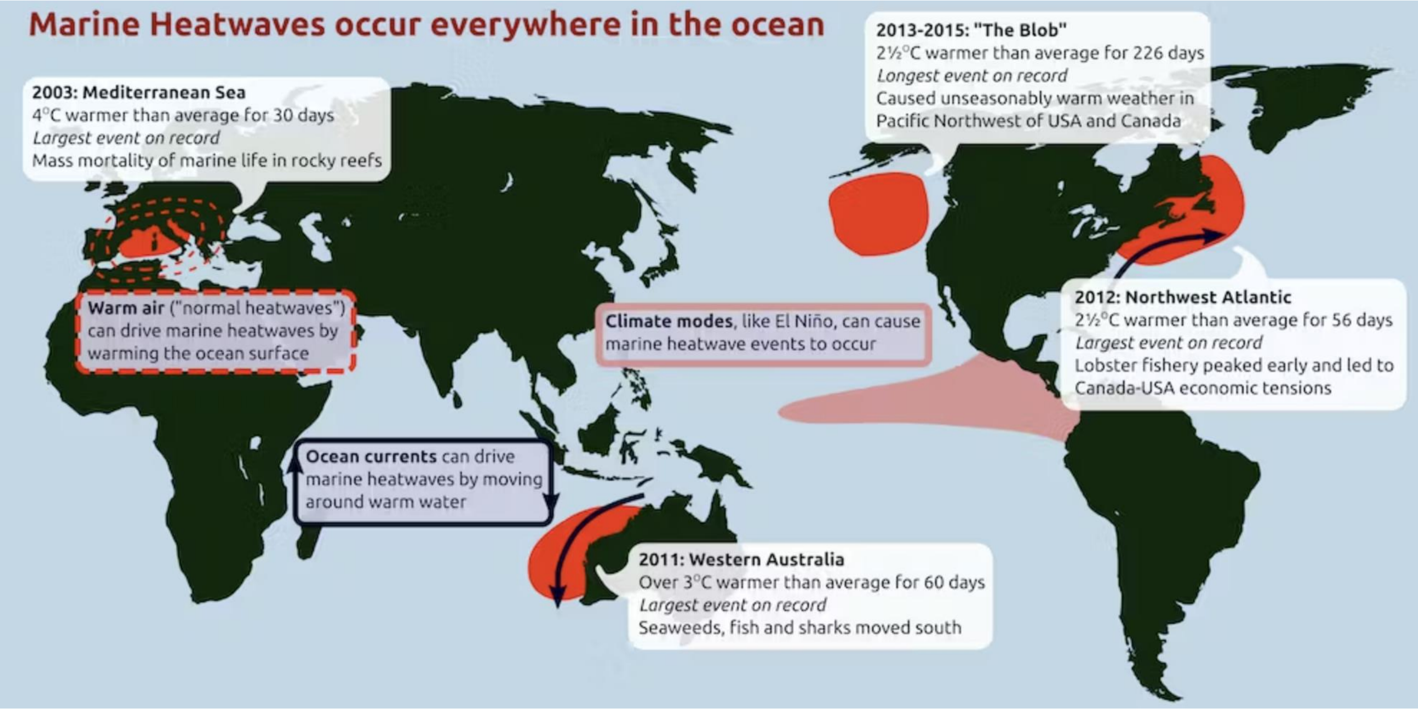
Introduction: Marine Heatwaves (MHWs)



https://www.marineheatwaves.org/

- persistent warm water extremes.
- ecological devastating.
- occur everywhere in the ocean.
- stronger in the future.



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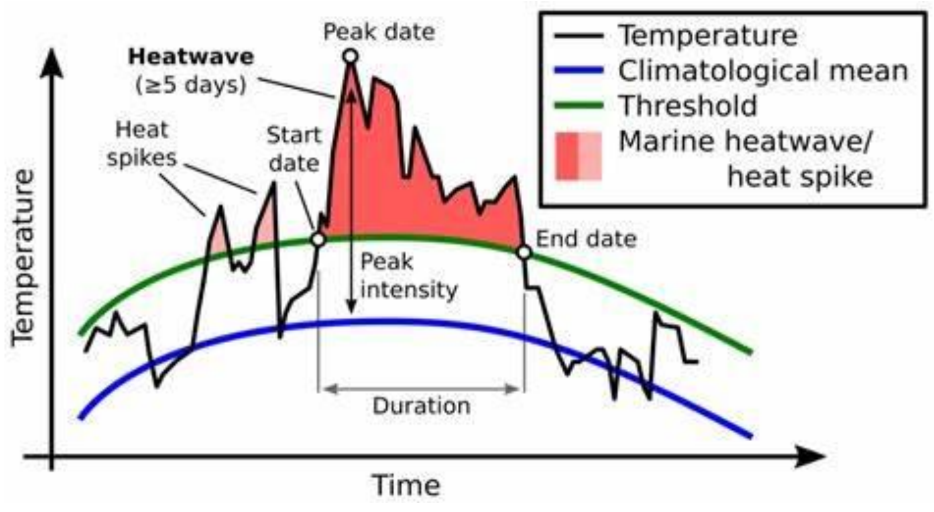

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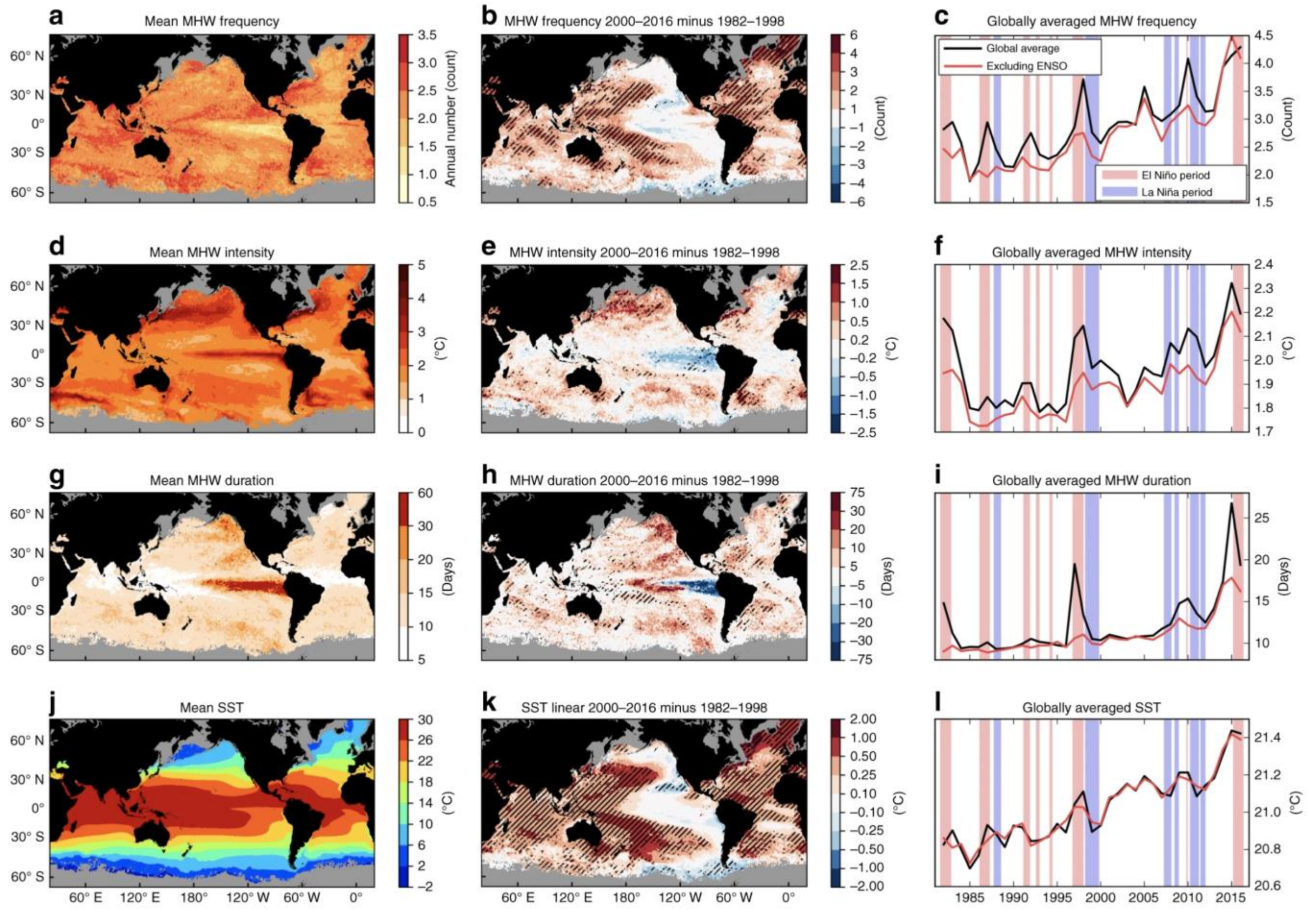

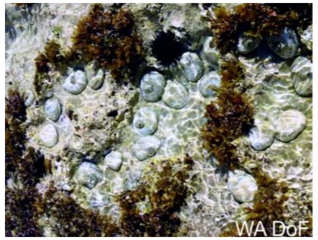

Introduction: Marine Heatwaves (MHWs)

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ARTICLE

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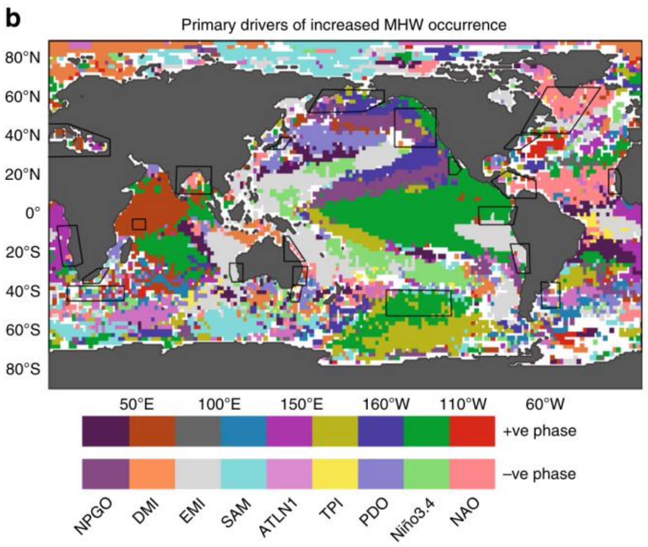
A global assessment of marine heatwaves and their drivers

Neil J. Holbrook[1,2], Hillary A. Scannell[3], Alexander Sen Gupta[4,5], Jessica A. Benthuysen[6], Ming Feng[7], Eric C.J. Oliver[1,2,8], Lisa V. Alexander[4,5], Michael T. Burrows[9], Markus G. Donat[5,10], Alistair J. Hobday[11], Pippa J. Moore[12], Sarah E. Perkins-Kirkpatrick[4,5], Dan A. Smale[13,14], Sandra C. Straub[14] & Thomas Wernberg[14]



(Holbrook et al.,2019)

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Drivers and impacts of the most extreme marine heatwave events

Alex Sen Gupta[1,2], Mads Thomsen[3], Jessica A. Benthuysen[4], Alistair J. Hobday[5], Eric Oliver[6], Lisa V. Alexander[1,2], Michael T. Burrows[7], Markus G. Donat[2,8], Ming Feng[9], Neil J. Holbrook[10,11], Sarah Perkins-Kirkpatrick[1,2], Pippa J. Moore[12], Regina R. Rodrigues[13], Hillary A. Scannell[14], Andréa S. Taschetto[1,2], Caroline C. Ummenhofer[15,2], Thomas Wernberg[16] & Dan A. Smale[16,17]

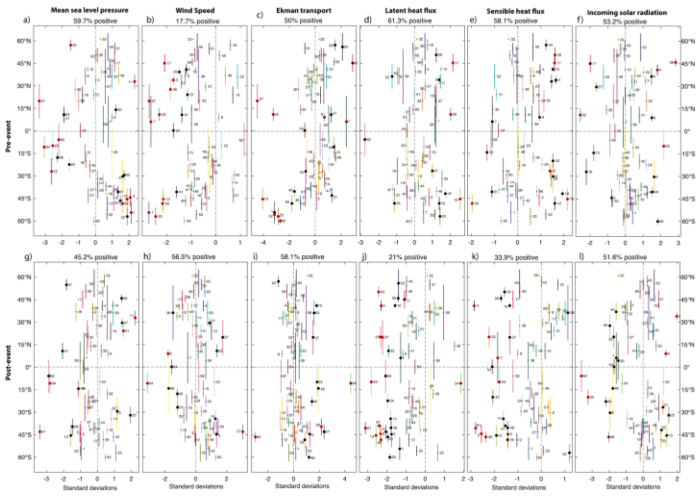

Figure 6. Normalised anomalies averaged over the 62 identified extreme MHW regions, before (average of 6 to 3 weeks prior to event peak, top panels) and after (average of 3 to 6 weeks after event peak, lower panels) the peak of the event. Coloured lines indicate the latitudinal extent of the MHW. Numbers indicate the regions shown in Fig. 5. Large, black circles indicate anomalies are within the top decile of anomalies for the same 4-week period across all years; large, red circles indicate the most extreme of all the anomalies for the same 4-week period across all years. Percentages above each panel indicate the percentage of regions for which anomalies are > 0.

(Gupta et al.,2020)

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ORIGINAL RESEARCH
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Local Drivers of Extreme Upper Ocean Marine Heatwaves Assessed Using a Global Ocean Circulation Model

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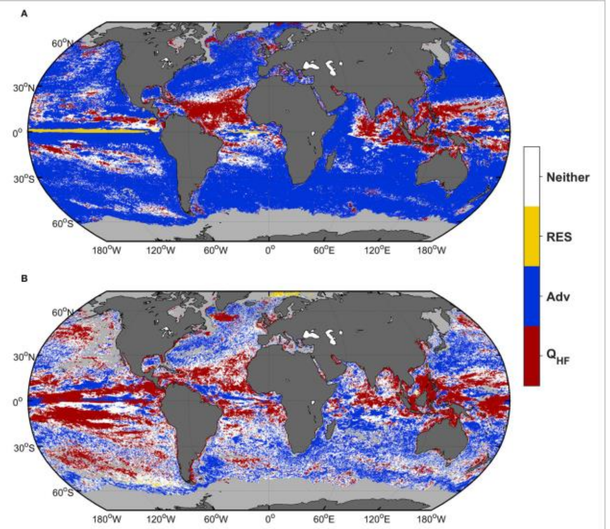
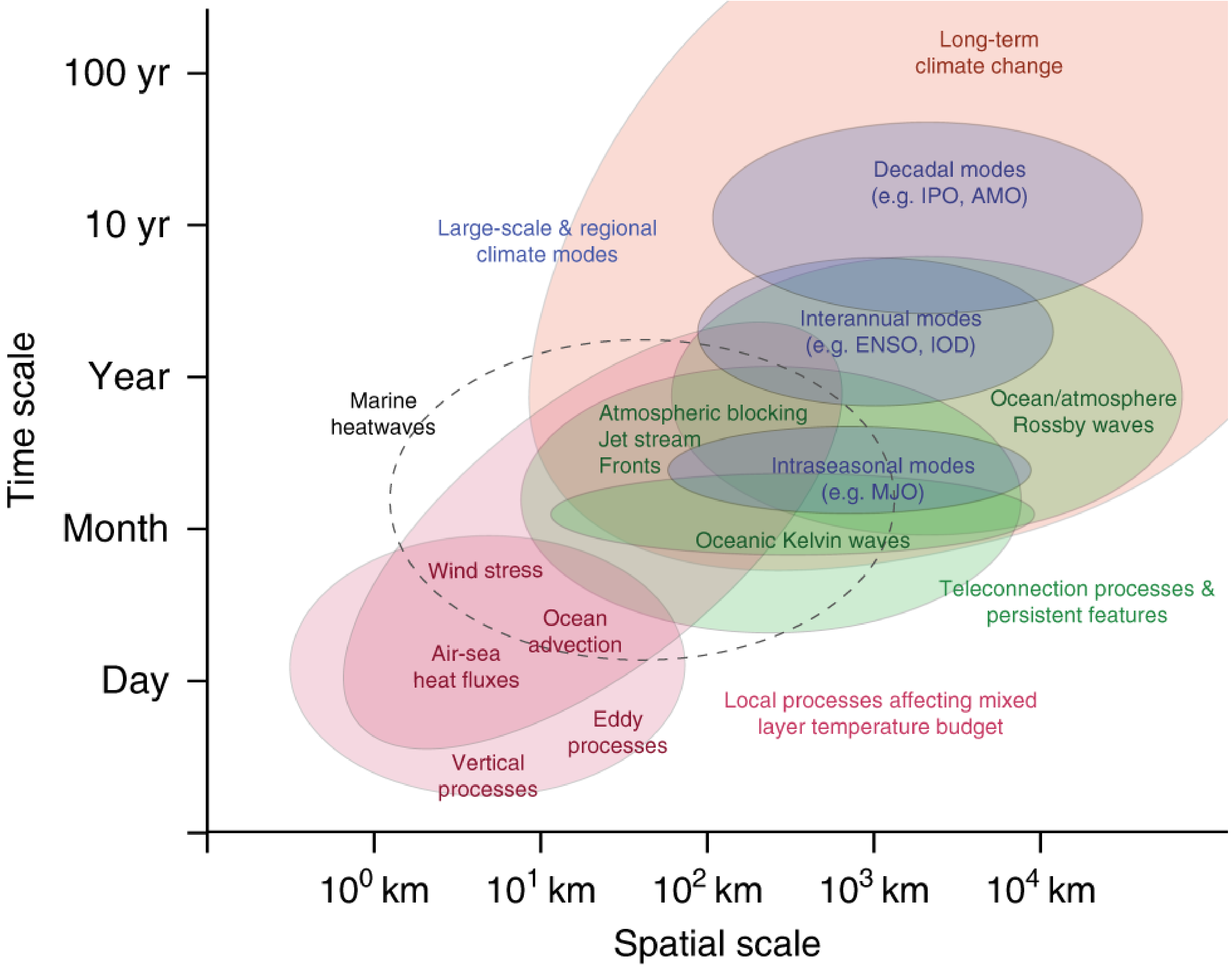


FIGURE 4 | Main driver of most extreme MHWs **(A)** onset (n = 1–3) and **(B)** decay (n = 1–3). A heat budget term was defined as the main term when the average percent contribution to the total temperature change during onset or decay period across all three most extreme MHWs was larger than 66.6%. Note that only positive contribution to total temperature change was considered. In the case where no term's contribution was larger than 66.6%, the main driver was defined as "neither" (white), indicating that MHW onset or decay was driven by two or more terms. Net surface air-sea heat flux (red), total advection (blue) and the residual (yellow) term were considered [see Equation (1)].

(Marin et al.,2022)

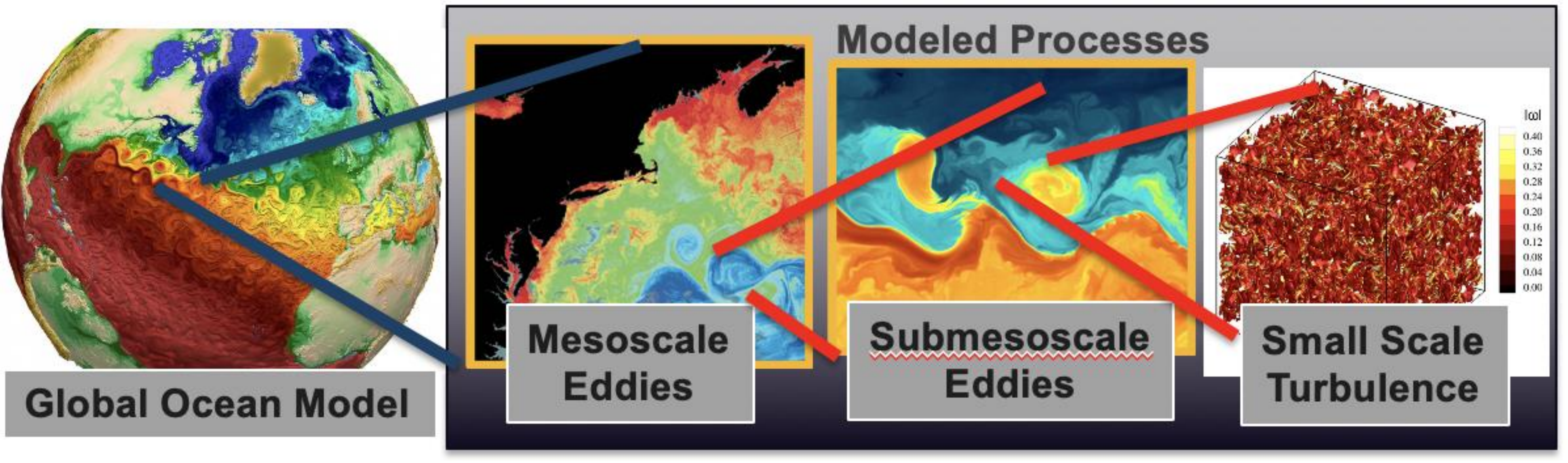
Introduction: Marine Heatwaves (MHWs)

(Holbrook et al.,2019)



(Holbrook et al.,2019)

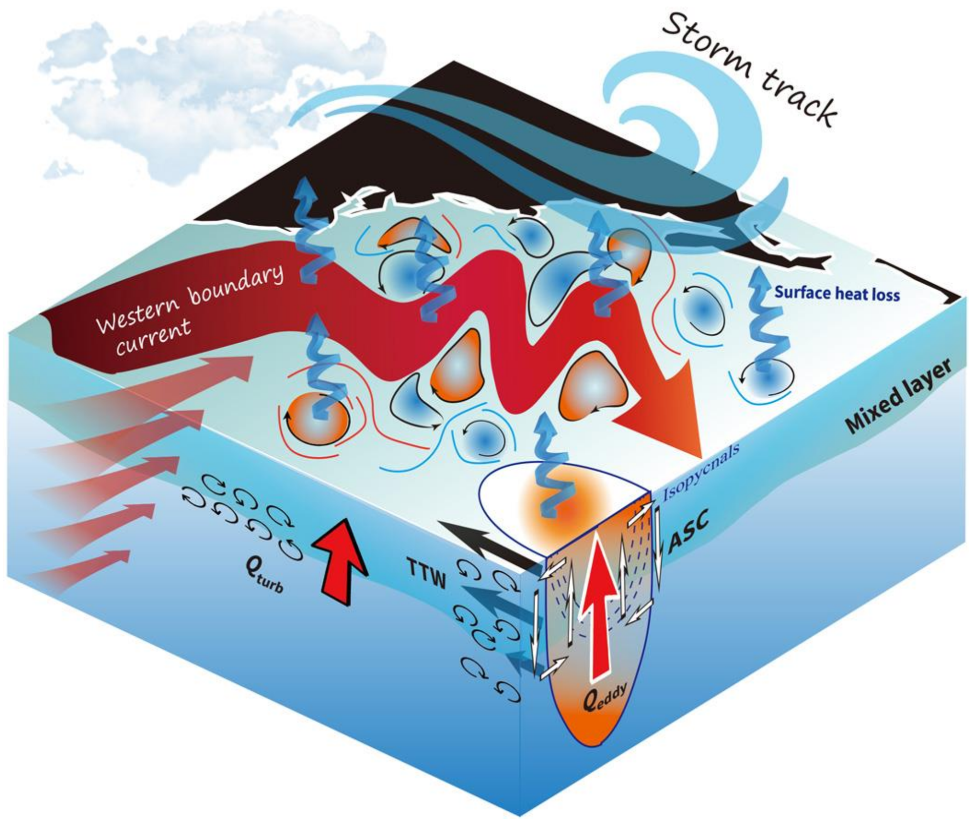
Oceanic mesoscale eddies



Introduction: Oceanic Mesoscale eddies

Features:

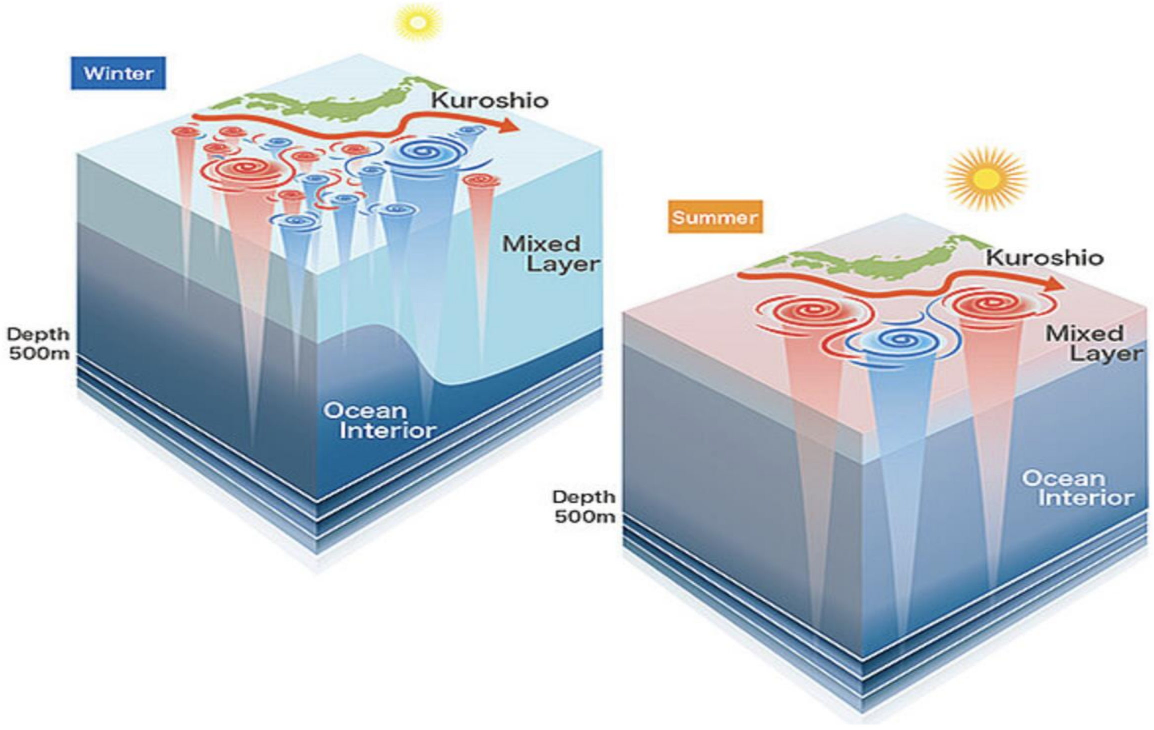
Oceanic mesoscale eddies with a horizontal scale from a few tens to several hundreds of kilometers, manifested in the form of fronts, filaments and coherent vortices, are the most prominent feature in the upper ocean. They account for 70% of oceanic kinetic energy and contribute importantly to the SST variability via their induced heat flux convergence. Yet the effects of mesoscale eddies on the MHW life cycles in the global ocean remain unexplored.



Introduction: Oceanic Mesoscale eddies

Oceanic eddies have seasonal features, though their occurrence and characteristics can vary significantly depending on geographic location and oceanographic conditions.

- **North Atlantic**: The Gulf Stream is known for intense eddy activity, with eddies more frequently detaching in the spring and early summer.
- **Western Pacific**: The Kuroshio Current off Japan also shows seasonal variations in eddy formation, often linked to changes in wind stress and stratification throughout the year.
- **Southern Ocean**: Eddy activity around Antarctica can be influenced by seasonal sea ice cover changes, impacting the formation and decay of eddies.

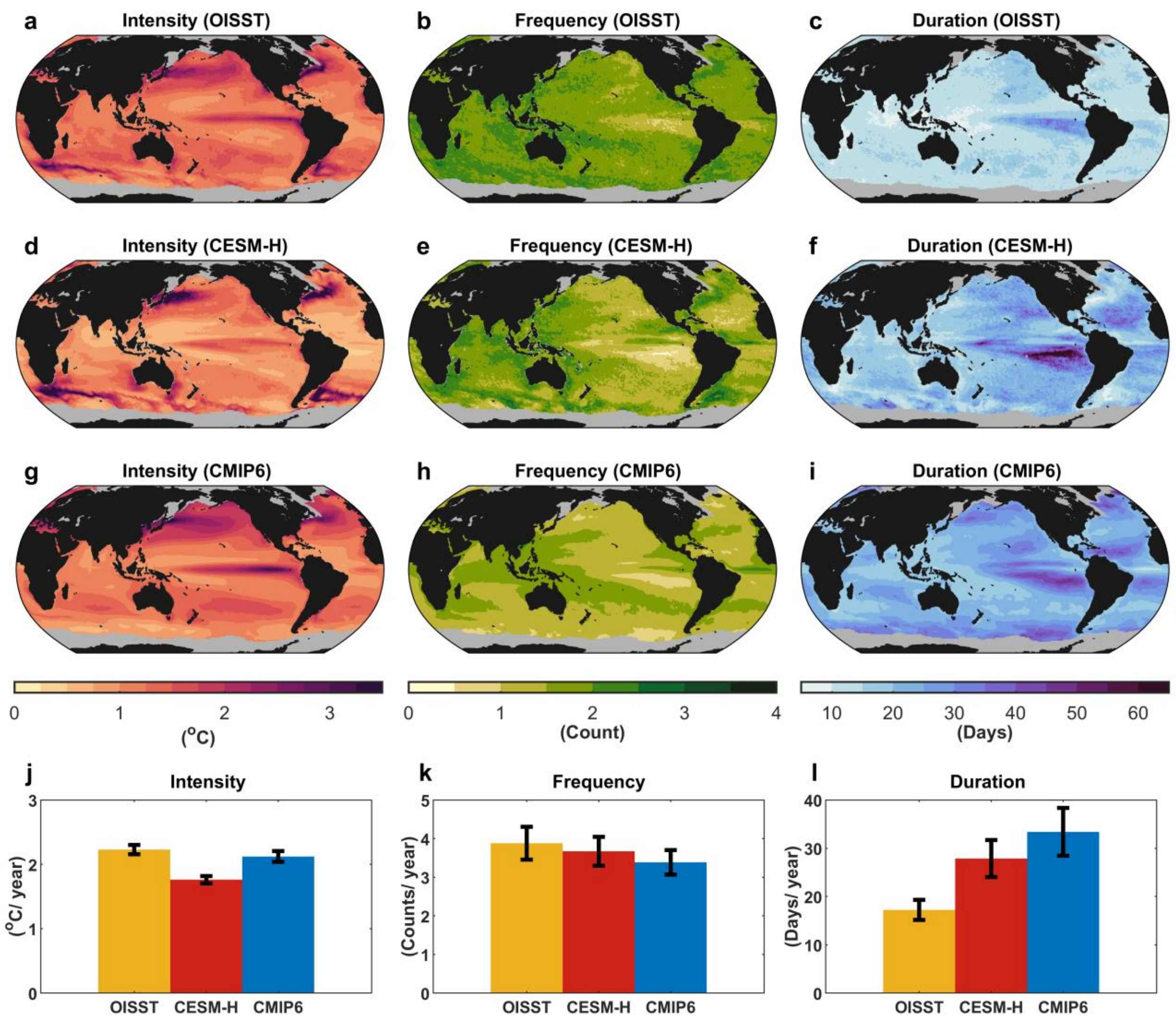


Model: MHW Statistics (during 1982-2021)

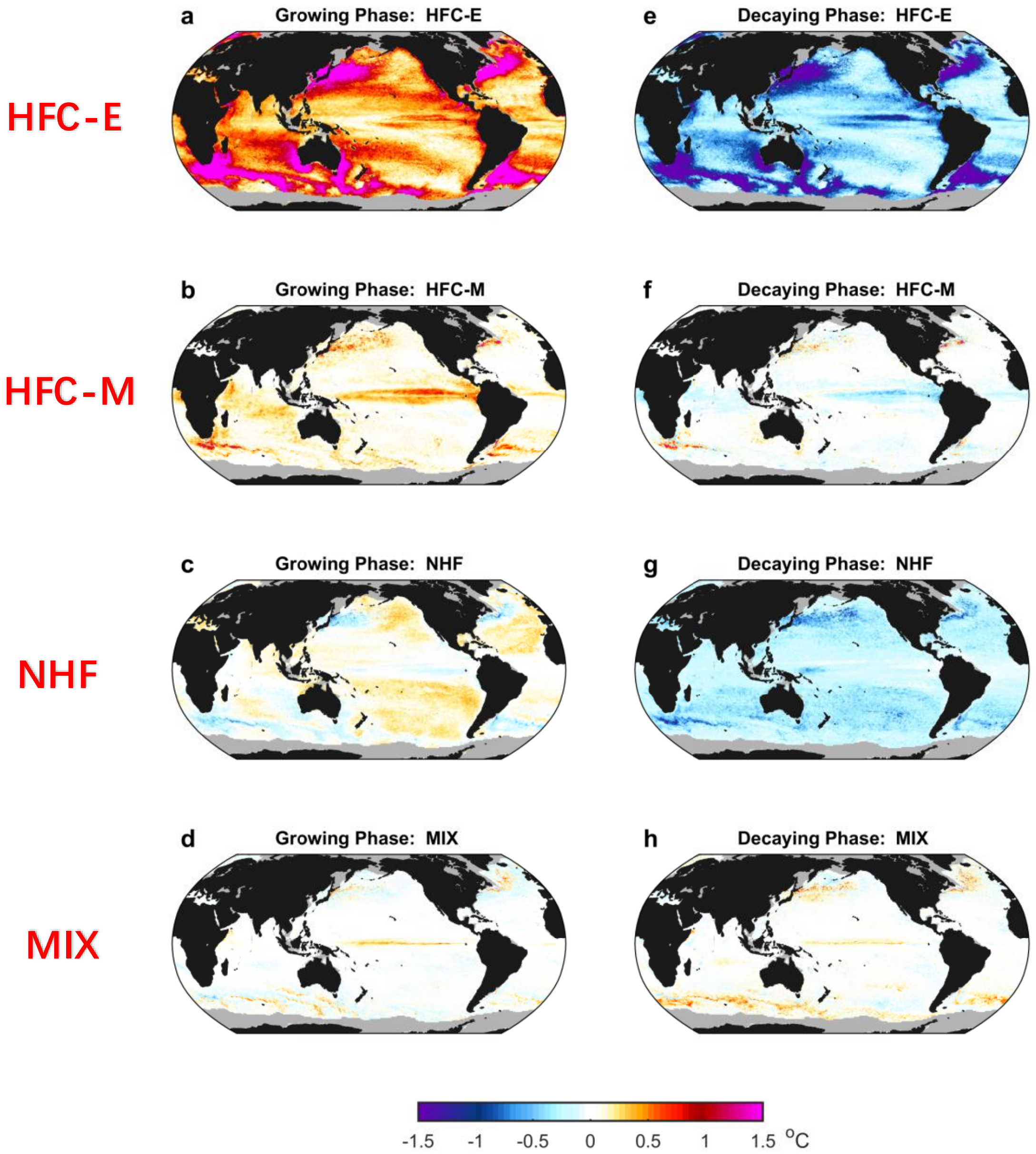
Our study is based on a coupled high-resolution simulation CESM-H. Performance of the CESM-H in simulating MHWs is evaluated against satellite observations and compared with an ensemble of coarse resolution CMIP6.

- The CESM-H reproduces MHW properties reasonably well.
- Better than coarse resolution simulations.

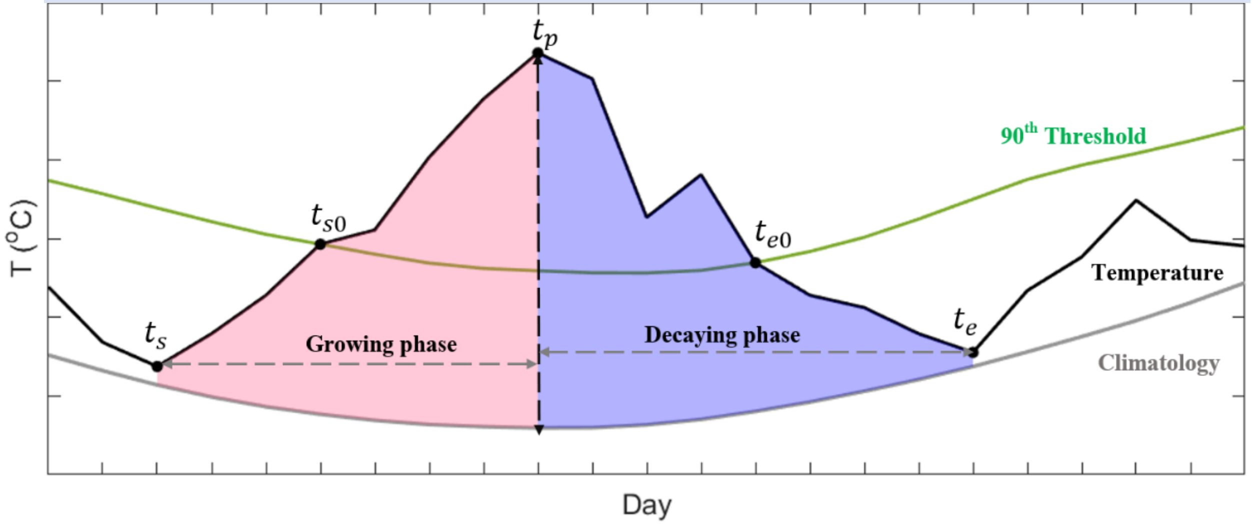
- 0.1° horizontal resolution for the ocean;
- 0.25° for the atmosphere and land component.
- Historical forcing from 1850 to 2005;
- RCP 8.5 forcing during 2006-2100.



Result: Drivers of global MHW life cycle



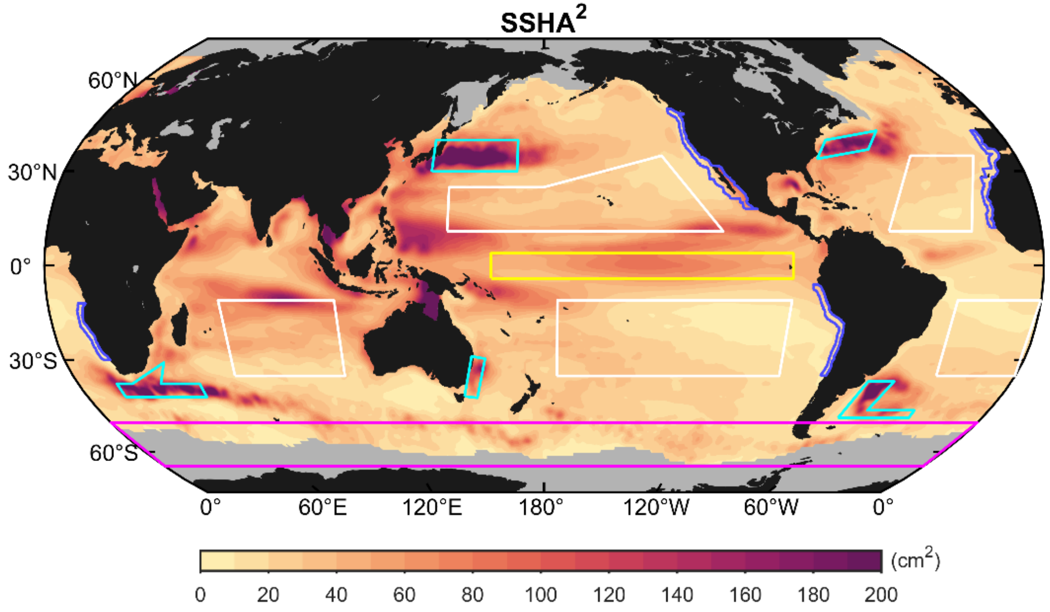
Schematic of a MHW growing and decaying phases



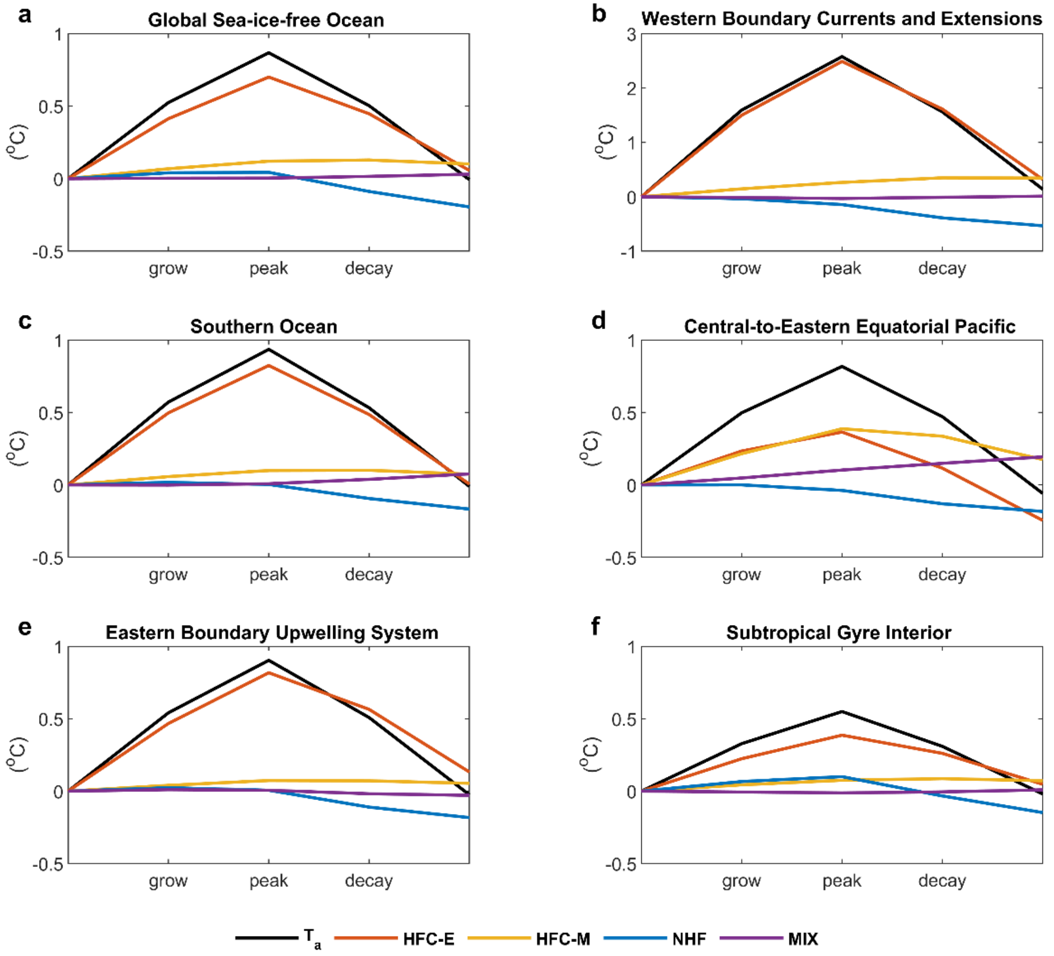
$$\left\langle \frac{\partial T}{\partial t} \right\rangle = \underbrace{\langle -\nabla \cdot (\bar{\mathbf{u}}\bar{T}) \rangle}_{\text{HFC-M}} + \underbrace{\langle -\nabla \cdot (\mathbf{u}'T') - \nabla \cdot (\bar{\mathbf{u}}T') - \nabla \cdot (\mathbf{u}'\bar{T}) \rangle}_{\text{HFC-E}} + \underbrace{\frac{Q_{\text{NHF}}}{\rho_0 C_p H}}_{\text{NHF}} + \underbrace{\langle \text{HMIX} \rangle + \langle \text{VMIX} \rangle}_{\text{MIX}}$$

Heat flux convergence by mesoscale eddies (HFC-E), is the crucial driver of global MHWs growth and decay.

Result: Dominant Drivers of global MHW life cycle in different regions

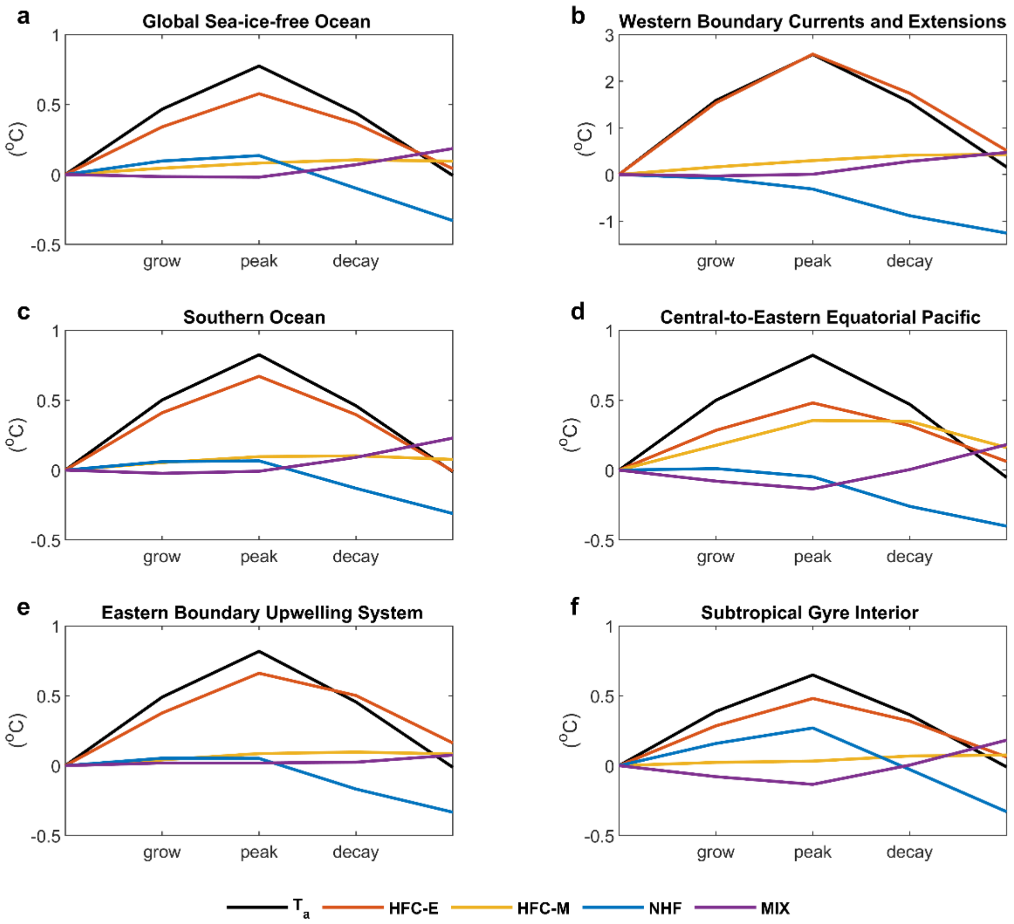


- The western boundary currents and their extensions (encompassed by light blue line),
- The Southern Ocean (pink lines),
- The central-to-eastern equatorial Pacific (yellow lines),
- The eastern boundary upwelling systems (deep blue lines),
- The subtropical gyre interior (white lines).

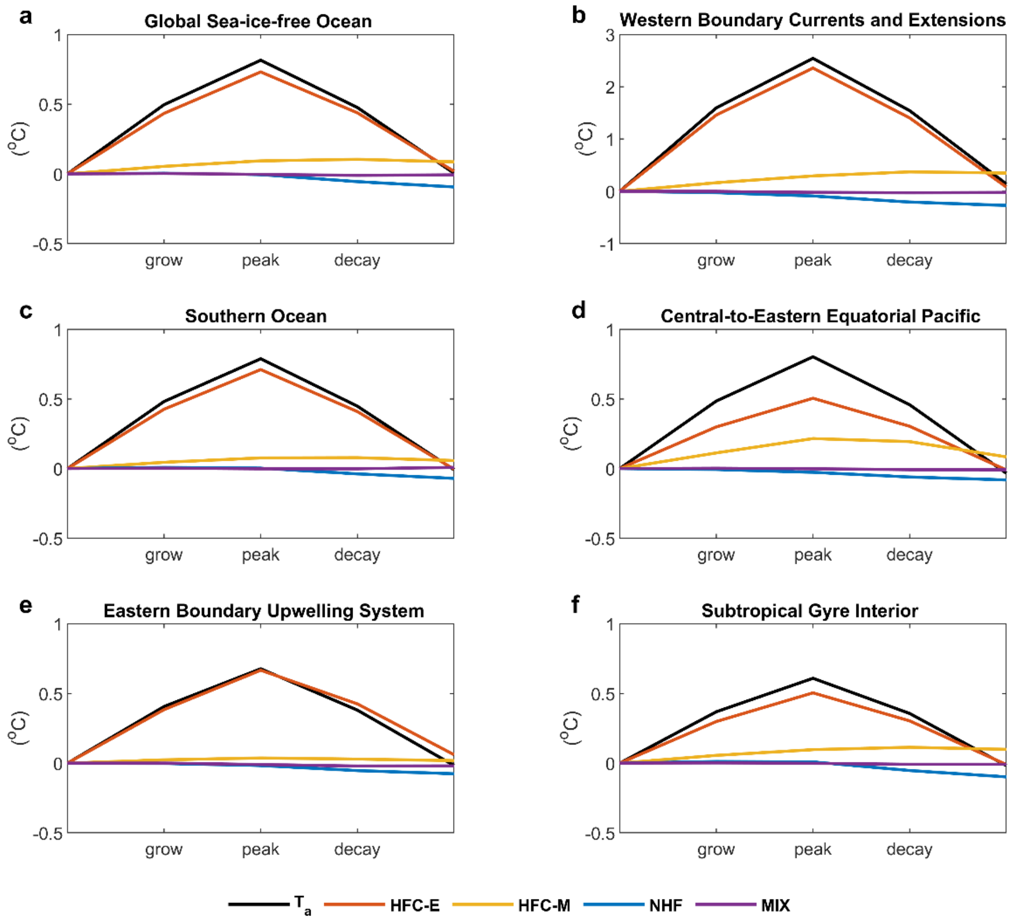


Result: Sensitive Test of MHW budget within different water volume

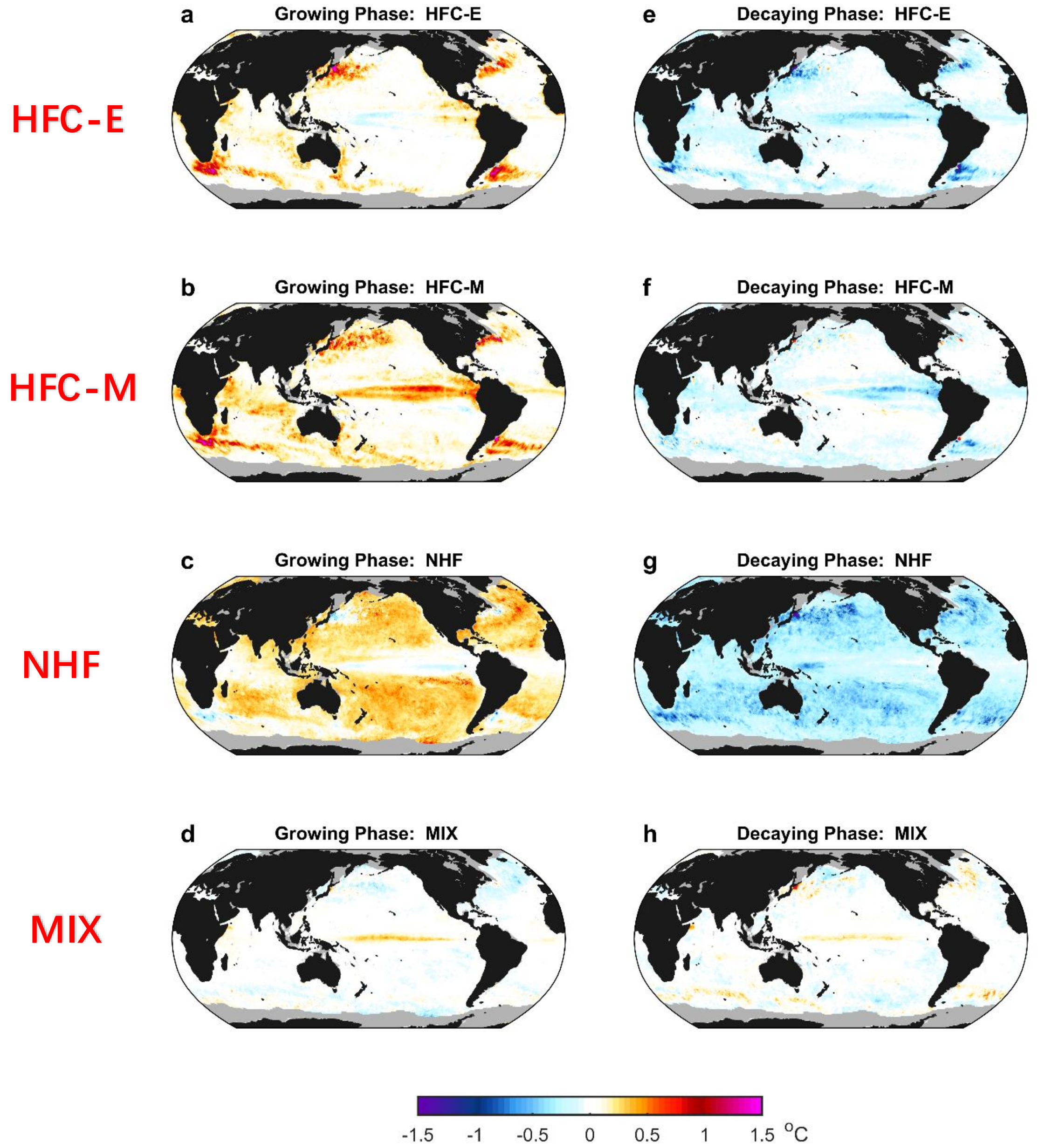
up 20m ocean budget

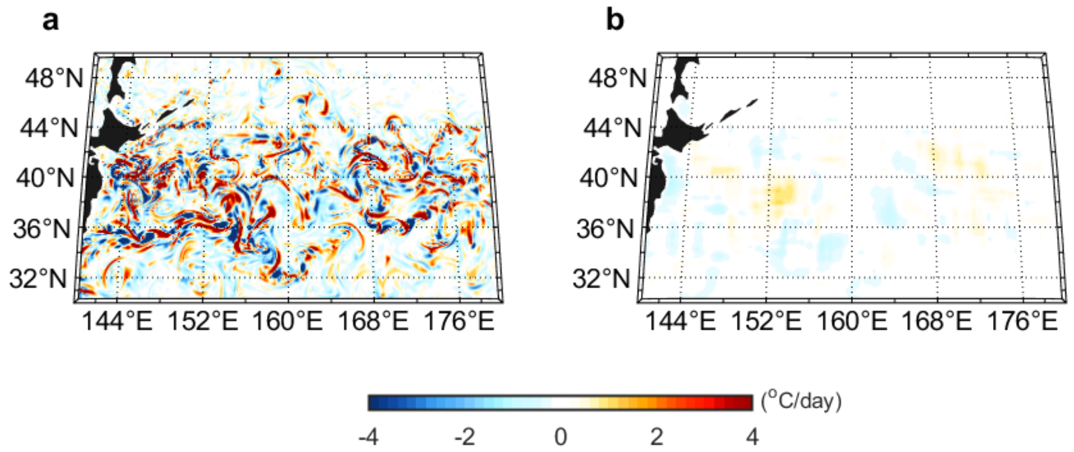


up 100m ocean budget



Result: Drivers of global MHW life cycle (whose spatial scale > spatial scale of mesoscale eddies)



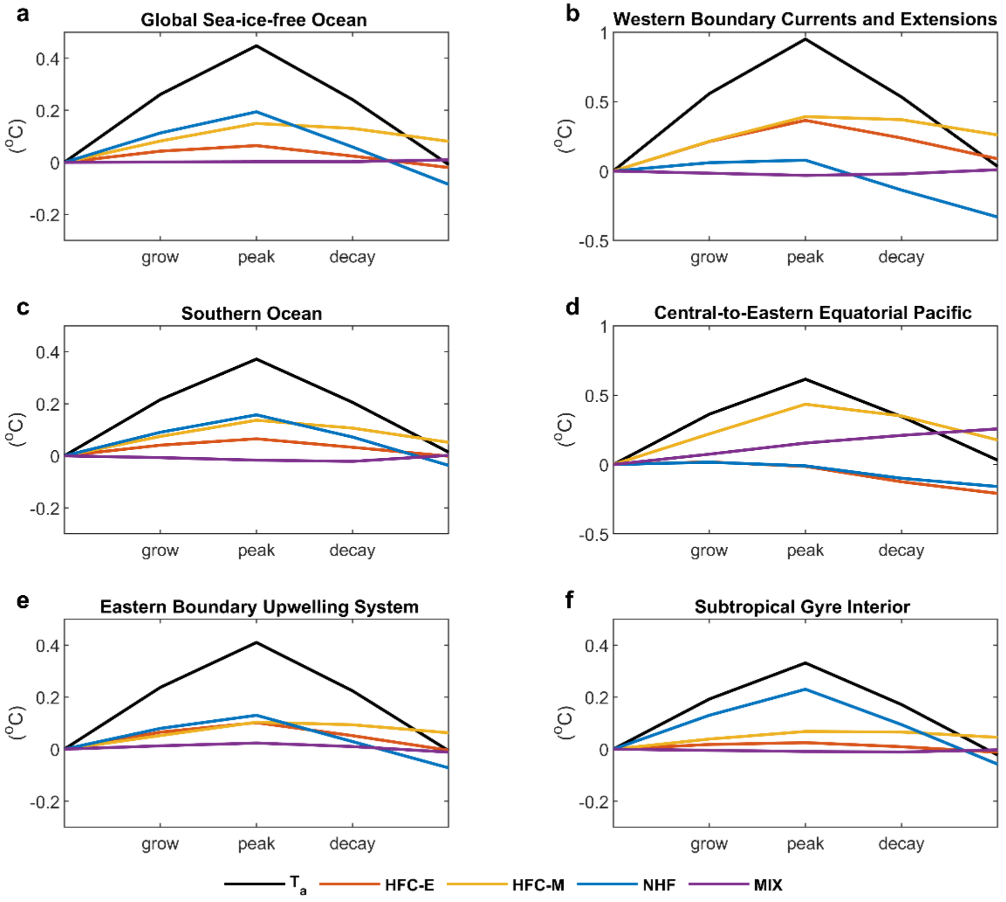


$$\left\langle \overline{\frac{\partial T}{\partial t}} \right\rangle = \underbrace{\left\langle \overline{-\nabla\cdot(\bar{\mathbf{u}}\bar{T})} \right\rangle}_{\text{HFC-M}} + \underbrace{\left\langle \overline{-\nabla\cdot(\mathbf{u}'T') - \nabla\cdot(\bar{\mathbf{u}}T') - \nabla\cdot(\mathbf{u}'\bar{T})} \right\rangle}_{\text{HFC-E}} + \underbrace{\frac{\overline{Q_{\text{NHF}}}}{\rho_0 C_p H}}_{\text{NHF}} + \underbrace{\overline{\langle \text{HMIX} \rangle + \langle \text{VMIX} \rangle}}_{\text{MIX}}$$

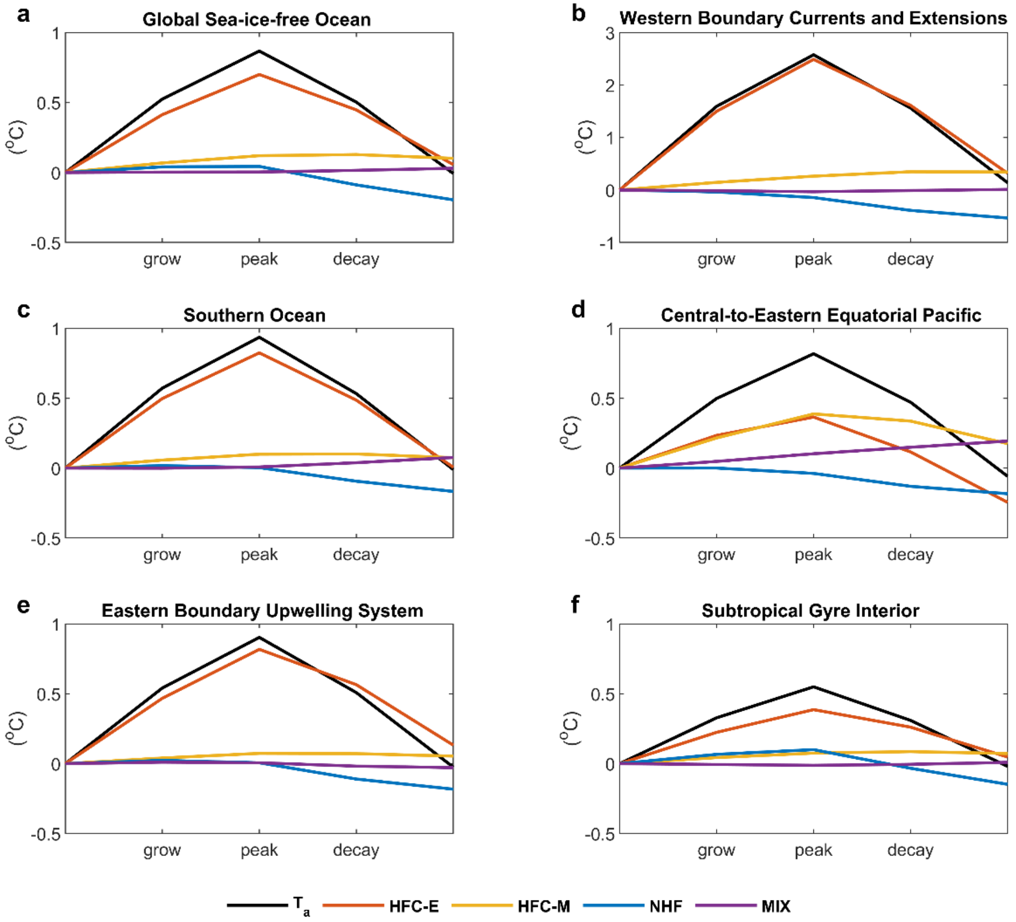
The dominant drivers of MHW life cycles taken over by HFC-M and NHF, while HFC-E still significant in WBCEs.

Result: Dominant Drivers of global MHW life cycle in different regions

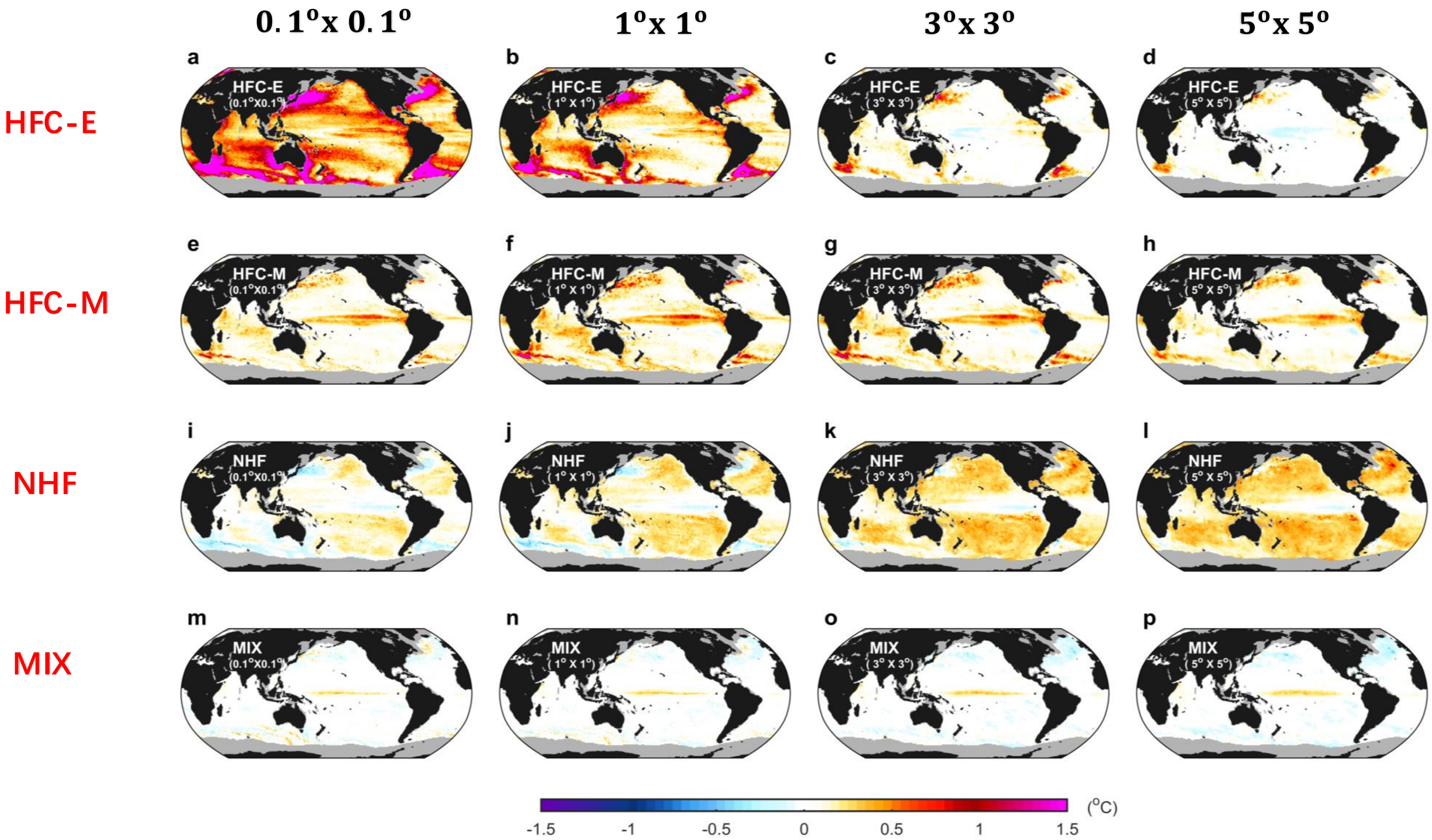
$3^{o} \times 3^{o}$



$0.1^{o} \times 0.1^{o}$

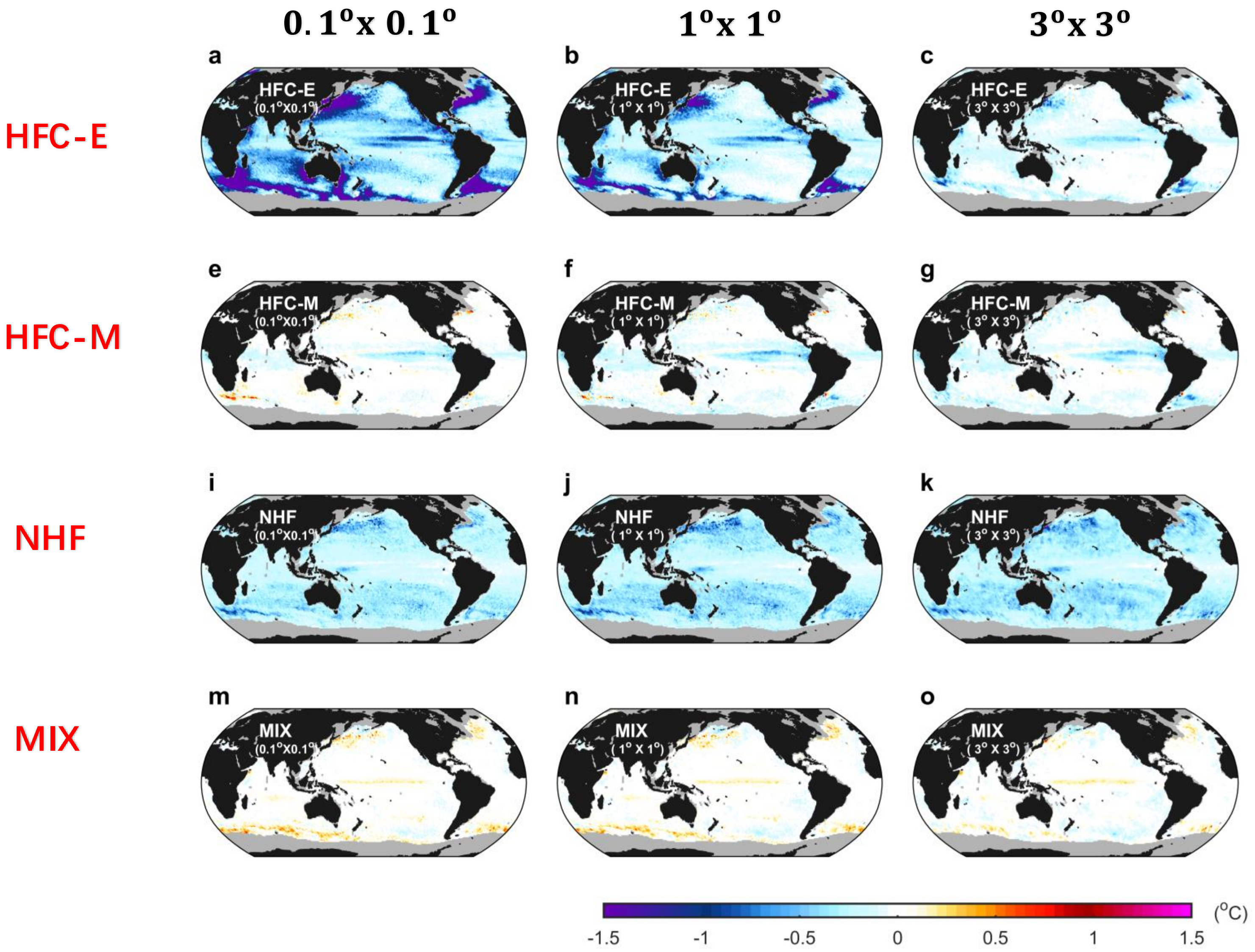


Result: Scale-dependent drivers of global MHWs (during the growing phase)



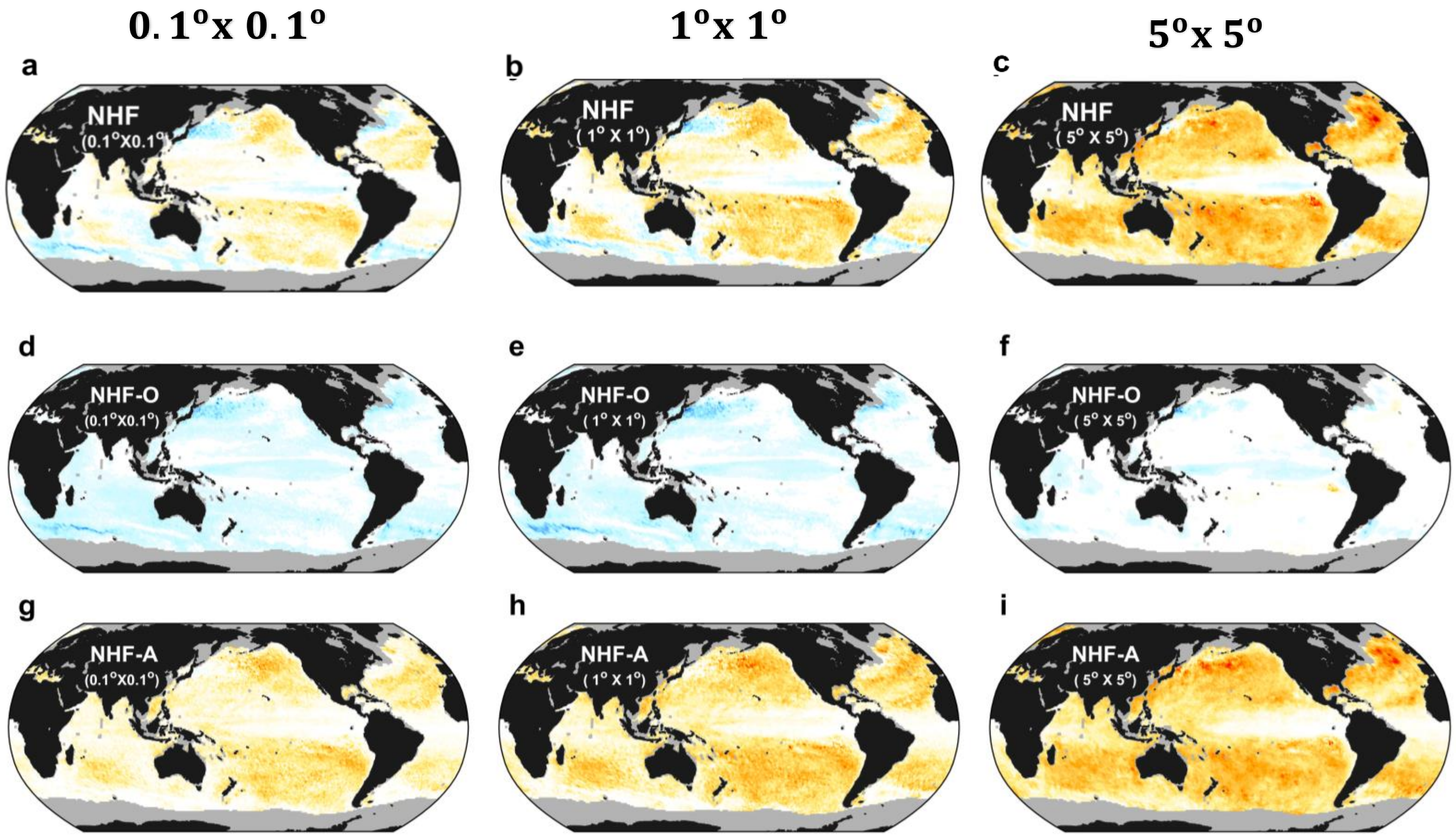
- Mesoscale eddy effects (HFC-E) decrease as MHW spatial scales increase. NHF on the contrary.

Result: Scale-dependent drivers of global MHWs (during the decaying phase)



- Same as MHW growing phase, but NHF cooling effect not obviously sensitive to spatial scales.

Result: NHF decomposition in MHW growing phase



NHF

$$Q'_{\mathrm{net}} = Q'_{\mathrm{A}} - \alpha \langle T \rangle'$$

=

NHF-O — Heat flux anomaly induced by ocean processes.

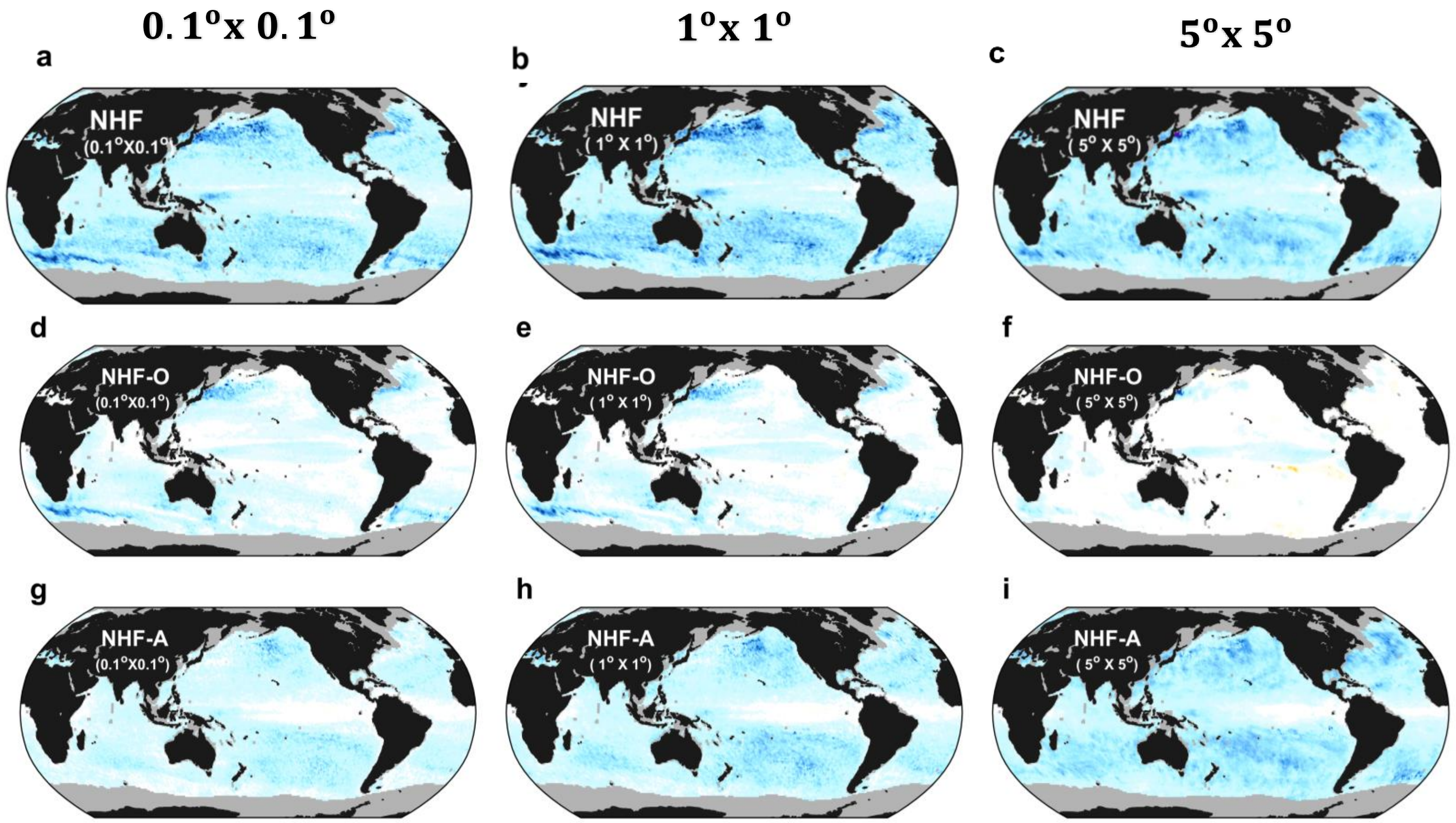
+

NHF-A — Heat flux anomaly induced by stochastic atmospheric forcing.

- Mesoscale eddies (NHF-O) damp atmospheric warming effect (NHF-A) to MHW growth, by enhancing turbulent heat flux.
- NHF-O and NHF-A change in opposite directions as MHW spatial scale increase.

(Frankignoul 1998,2002)

Result: NHF decomposition in MHW decaying phase



NHF

$$Q'_{\mathrm{net}} = Q'_{\mathrm{A}} - \alpha\langle T\rangle'$$

=

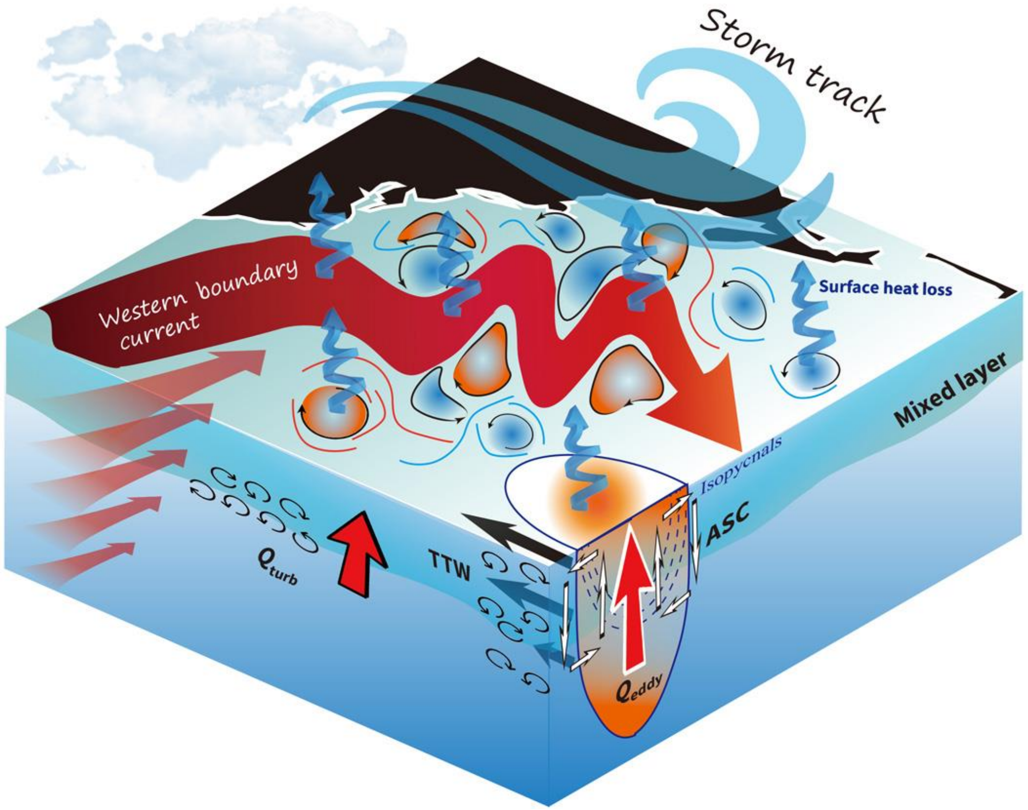
NHF-O — Heat flux anomaly induced by ocean processes.

+

NHF-A — Heat flux anomaly induced by stochastic atmospheric forcing.

- Mesoscale eddies (NHF-O) **cool** MHW throughout the whole MHW life cycle.
- The NHF does not appear to change significantly across MHW spatial scales due to the opposite directions of NHF-O and NHF-A.

Method: Two way of mesoscale eddies contribute to MHWs



Mesoscale eddy roles

=

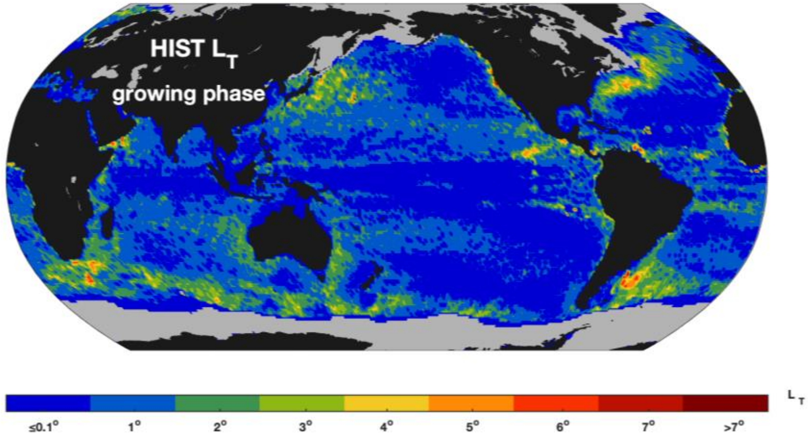
Eddy advection

+

Eddy-induced ASHF

Result: Transition Scale of global MHWs (according to mesoscale eddy significant)

a



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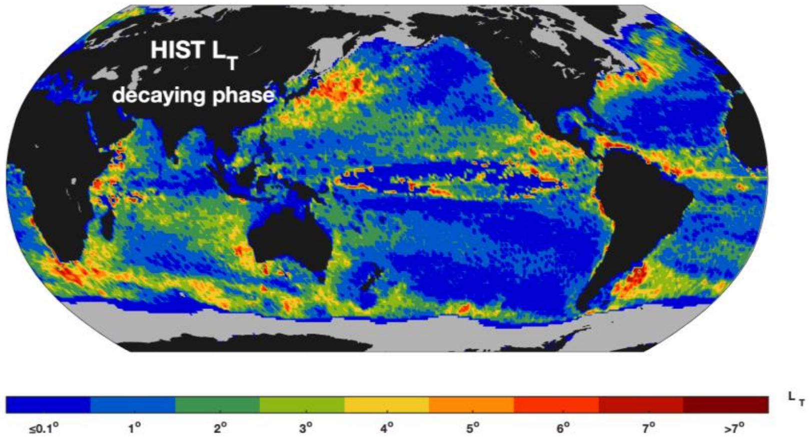


Transition Scale (L_T): The spatial scale where MHWs shift from being predominantly driven by mesoscale eddies to other factors.

(HFC-E + NHF-O) < (HFC-M + NHF-A + MIX)

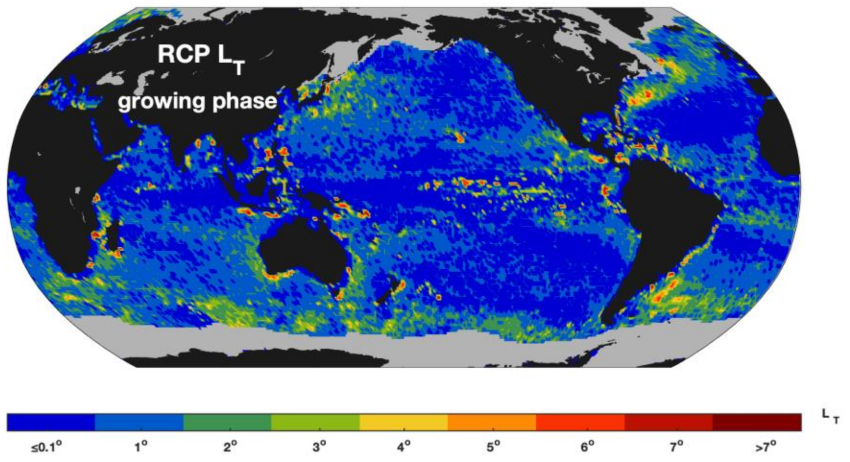
- **Larger L_T**, *meososcale eddies* are essential for MHW growth.
- **Smaller L_T**, *meosocale eddies* are **not** significant for MHWs.

$$\langle\frac{\partial T}{\partial t}\rangle = \underbrace{\langle -\nabla\cdot(\bar{\mathbf{u}}\bar{T})\rangle}_{\text{HFC-M}} + \underbrace{\langle -\nabla\cdot(\mathbf{u}'T') - \nabla\cdot(\bar{\mathbf{u}}T') - \nabla\cdot(\mathbf{u}'\bar{T})\rangle}_{\text{HFC-E}}, \underbrace{-\frac{\alpha\langle T\rangle'}{\rho_0 C_p H}}_{\text{NHF-O}} + \underbrace{\frac{Q_A{}'}{\rho_0 C_p H}}_{\text{NHF-A}} + \underbrace{\langle\text{HMIX}\rangle + \langle\text{VMIX}\rangle}_{\text{MIX}}$$

L_T varies geographically, being largest in the WBCEs and EBUs, but smallest in the subtropical gyre interior.

Result: Transition Scale in the future (according to mesoscale eddy significant)

a



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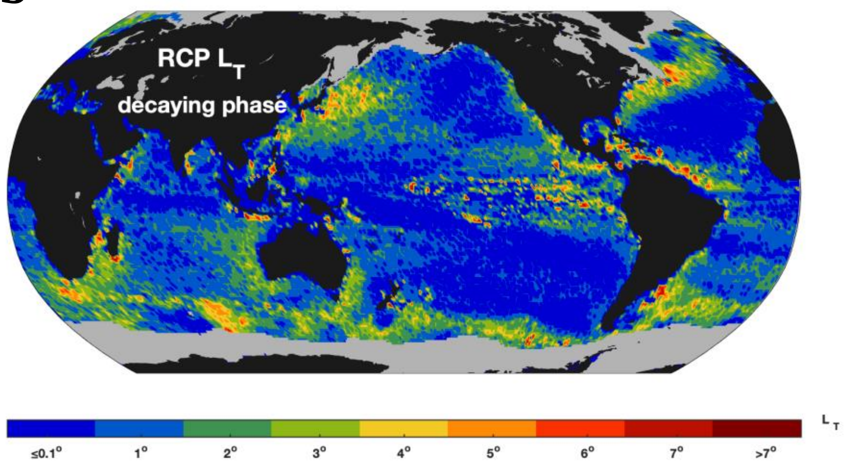

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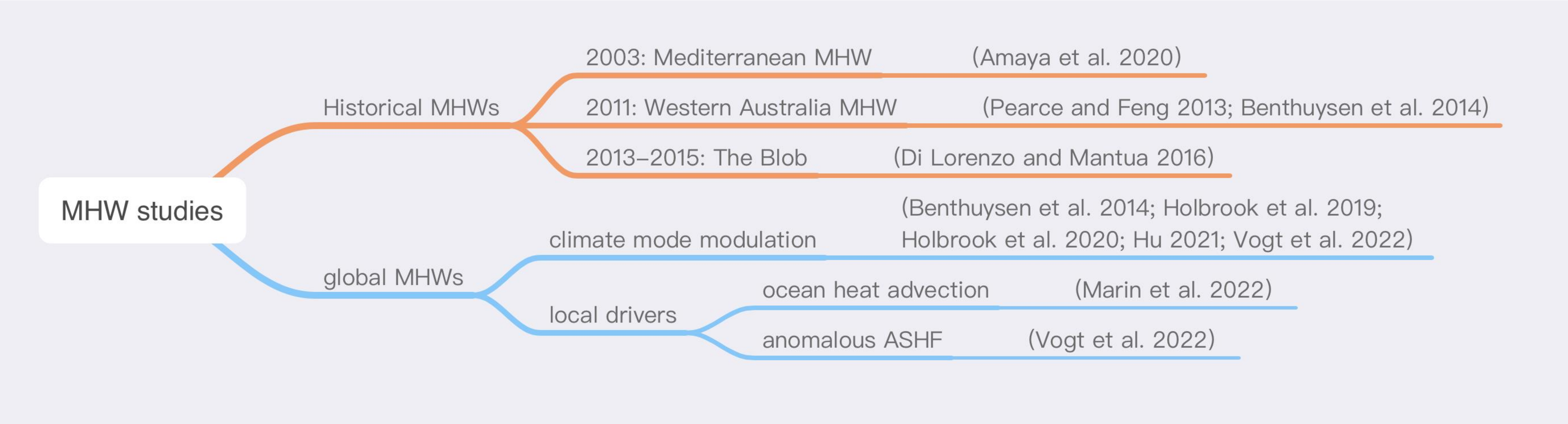
- Global warming reduced mesoscale eddy effects, while larger-scale processes become relatively significant, making MHWs prediction more stable in the future.

Summary 1: Oceanic Mesoscale Eddies as a Crucial Drivers of Global Marine Heatwaves

- Here, we use a historical simulation from a global eddy-resolving climate model with improved representation of MHWs, and show that heat flux convergence by oceanic mesoscale eddies acts as a dominant driver of MHW life cycles over most parts of the global ocean.
- In particular, the mesoscale eddies make an important contribution to growth and decay of MHWs, whose characteristic spatial scale is comparable or even larger than that of mesoscale eddies.
- The effect of mesoscale eddies is spatially heterogeneous, becoming more dominant in the western boundary currents and their extensions, the Southern Ocean, as well as the eastern boundary upwelling systems.
- This study reveals the crucial role of mesoscale eddies in controlling the global MHW life cycles and highlights that using eddy-resolving ocean models is essential, albeit not necessarily fully sufficient, for accurate MHW forecasts.

Question: Ocean or Atmospheric-driven MHWs ?



Paradox in previous studies.

Result: Ocean or Atmospheric-driven MHWs?

Spatial scales | $0.1^o \times 0.1^o$ | $1^o \times 1^o$ | $5^o \times 5^o$

Ocean

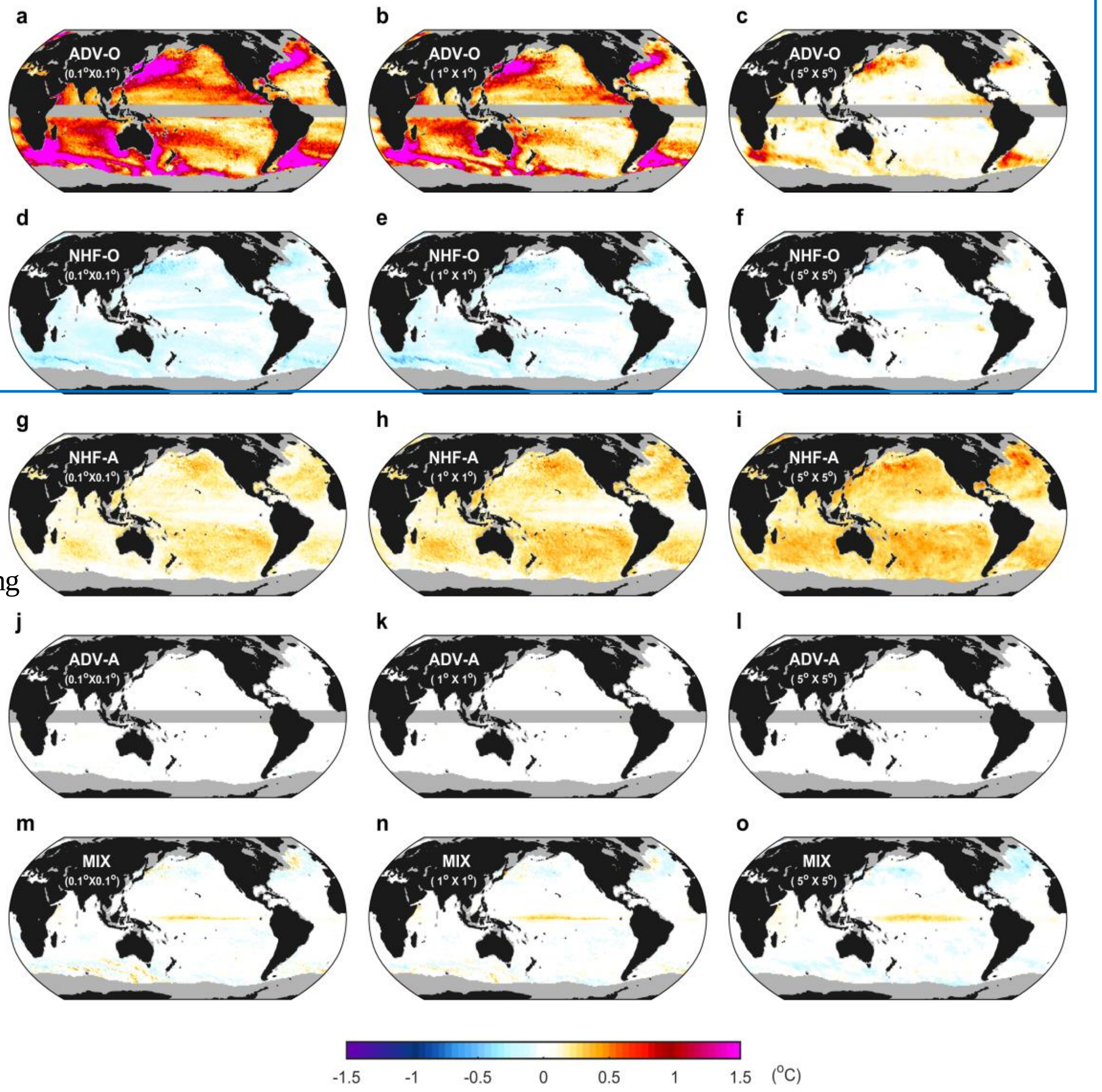
ADV-O
Ocean-driven advection

NHF-O
NHF induced by ocean processes.

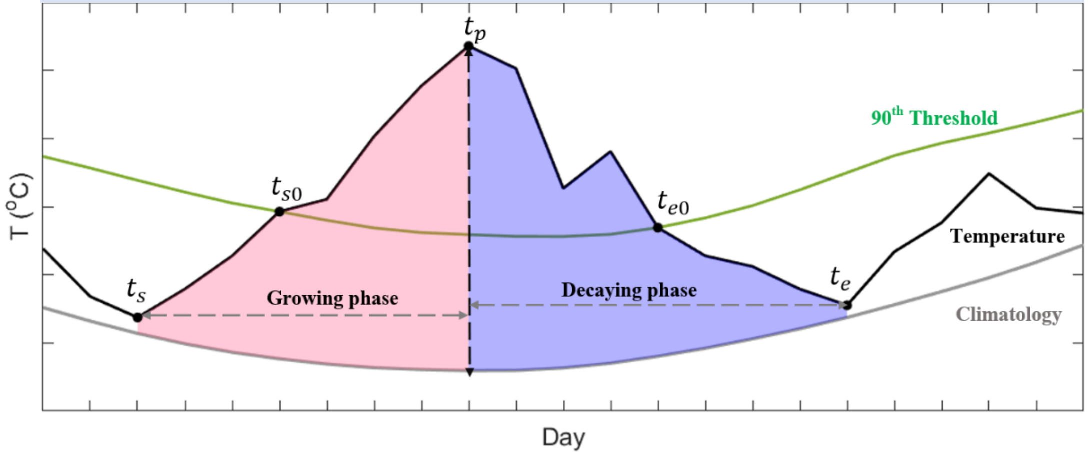
NHF-A
by stochastic atmospheric forcing

ADV-A
wind-driven advection

MIX



Schematic of a MHW growing and decaying phases



$$\left\langle \frac{\partial T}{\partial t}\right\rangle' = \underbrace{\langle -\nabla\cdot(\mathbf{u}_{O}T)\rangle'}_{\text{ADV-O}} - \underbrace{\frac{\alpha\langle T\rangle'}{\rho_0 C_p H}}_{\text{NHF-O}} + \underbrace{\frac{Q_A{}'}{\rho_0 C_p H}}_{\text{NHF-A}} + \underbrace{\langle -\nabla_{H}\cdot(\mathbf{u}_{E}T)\rangle'}_{\text{ADV-A}} + \langle \text{MIX}\rangle'$$

Oceanic processes primarily drive the life cycles of global MHWs via the ADV-O.

Result: Ocean or Atmospheric-driven MHWs?

Spatial scales | $0.1^o \times 0.1^o$ | $1^o \times 1^o$ | $5^o \times 5^o$

Ocean

ADV-O
Ocean-driven advection

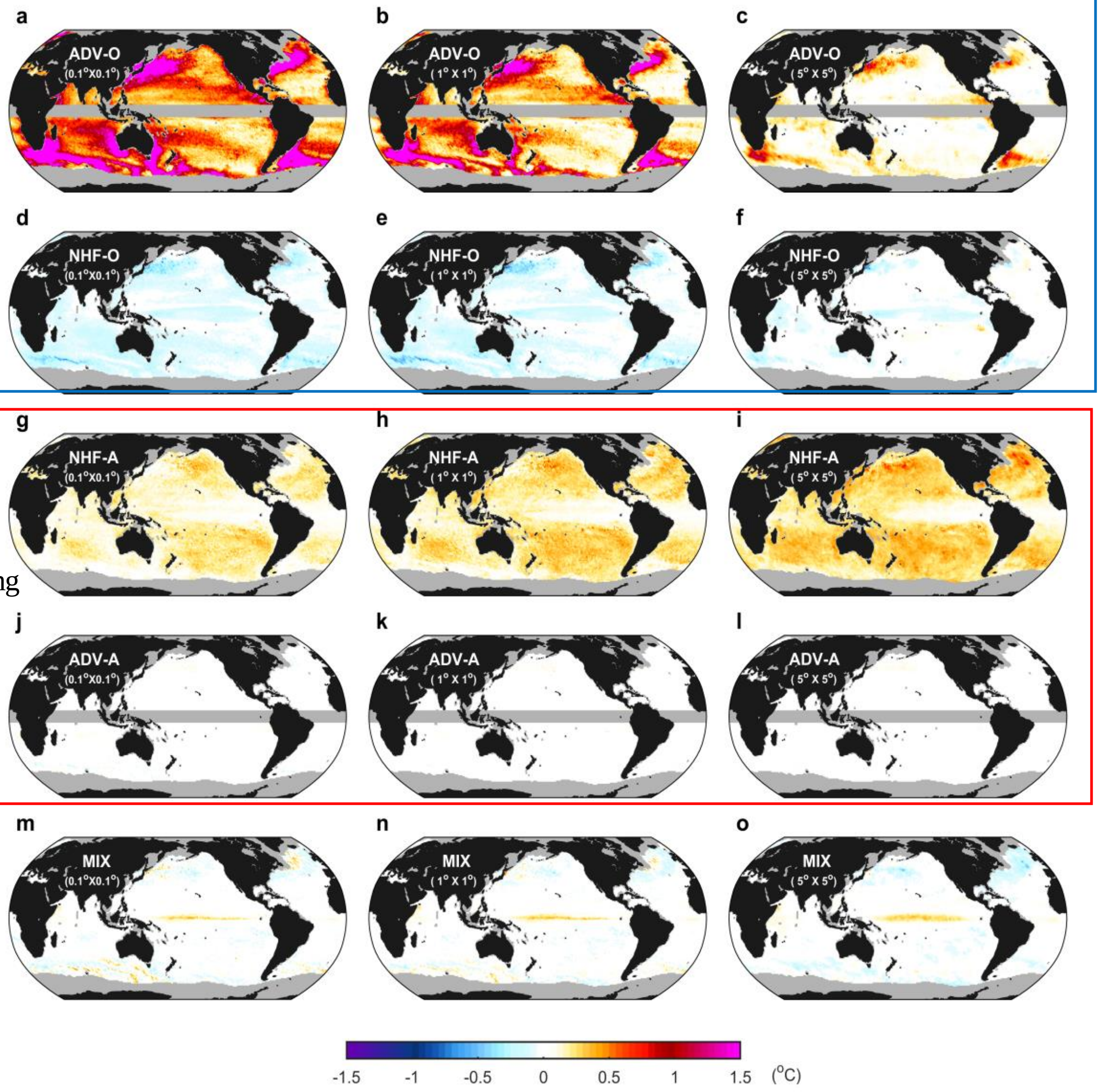
NHF-O
NHF induced by ocean processes.

Air

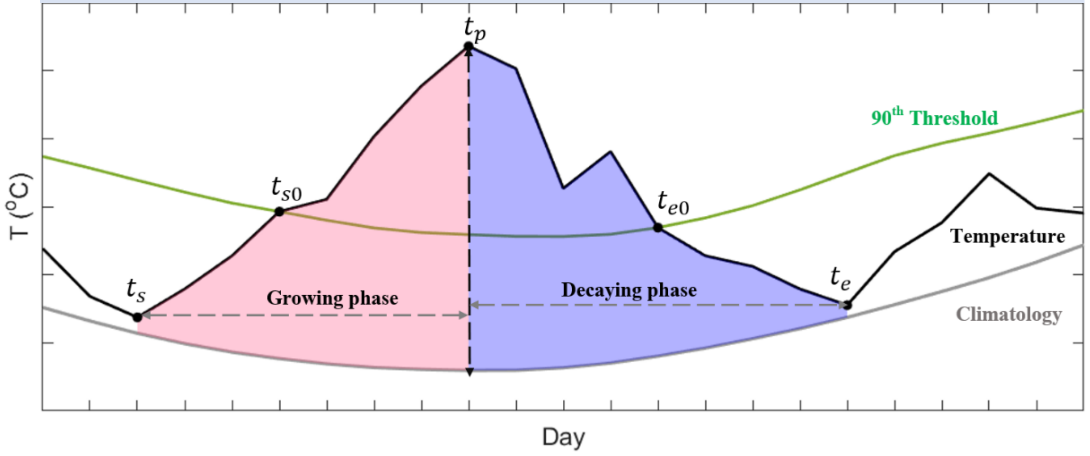
NHF-A
by stochastic atmospheric forcing

ADV-A
wind-driven advection

MIX



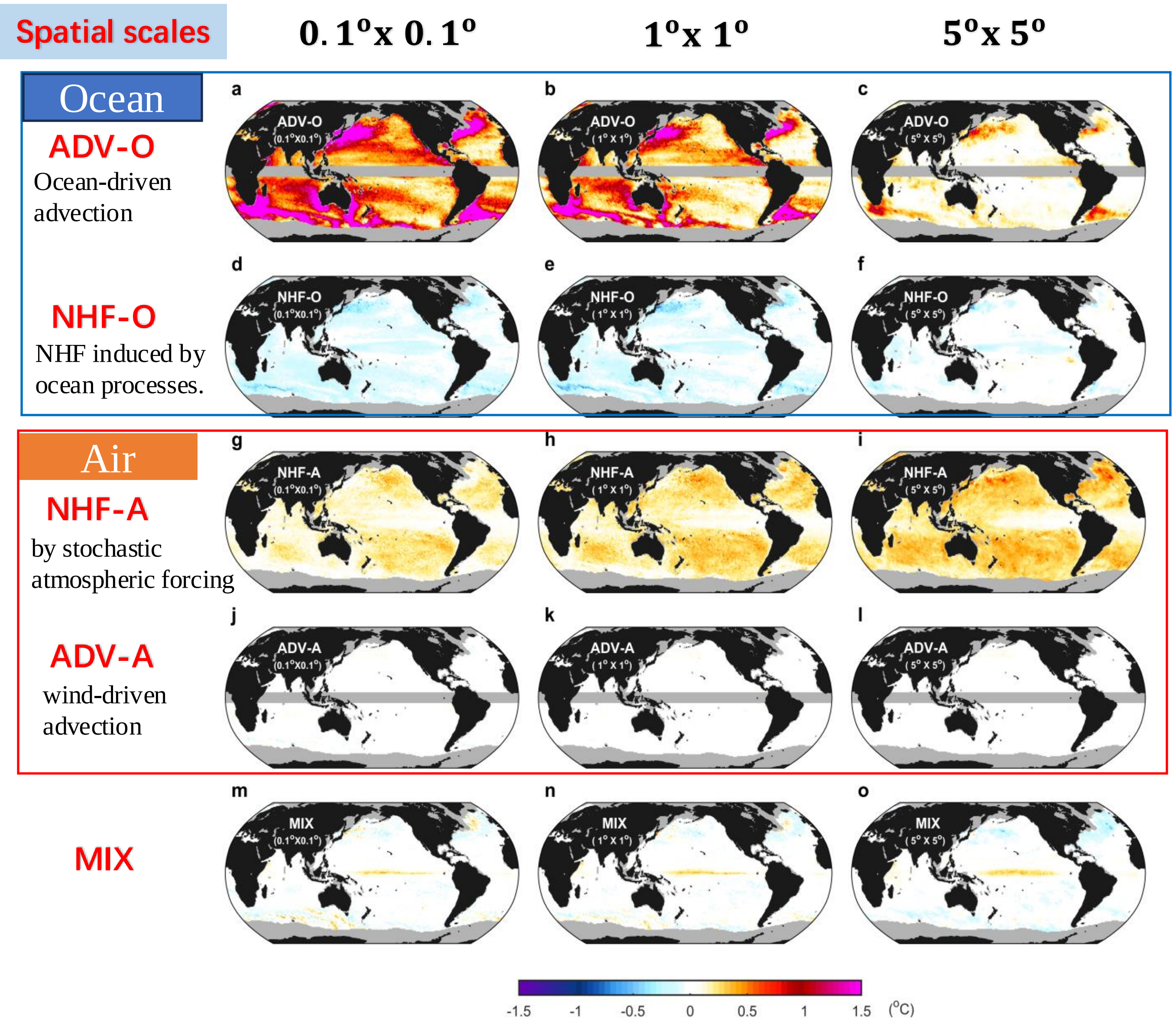
Schematic of a MHW growing and decaying phases



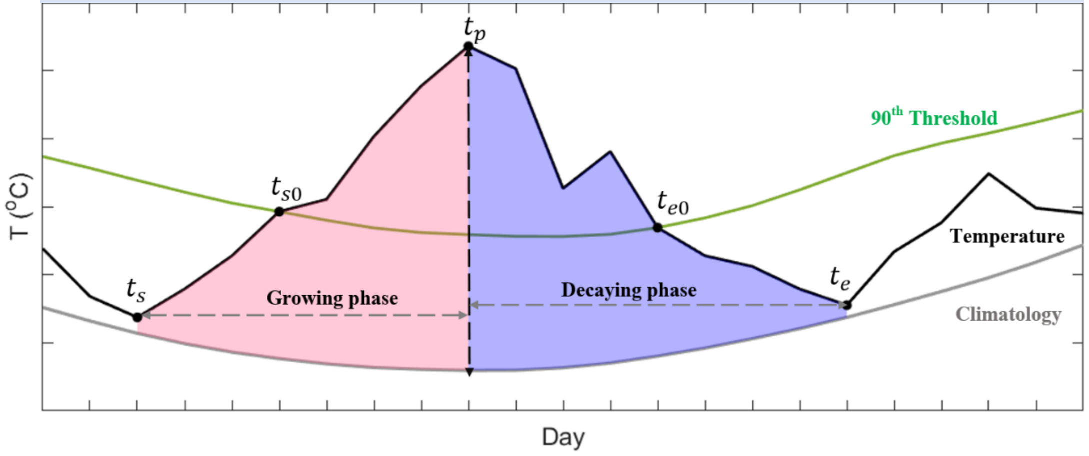
$$\langle\frac{\partial T}{\partial t}\rangle' = \underbrace{\langle-\nabla\cdot(\mathbf{u}_O T)\rangle'}_{ADV-O} \underbrace{-\frac{\alpha\langle T\rangle'}{\rho_0 C_p H}}_{NHF-O} + \underbrace{\frac{Q_A{}'}{\rho_0 C_p H}}_{NHF-A} + \underbrace{\langle-\nabla_H\cdot(\mathbf{u}_E T)\rangle'}_{ADV-A} + \langle MIX\rangle'$$

The NHF-A are much smaller in magnitude compared to ADV-O and play secondary roles in driving the MHW life cycles

Result: Ocean or Atmospheric-driven MHWs?



Schematic of a MHW growing and decaying phases



$$\langle \frac{\partial T}{\partial t} \rangle' = \underbrace{\langle -\nabla \cdot (\mathbf{u}_O T) \rangle'}_{\text{ADV-O}} \underbrace{- \frac{\alpha \langle T \rangle'}{\rho_0 C_p H}}_{\text{NHF-O}} + \underbrace{\frac{{Q_A}'}{\rho_0 C_p H}}_{\text{NHF-A}} + \underbrace{\langle -\nabla_H \cdot (\mathbf{u}_E T) \rangle'}_{\text{ADV-A}} + \langle \text{MIX} \rangle'$$

- Contribution of **ocean processes** decrease ↓ with MHW spatial scale increase ↑.
- Contribution of **atmospheric processes** increase ↑ with MHW spatial scale increase ↑.

Result: Ocean or Atmospheric-driven MHWs? (decaying phase)

Spatial scales | $0.1^o x\ 0.1^o$ | $1^o x\ 1^o$ | $5^o x\ 5^o$

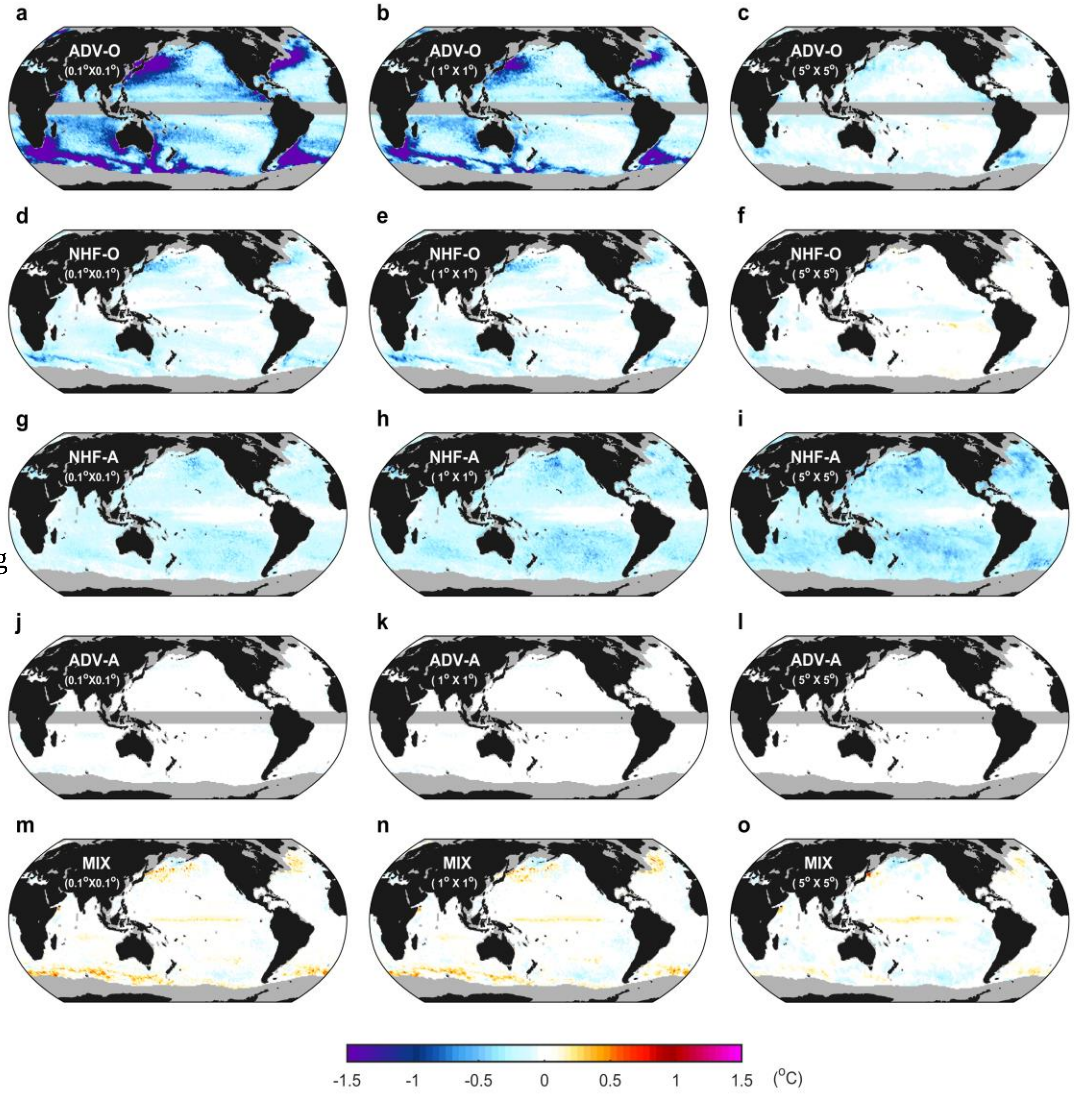
ADV-O
Ocean-driven advection

NHF-O
NHF induced by ocean processes.

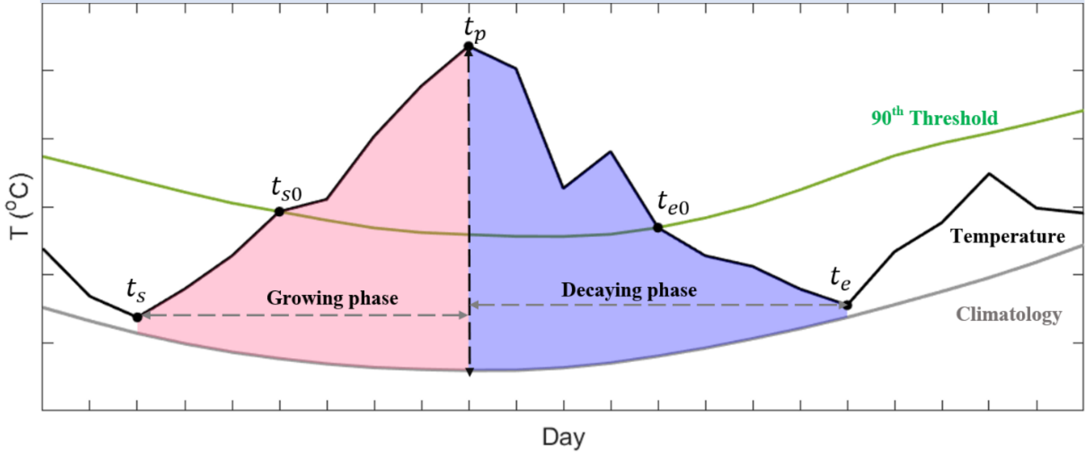
NHF-A
by stochastic atmospheric forcing

ADV-A
wind-driven advection

MIX



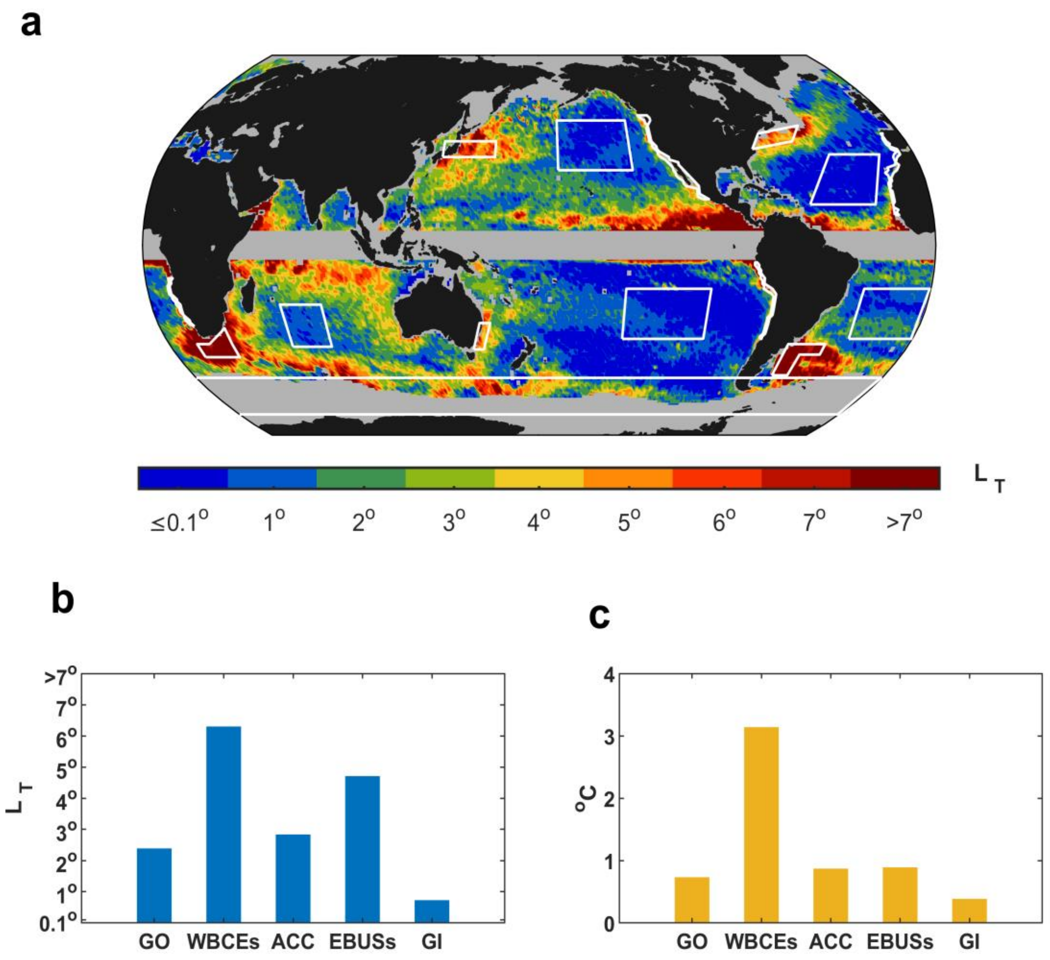
Schematic of a MHW growing and decaying phases



$$\langle\frac{\partial T}{\partial t}\rangle' = \underbrace{\langle -\nabla\cdot(\mathbf{u}_O T)\rangle'}_{\text{ADV}-\text{O}} \underbrace{- \frac{\alpha\langle T\rangle'}{\rho_0 C_p H}}_{\text{NHF}-\text{O}} + \underbrace{\frac{Q_A{}'}{\rho_0 C_p H}}_{\text{NHF}-\text{A}} + \underbrace{\langle -\nabla_H\cdot(\mathbf{u}_E T)\rangle'}_{\text{ADV}-\text{A}} + \langle \text{MIX}\rangle'$$

- Contribution in the **decaying phase** is similar with the growing phase.
- The NHF-O always **cool** MHWs, because $\langle T\rangle'$ induces a surface heat flux anomaly damping itself.

Result: Scale-dependent drivers of global MHWs



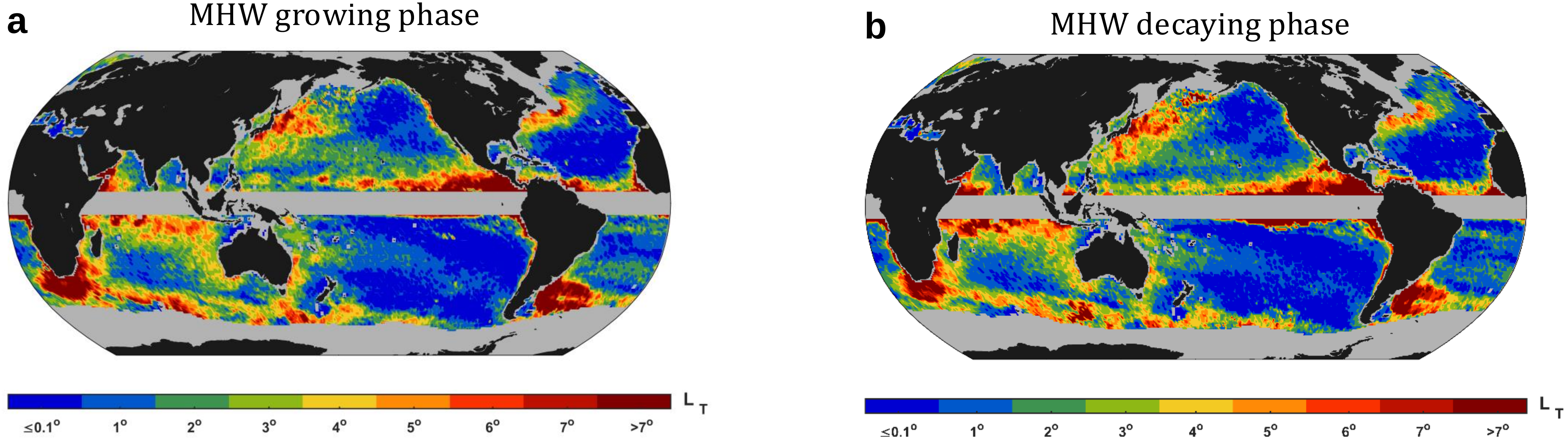
Transition Scale （L_T ） Spatial scale that MHWs change from ocean-driven to atmospheric-driven.

- **Larger L_T**, oceanic processes are essential for MHW growth.
- **Smaller L_T**, atmospheric processes are more important for MHWs.

(ADV-O + NHF-O) < (ADV-A + NHF-A)

- The paradox in previous studies can be explained by the fact that L_T varies geographically.
- L_T help to guide on focus and methods for improving MHW forecast capacity.

Result: Ocean or Atmospheric-driven MHWs?



- L_T are similar during the MHW growing and decaying phases.
- L_T is larger in **eddy-rich regions** while smaller in gyre interior.

Summary

1

Mesoscale eddies are crucial drivers of global MHWs life cycle.

Mesoscale eddies are important drivers of MHWs when their spatial scales are smaller than the transition scale.

2

Global MHW transition scales varies geographically.

It is essential to improve the quality of in-situ observation system in large L_T regions, such as WBCEs and EBUs.

3

Eddy effects to global MHWs intensified in a warmer future.

Mesoscale eddies will be less significant in global MHWs in a warmer future, making MHW prediction more stable.

Thanks !