Maurice Huguenin

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ETH zürich ➡

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Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra
MeteoSwiss

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ETH zürich → Schweizerische Eidgenossenschaft Confédération suisse Confederazione Svizzera Confederaziun svizra MeteoSwiss → UNSW SYDNEY → WOODS HOLE OCEANOGRAPHIC INSTITUTION

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Disclaimer: It was more like this

Acknowledgment of Country

Mindil Beach, Darwin, AU

Acknowledgment of Country

- **Bedegal people**

- sovereignty has never been ceded
- climate justice for First Nations people

Mindil Beach, Darwin, AU


ACEAS
Australian Centre for Excellence
in Antarctic Science

Australian Government
Australian Research Council

The Australian Centre for Excellence in Antarctic Science is a Special Research Initiative funded by the Australian Research Council

University of Tasmania
IMAS
Australian National University
UNSW Sydney
The University of Melbourne
Curtin University
University of South Australia
The University of Western Australia
University of Canberra

This research was supported by the Australian Research Council Special Research Initiative, Australian Centre for Excellence in Antarctic Science (Project Number SR200100008)

Drivers and distribution of global ocean heat uptake over the last half century

Maurice F. Huguenin, Ryan M. Holmes and Matthew H. England

Nature Communications

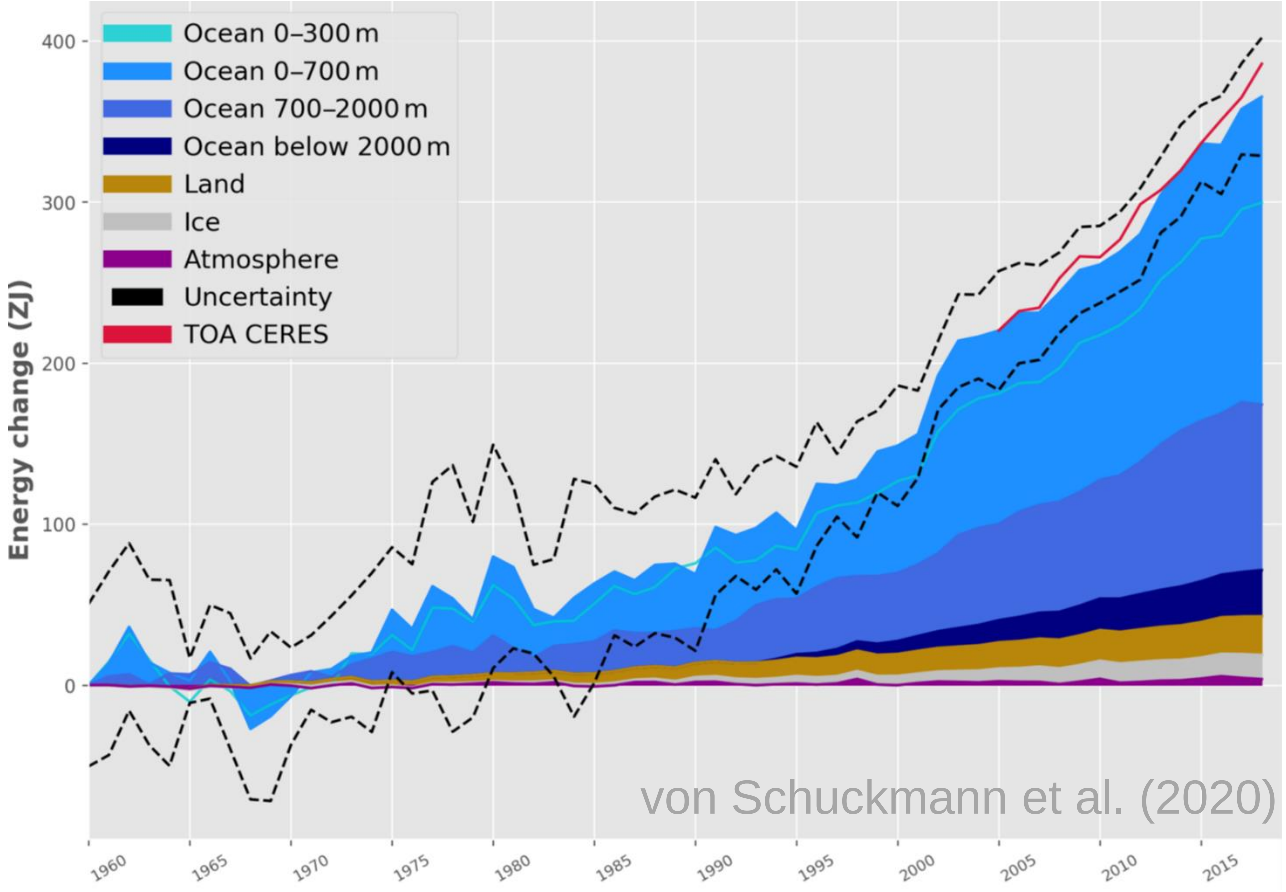
Australian Government
Australian Research Council

The Australian Centre for Excellence in Antarctic Science is a Special Research Initiative funded by the Australian Research Council

This research was supported by the Australian Research Council Special Research Initiative, Australian Centre for Excellence in Antarctic Science (Project Number SR200100008)

Importance of ocean heat content

Earth heat inventory relative to 1960 (ZJ = 10^{21} J)



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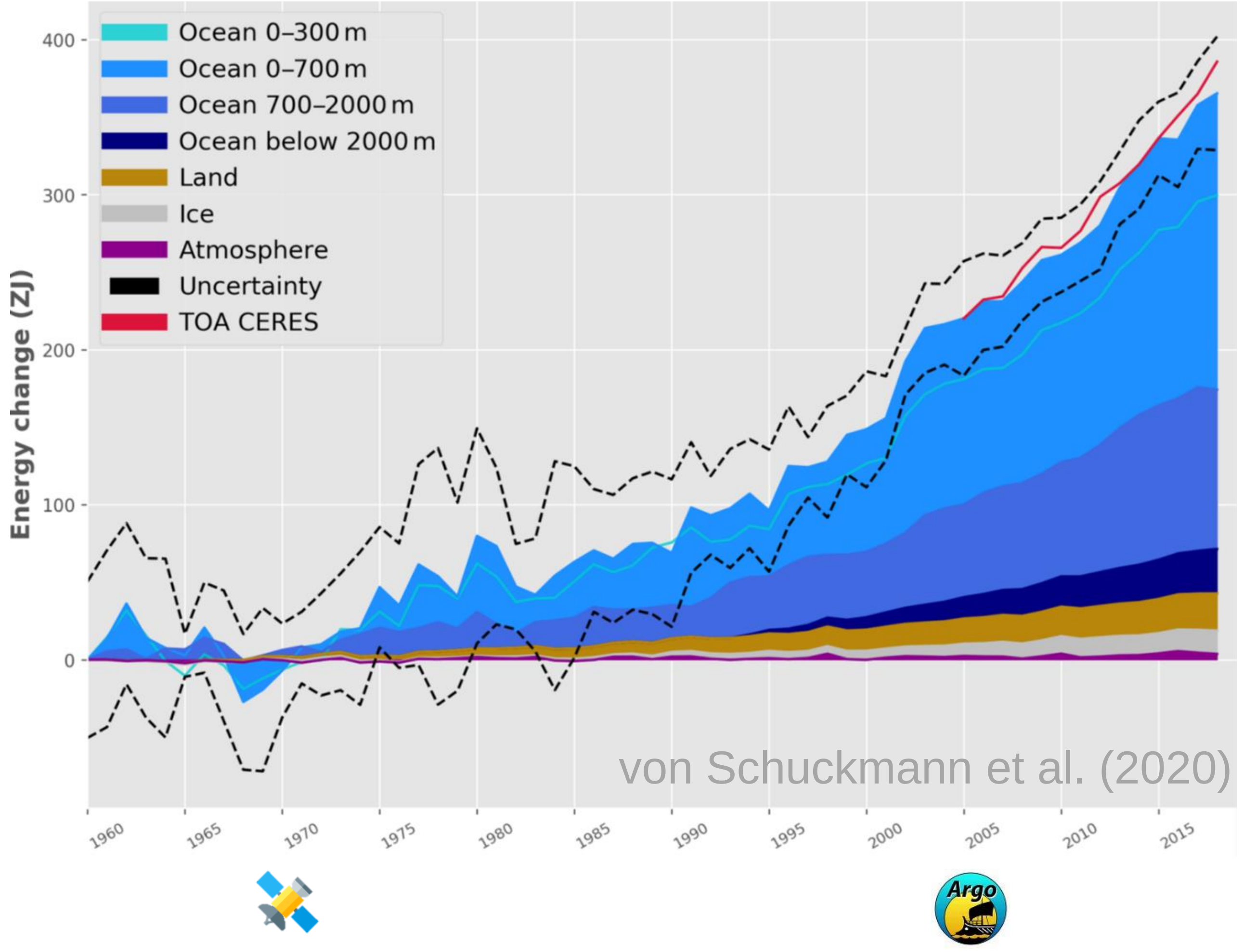

- Where has heat entered the ocean?
- Where is it today?
- What are the roles of wind and thermal forcing?

Importance of ocean heat content

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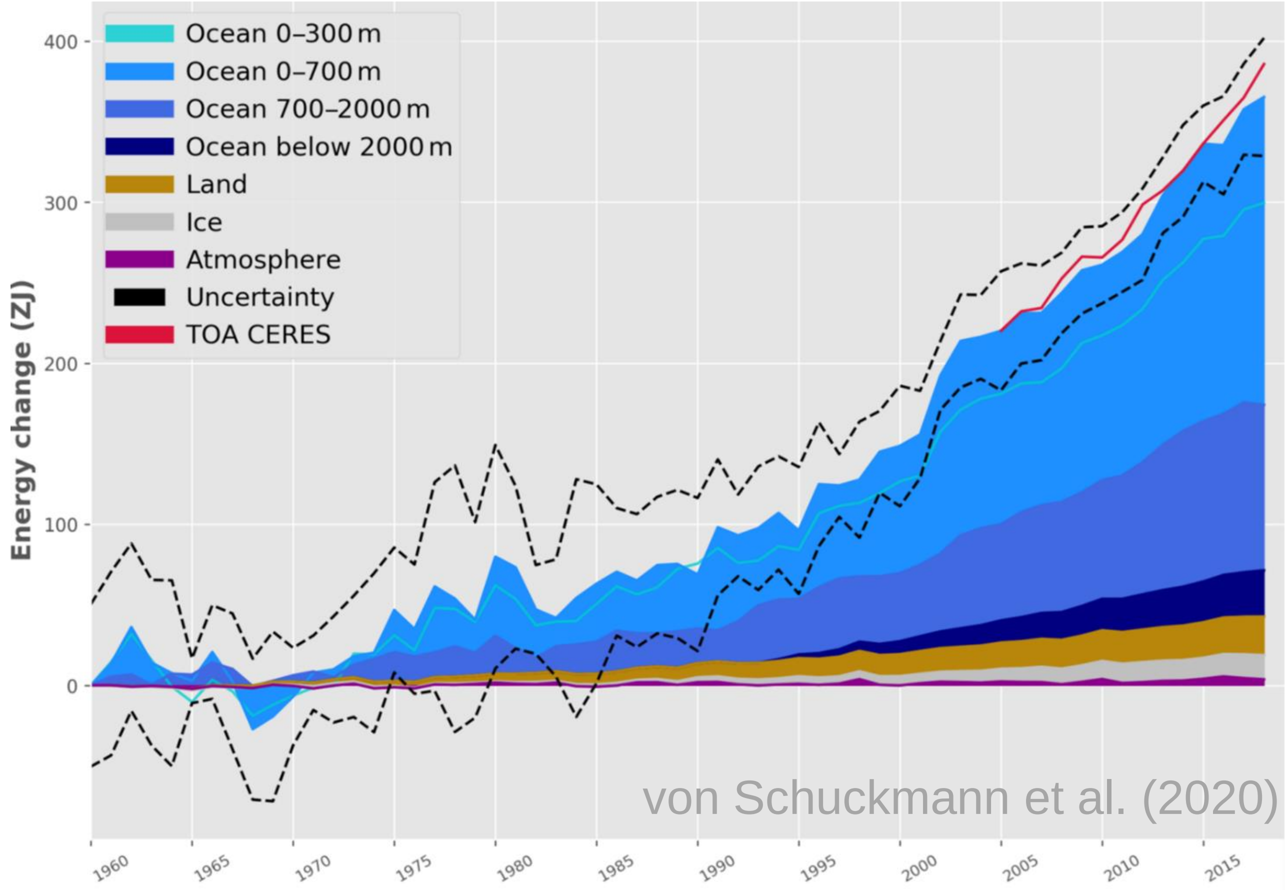
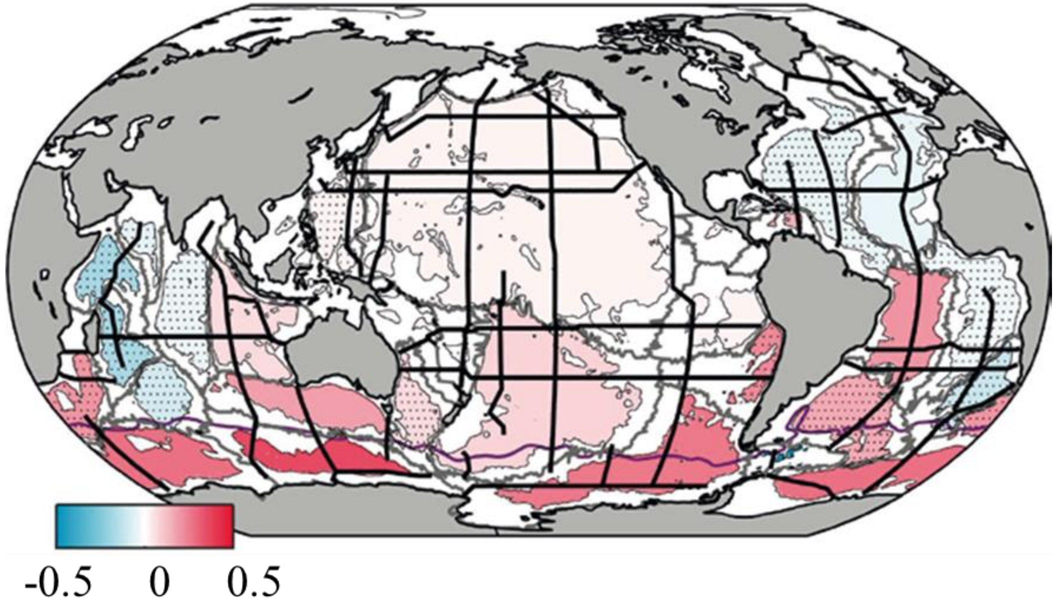


Warming rate (°C century^{-1}) below 4000 m



IPCC SROCC, Ch. 5, Fig. 5.4b, Allison et al. (2019)

- Where has heat entered the ocean?
- Where is it today?
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Global ocean-sea ice model

- ACCESS-OM2 (Kiss et al., 2019)
- MOM5.1, CICE5.1.2
- Input: atmospheric reanalysis JRA55-do (Tsujino et al., 2018)

UNSW SYDNEY

COSIMA

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ARC linkage grant funds ~2 positions

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access-hive.org.au

ARC linkage grant funds ~2 positions

Welcome to ACCESS-Hive Docs!

Documentation for ACCESS users: getting set up, running models and model evaluation

New ACCESS user?

Get Started on NCI

Need help?

FAQ / Support

Want to collaborate?

Contribute

Models

Run a Model

Data and Model Evaluation

Community Resources

Acknowledgement of Country

We at ACCESS-NRI acknowledge the Traditional Owners of the land on which our research infrastructure and community operate across Australia and pay our respects to Elders past and present. We recognise the thousands of years of accumulated knowledge and deep connection they have with all the Earth systems we simulate.

Global ocean-sea ice model

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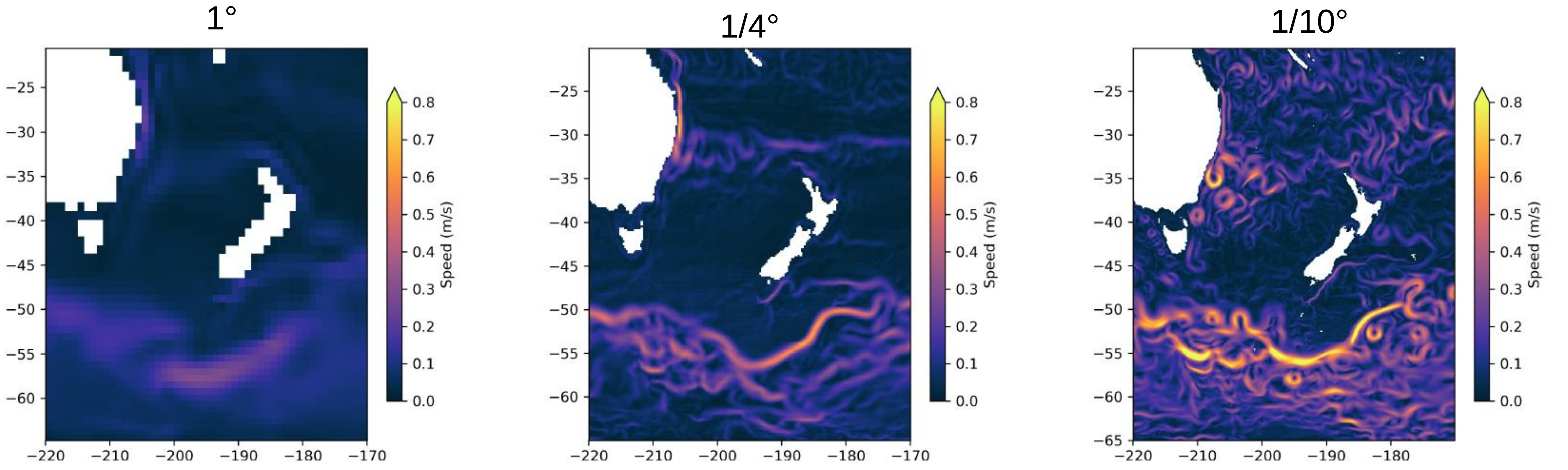

Kiss et al. (2019)

COSIMA Cookbook

Welcome to the COSIMA Cookbook!

This repository is a Cookbook of Recipes 👩🏾‍🍳 🧑🏻‍🍳.

We explain: a "recipe" here is an example an analysis of some ocean-sea ice model output or some ocean-related observational datasets. Each "recipe" comes in a self-contained and well-documented Jupyter notebook. All the recipes combined form a cookbook 📒!

Happy cooking! 😋 🥙 🍱 🍲

To get started have a look at the tutorials and then browse through the available recipes to find something the better suits your 'taste' (i.e., your needs)!

Contents:

COSIMA Cookbook

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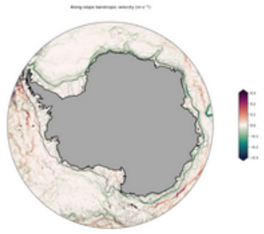
Contents:

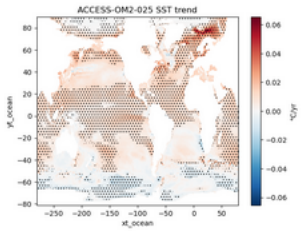
- Tutorials
- Recipes
- Notebook Guidelines
- Contributing to the Cookbook
- GitHub Repository

Recipes

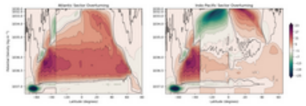
Recipes



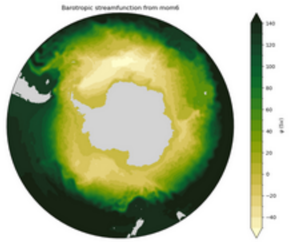
Along-slope velocity



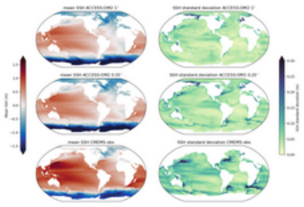
Using xarray.apply_ufunc to apply a function to every gridpoint



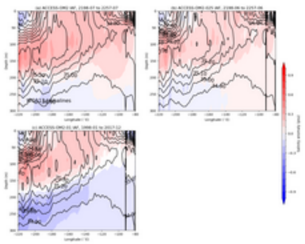
Atlantic and Indopacific basin averaged Merdional Overturning Circulation



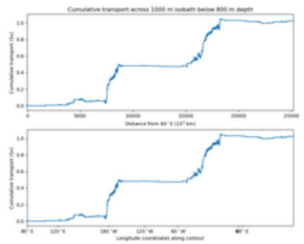
Barotropic Streamfunction



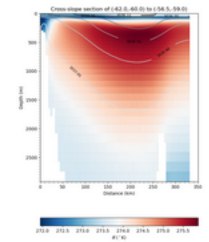
Compare sea surface height model output and observations



Compare Temperature and Salinity from ACCESS-OM2 to WOA13



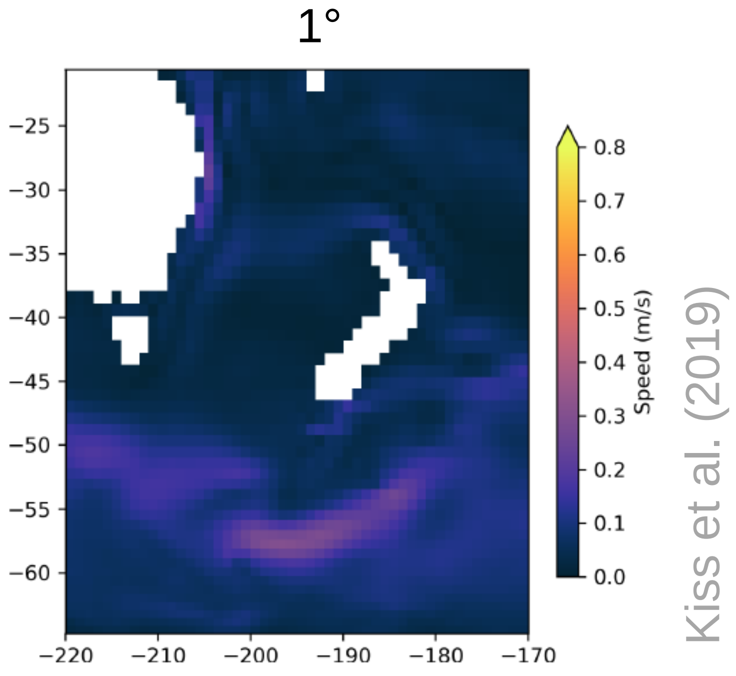
Cross-contour transport



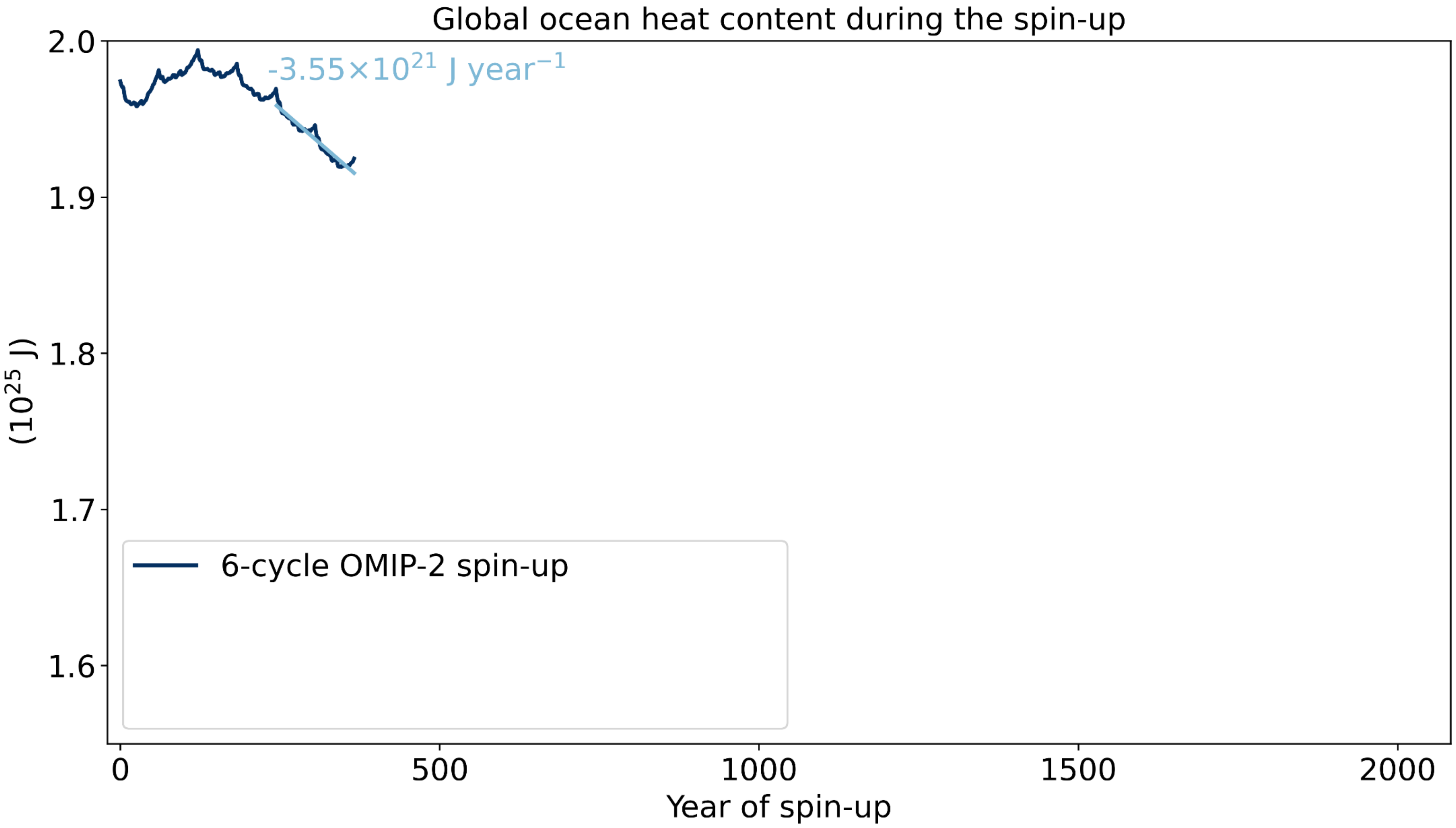
Cross-slope section

Global ocean-sea ice model

- ACCESS-OM2 (Kiss et al., 2019)
- MOM5.1, CICE5.1.2
- Input: atmospheric reanalysis JRA55-do (Tsujino et al., 2018)



Spin-up for ocean-sea ice models



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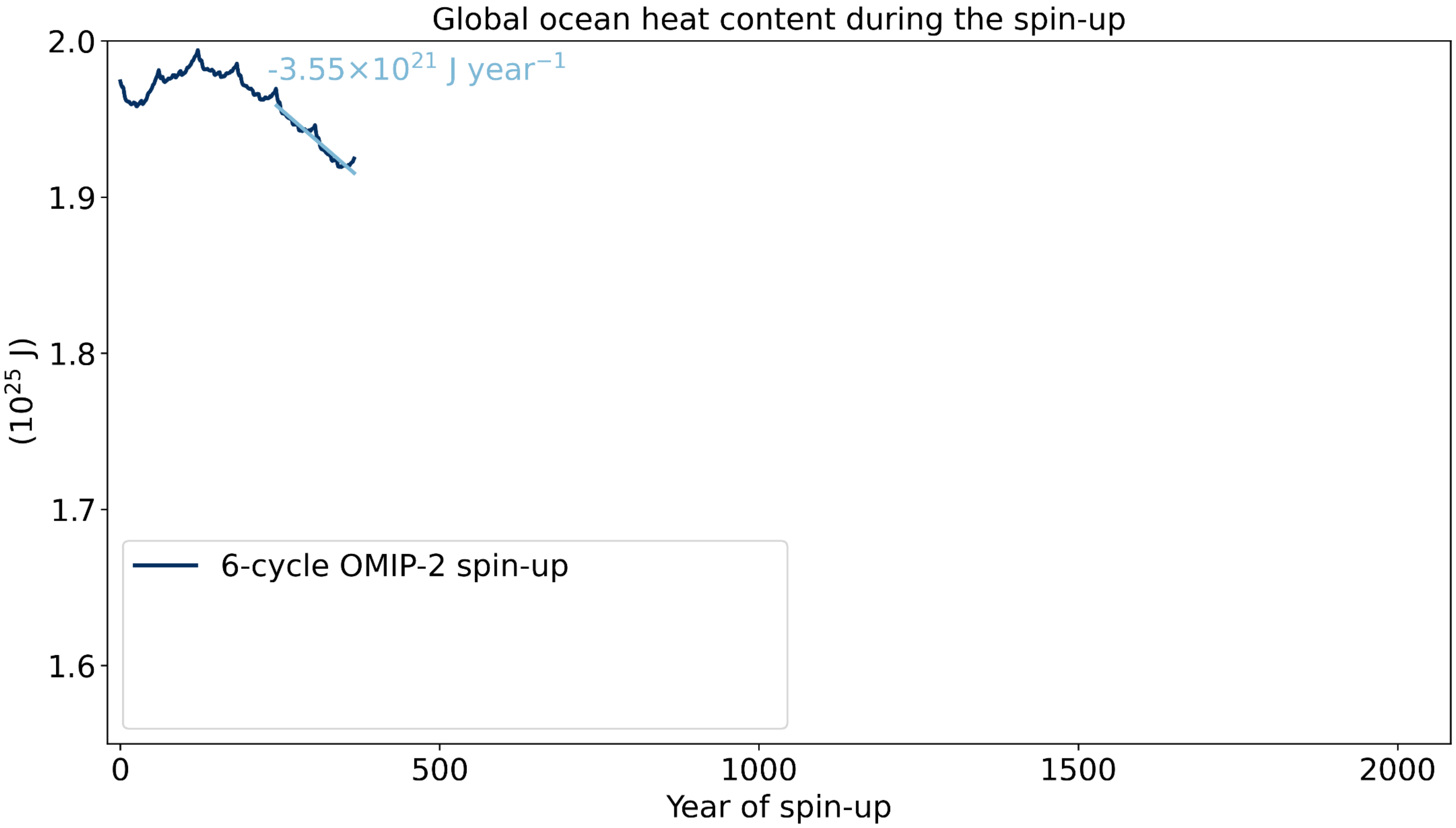
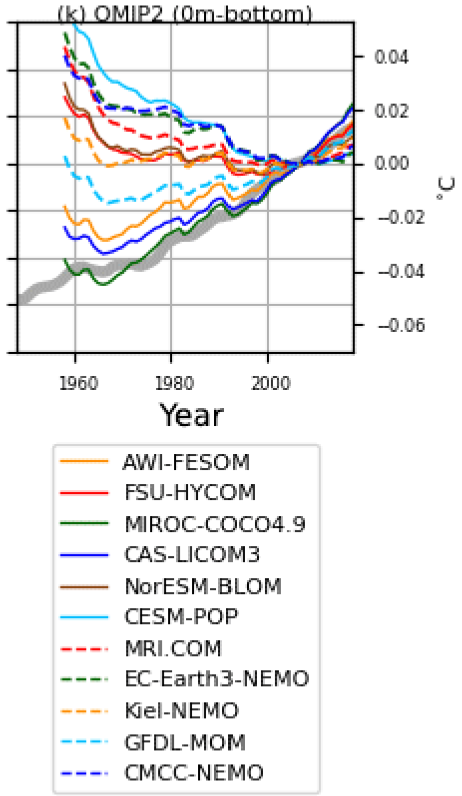
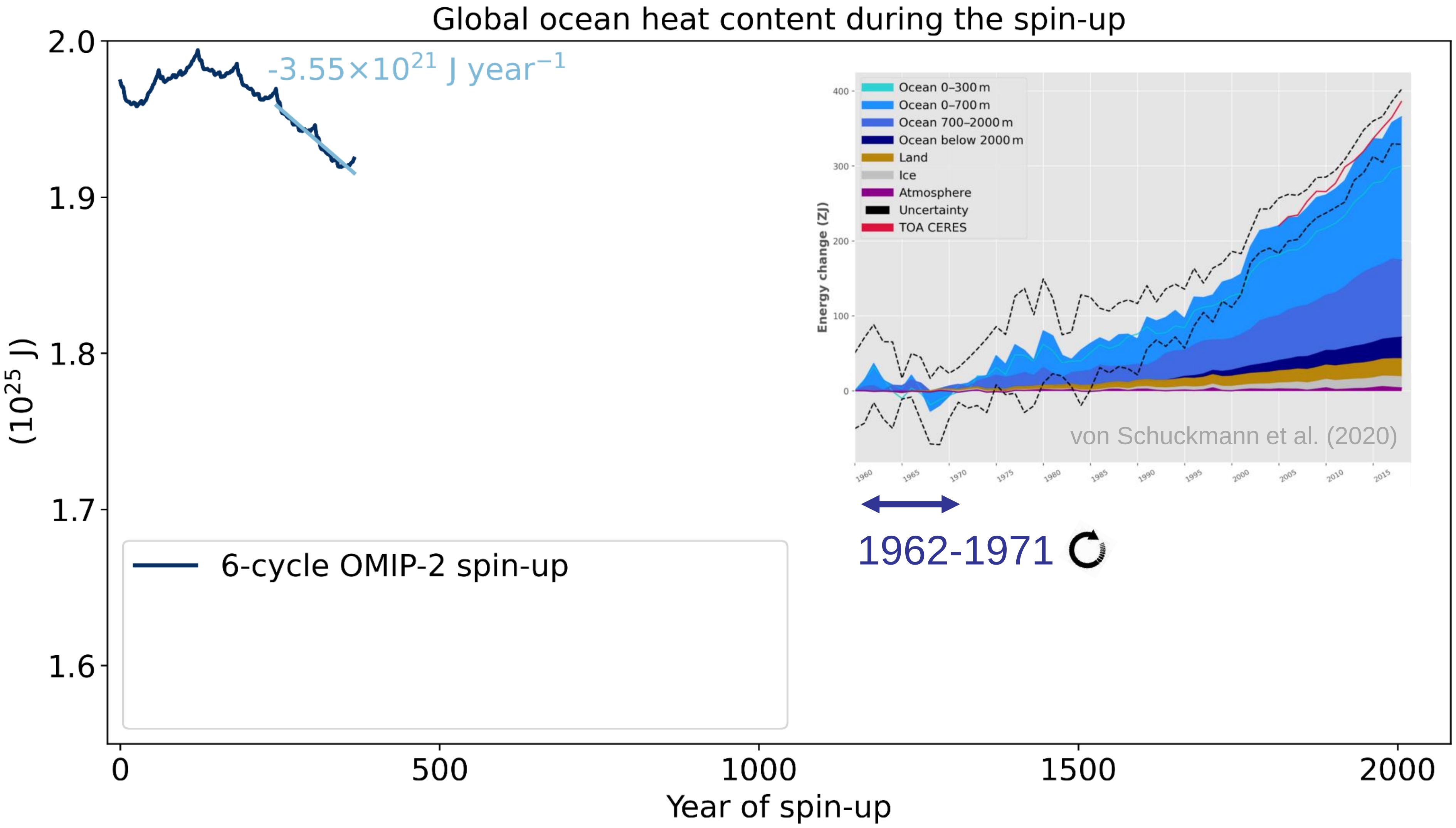
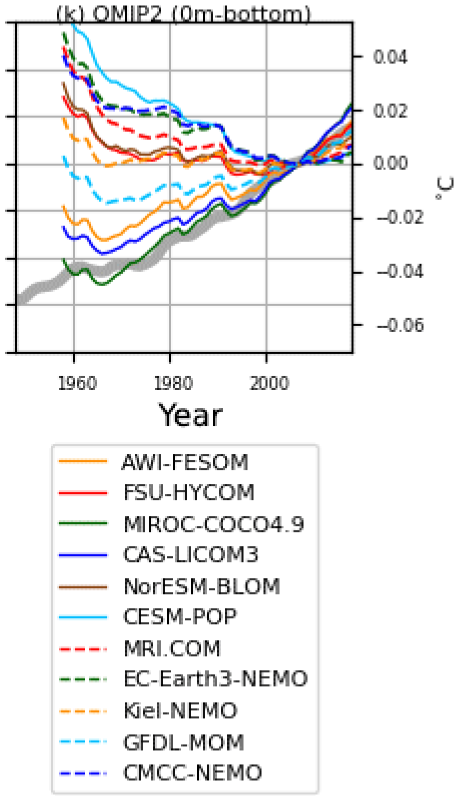




Tsujino et al. (2020)

New spin-up for ocean-sea ice models





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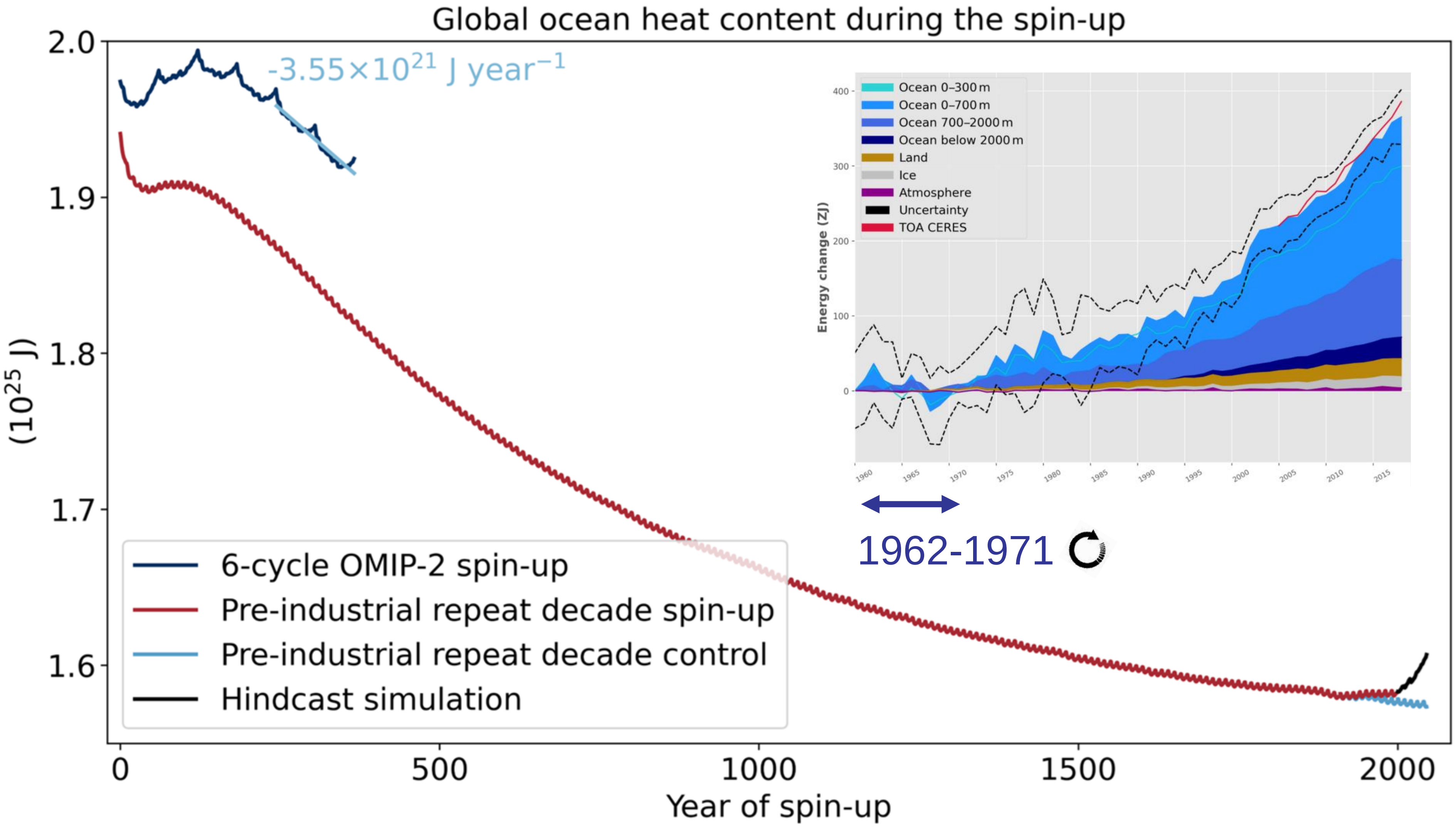

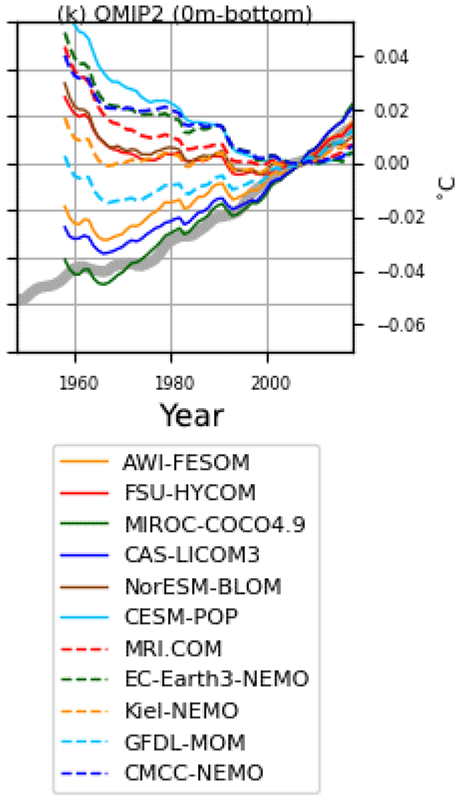

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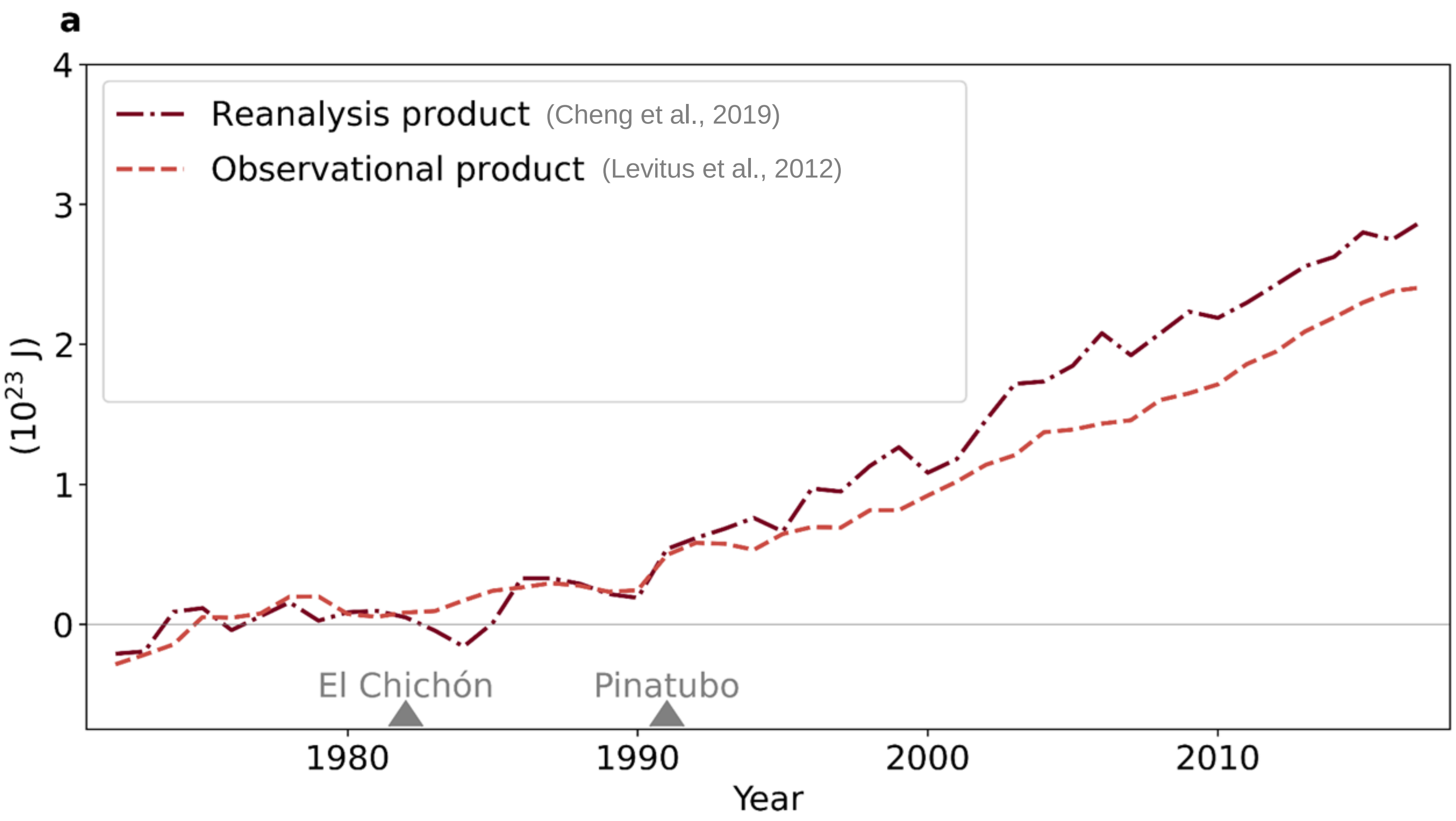
Global ocean heat content anomalies, 0-2000 m



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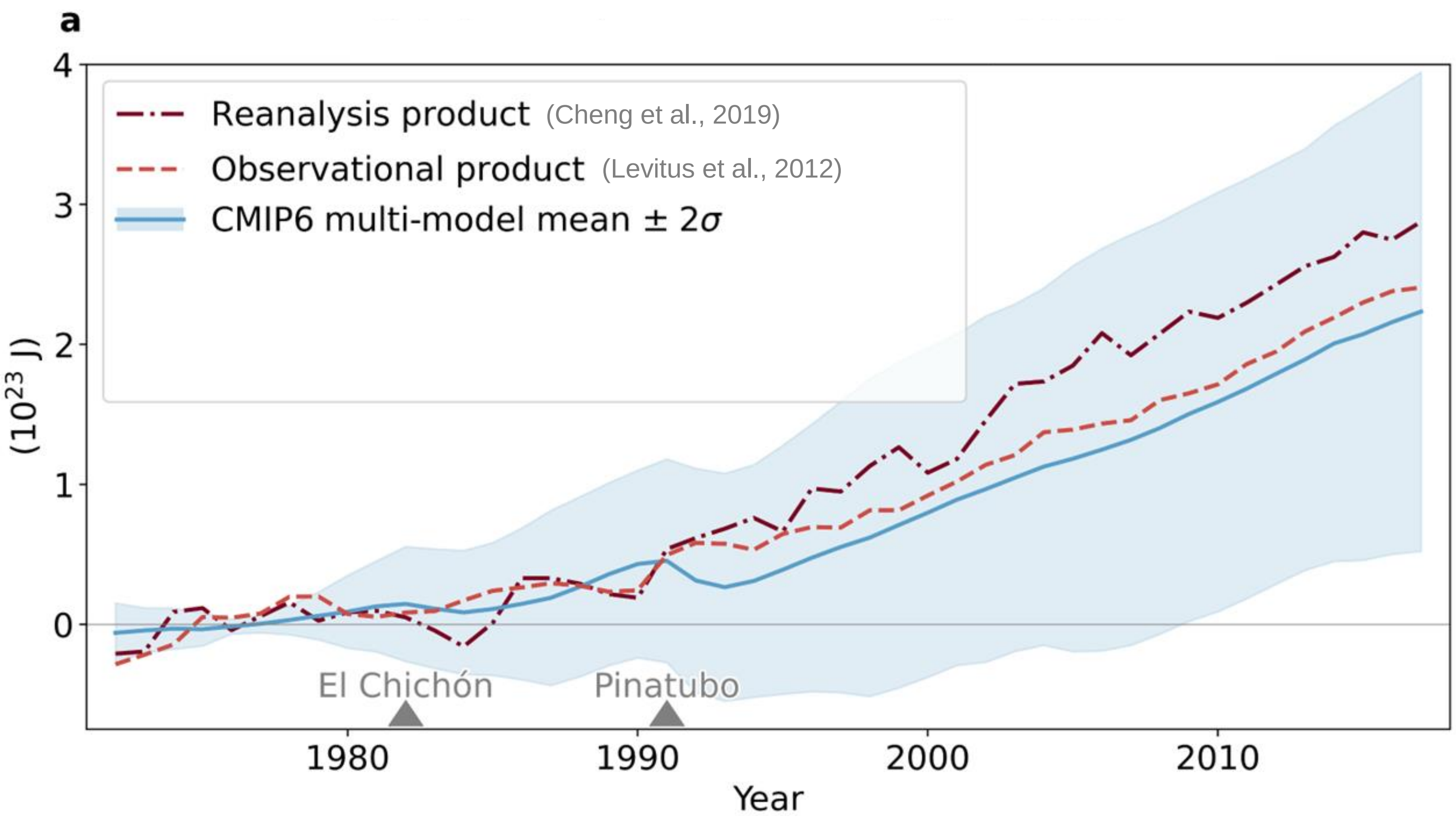

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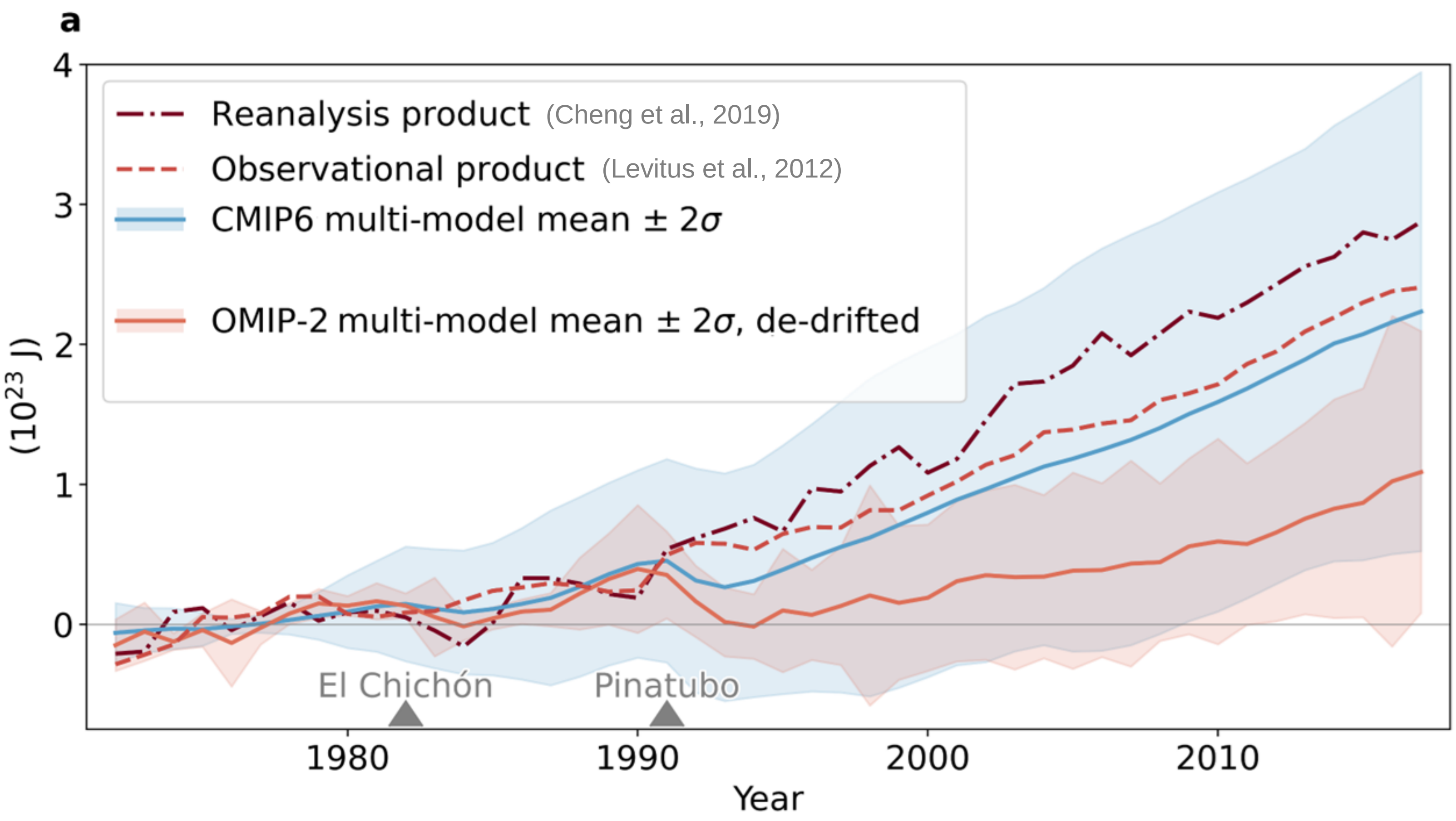

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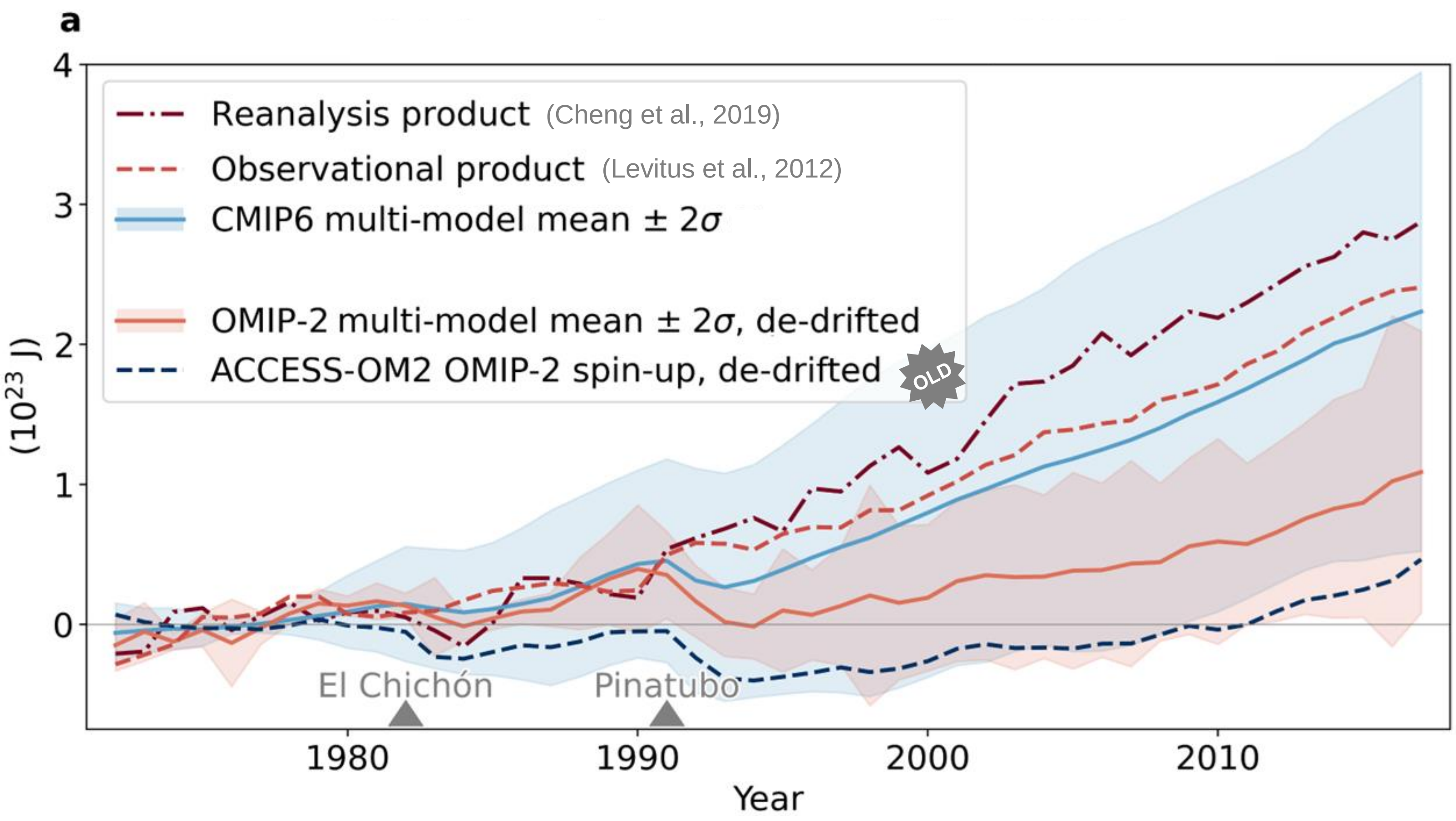

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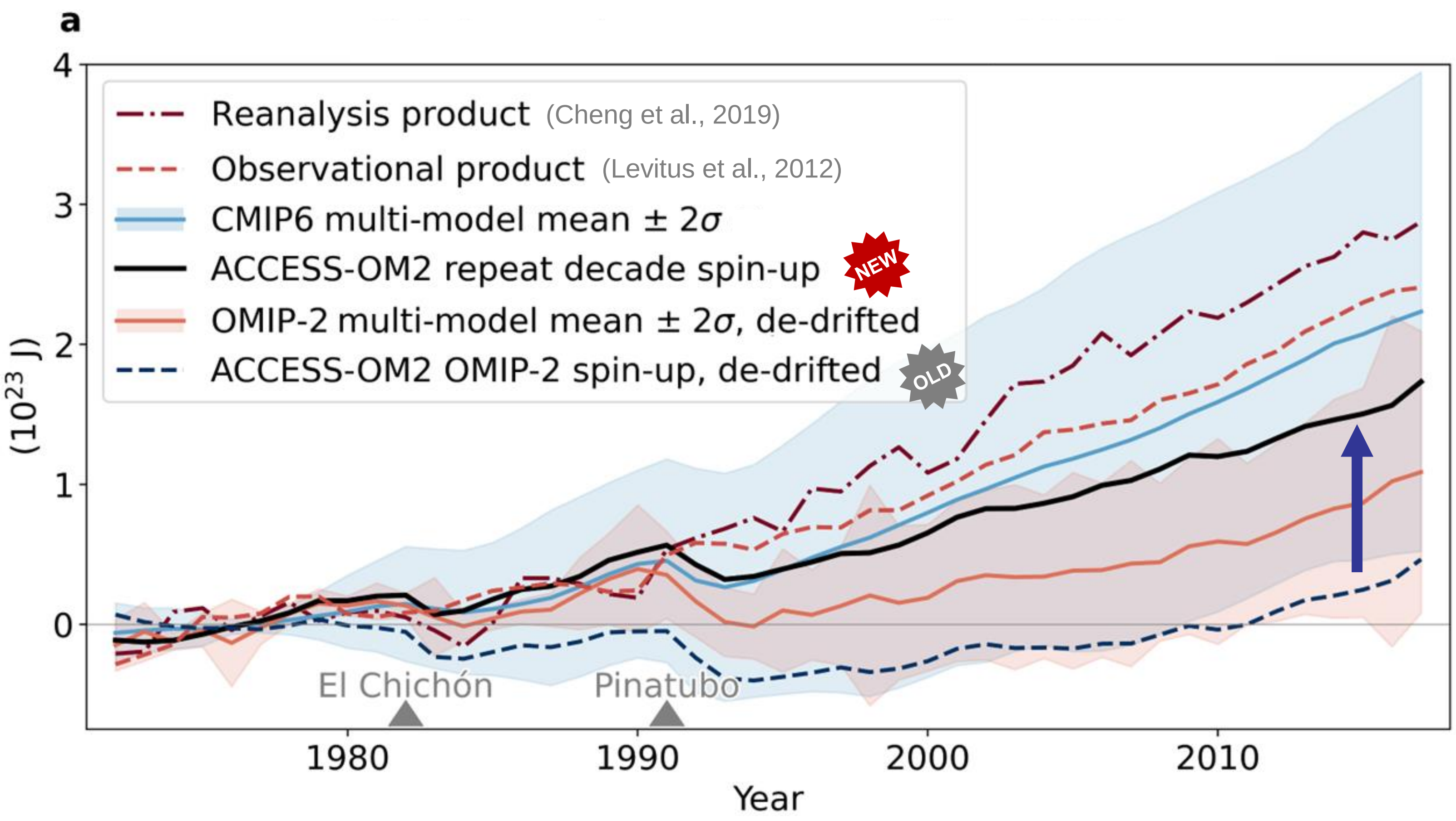

Schematic

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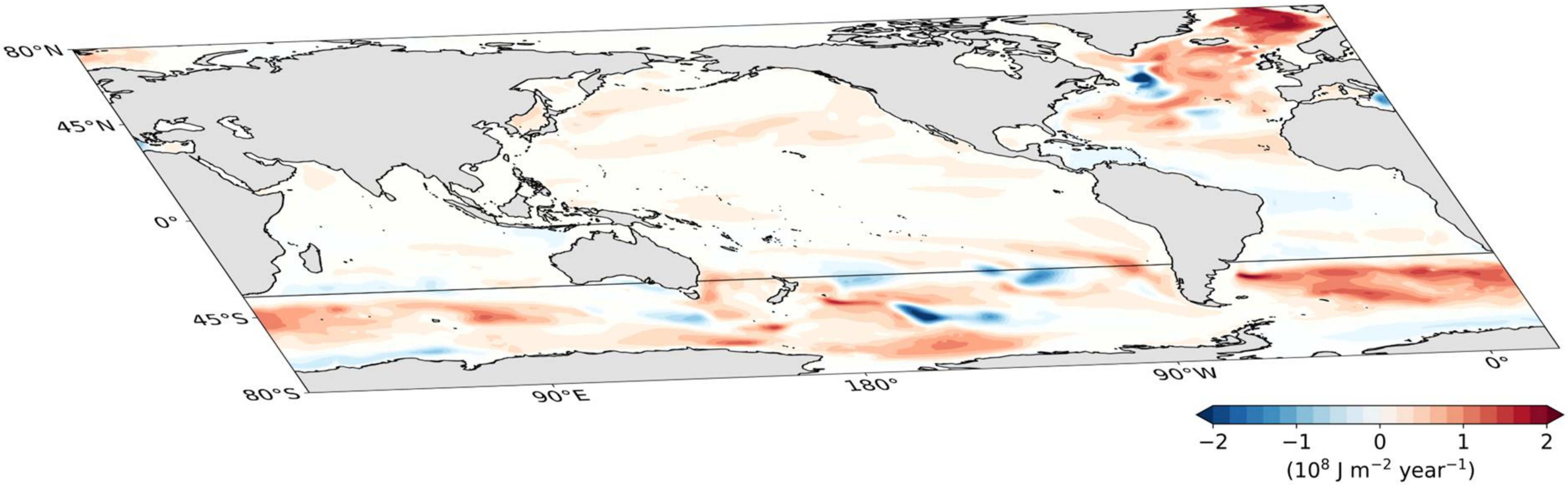

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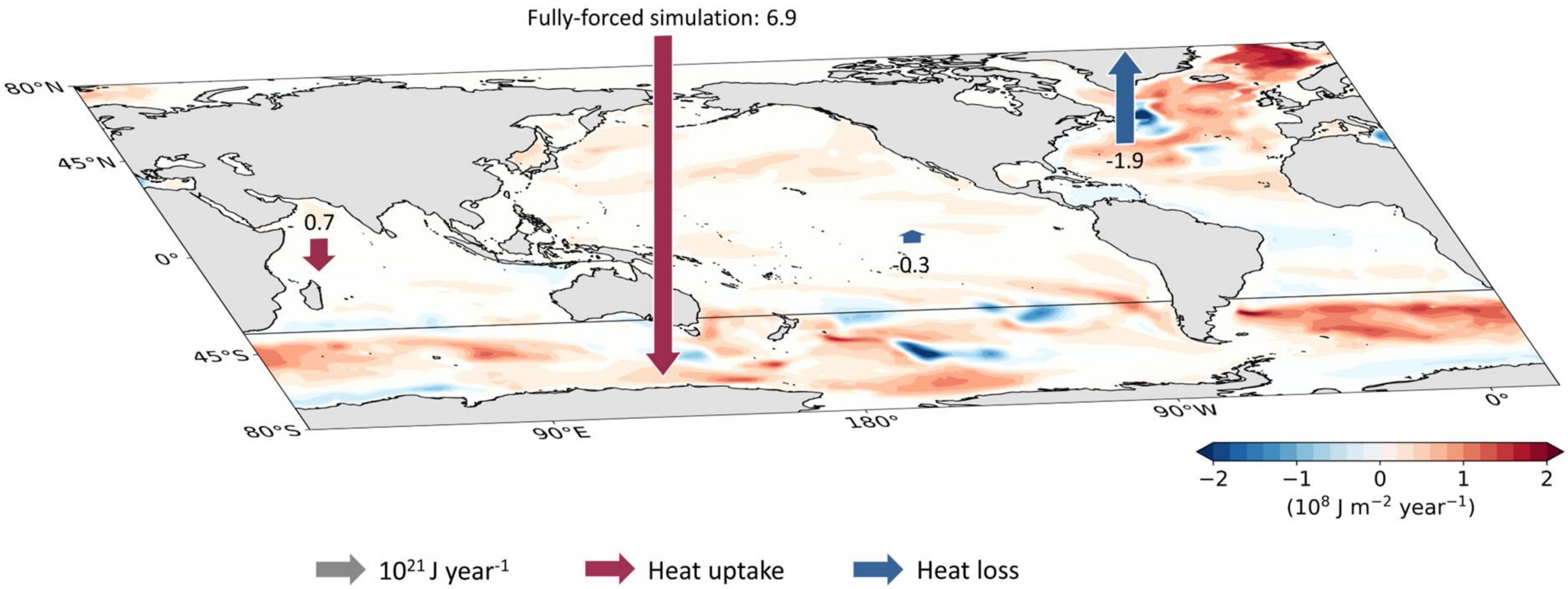
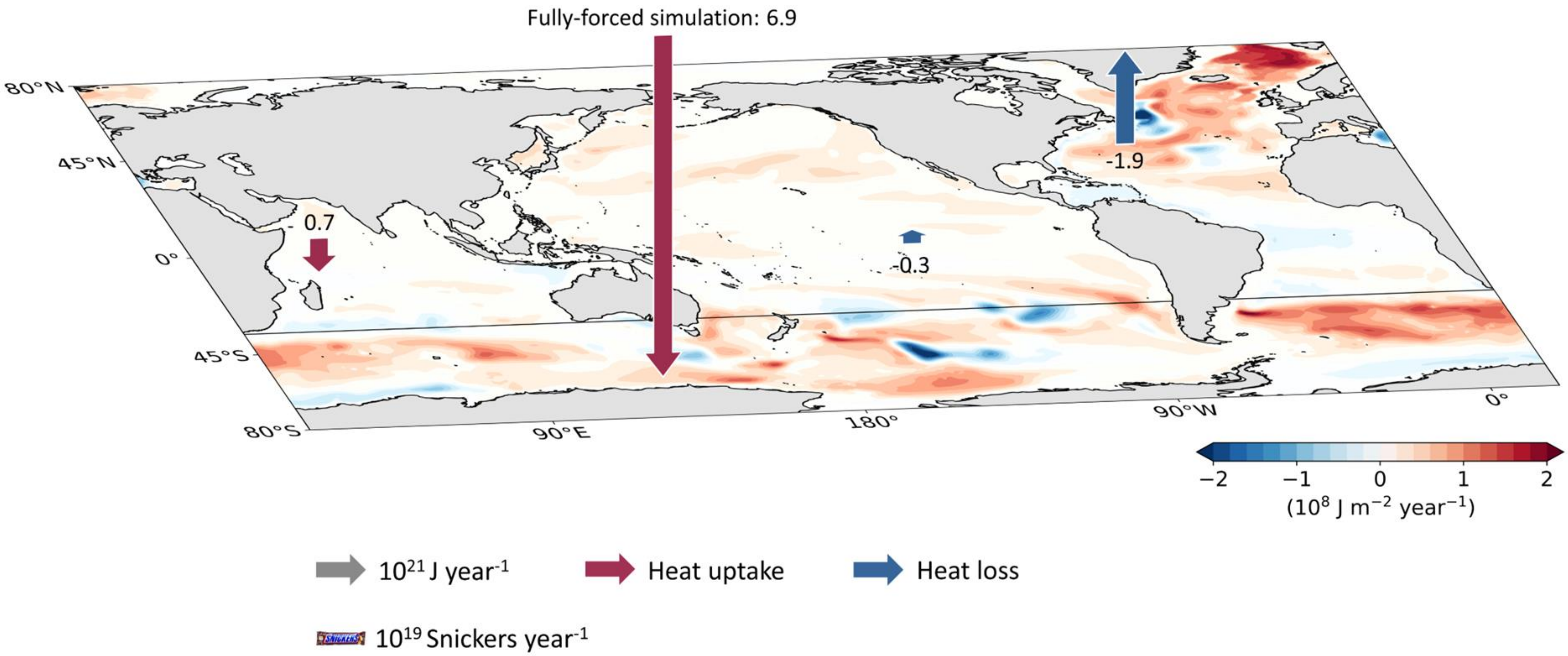


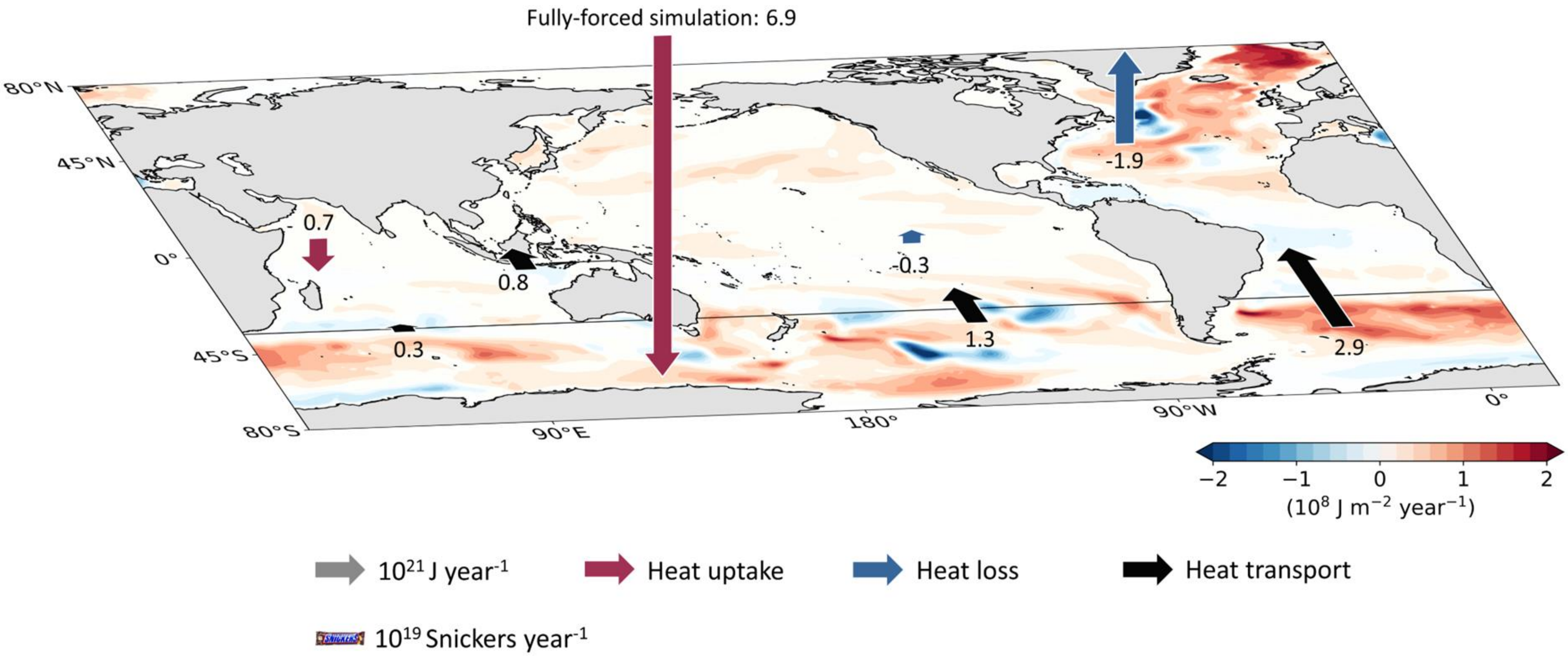
Fully-forced simulation: 6.9
80°N
45°N
0°
45°S
80°S
90°E
180°
90°W
0°
0.7
-0.3
-1.9
−2
−1
0
1
2
(10^8 J m^{-2} year^{-1})
10^{21} J year^{-1}
Heat uptake
Heat loss

Schematic



Fully-forced simulation: 6.9
0.7
-0.3
-1.9
80°N
45°N
0°
45°S
80°S
90°E
180°
90°W
0°
−2
−1
0
1
2
(10^8 J m^−2 year^−1)
10^21 J year^-1
Heat uptake
Heat loss
10^19 Snickers year^-1

Schematic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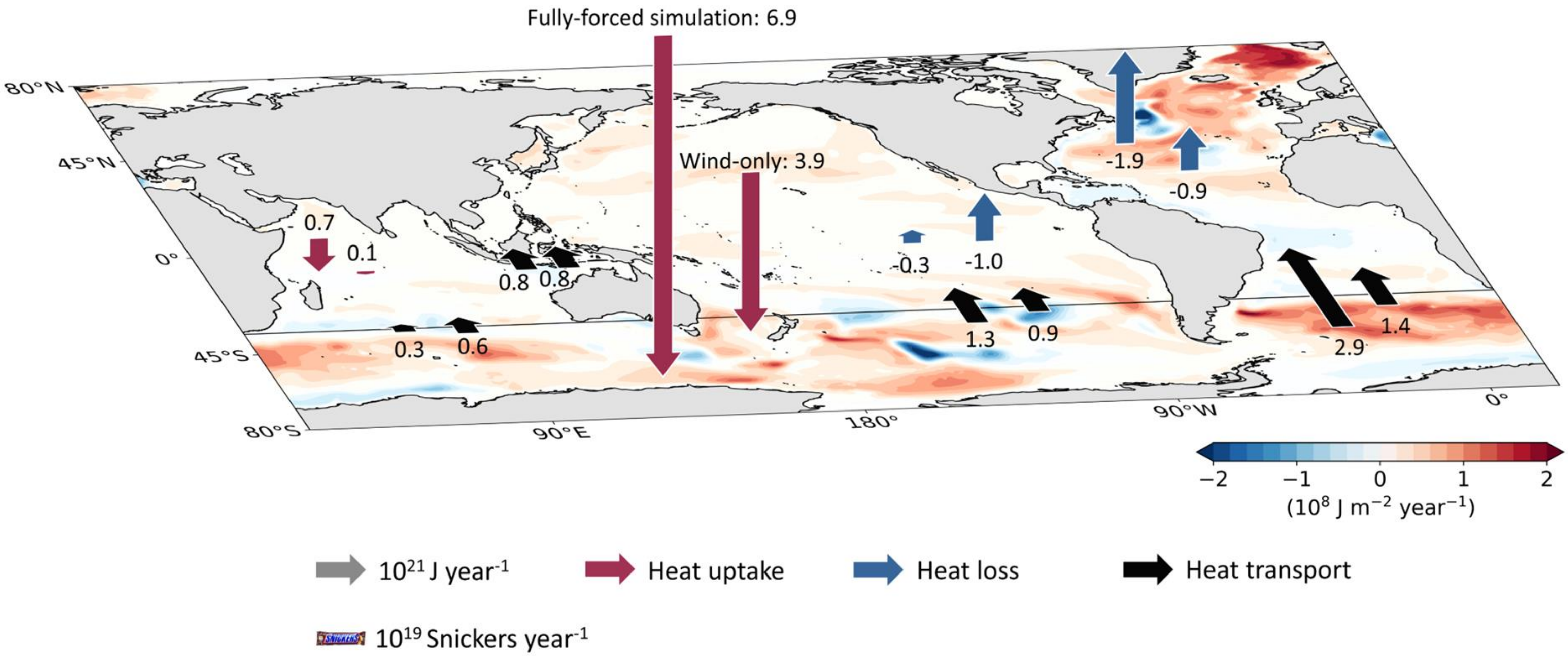
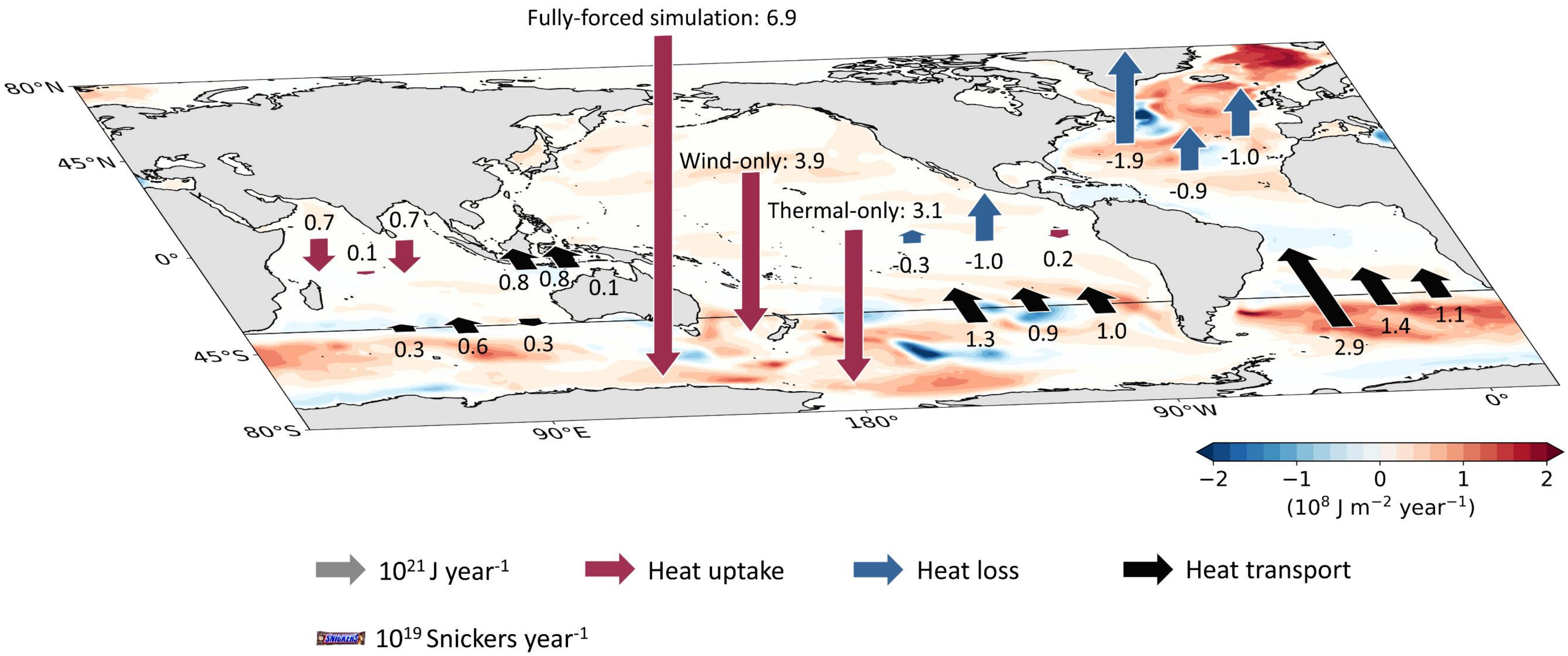
80°N
45°N
0°
45°S
80°S
90°E
180°
90°W
0°
0.7
0.8
0.3
-0.3
1.3
-1.9
2.9
−2
−1
0
1
2
(10^8 J m^{-2} $year^{-1}$)
10^{21} J $year^{-1}$
Heat uptake
Heat loss
Heat transport
10^{19} Snickers $year^{-1}$

Schematic



Fully-forced simulation: 6.9
Wind-only: 3.9
80°N
45°N
0°
45°S
80°S
90°E
180°
90°W
0°
0.7
0.1
0.8
0.8
0.3
0.6
-0.3
-1.0
-1.9
-0.9
1.3
0.9
2.9
1.4
−2
−1
0
1
2
(10^8 J m^{-2} $year^{-1}$)
10^{21} J $year^{-1}$
Heat uptake
Heat loss
Heat transport
10^{19} Snickers $year^{-1}$

Schematic



Fully-forced simulation: 6.9
Wind-only: 3.9
Thermal-only: 3.1
80°N
45°N
0°
45°S
80°S
90°E
180°
90°W
0°
0.7
0.1
0.7
0.8
0.8
0.1
0.3
0.6
0.3
-0.3
-1.0
0.2
1.3
0.9
1.0
-1.9
-0.9
-1.0
2.9
1.4
1.1
−2
−1
0
1
2
(10^8 J m^{-2} $year^{-1}$)
10^{21} J $year^{-1}$
Heat uptake
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Heat transport
10^{19} Snickers $year^{-1}$

7 April 2022

7 April 2022

rm –rf *

- deleted 12 TB of data
- everything from every project

7 April 2022

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It's such a horrible feeling when you realise what you've done - but it's so common! In addition to deleting a control run during my PhD, I also incorrectly ran an ensemble of runs last year. Luckily ESM1.5 is (relatively) cheap and fast to re-run... but I felt ridiculous and like a modelling imposter who has no idea what they're doing. I messaged a friend (who's much better at running models than me!) and she was like "oh, don't worry, once I did something similar and ran a whole simulation with X set as -1 instead of 1" and I felt so much better! Hearing these stories make it so much more bearable I think!

Great to hear that you have got things going already and that your results are reproducible. I hope the run completes easily.

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Cruise break

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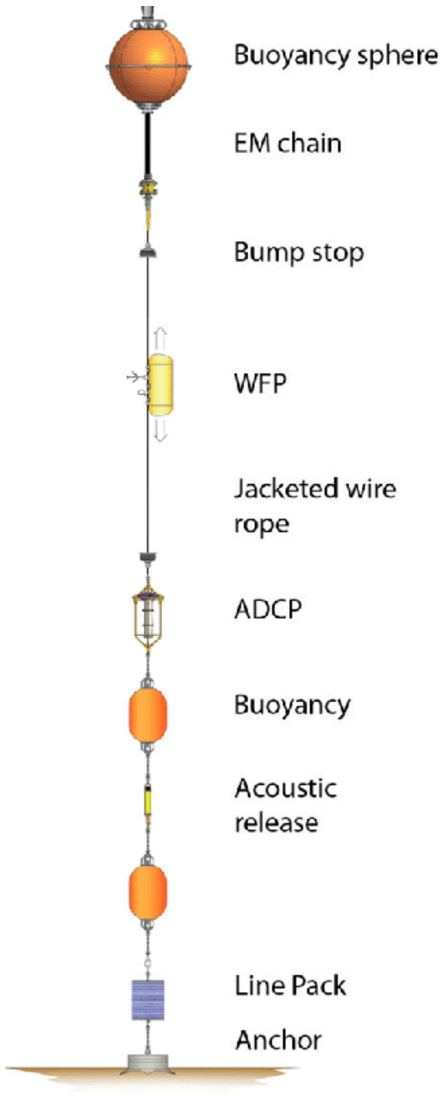
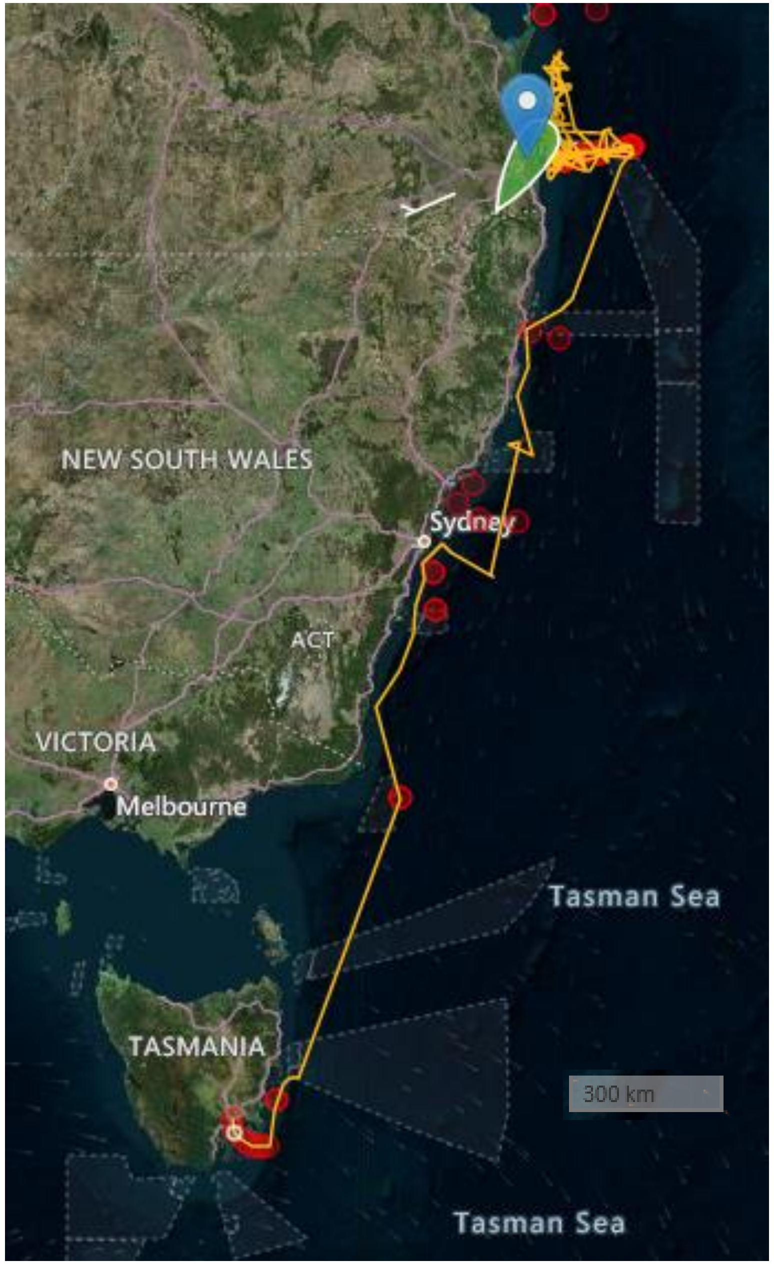


Thanks Amandine Schaeffer, Chris Chapman & Iain Suthers



Subsurface warming of the West Antarctic continental shelf linked to El Niño events

Maurice F. Huguenin, Ryan M. Holmes, Paul Spence and Matthew H. England

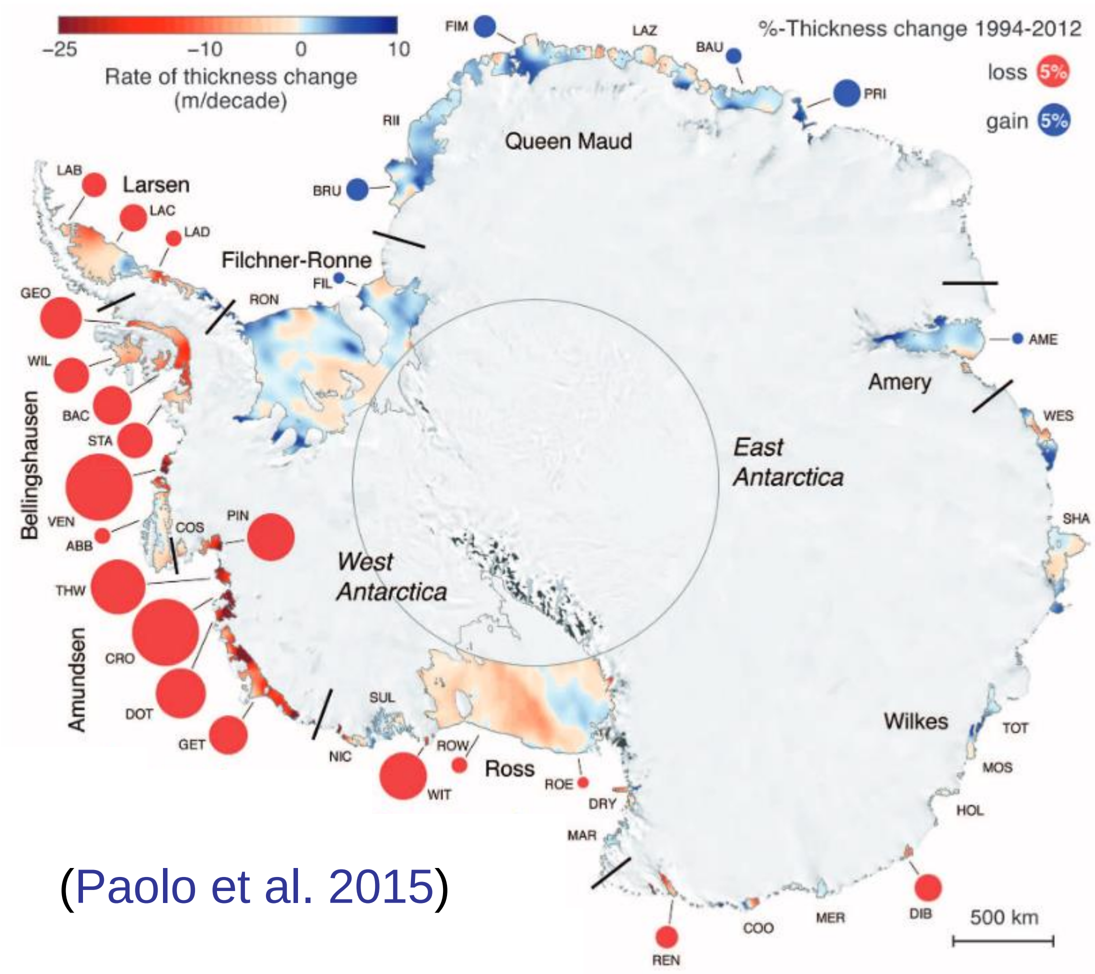
Geophysical Research Letters

Australian Government
Australian Research Council

The Australian Centre for Excellence in Antarctic Science is a Special Research Initiative funded by the Australian Research Council

This research was supported by the Australian Research Council Special Research Initiative, Australian Centre for Excellence in Antarctic Science (Project Number SR200100008)

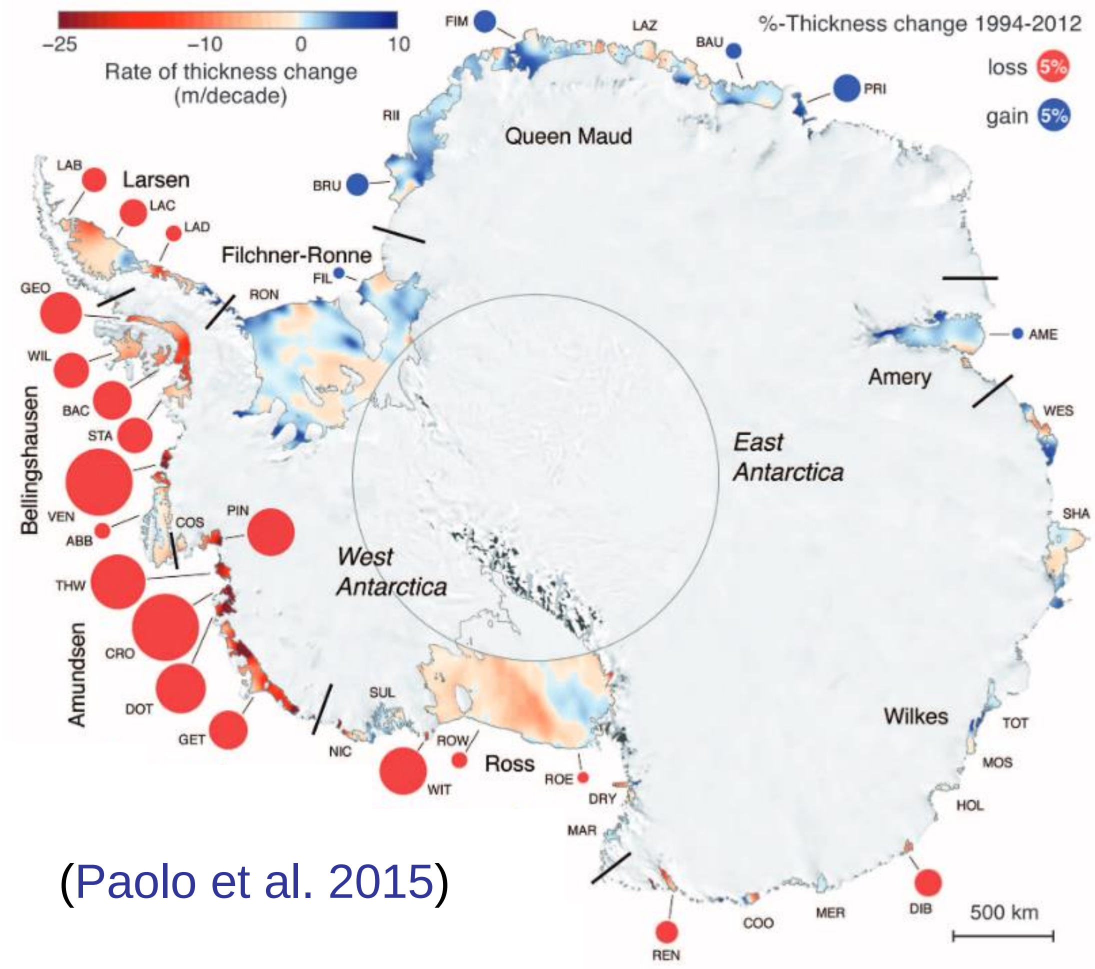
Background



(Paolo et al. 2015)

Background

- Volume loss from Antarctic ice shelves is accelerating (Paolo et al. 2015)



(Paolo et al. 2015)

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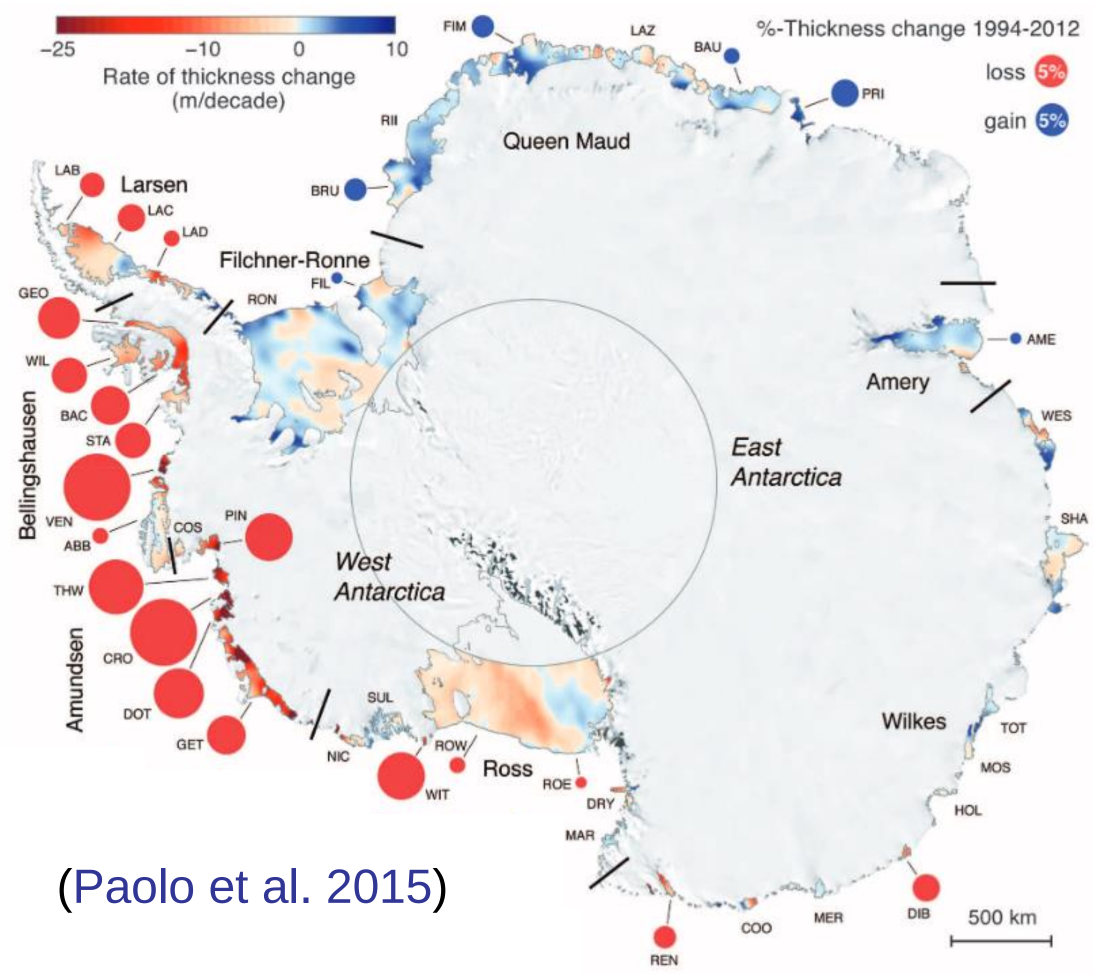
- Volume loss from Antarctic ice shelves is accelerating (Paolo et al. 2015)

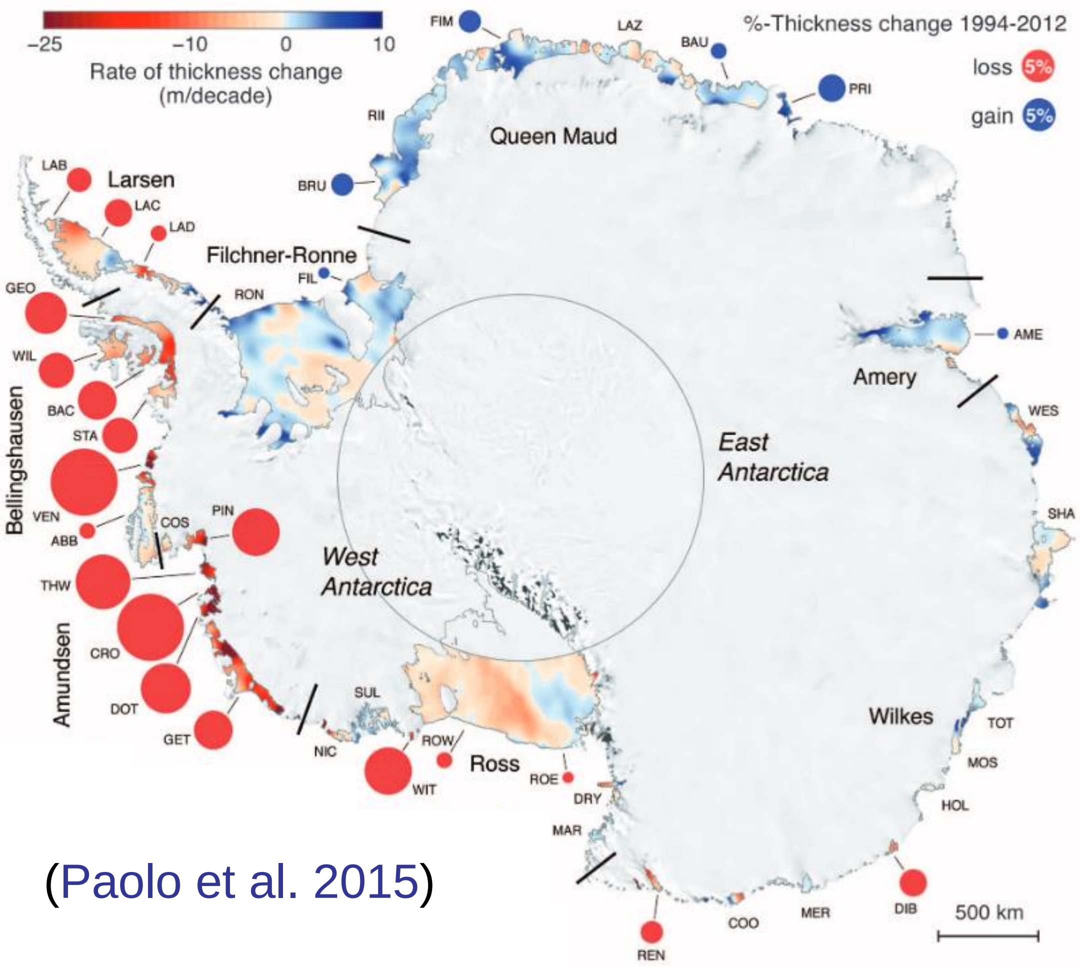
- Ice loss influenced by internal climate variability and anthropogenic forcing (Holland et al. 2019)



(Paolo et al. 2015)

Background

- Volume loss from Antarctic ice shelves is accelerating (Paolo et al. 2015)
- Ice loss influenced by internal climate variability and anthropogenic forcing (Holland et al. 2019)
- El Niño: ↑height but ↓mass of West Antarctic ice shelves (Paolo et al. 2018)



(Paolo et al. 2015)

The questions

- How do El Niño & La Niña impact the West Antarctic shelf circulation?

- What processes are responsible for warming and cooling on the shelf?

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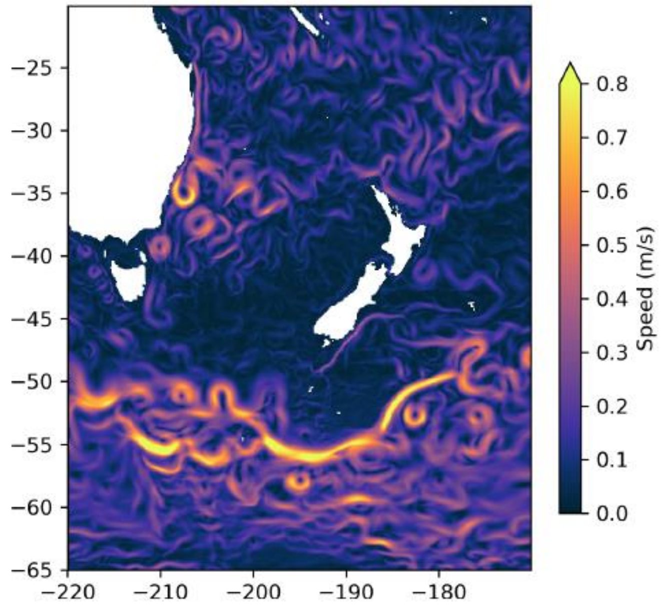
- What processes are responsible for warming and cooling on the shelf?

The method

- ACCESS-OM2 (Kiss et al. 2020)
  - 1/10° configuration
  - JRA55-do reanalysis (Tsujino et al. 2018)

1/10°



Kiss et al. (2019)

- Repeat-year forcing spin-up
- ENSO anomalies on top

Forcing for the idealised simulations

Repeat-year forcing [t, x, y]

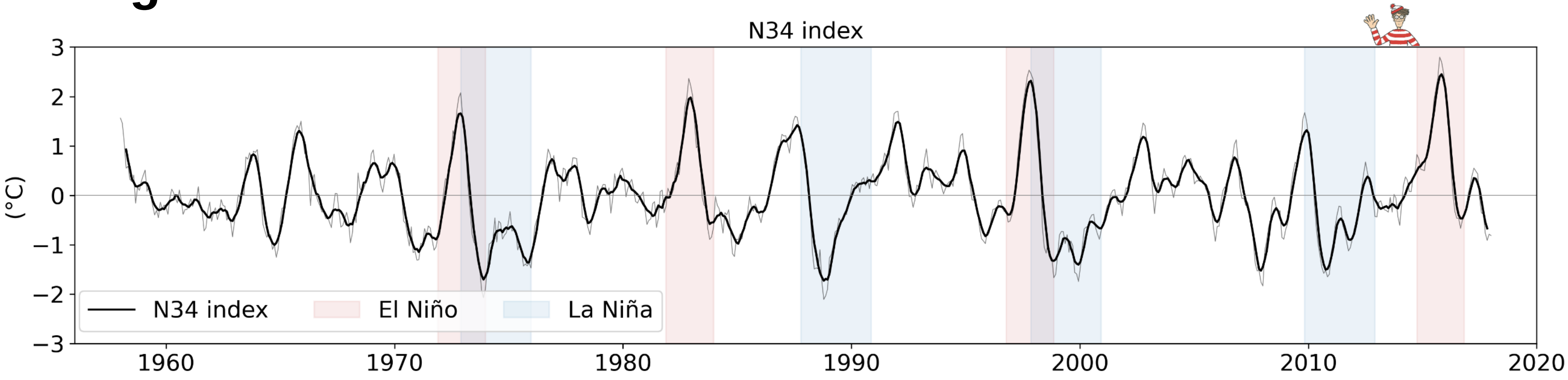
Forcing for the idealised simulations

Repeat-year forcing [t, x, y]

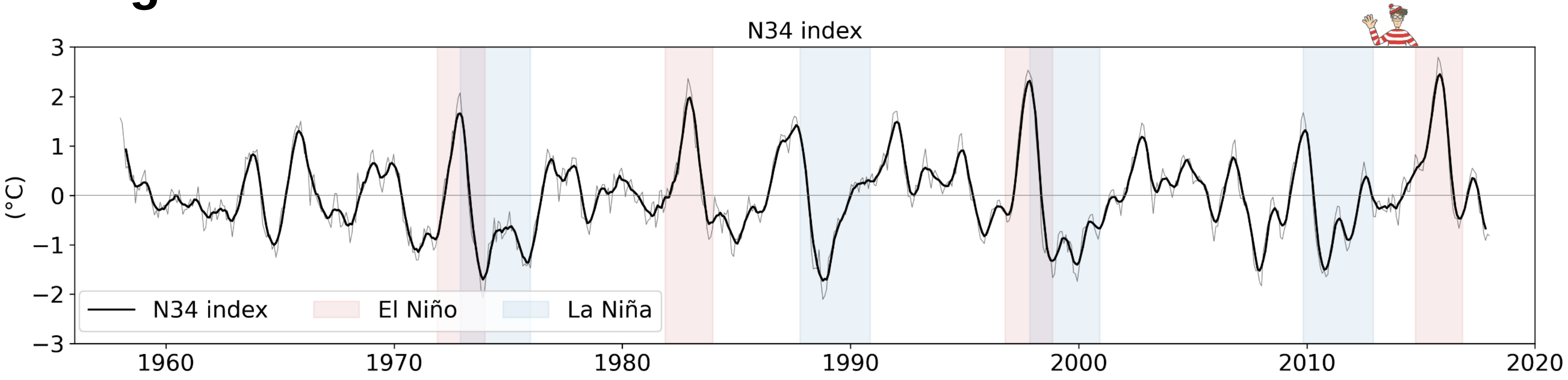
+

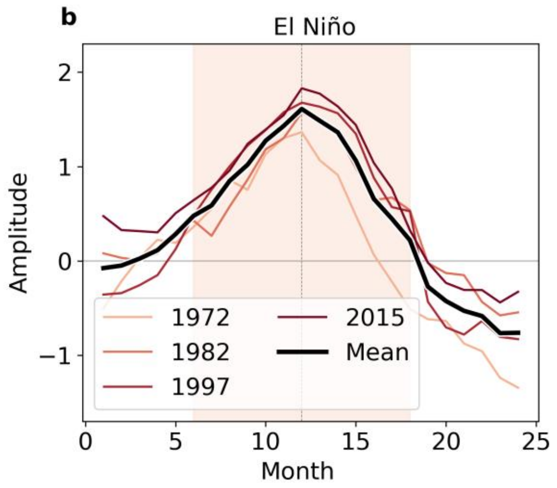
ENSO anomalies (time series [t] × spatial pattern [x,y])

Forcing for the idealised simulations

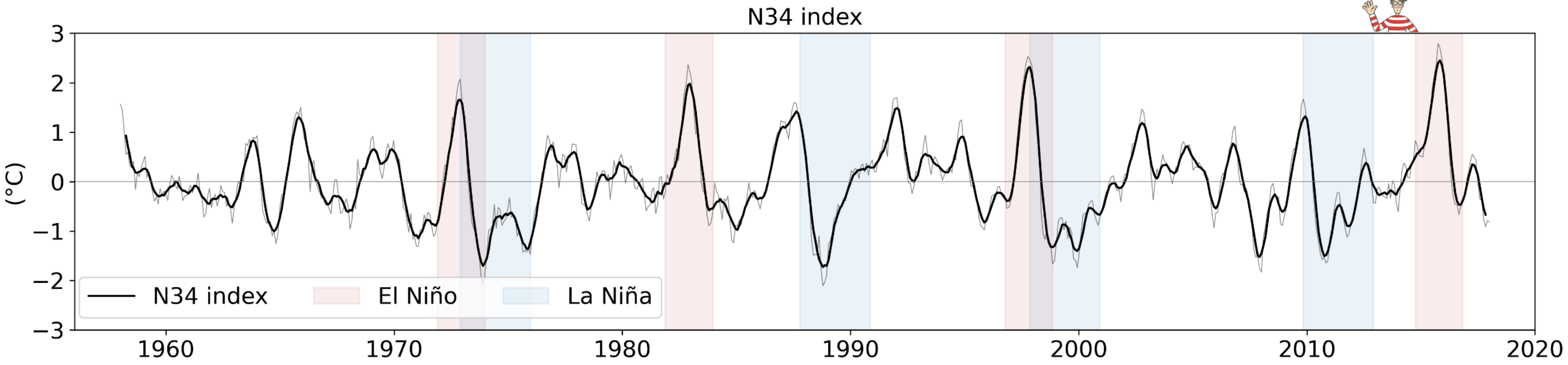


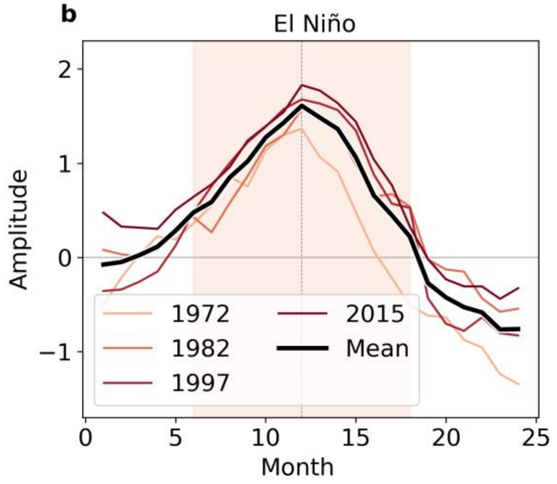
Forcing for the idealised simulations

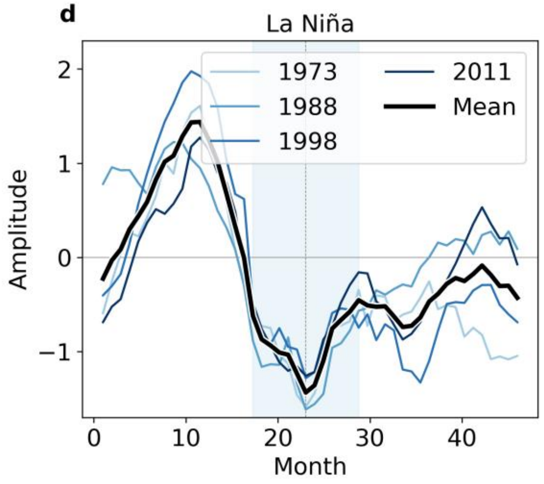




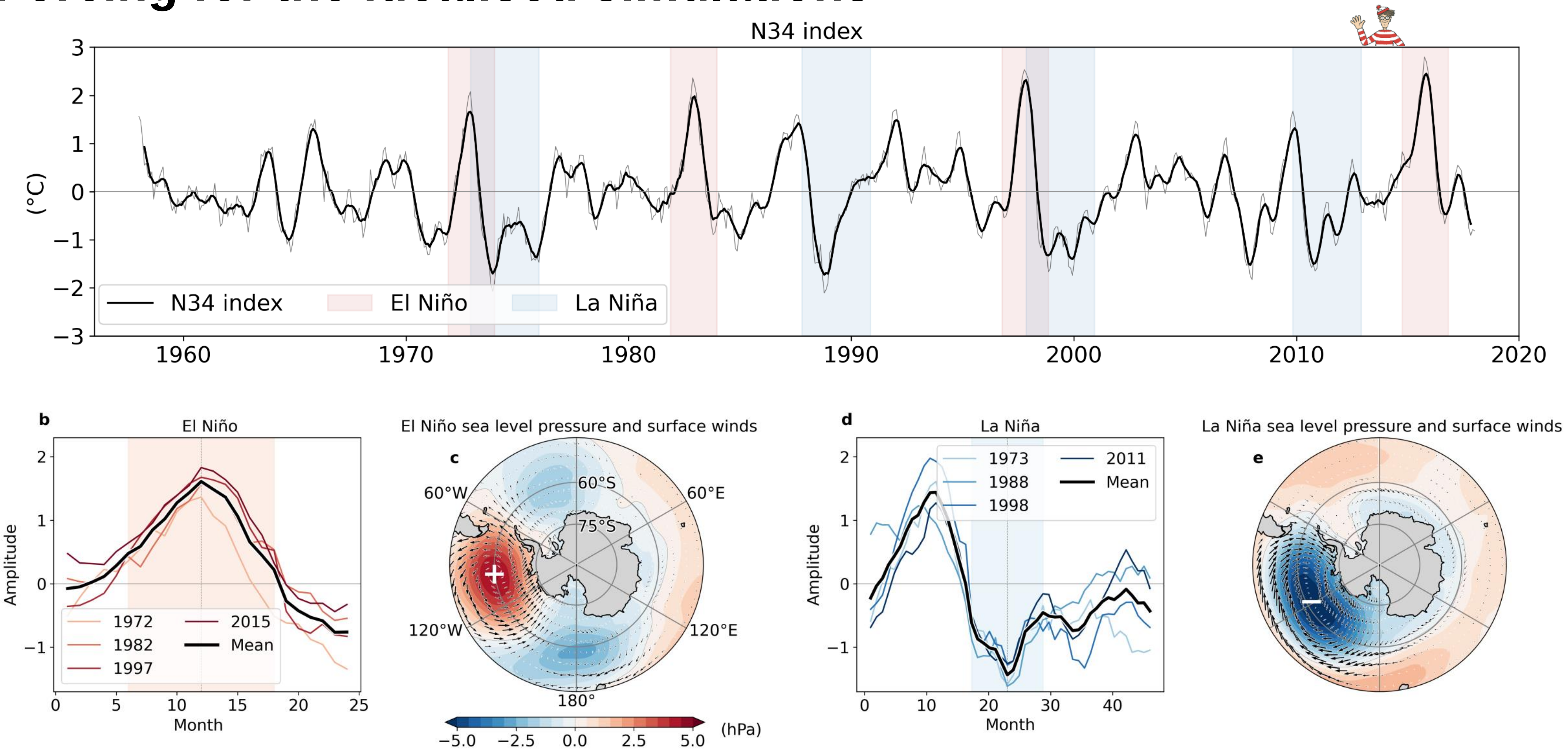
Forcing for the idealised simulations



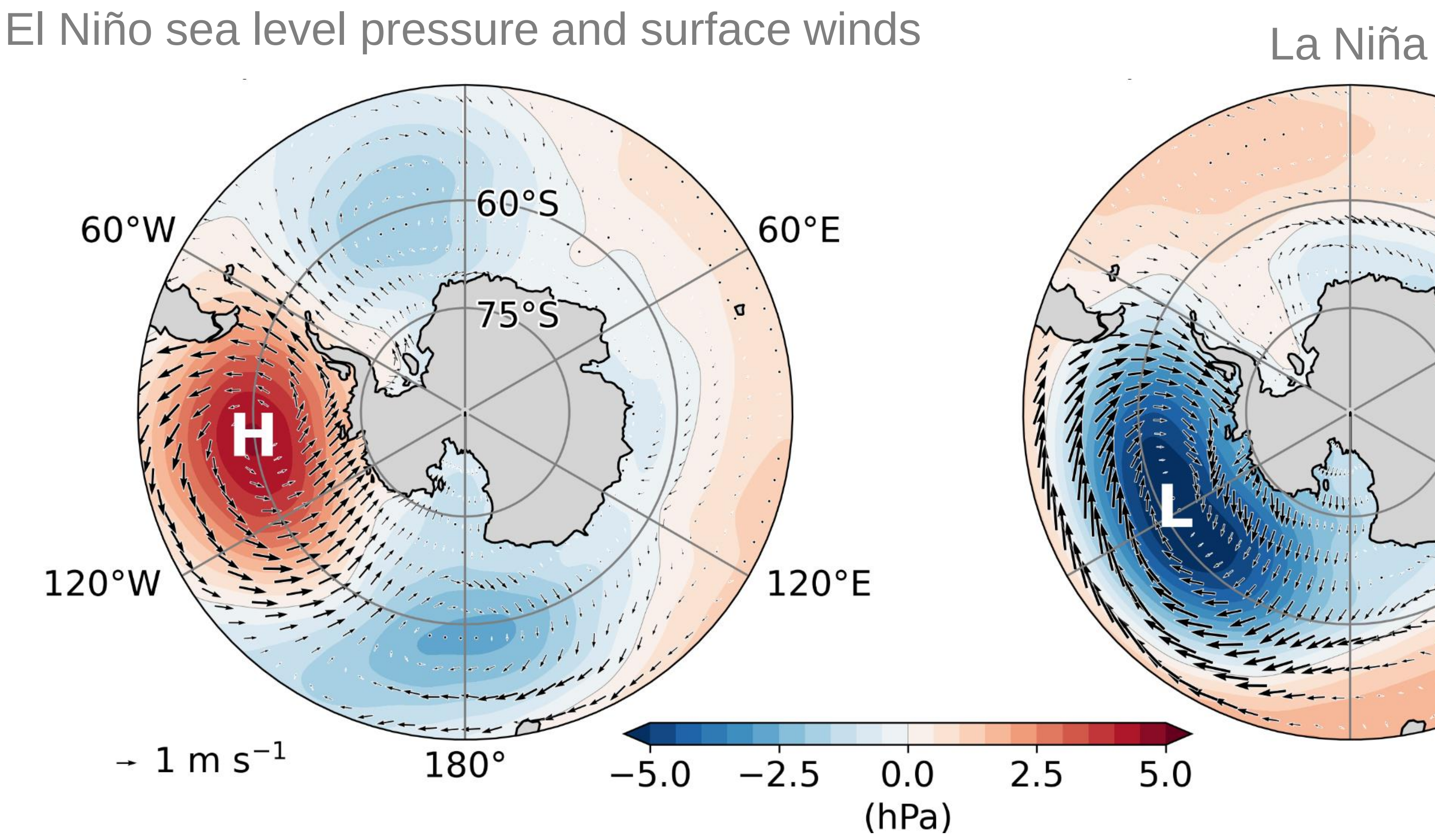




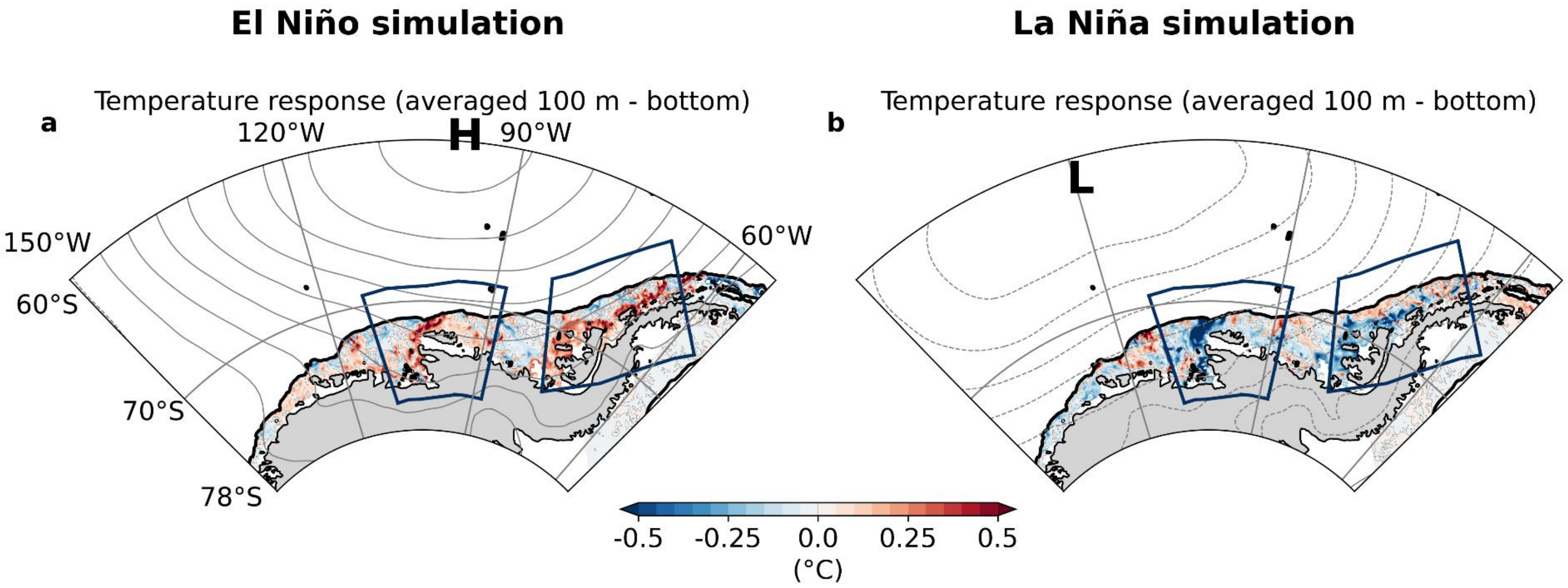
Forcing for the idealised simulations



Forcing for the idealised simulations



Shelf response to ENSO forcing



isopycnals

0°C isotherm

Shelf response to ENSO forcing

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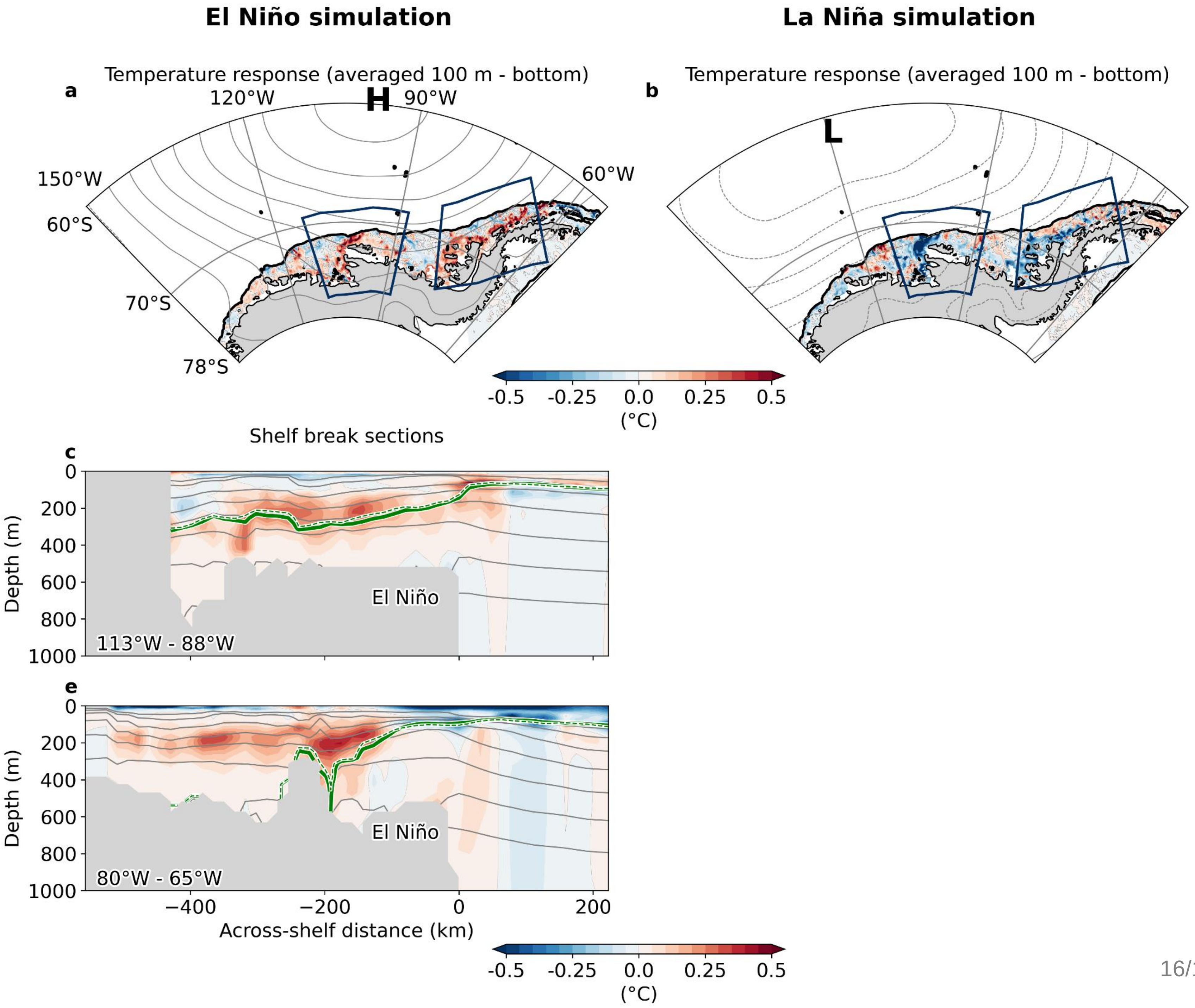
0°C isotherm



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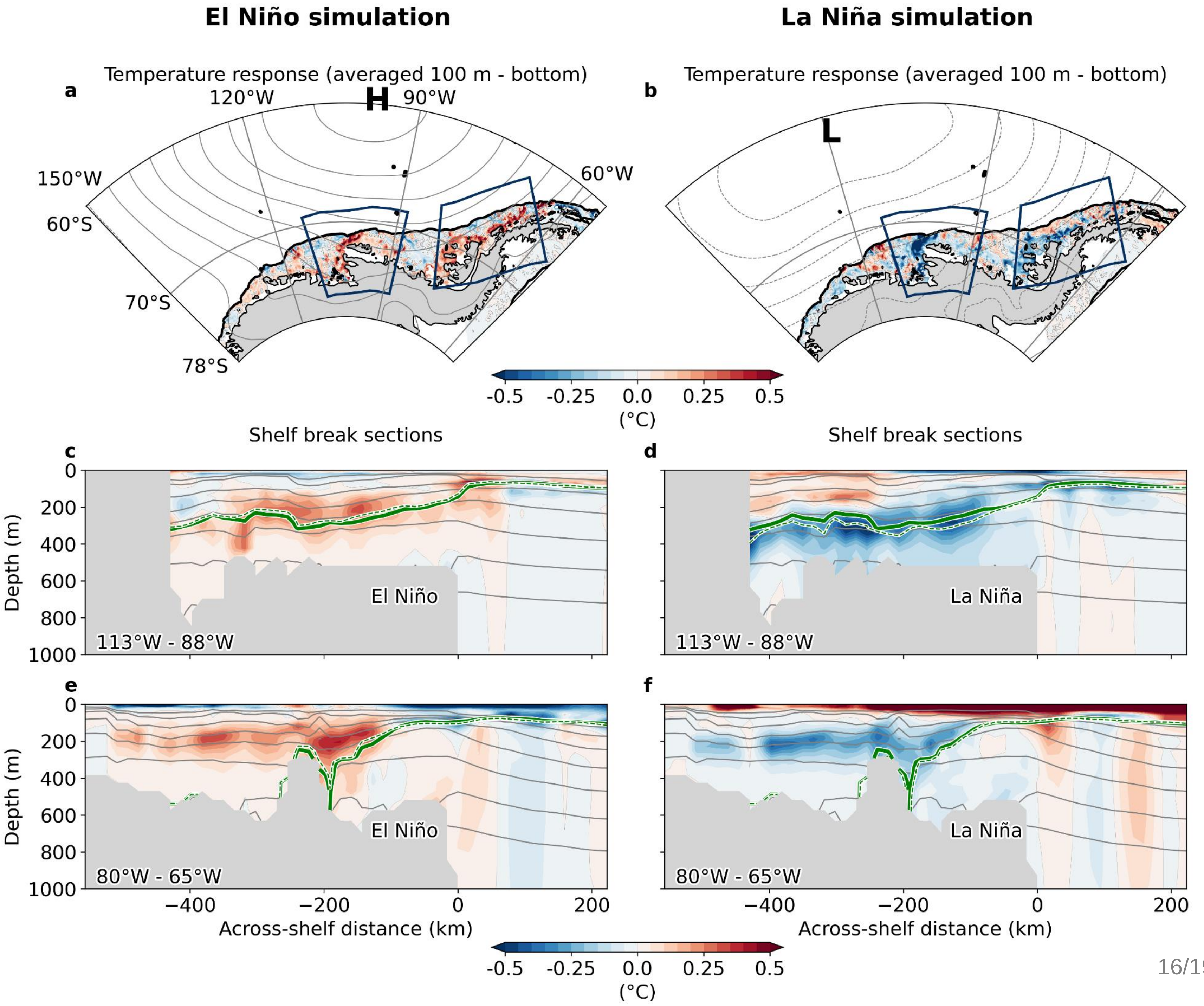

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The subsurface heat budget

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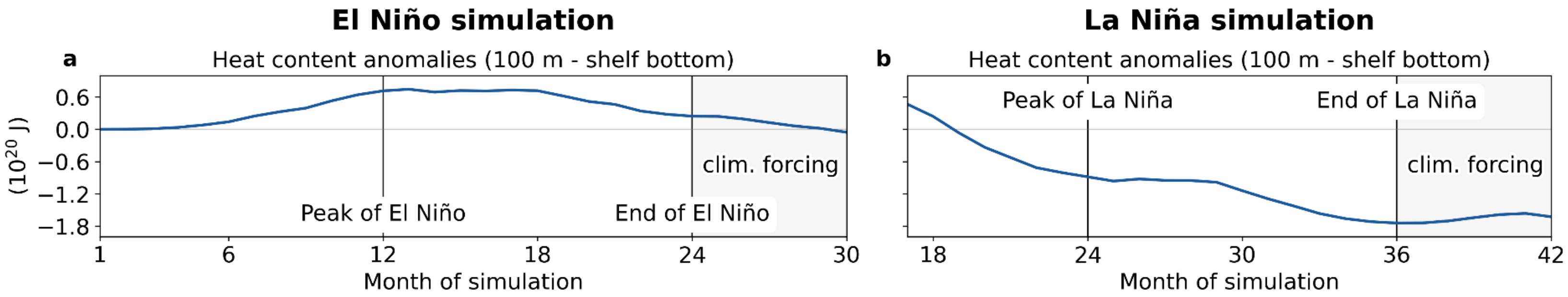

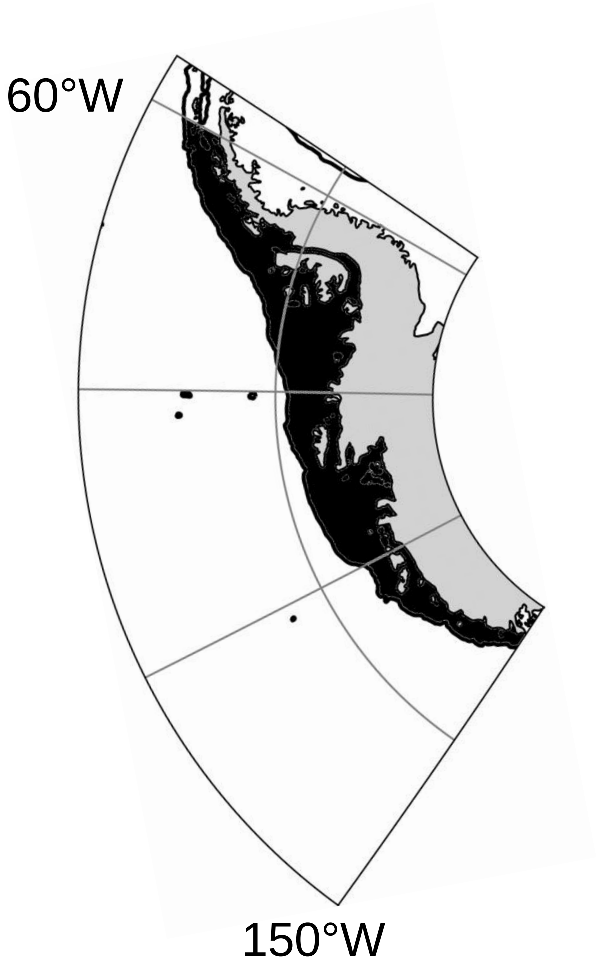

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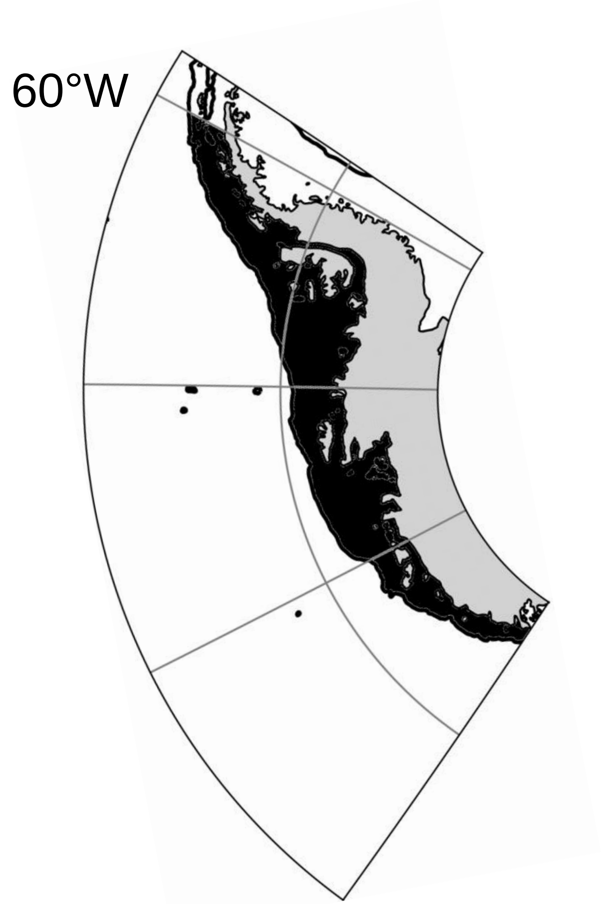

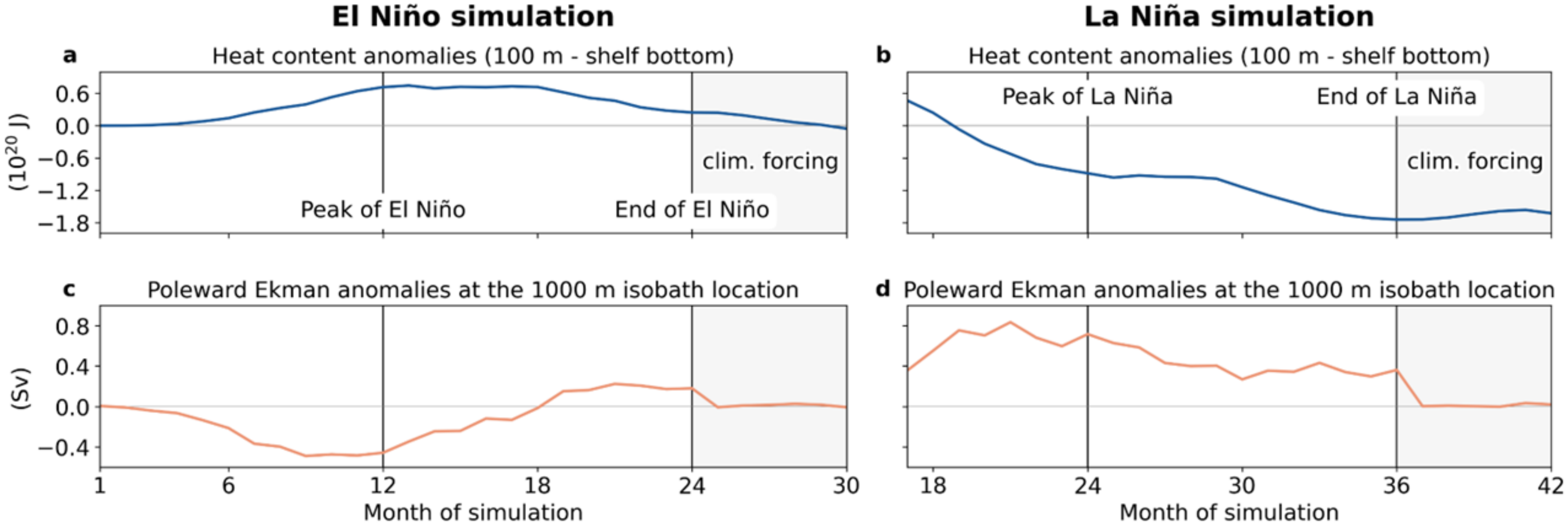

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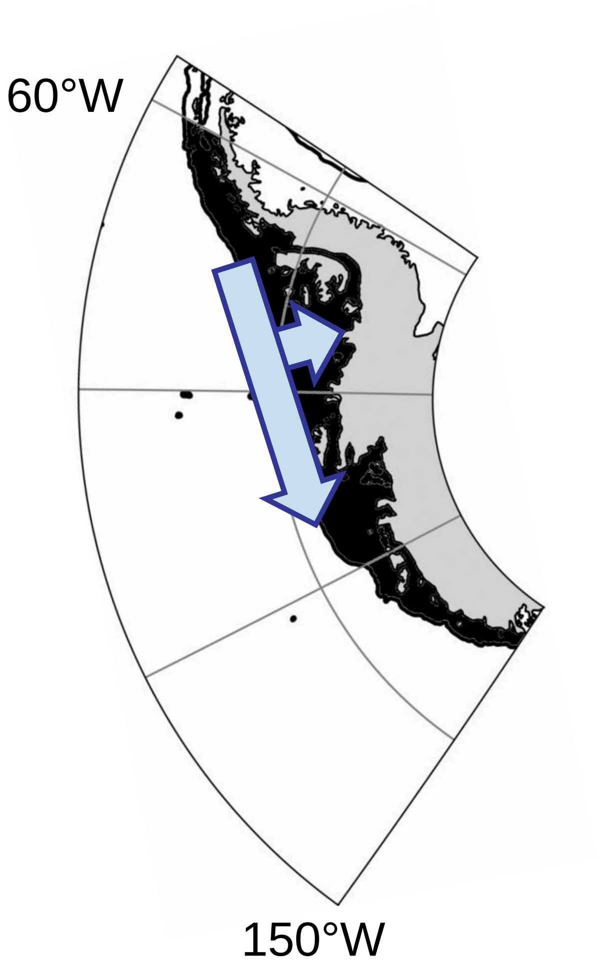

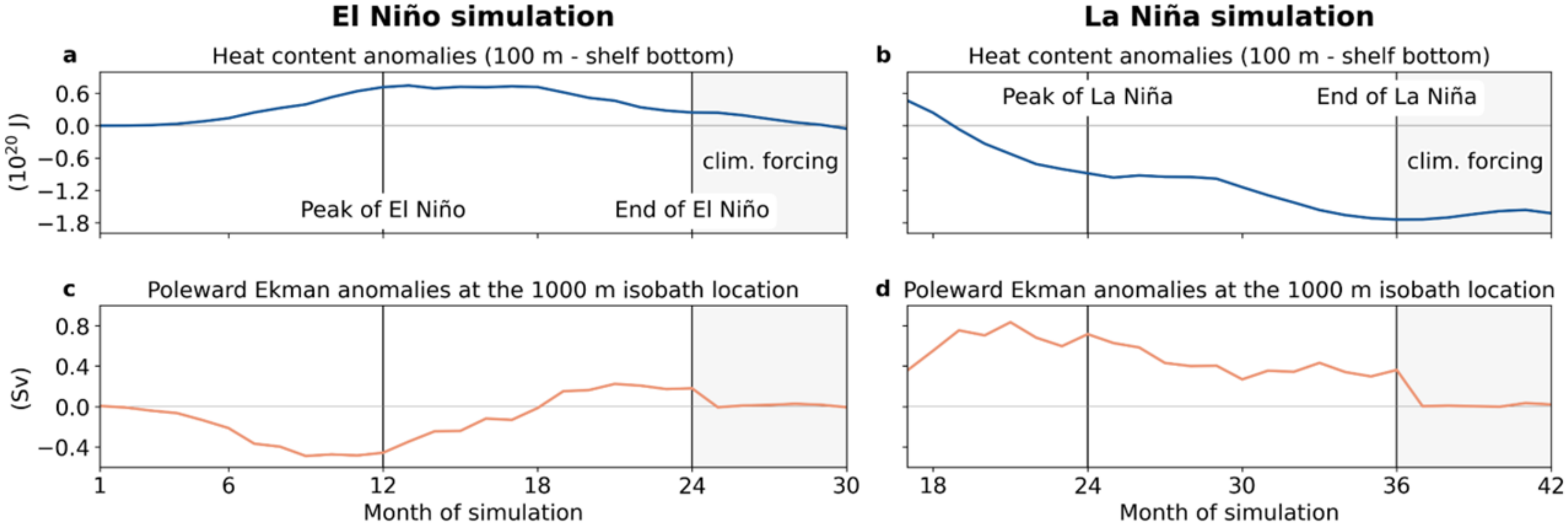

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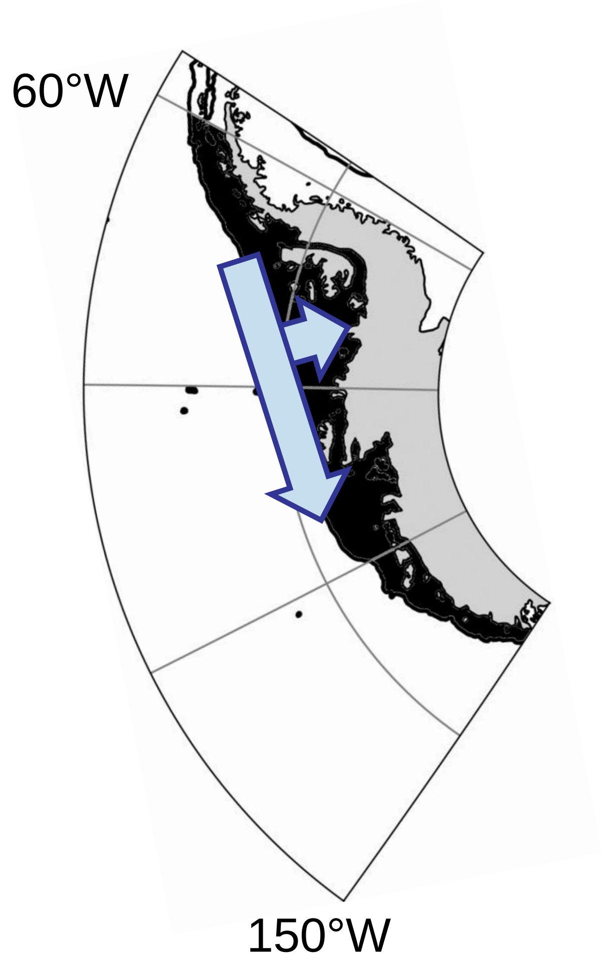

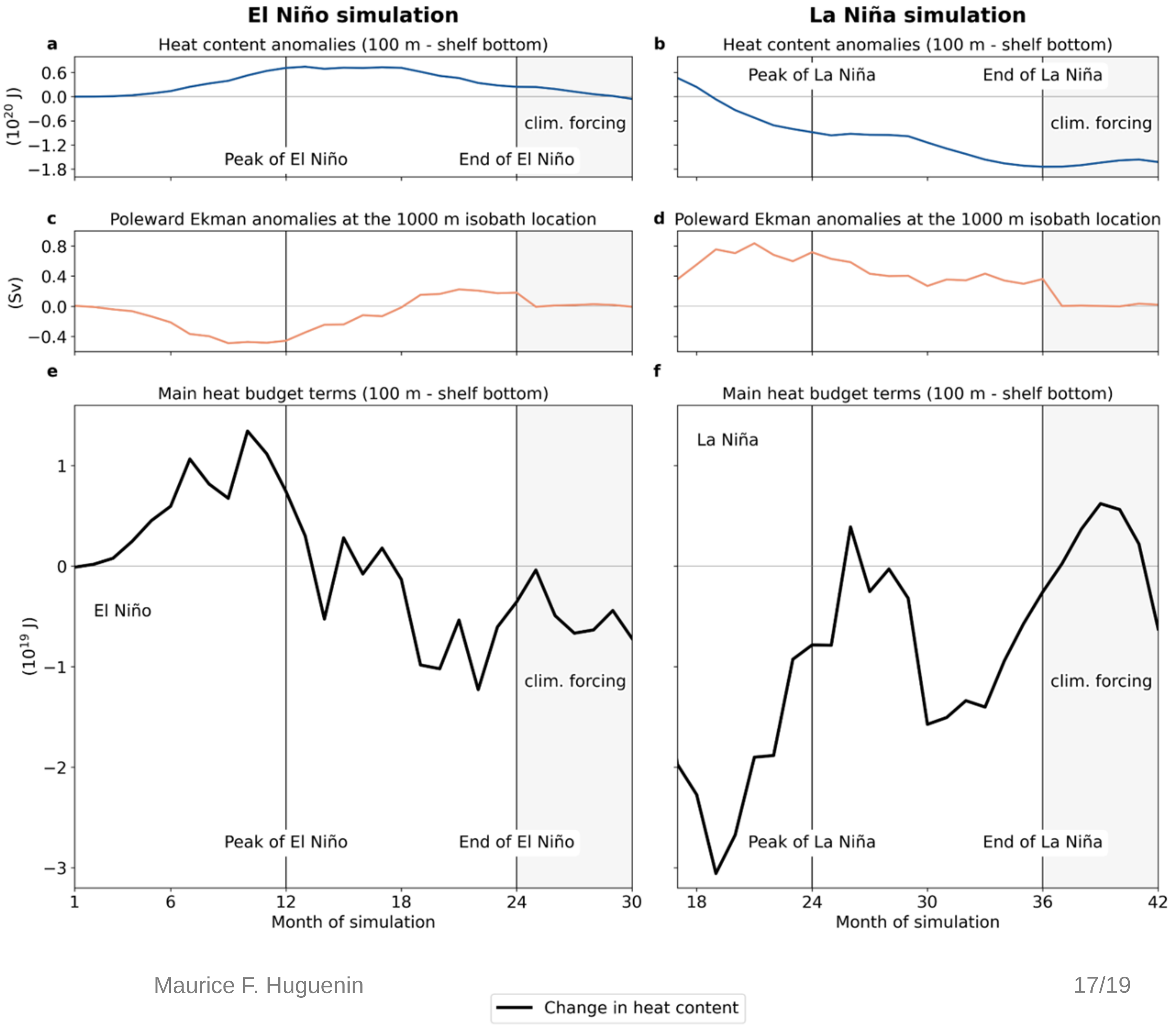

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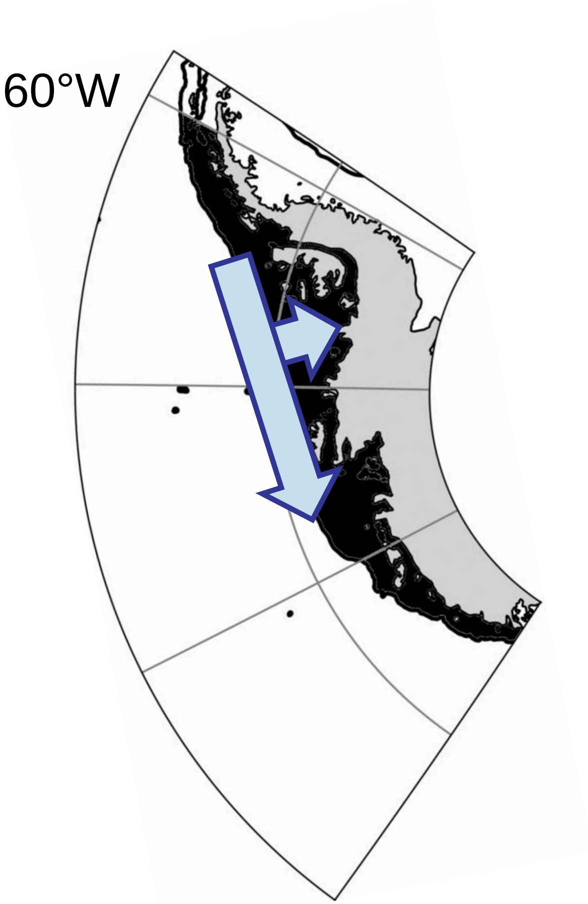

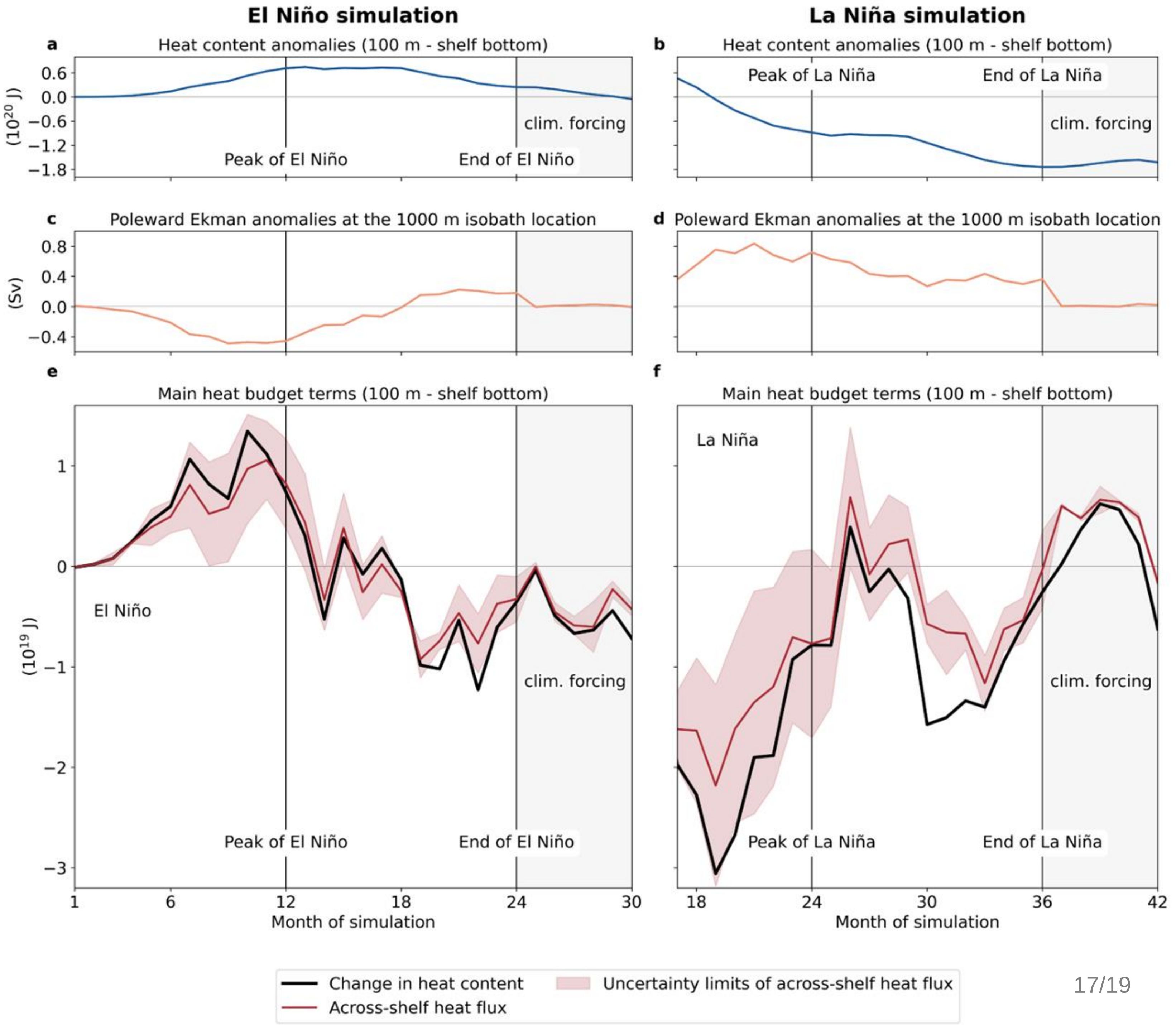

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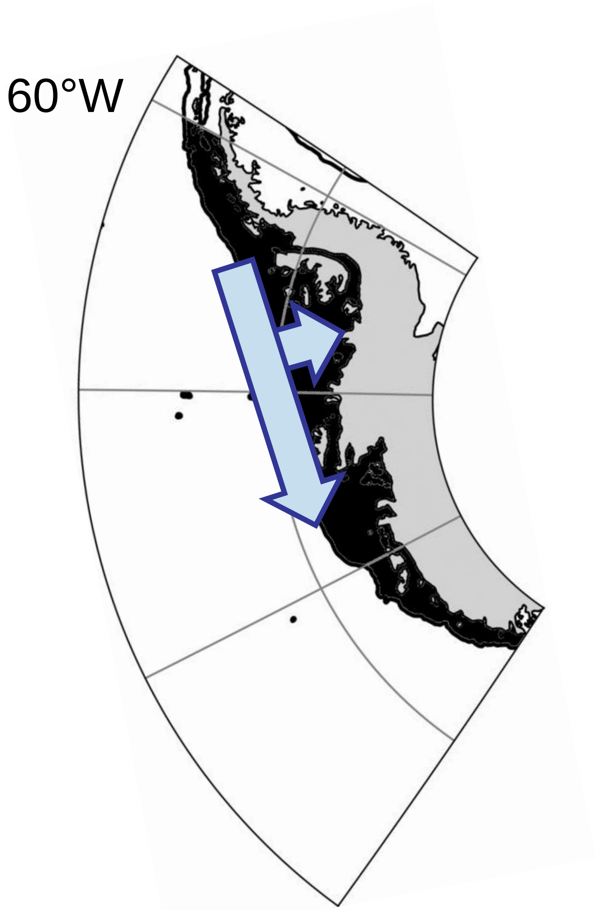

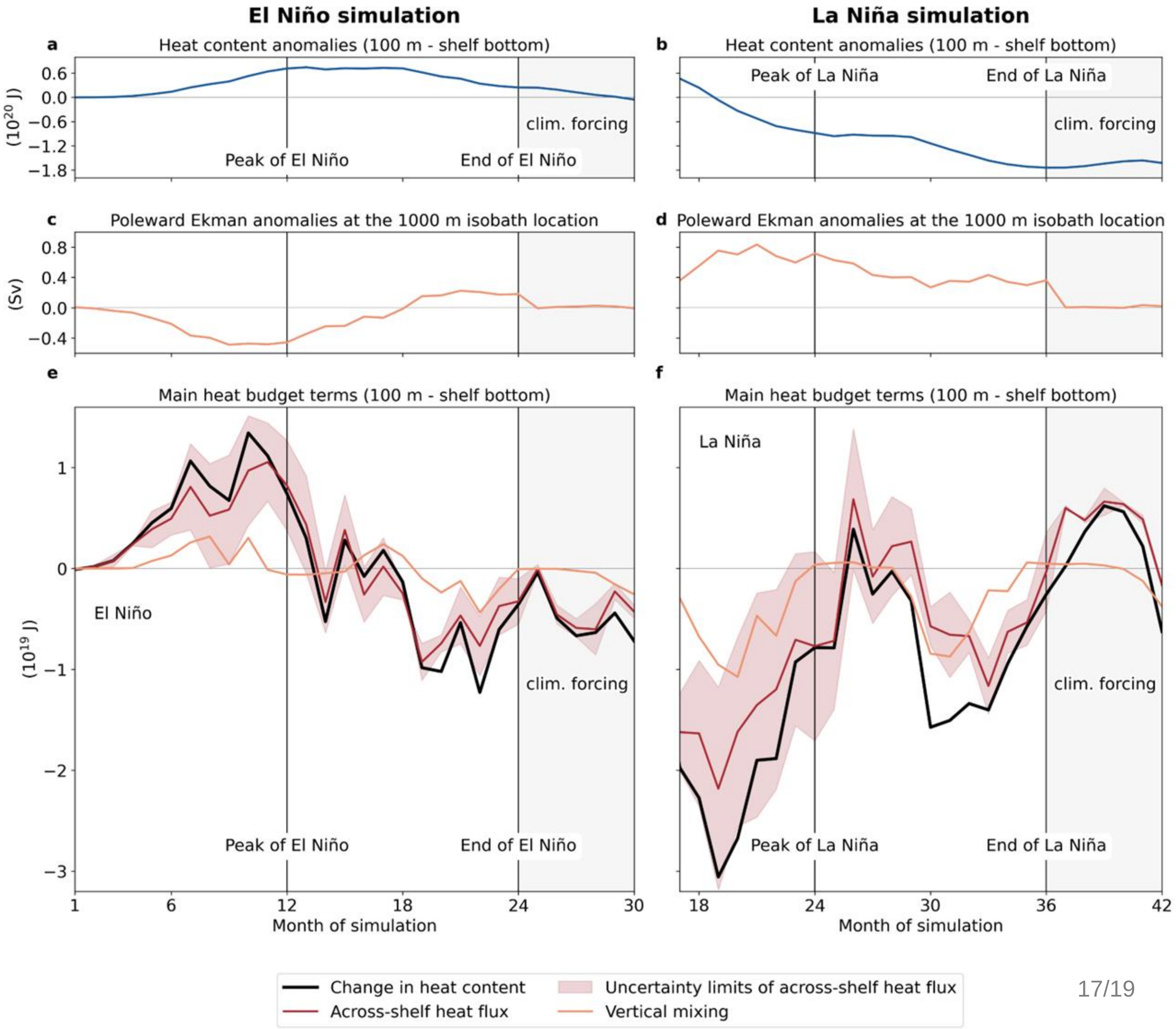

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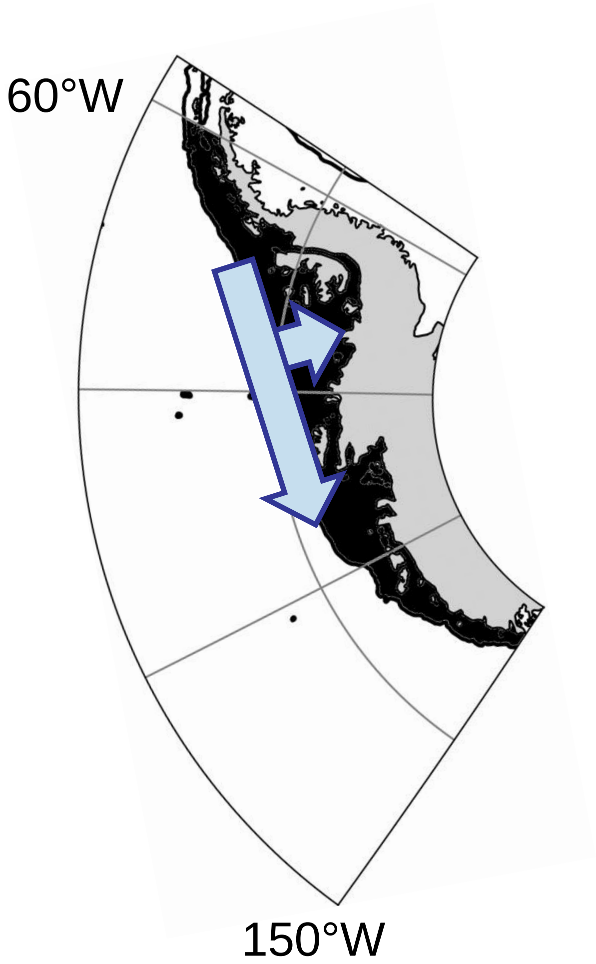
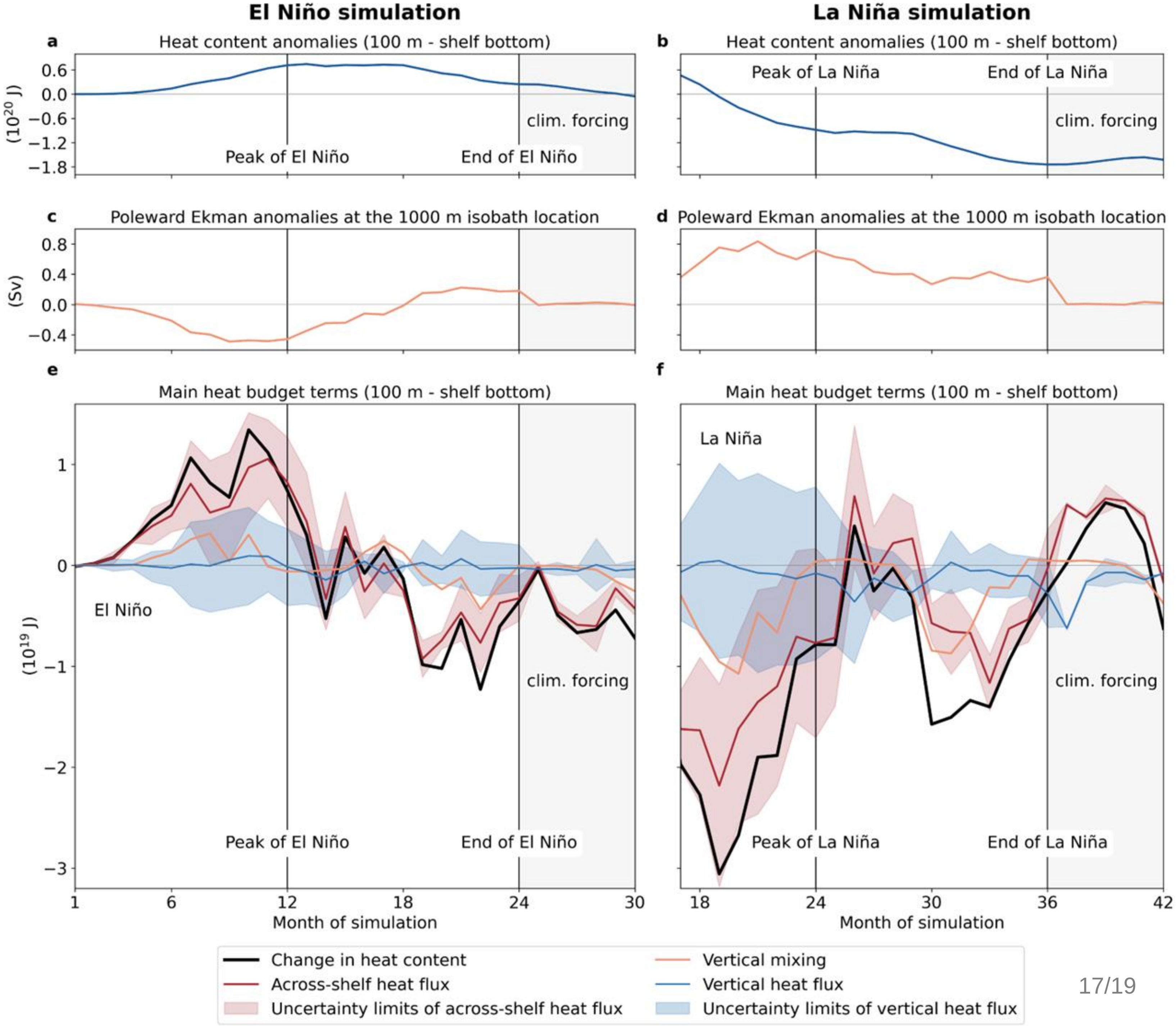
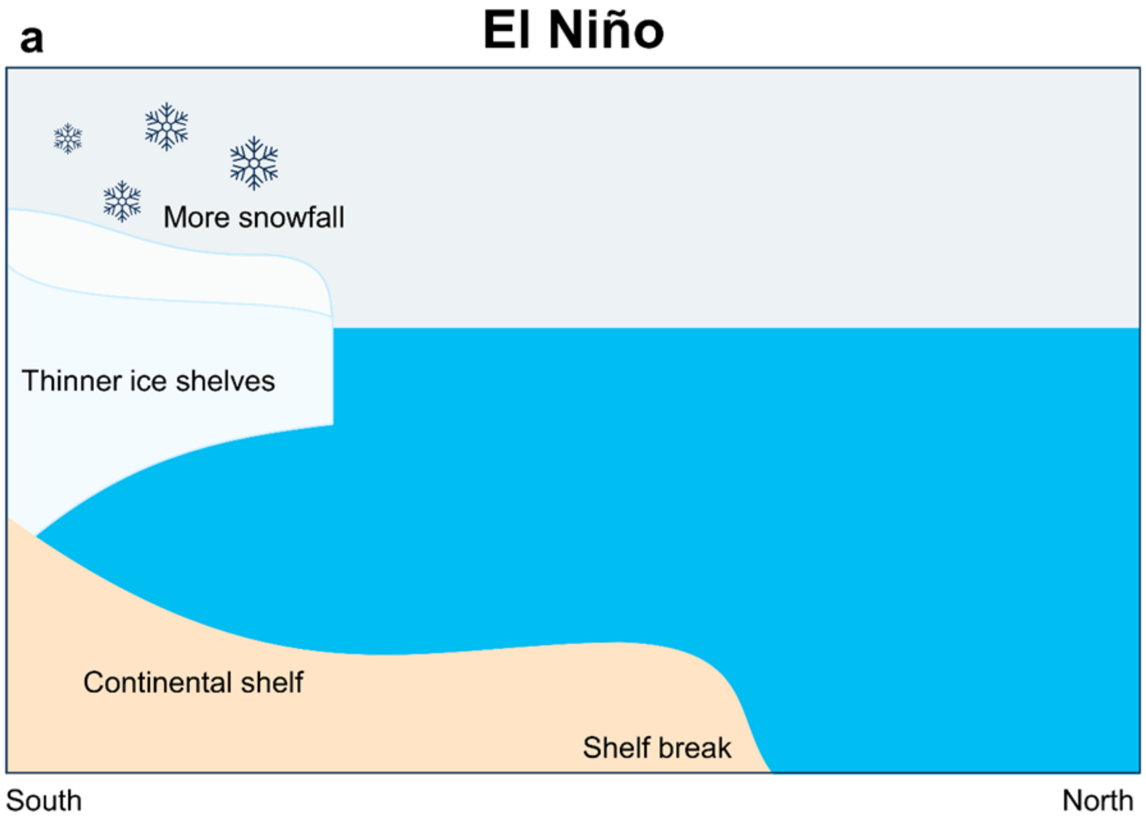
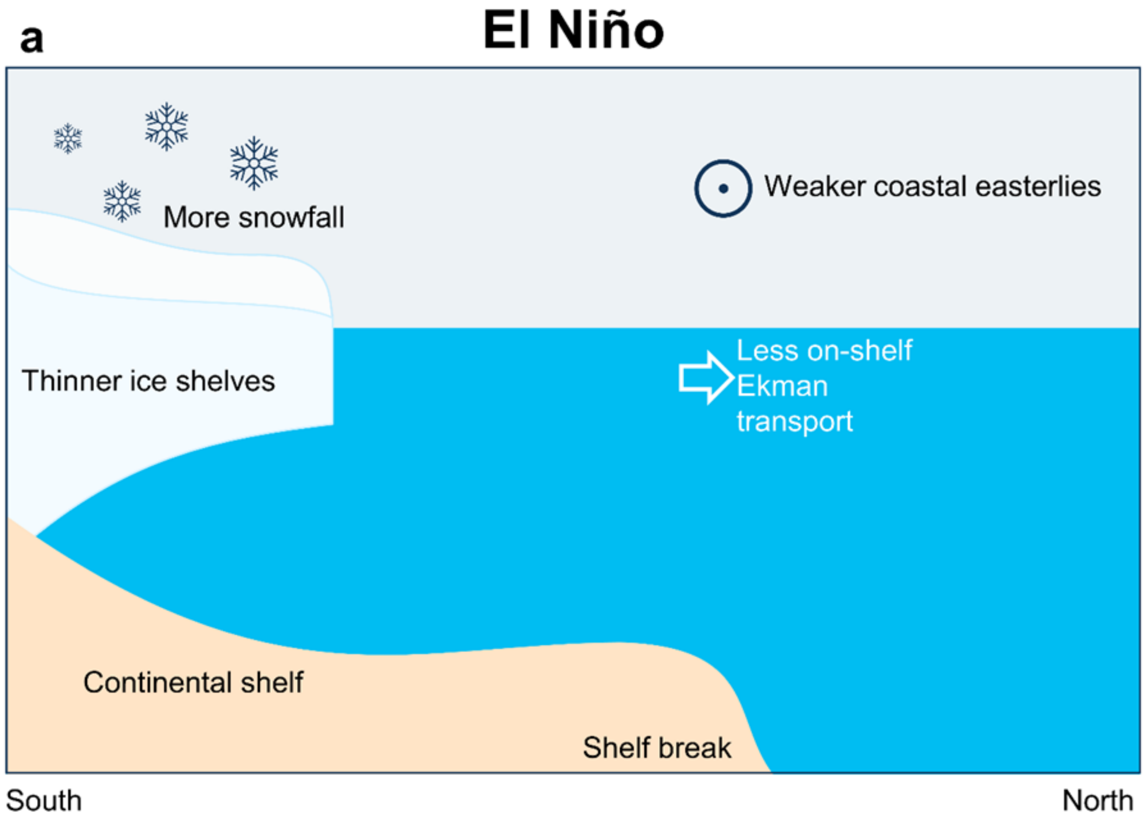




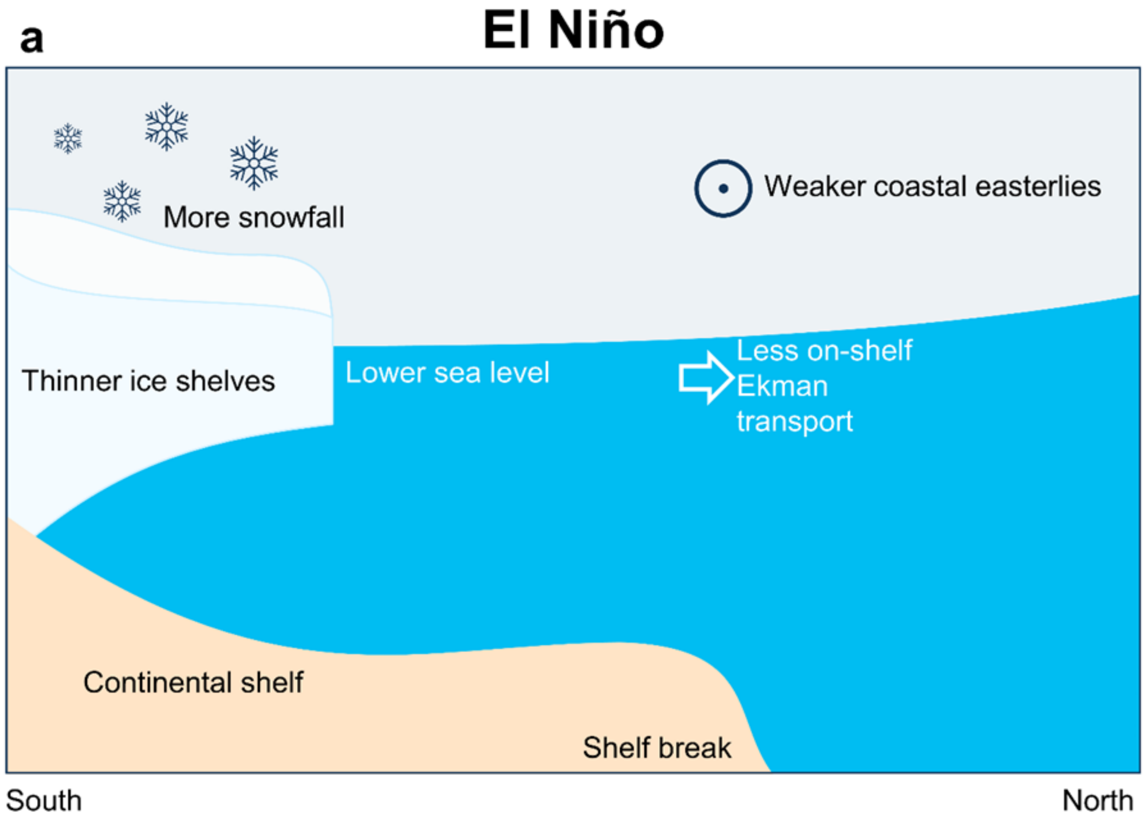
Schematic


a
El Niño
More snowfall
Thinner ice shelves
Continental shelf
Shelf break
South
North

Schematic


a
El Niño
More snowfall
Weaker coastal easterlies
Thinner ice shelves
Less on-shelf Ekman transport
Continental shelf
Shelf break
South
North

Schematic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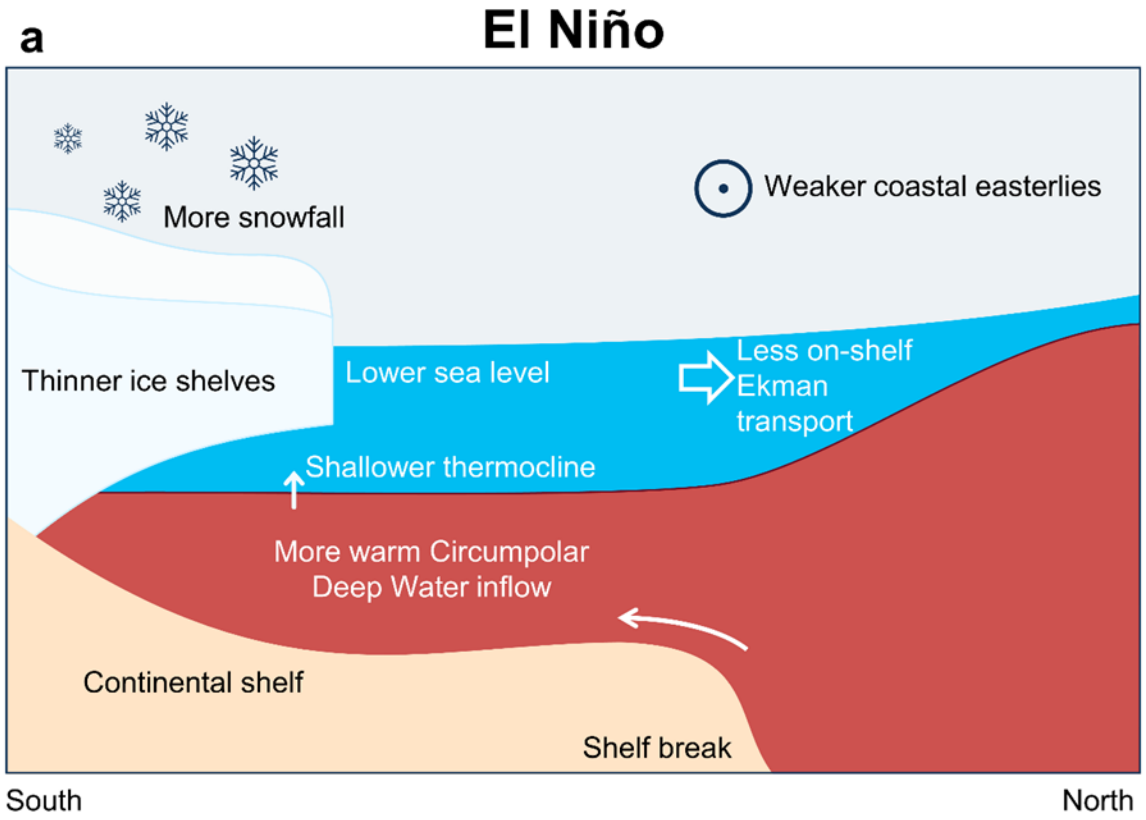
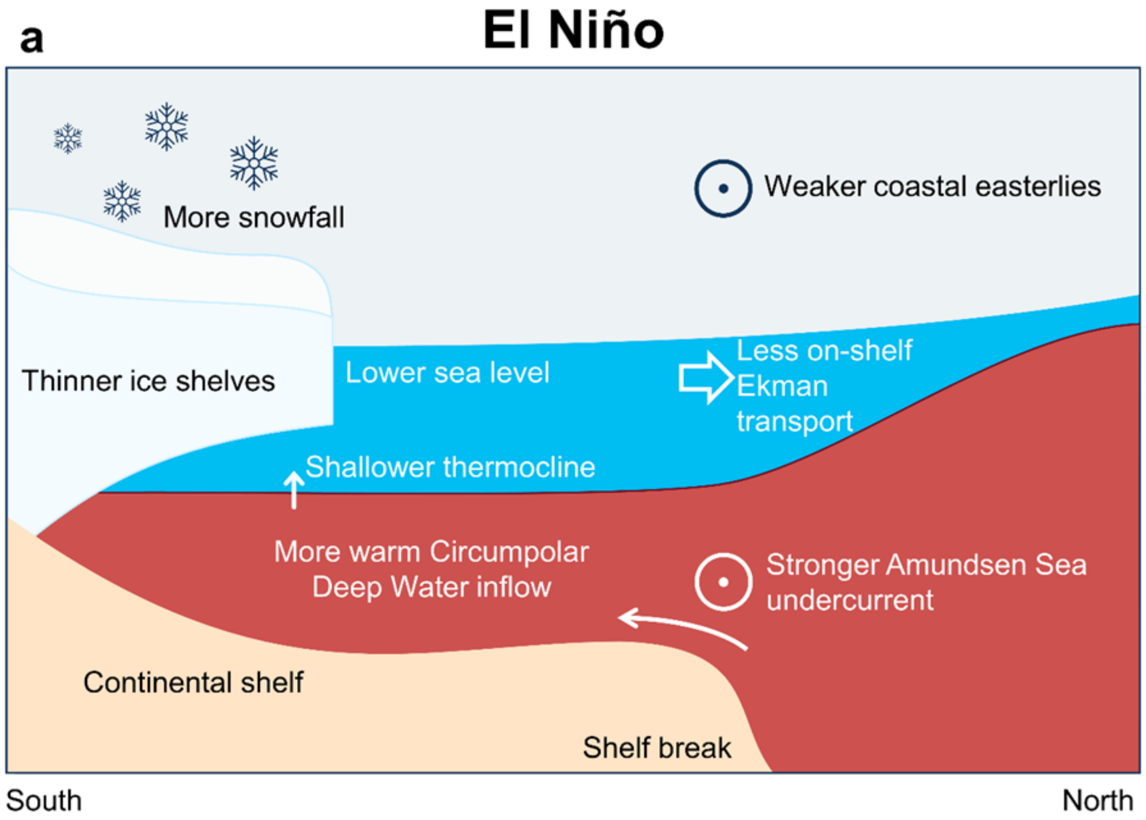


- *bottom Ekman response*
- *baroclinic adjustment*
- *Amundsen Sea undercurrent*
- *eddies*

Schematic



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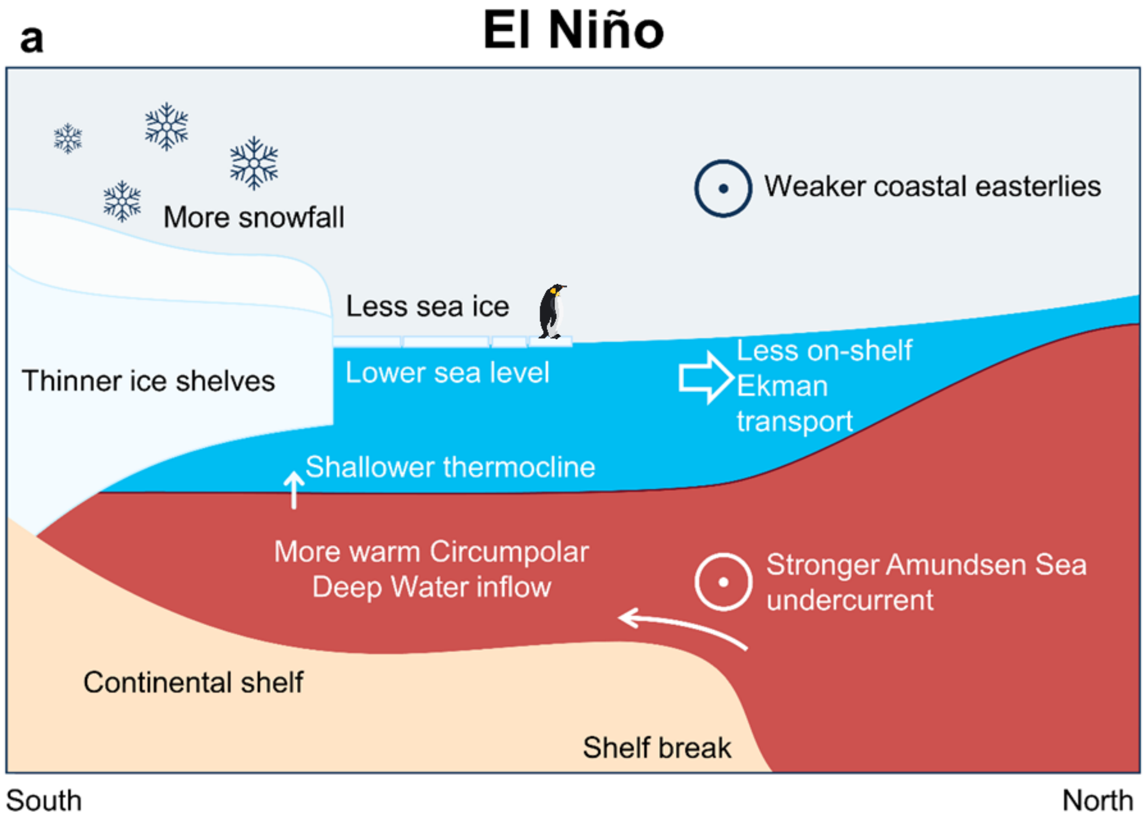

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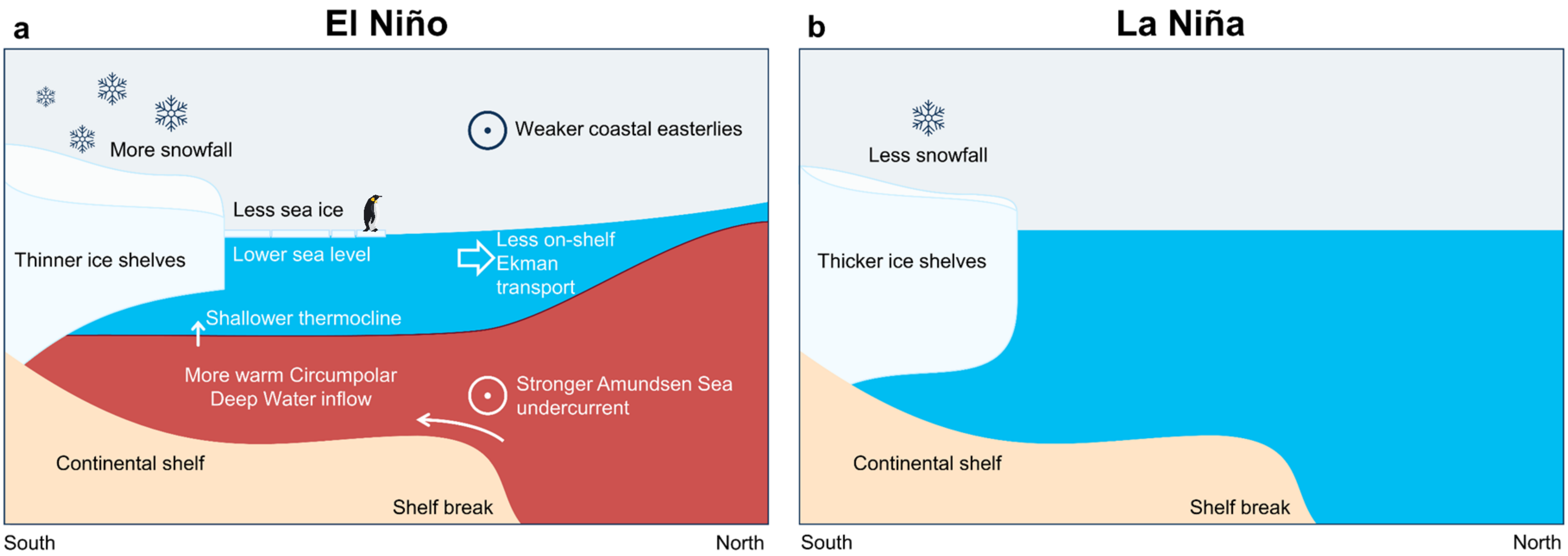

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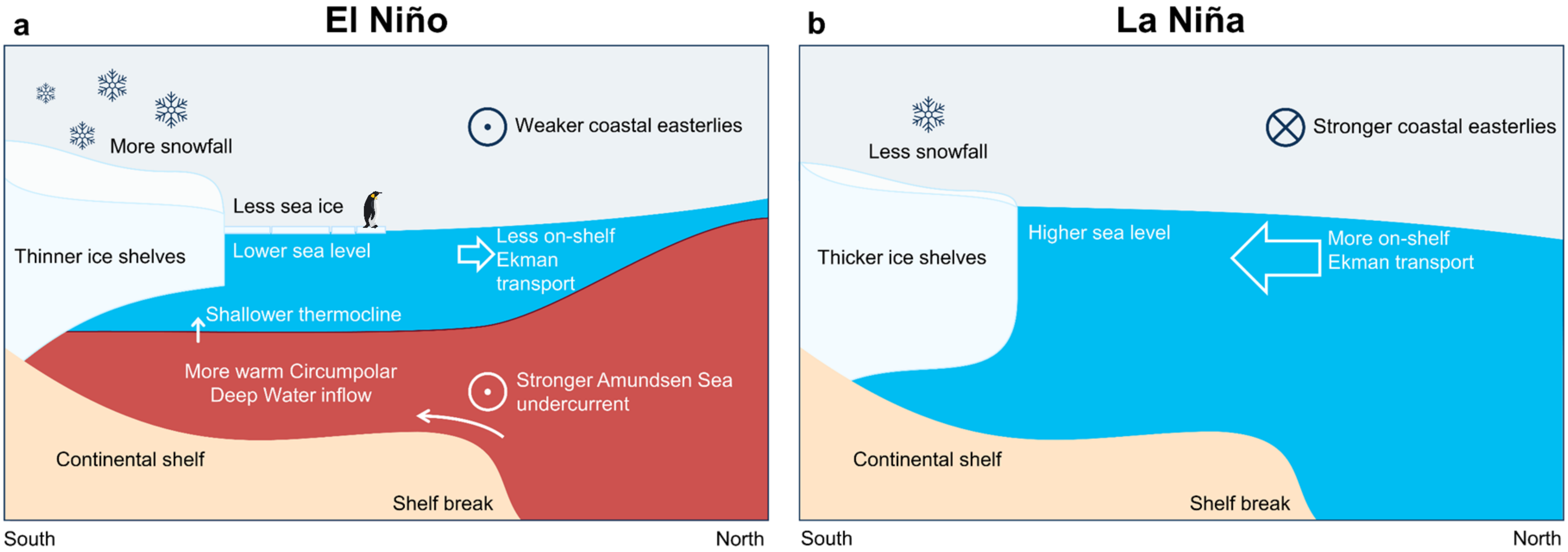

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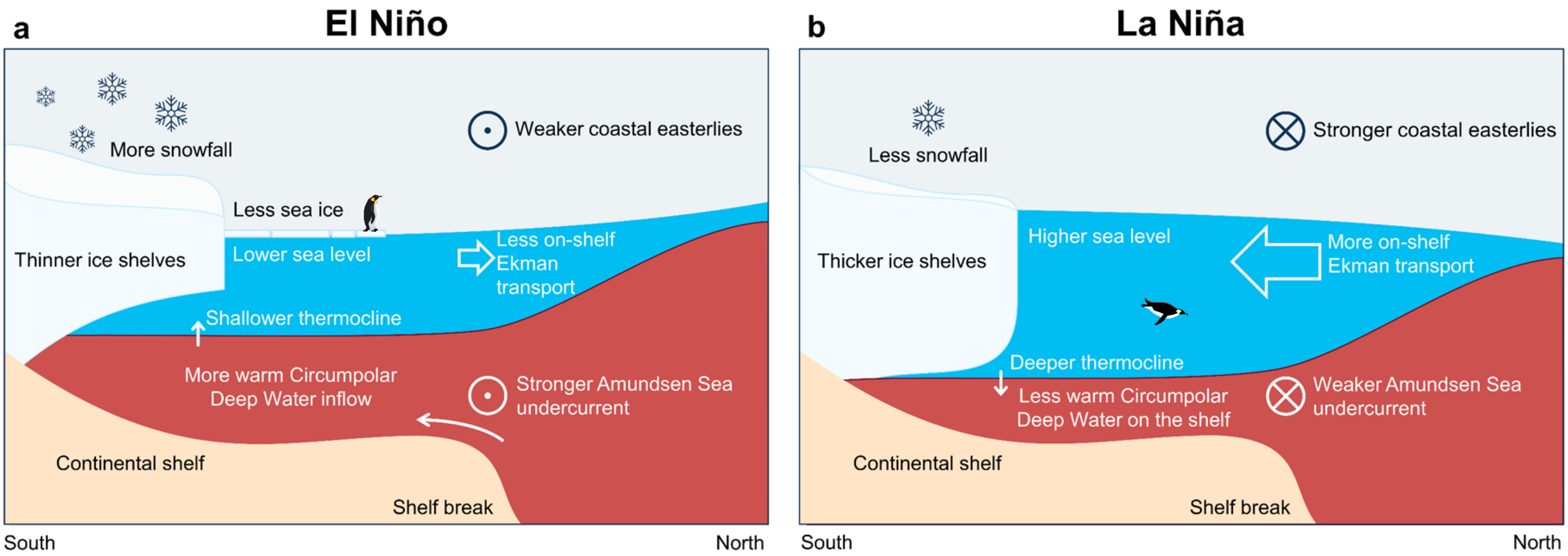

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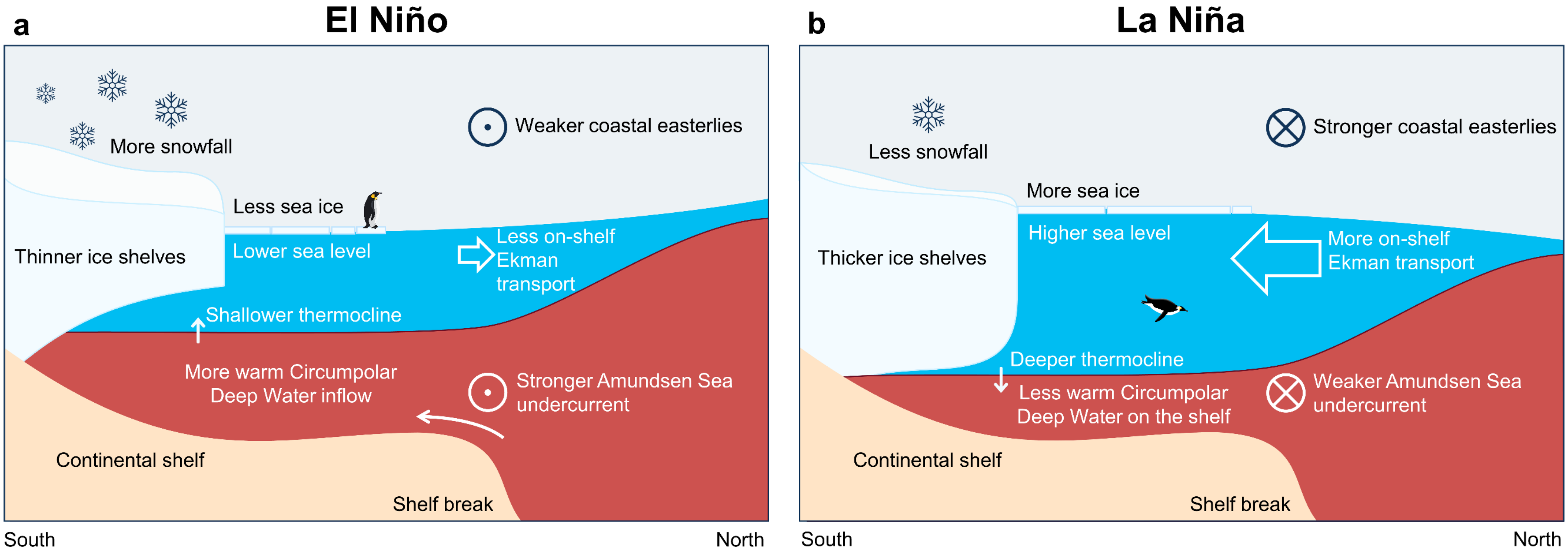

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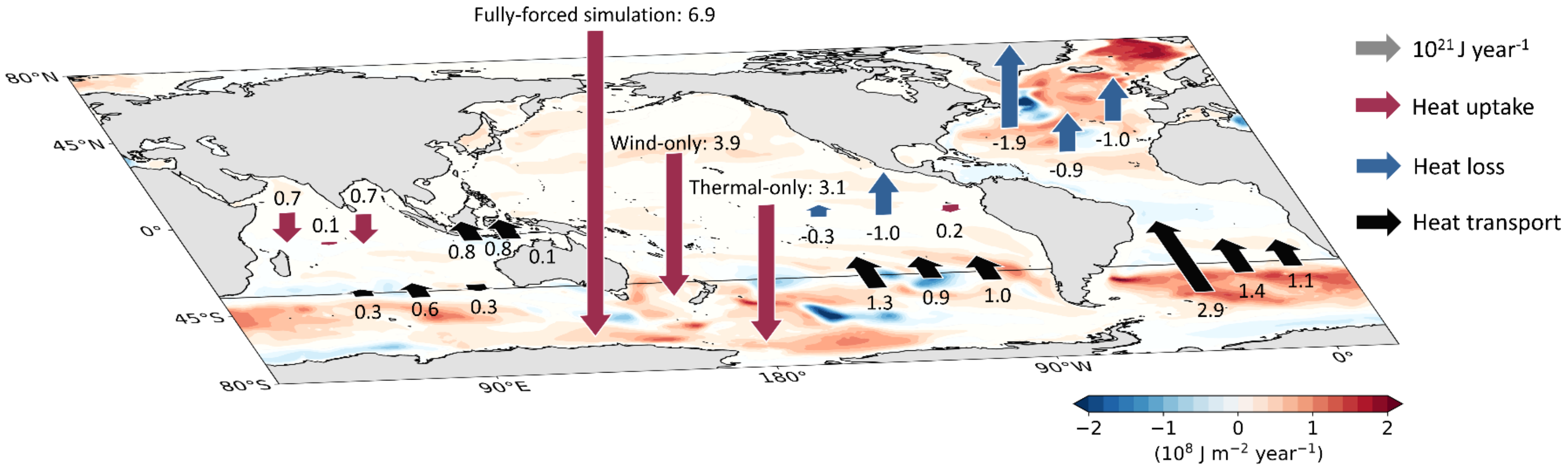
A journey through two research projects

1. **Drivers and distribution of global ocean heat uptake over the last half century**
   (Huguenin et al. 2022, Nat. Comms.)



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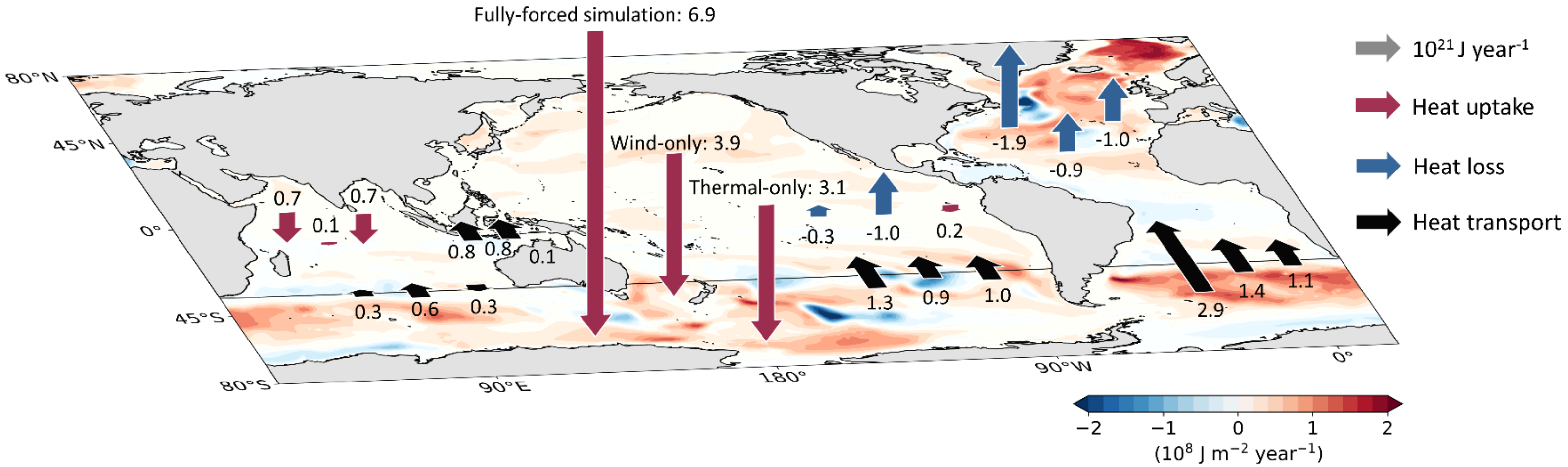
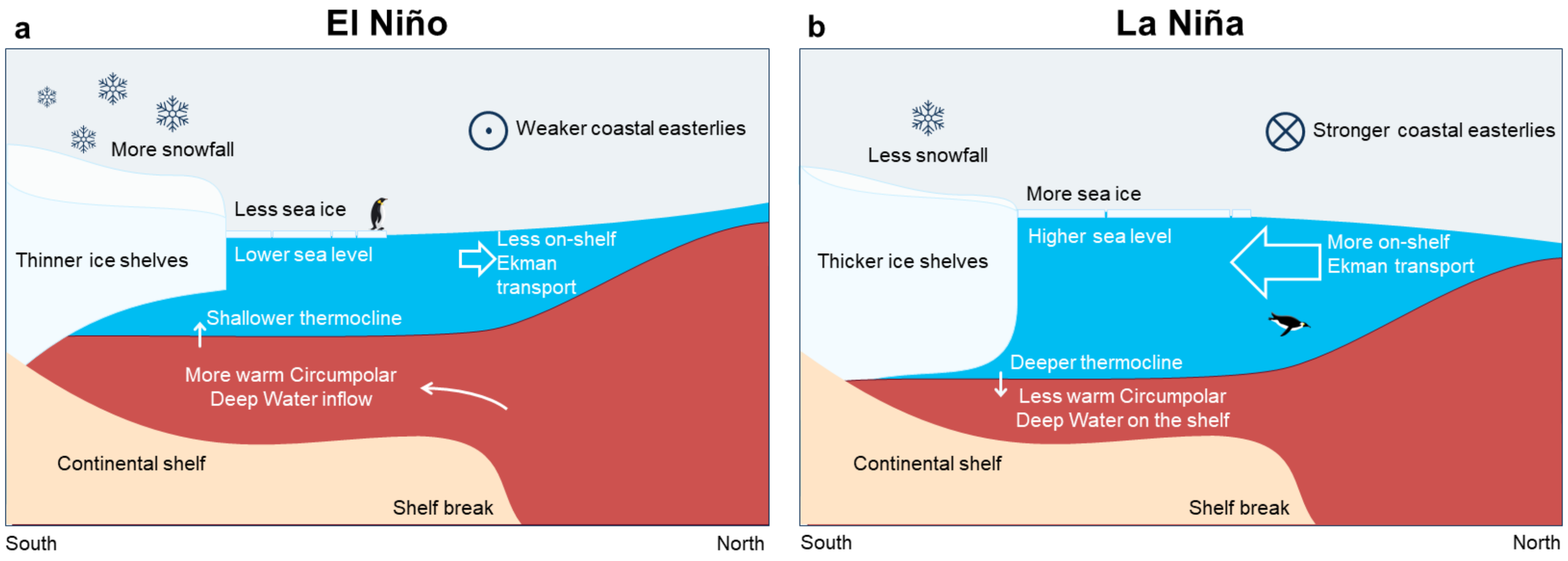


2. **Subsurface warming of West Antarctic coastal waters linked to El Niño events**
   (Huguenin et al., 2020, J. Clim.)



...but wait, there’s more!

Linking the recent decrease in Weddell Sea dense shelf water to changes in the IPO

Maurice F. Huguenin, Svenja Ryan, Caroline Ummenhofer and Matthew H. England, *in preparation.*

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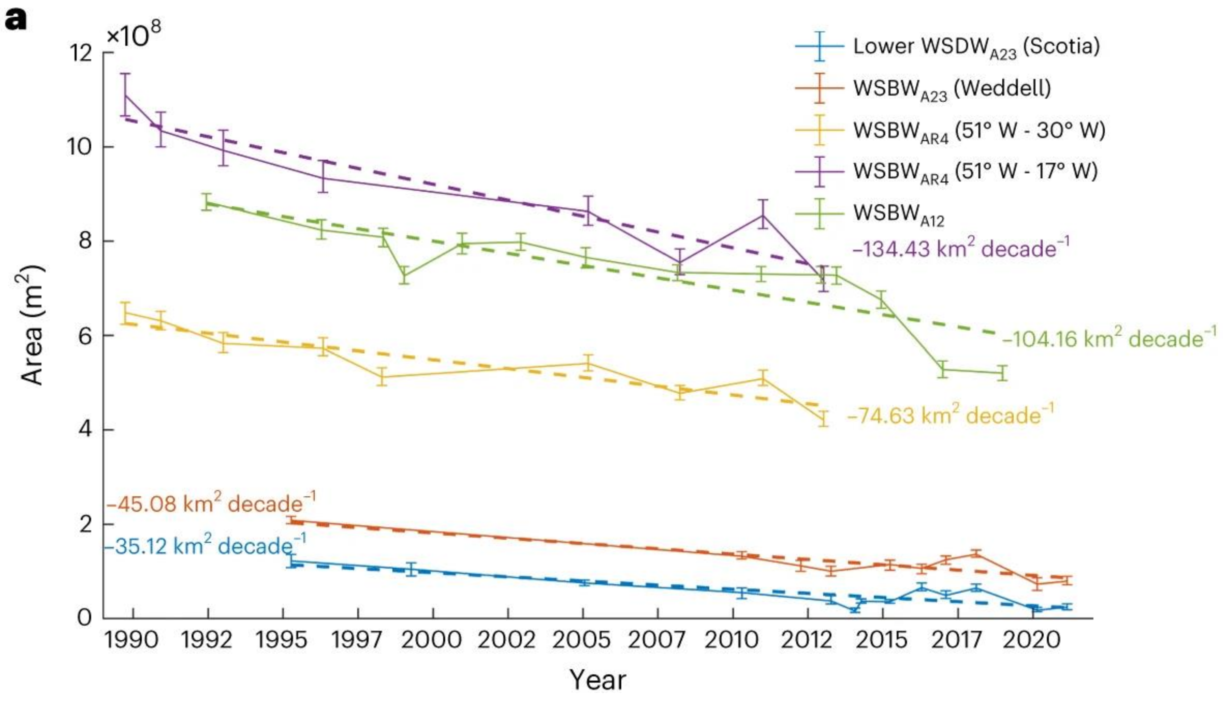
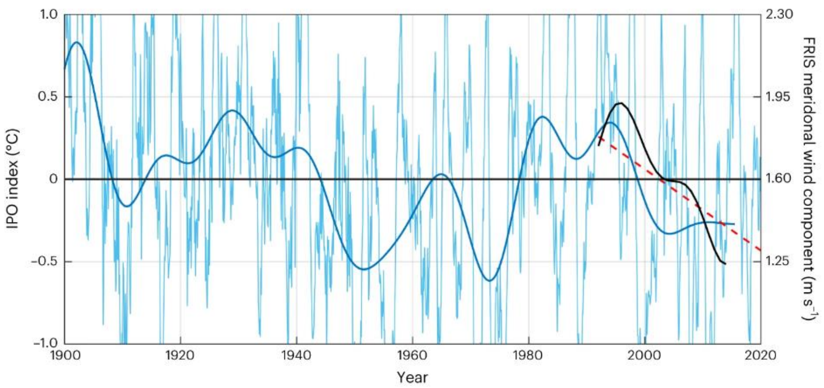
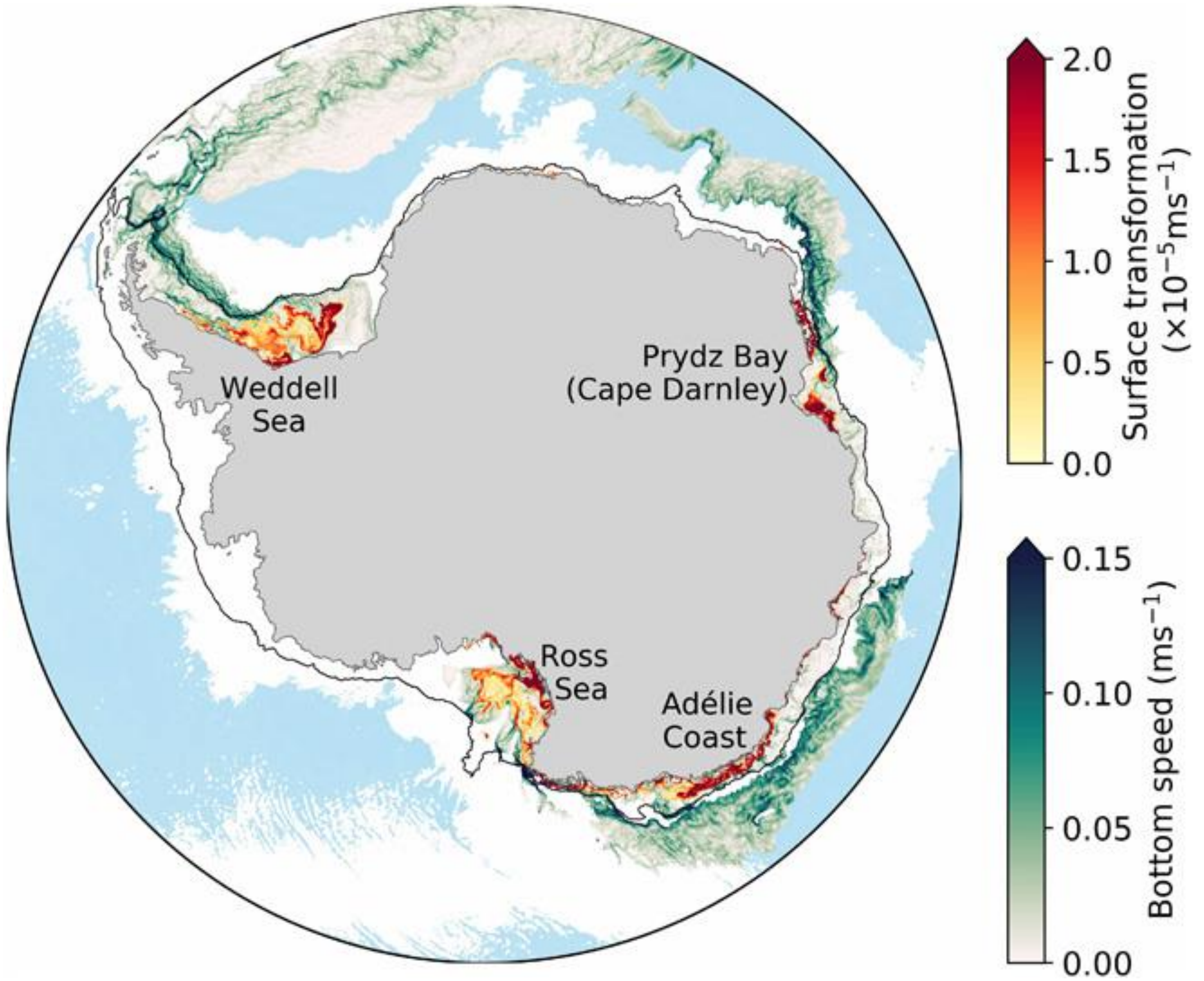
- Zhuo et al. (2023)

- water-mass area along three hydrographic transects
- observed 30% reduction of Weddell Sea Bottom Water volume since 1992





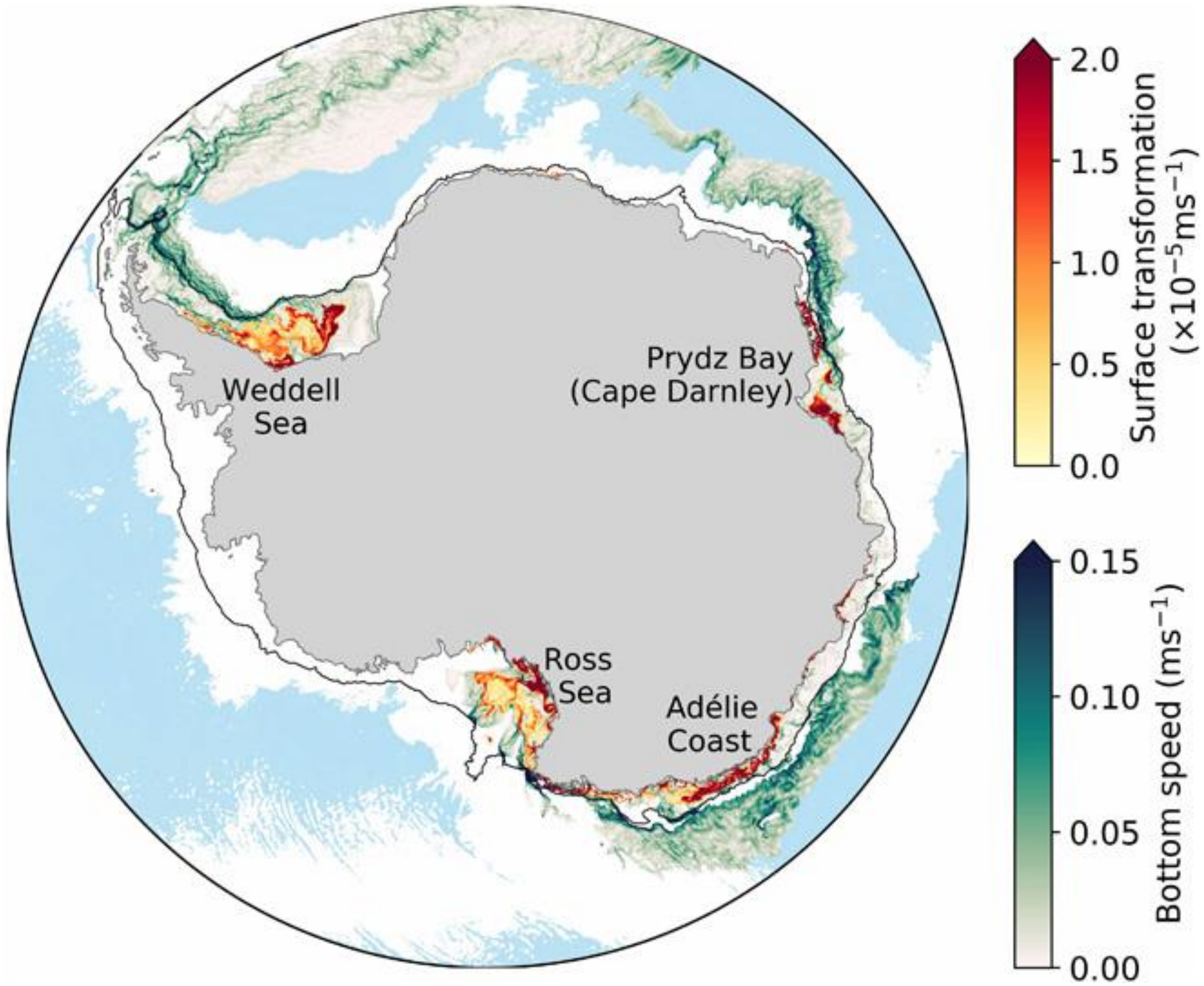
Surface water mass transformation



Morrison et al. (2019)

Surface water mass transformation

Surface water-mass transformation may be defined as the volume flux into a given density class (σ) from lighter density classes (σ′ < σ) due to surface buoyancy forcing.



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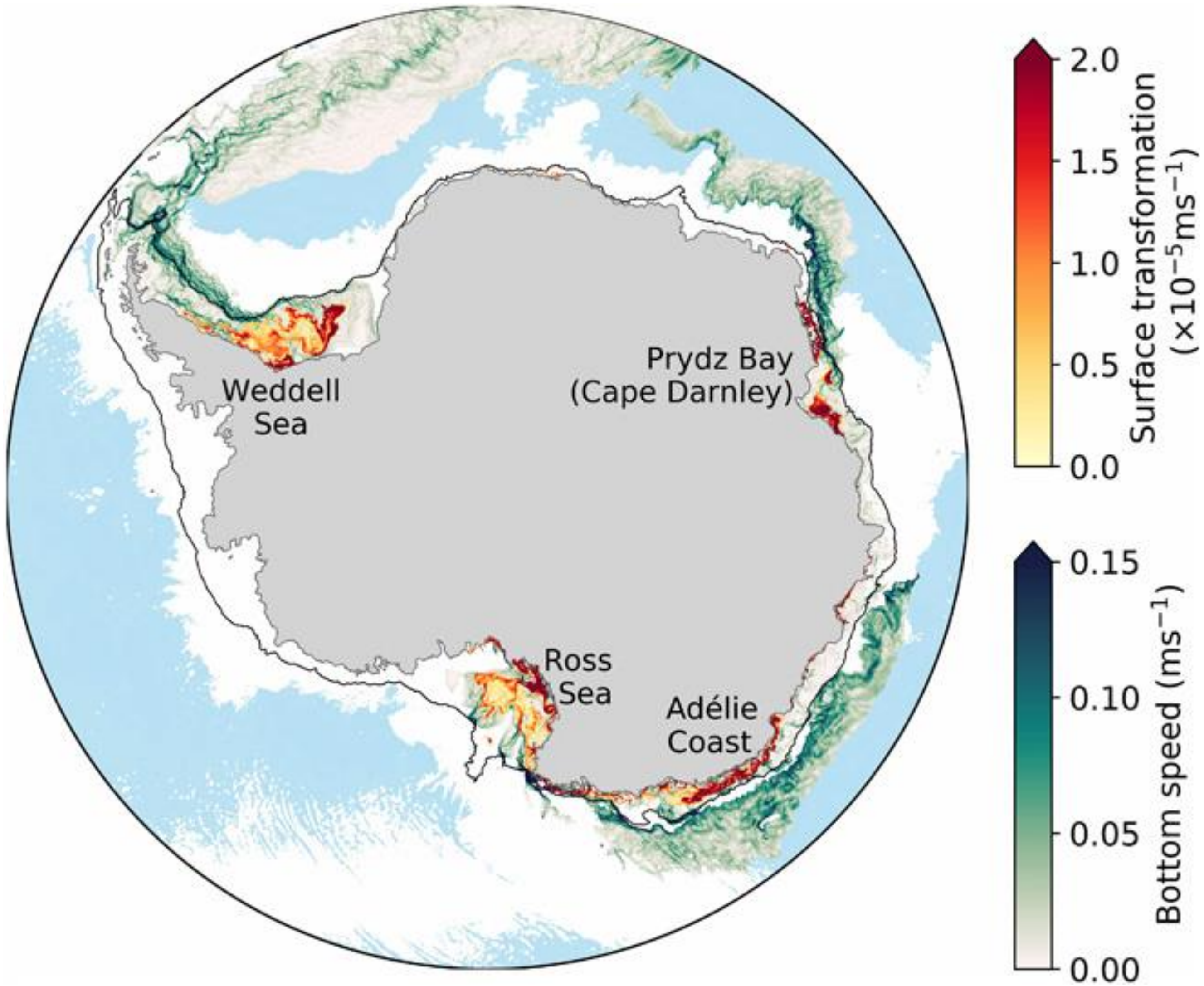
https://cosima-recipes.readthedocs.io/en/latest/index.html



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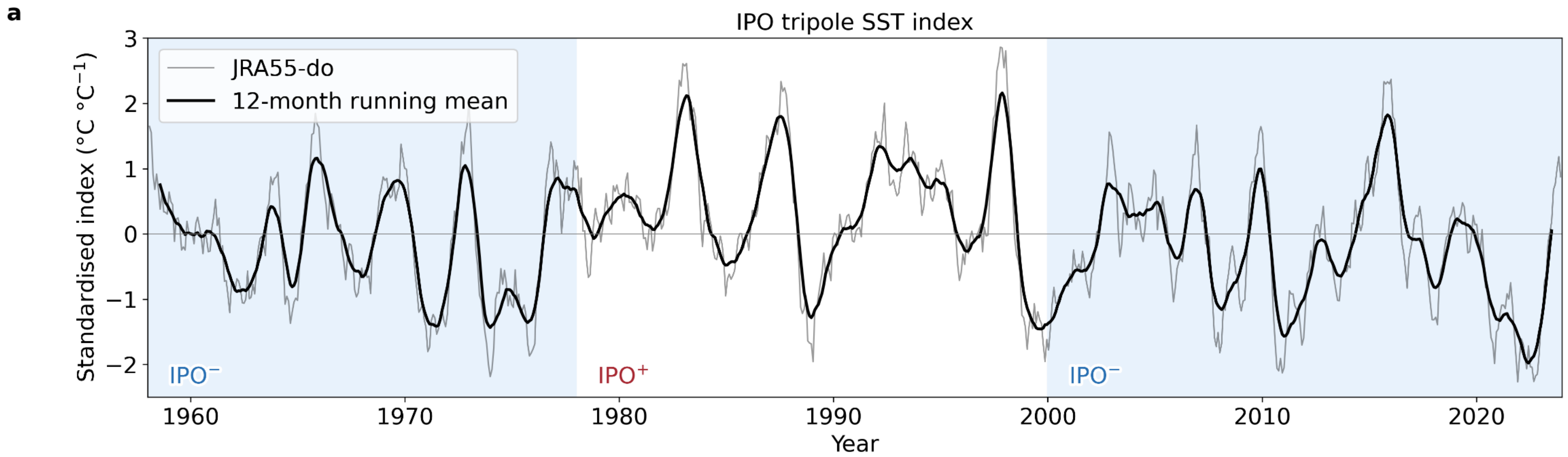
Experimental setup



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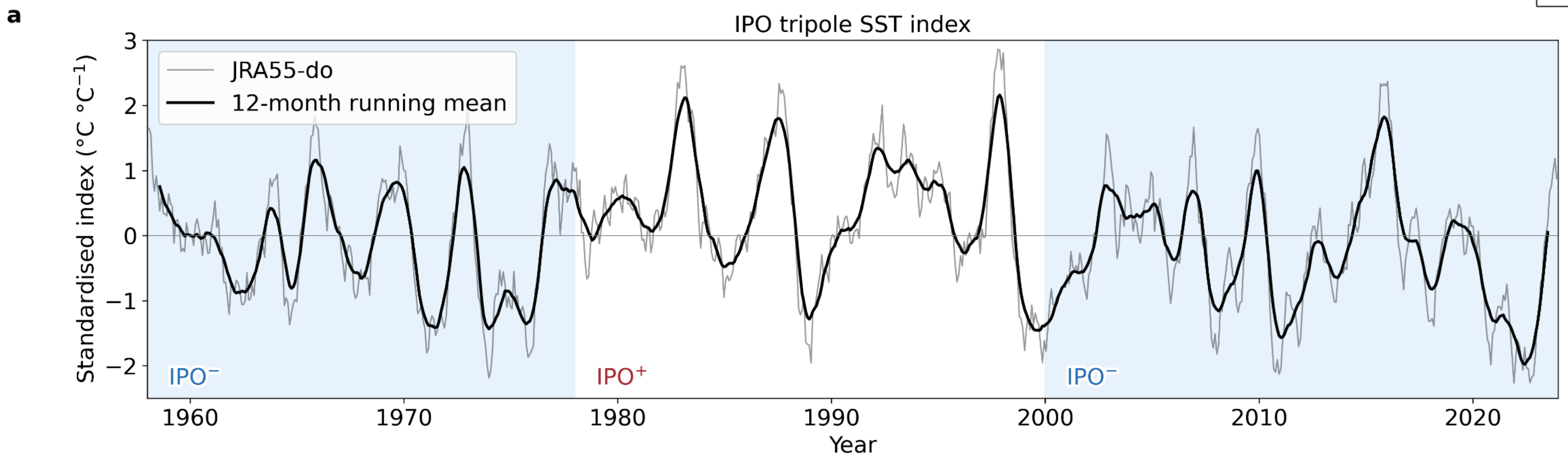

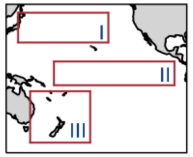

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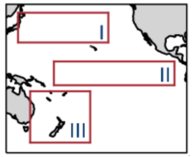

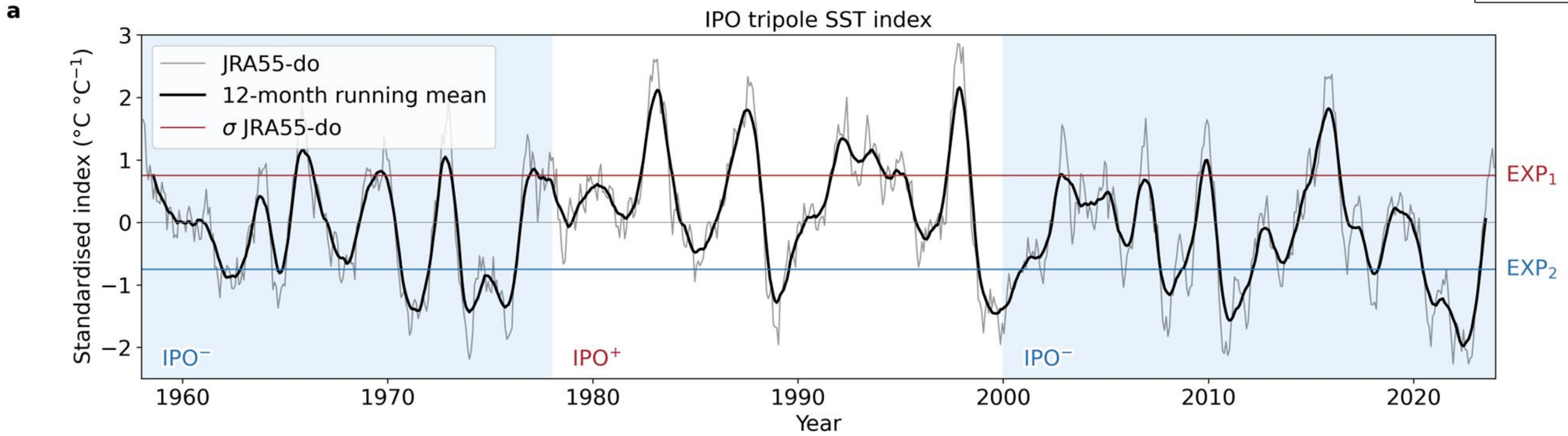

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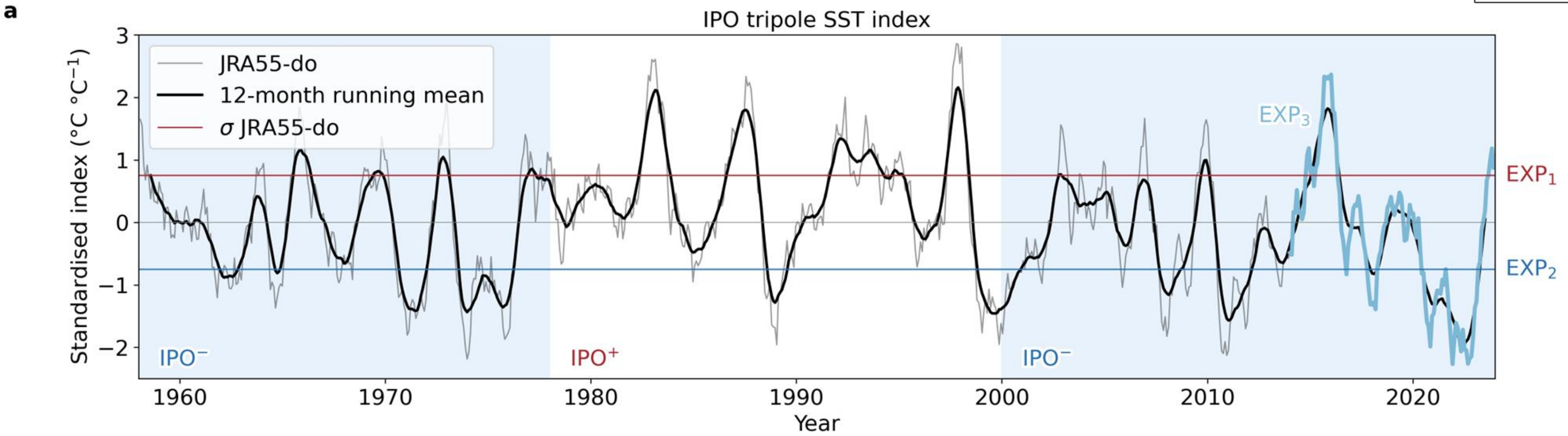

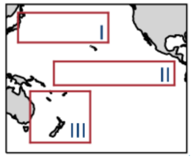

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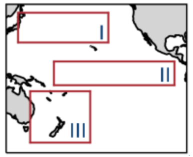

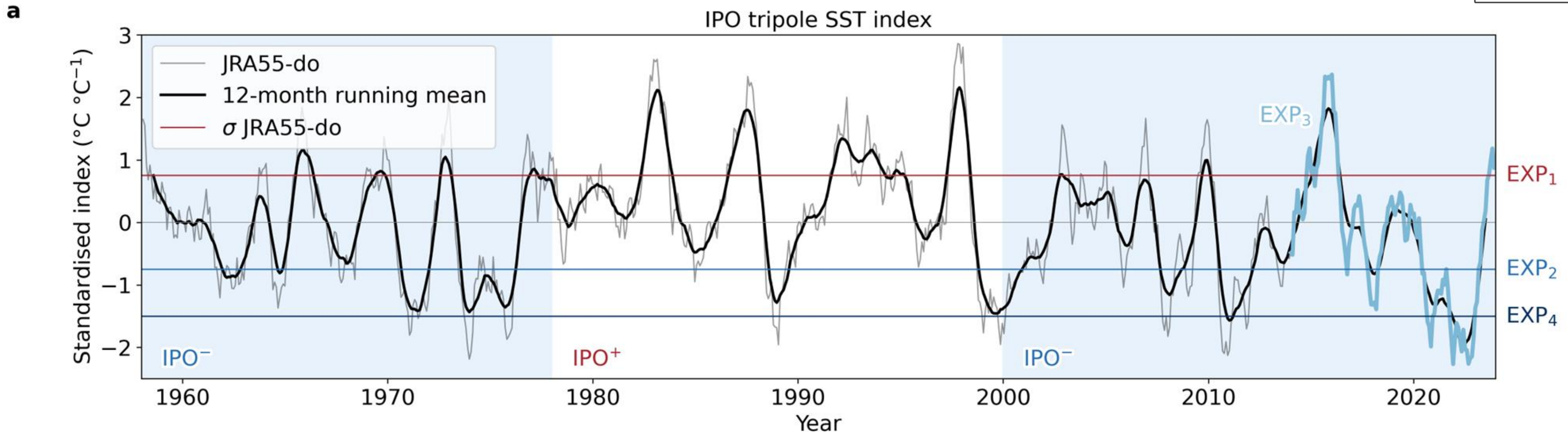

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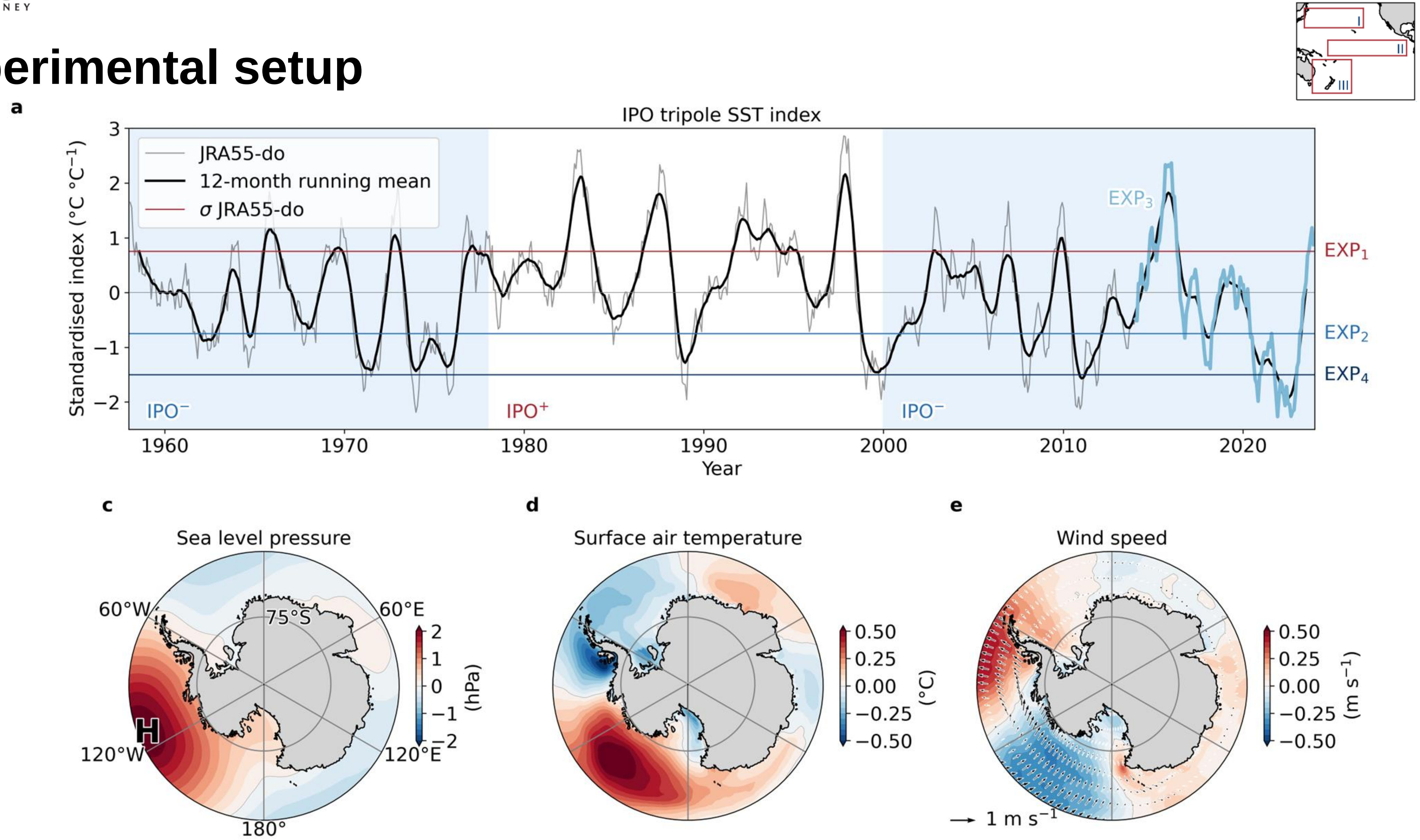

IPO changes in dense shelf water formation

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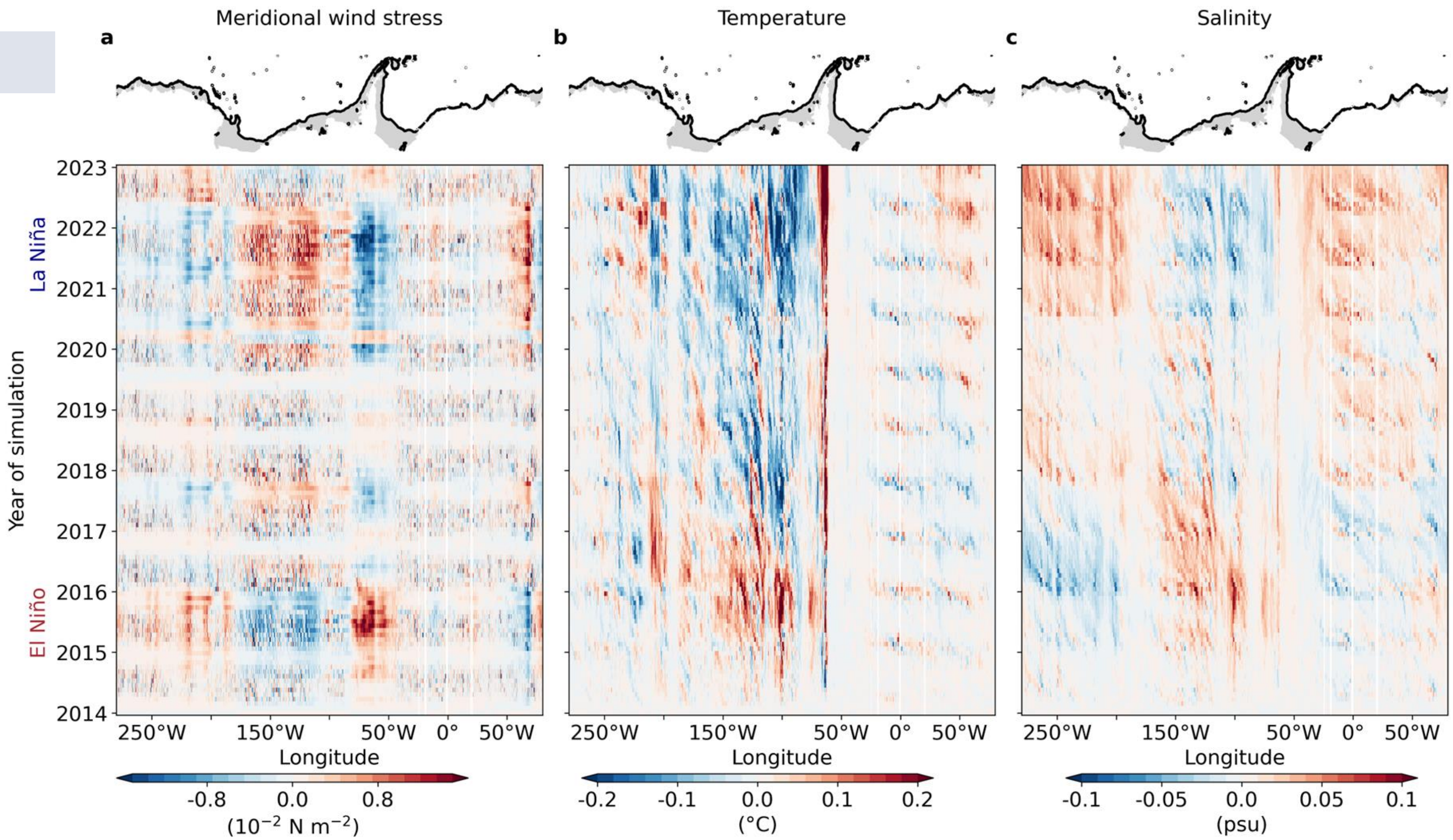
Interannual simulation



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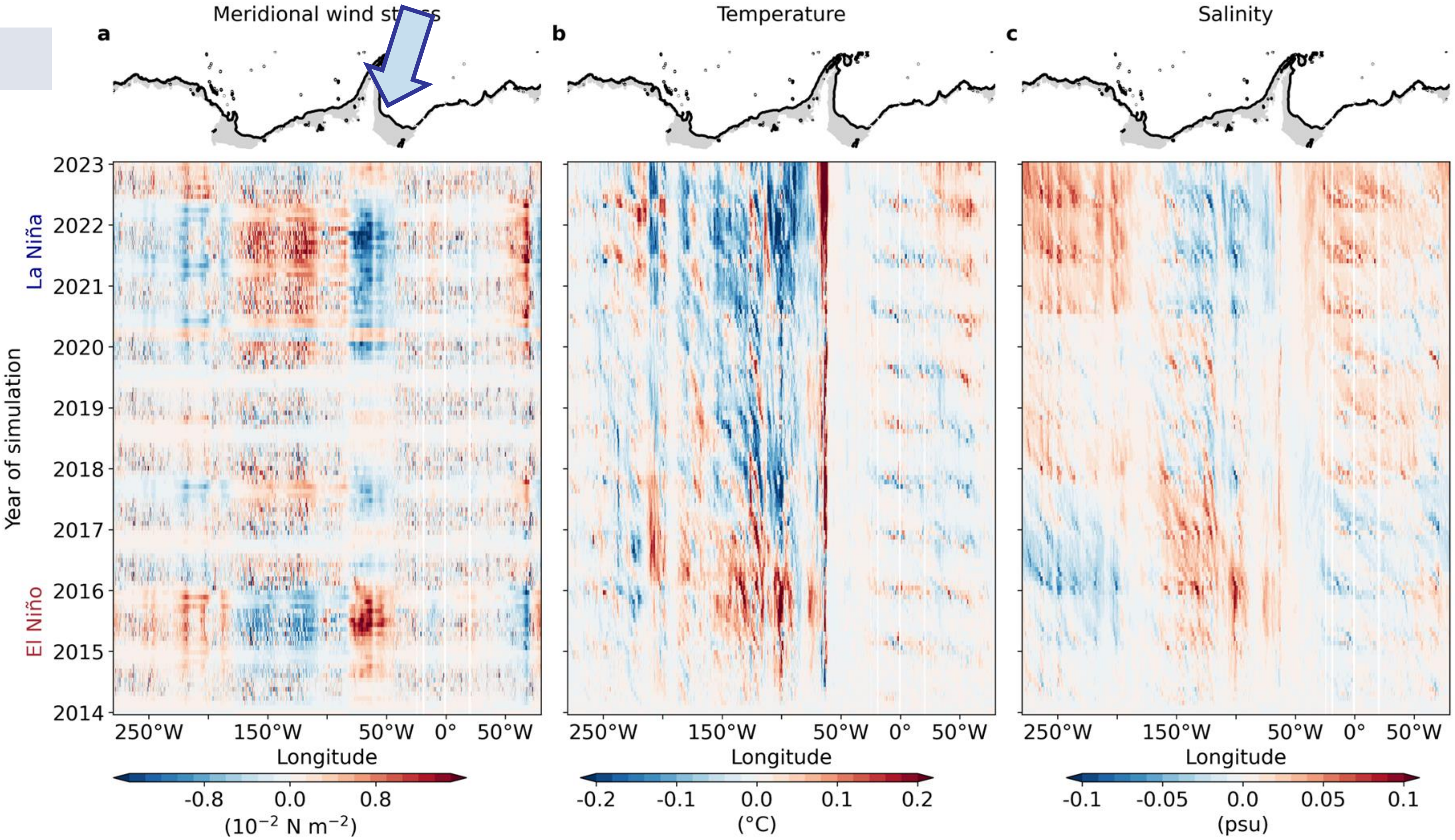
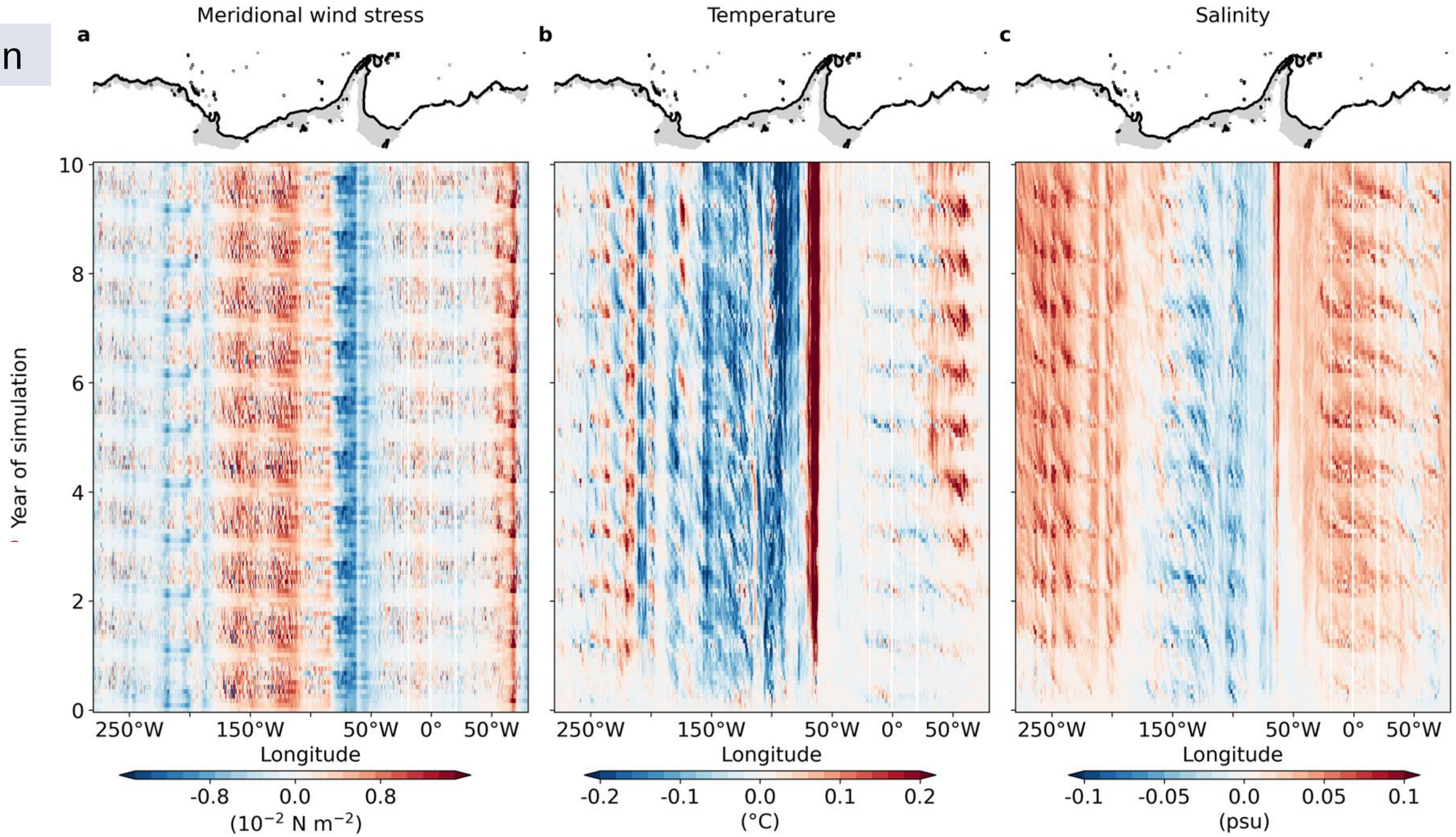


IPO changes in dense shelf water formation

2σ negative IPO simulation



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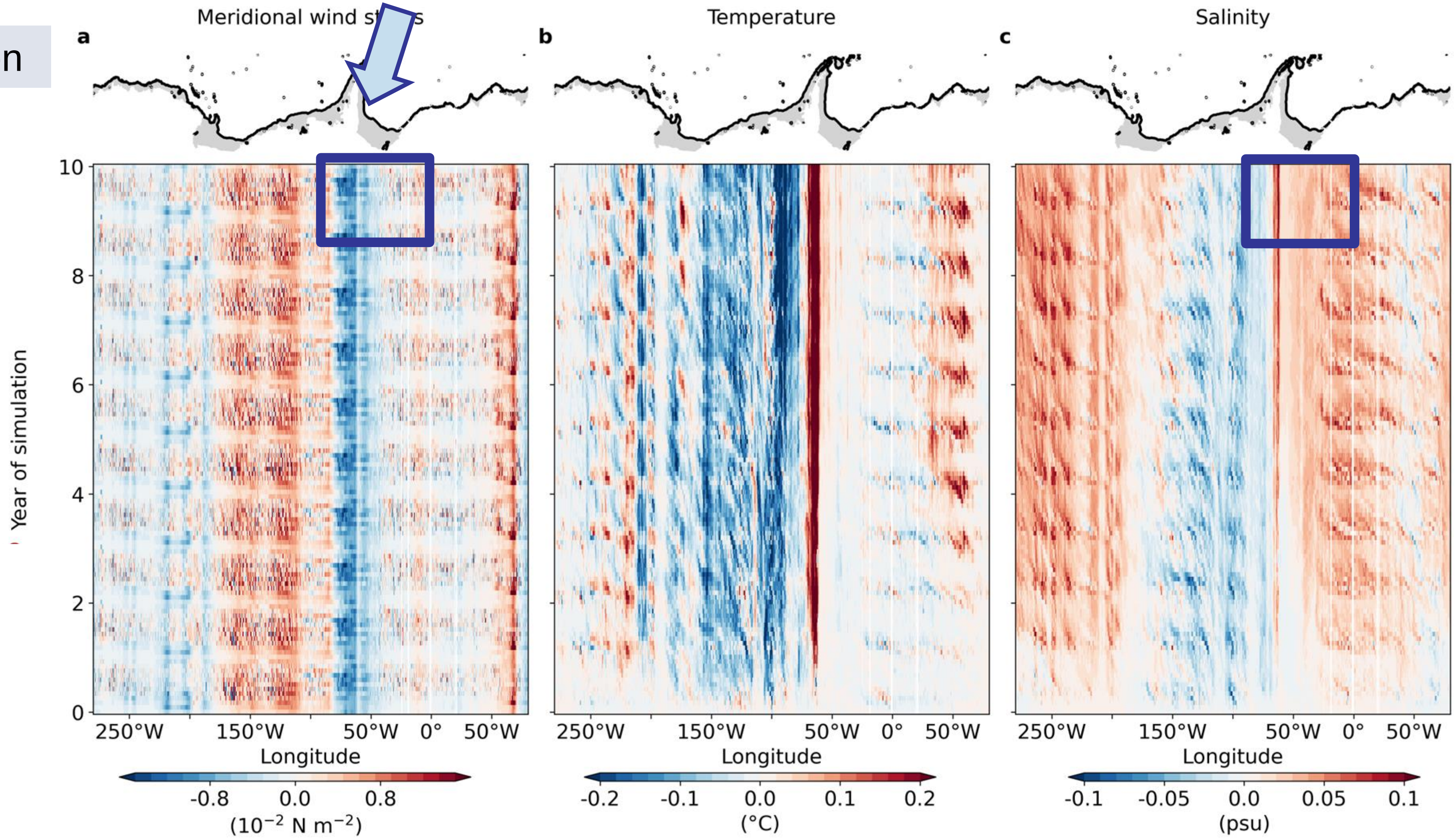

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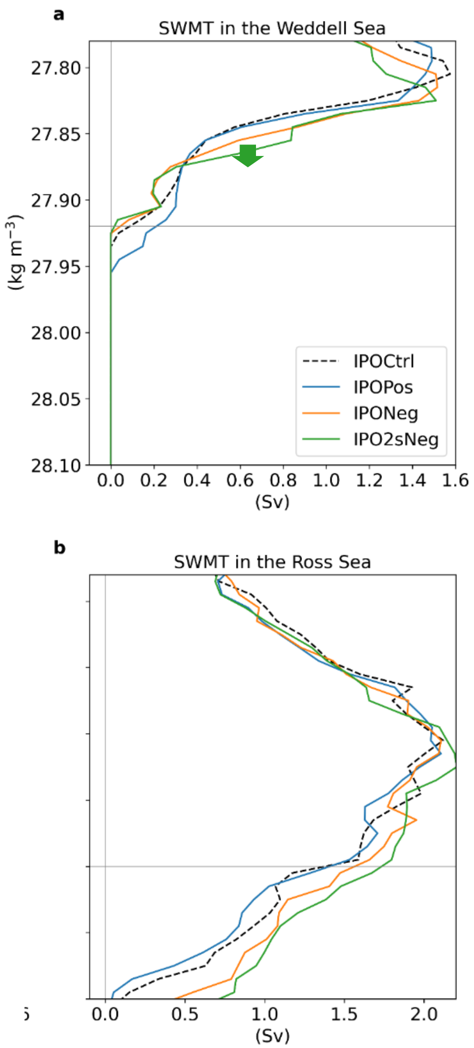
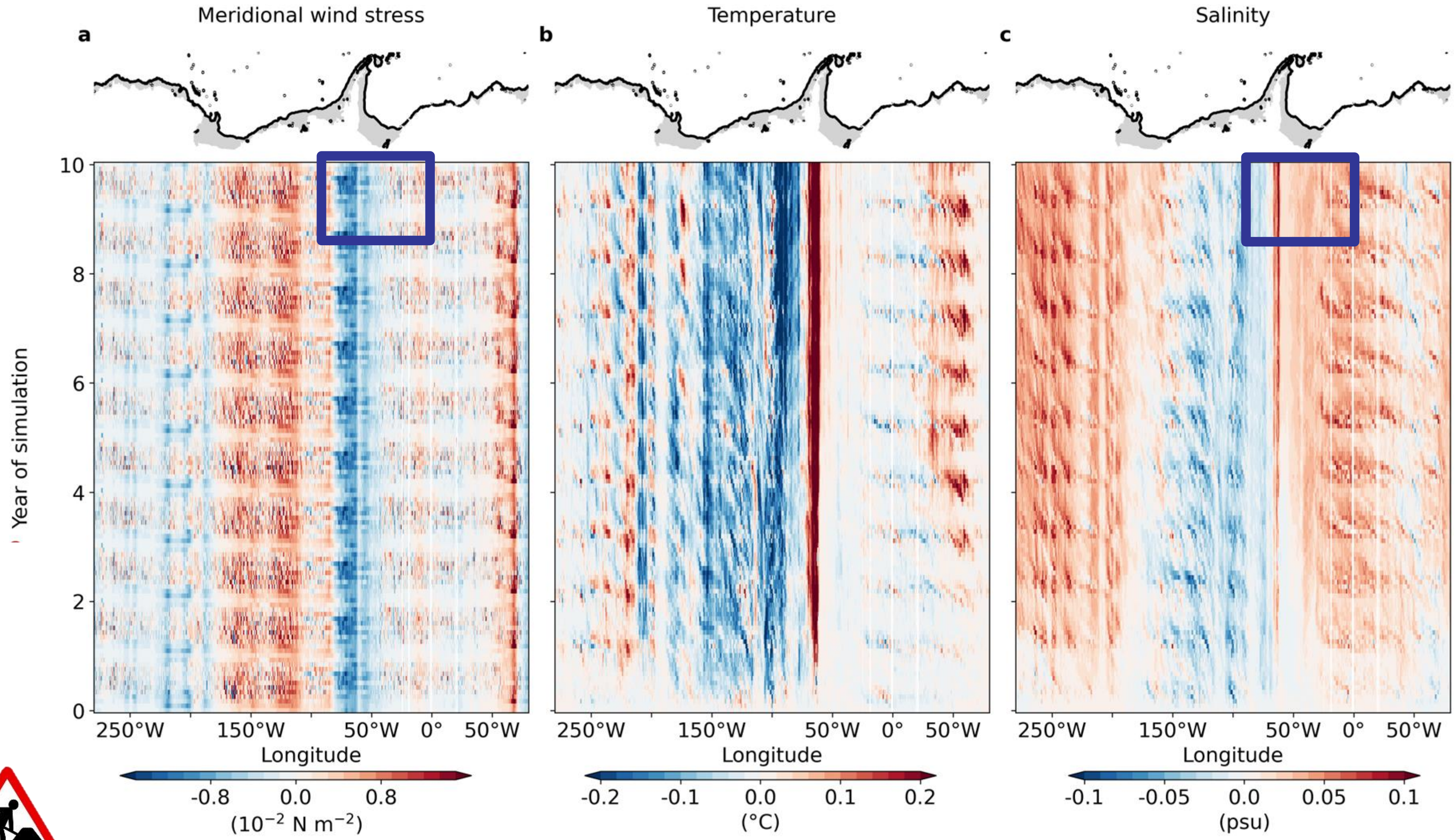
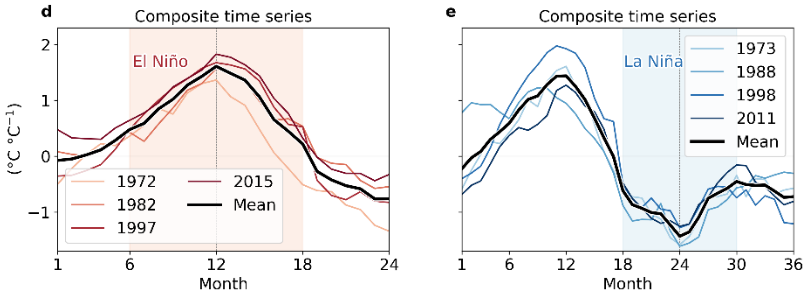


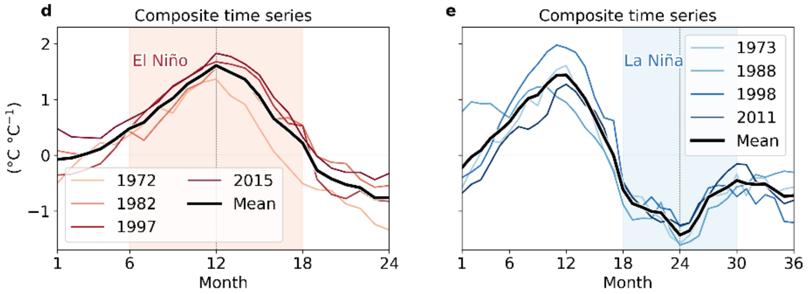


... but wait, there is more!

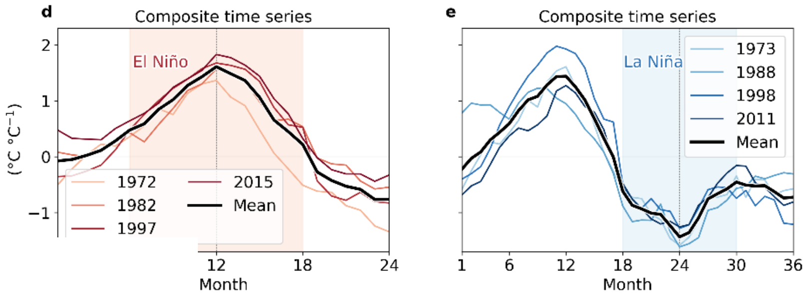
ENSOAntarctica project



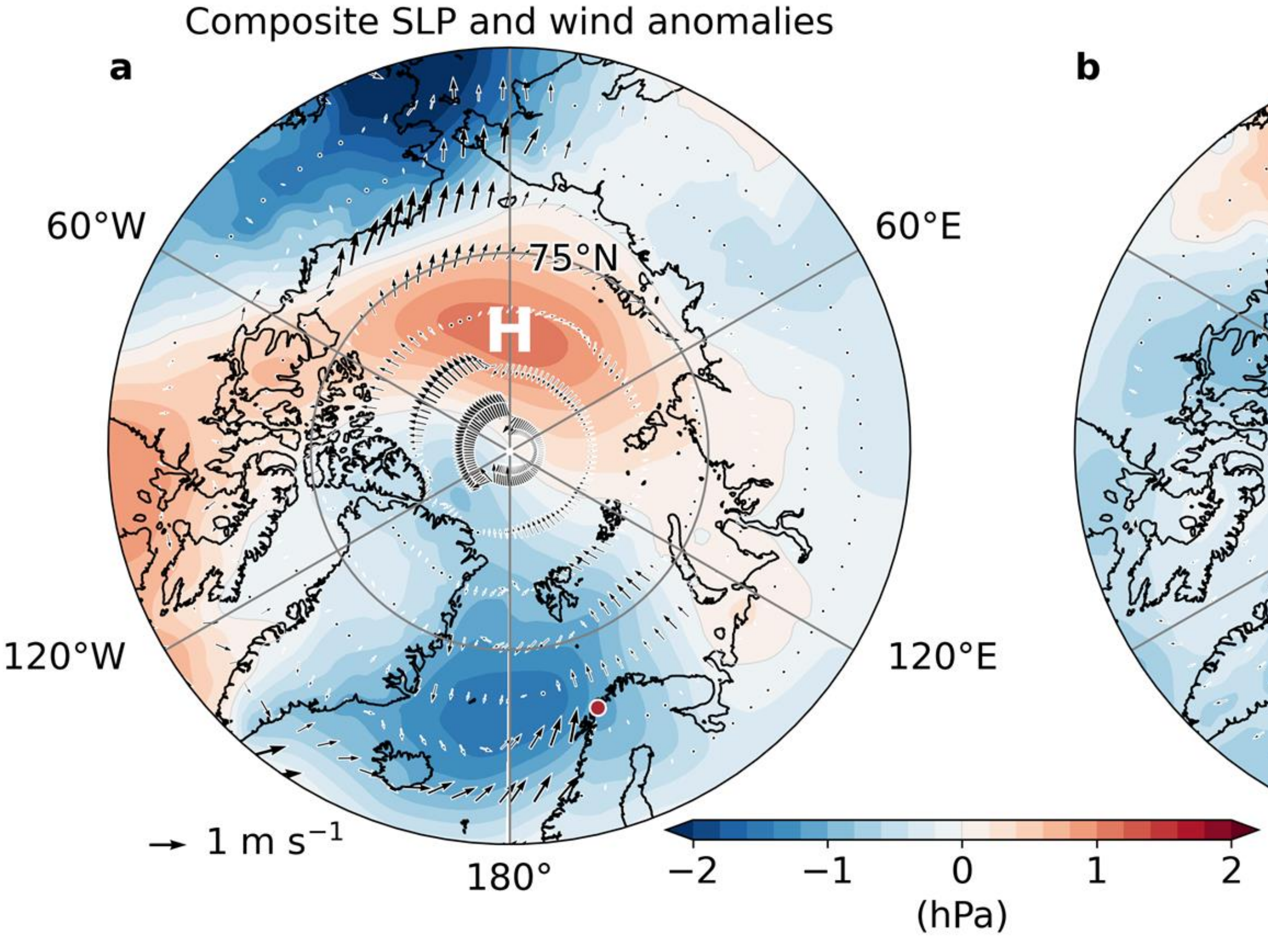
ENSO~~Ant~~Arctic project!



ENSO~~Ant~~Arctic project!



El Niño | **La Niña**



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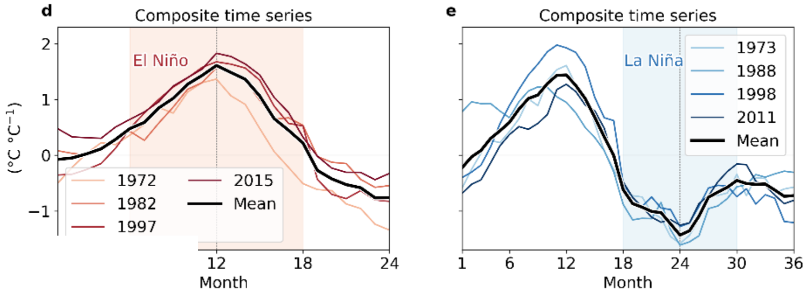
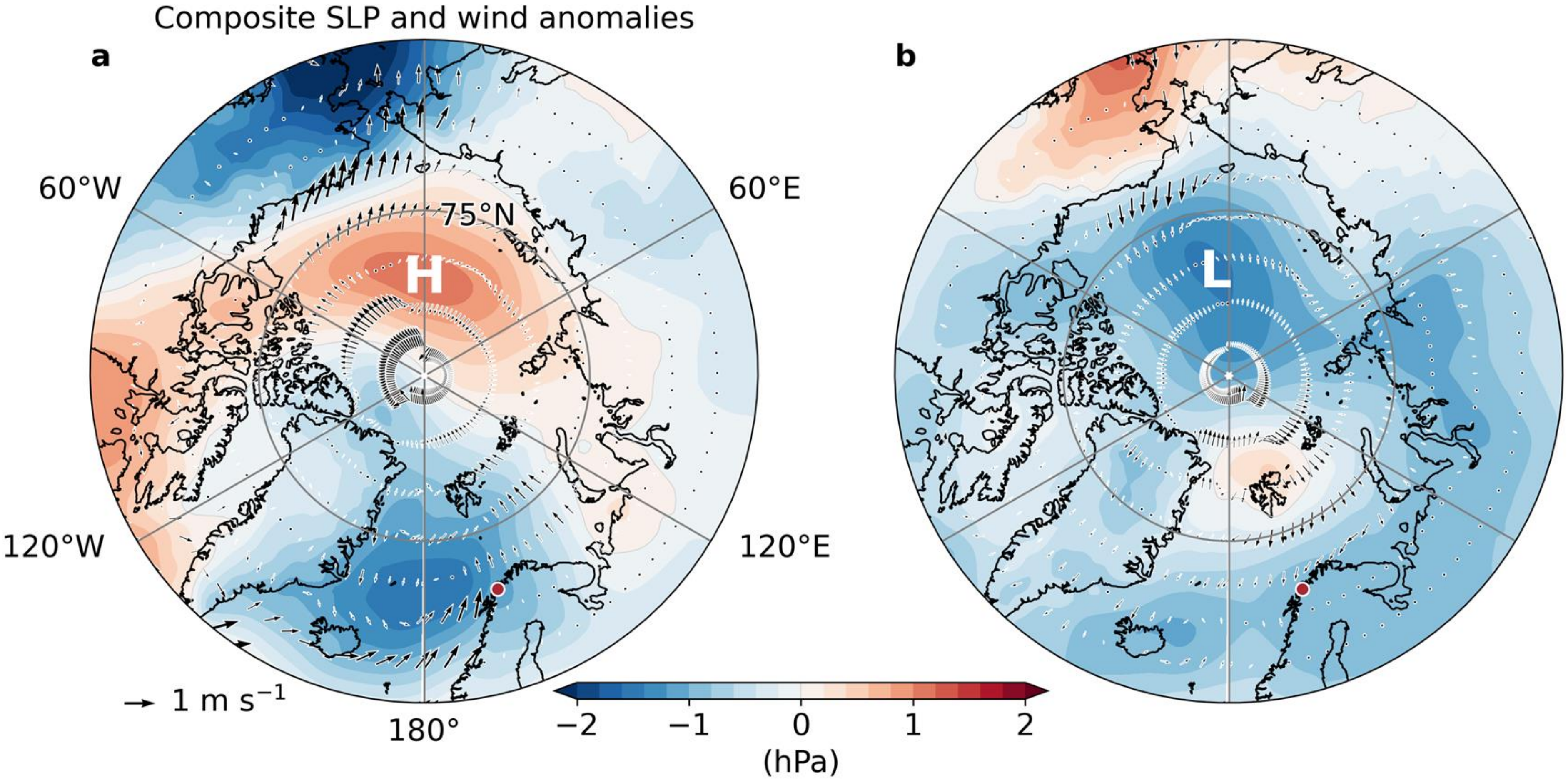


El Niño

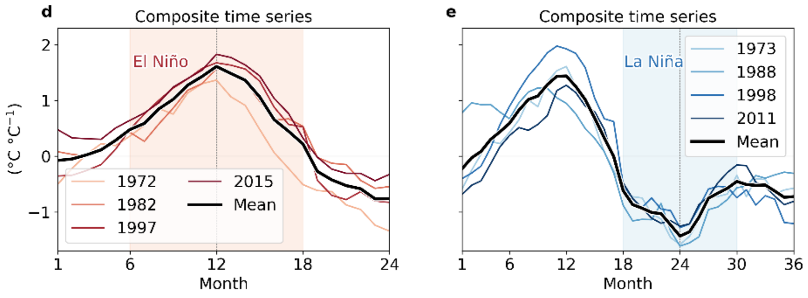
La Niña



- *Impacts on sea ice?*
- *Impacts on heat budget?*
- *More heat advection through Spitsbergen current?*
- *What happens to the Greenland coastal current?*
- *Are the anomalies too weak?*

[-5, 5] hPa was colour bar for W. Antarctica

ENSO~~Ant~~Arctic project!



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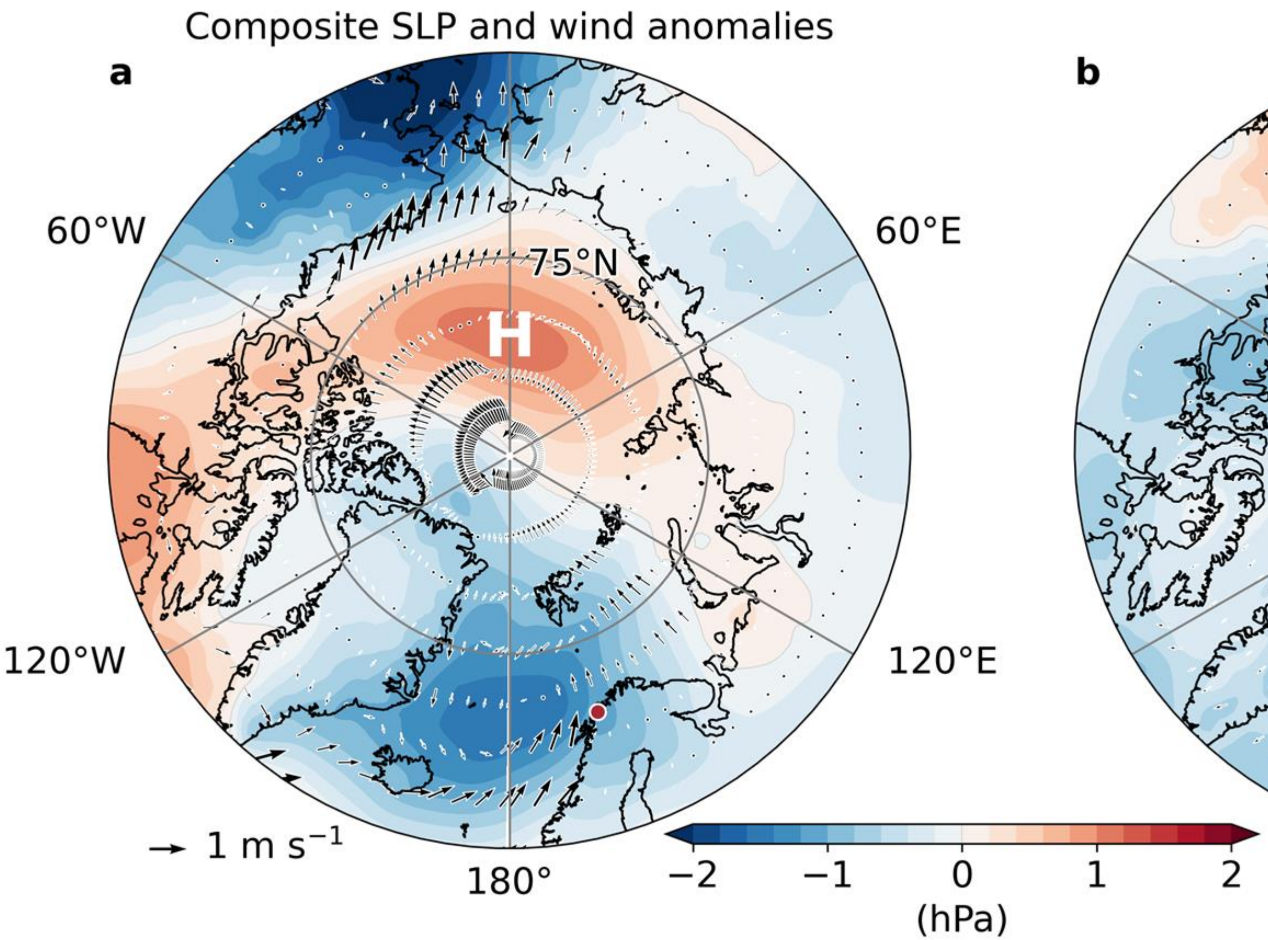

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- *Impacts on heat budget?*
- *More heat advection through Spitsbergen current?*
- *What happens to the Greenland coastal current?*
- *Are the anomalies too weak?*

Come chat with me!
Clark 349

[-5, 5] hPa was colour bar for W. Antarctica

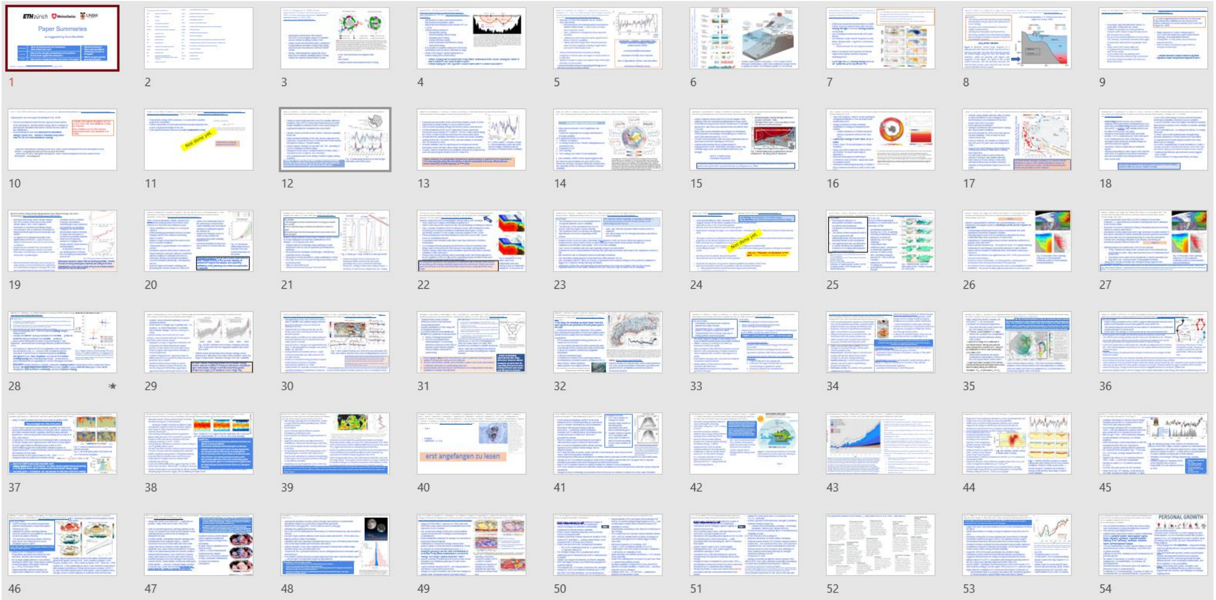
48:20.46	37:17.17	37:31.56	37:26.94	39:48.61
39:26.58				

... but wait, there is more!

4 habits that helped me in my PhD

4 habits that helped me in my PhD

1. One paper, one powerpoint slide



Anna Merrifield's idea

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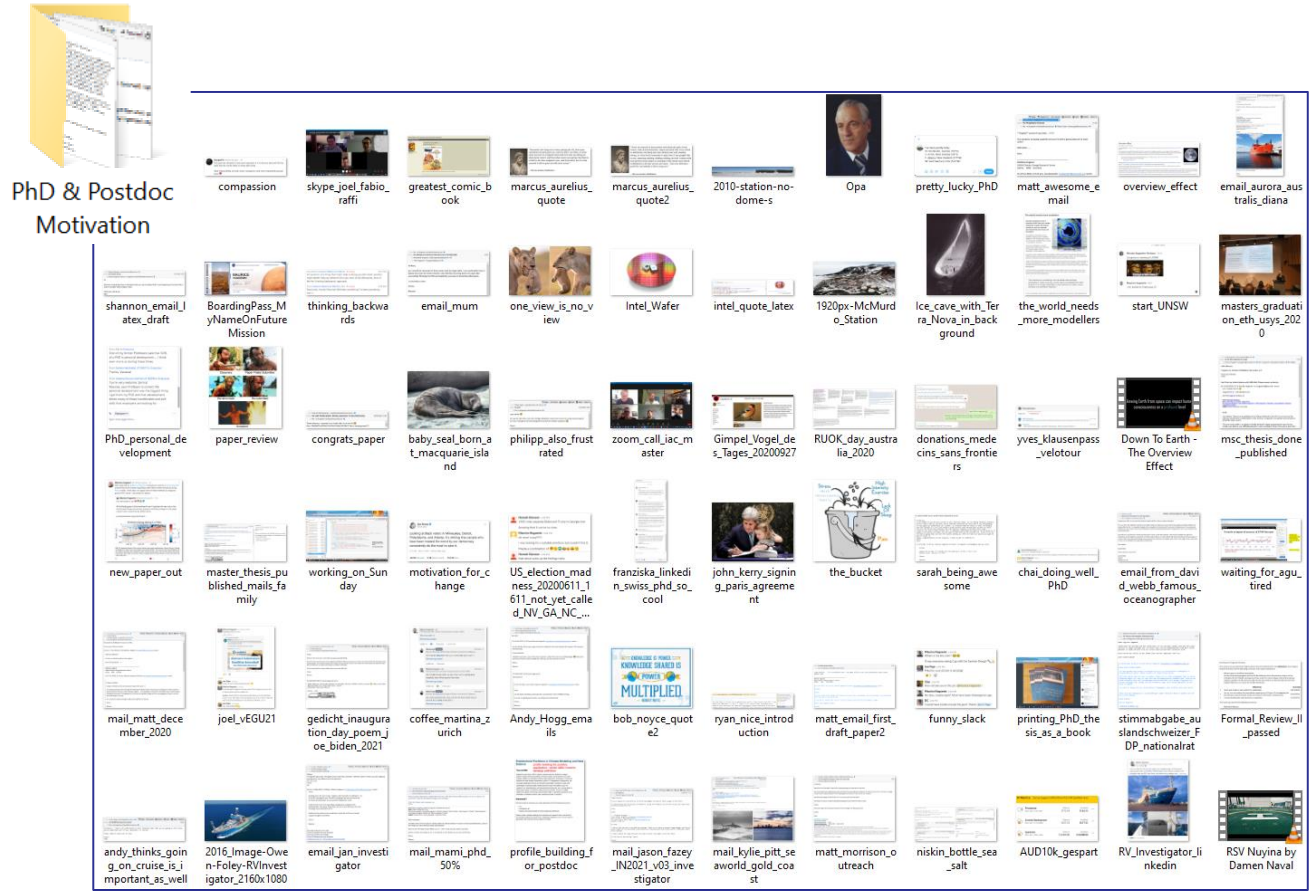
4 habits that helped me in my PhD

1. One paper, one powerpoint slide
2. Chocolate countdown

4 habits that helped me in my PhD

1. One paper, one powerpoint slide
2. Chocolate countdown
3. PhD Motivation folder



4 habits that helped me in my PhD

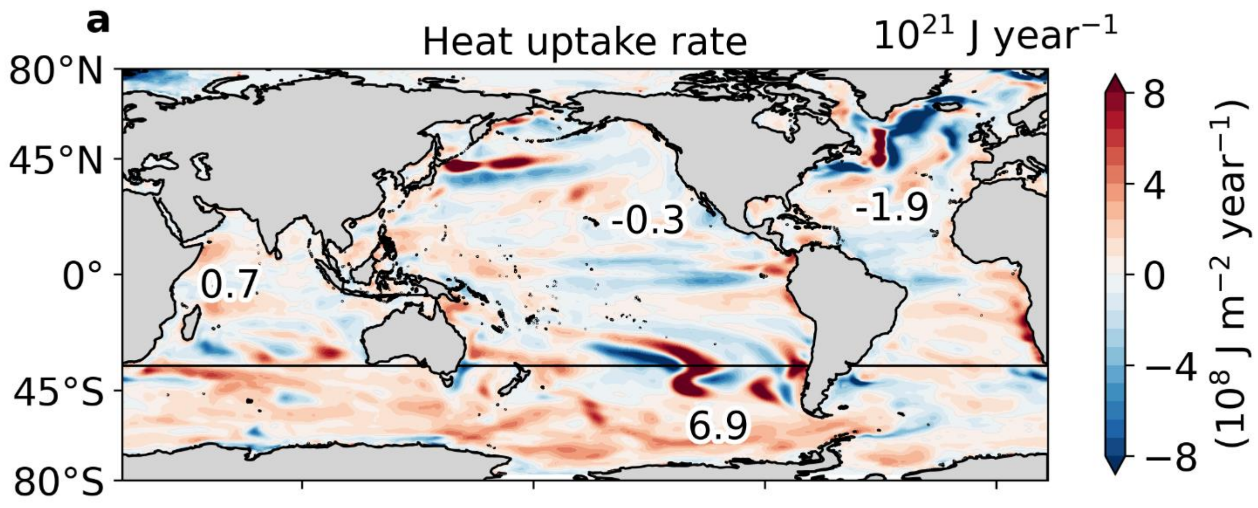
1. One paper, one powerpoint slide
2. Chocolate countdown
3. PhD Motivation folder
4. CBT

"Come talk to me about the other six habits."

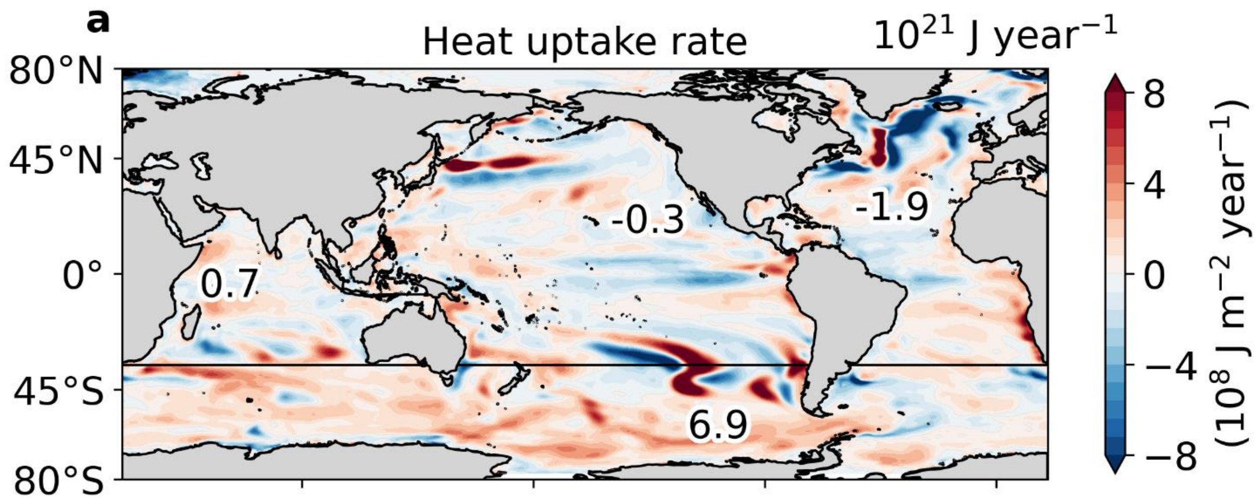
old slides

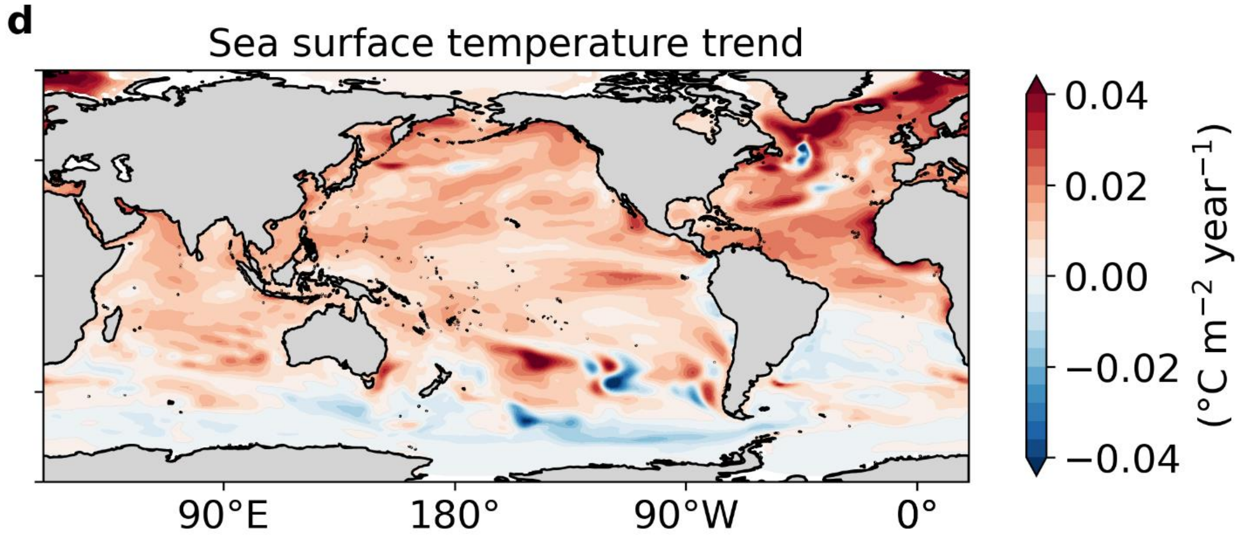
Ocean heat uptake, transport and storage

Ocean heat uptake, transport and storage

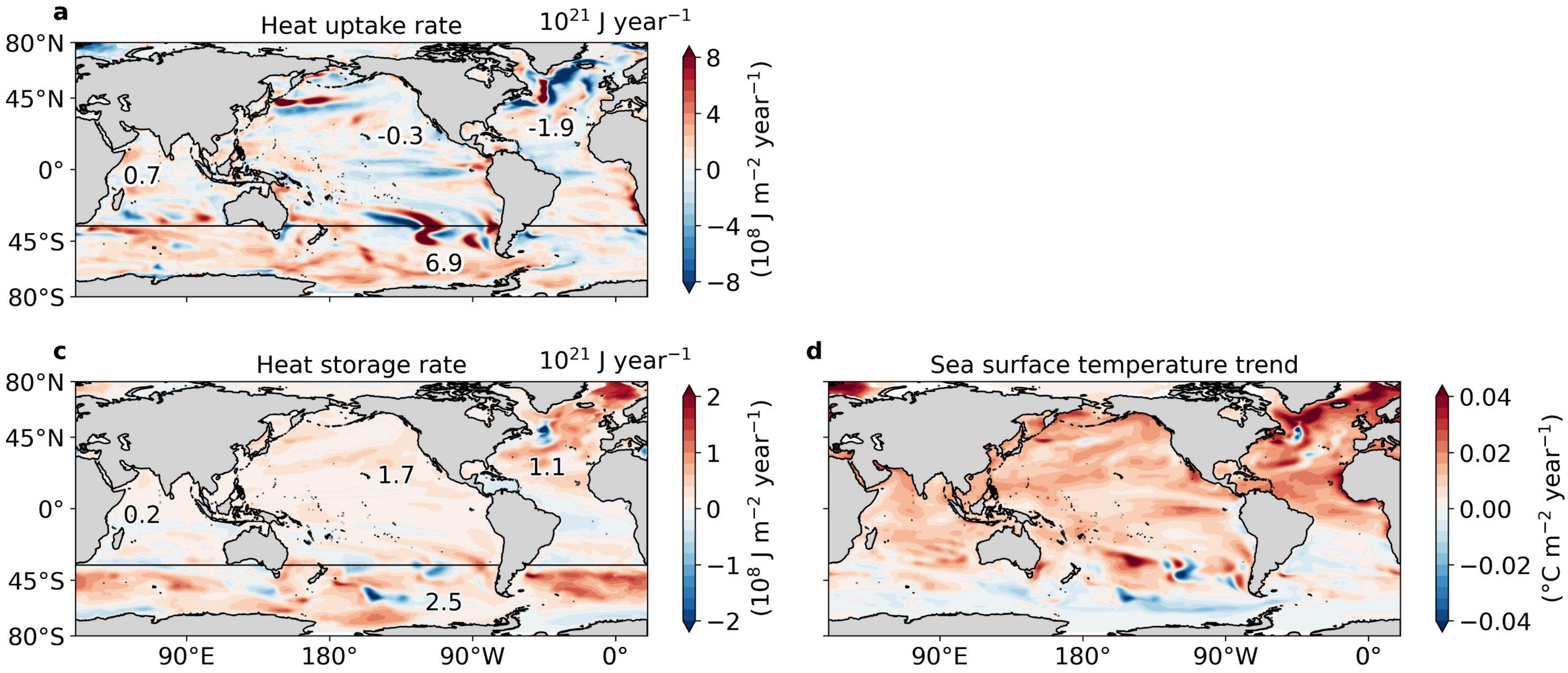


Ocean heat uptake, transport and storage

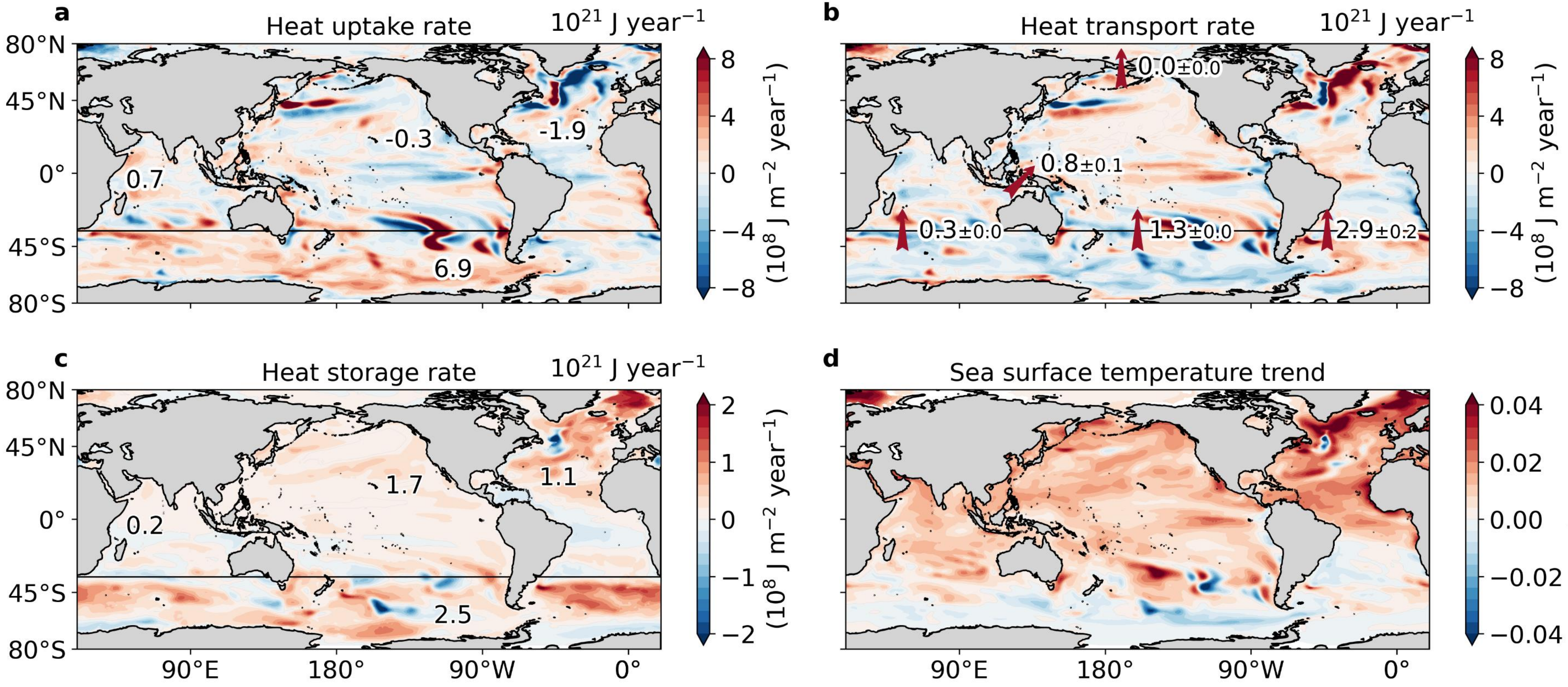




Ocean heat uptake, transport and storage



Ocean heat uptake, transport and storage



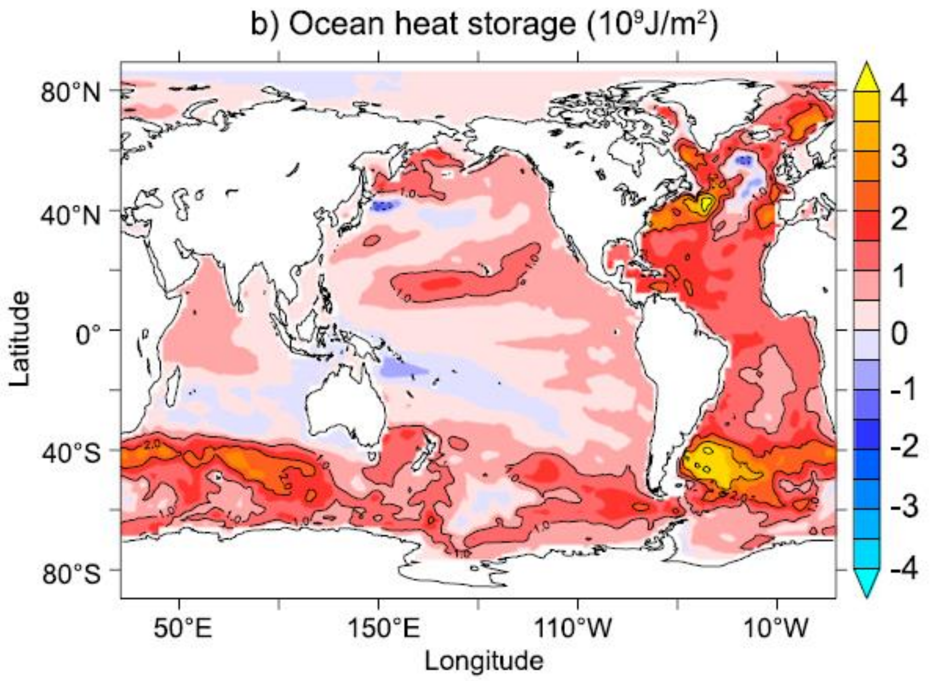
Take Home

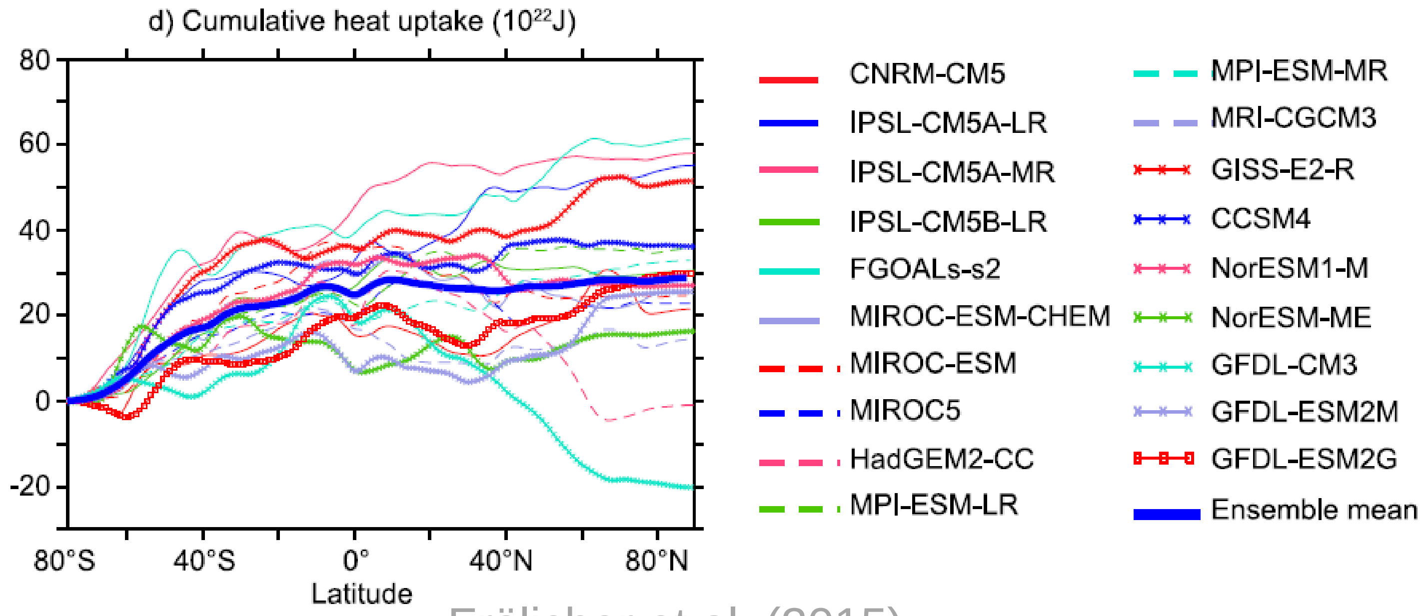
1. **Isolated strong ENSO** simulations illustrate how they modulate subsurface West Antarctic shelf temperatures

2. **El Niño weakens** coastal **easterlies**, **reduced** cold poleward **Ekman** transport & causes cross-shelf **upwelling** of warm **CDW**

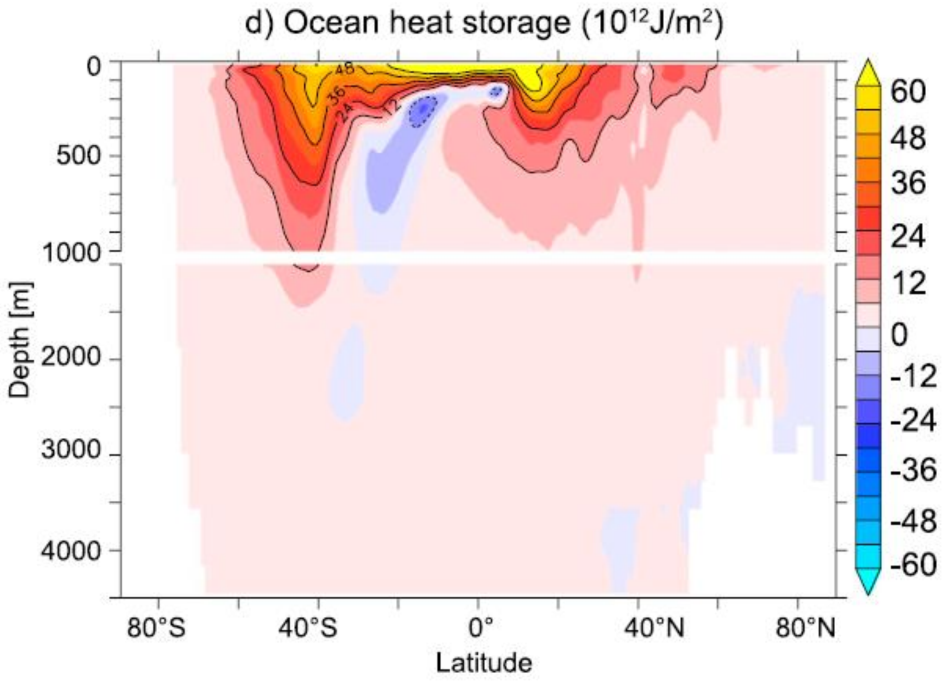
3. **La Niña** shelf circulation **response** largely **opposite** & inhibits cross-shelf upwelling of CDW

Importance of ocean heat content





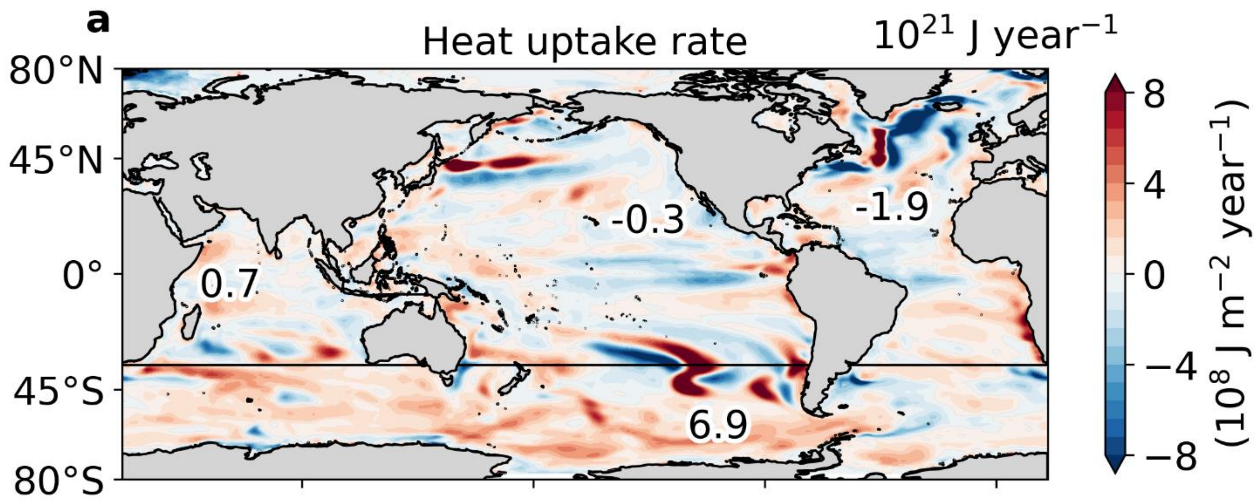
Frölicher et al. (2015)



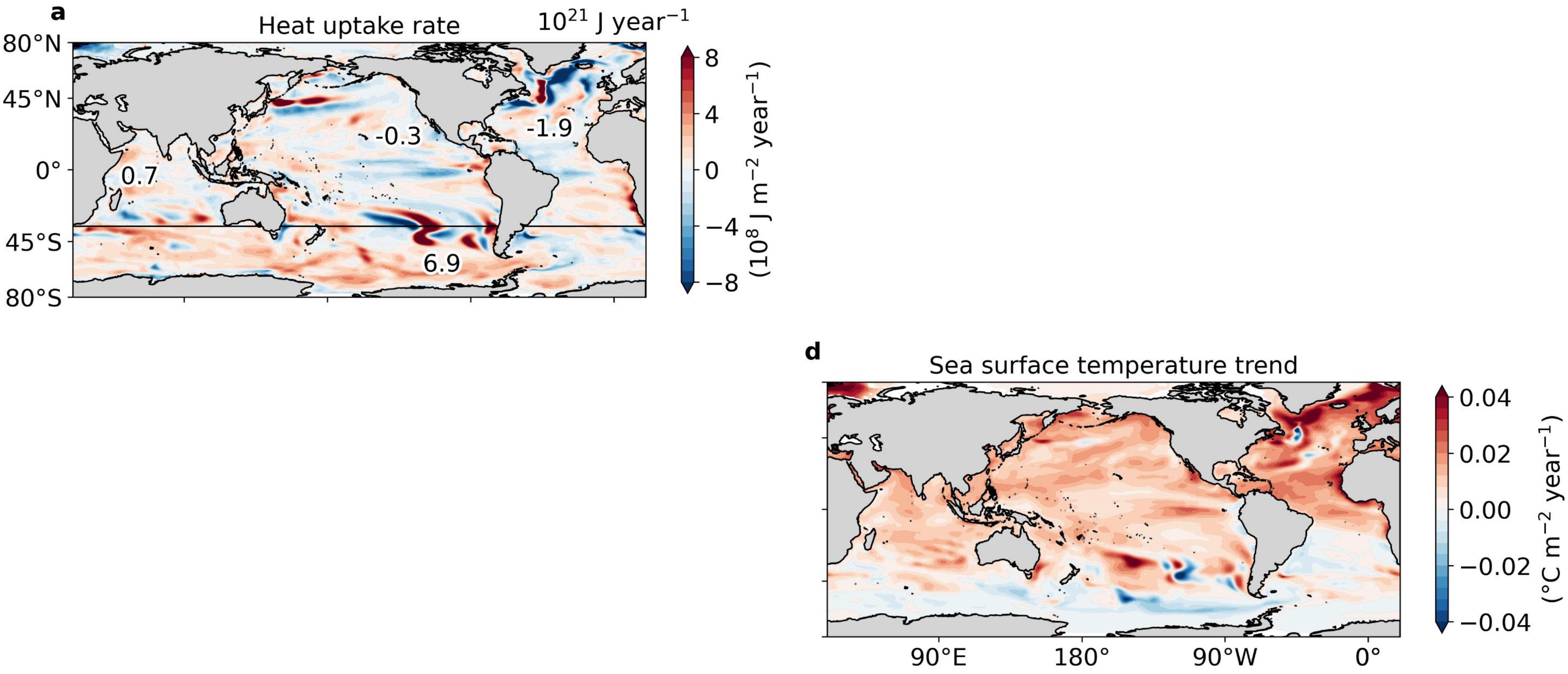
Frölicher et al. (2015)

Ocean heat uptake, transport and storage

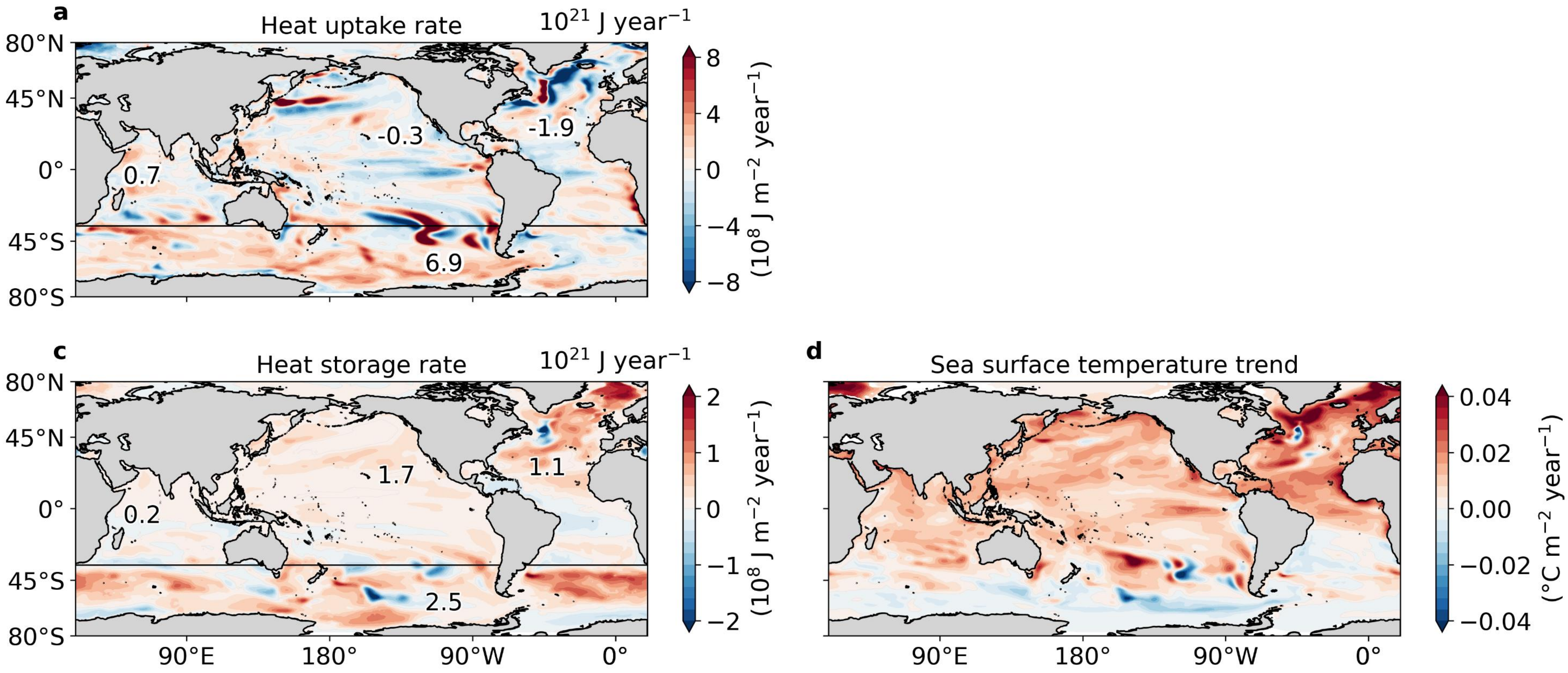
Ocean heat uptake, transport and storage



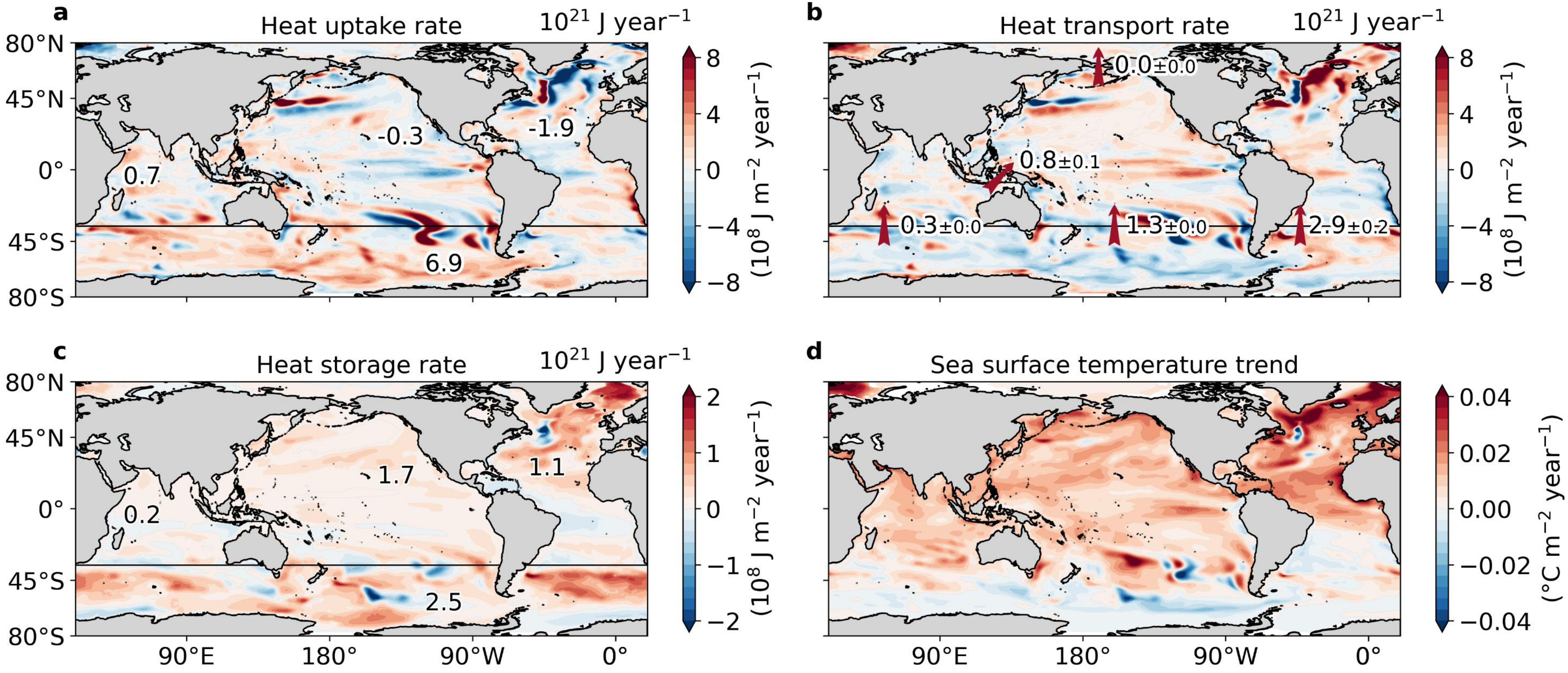
Ocean heat uptake, transport and storage



Ocean heat uptake, transport and storage



Ocean heat uptake, transport and storage



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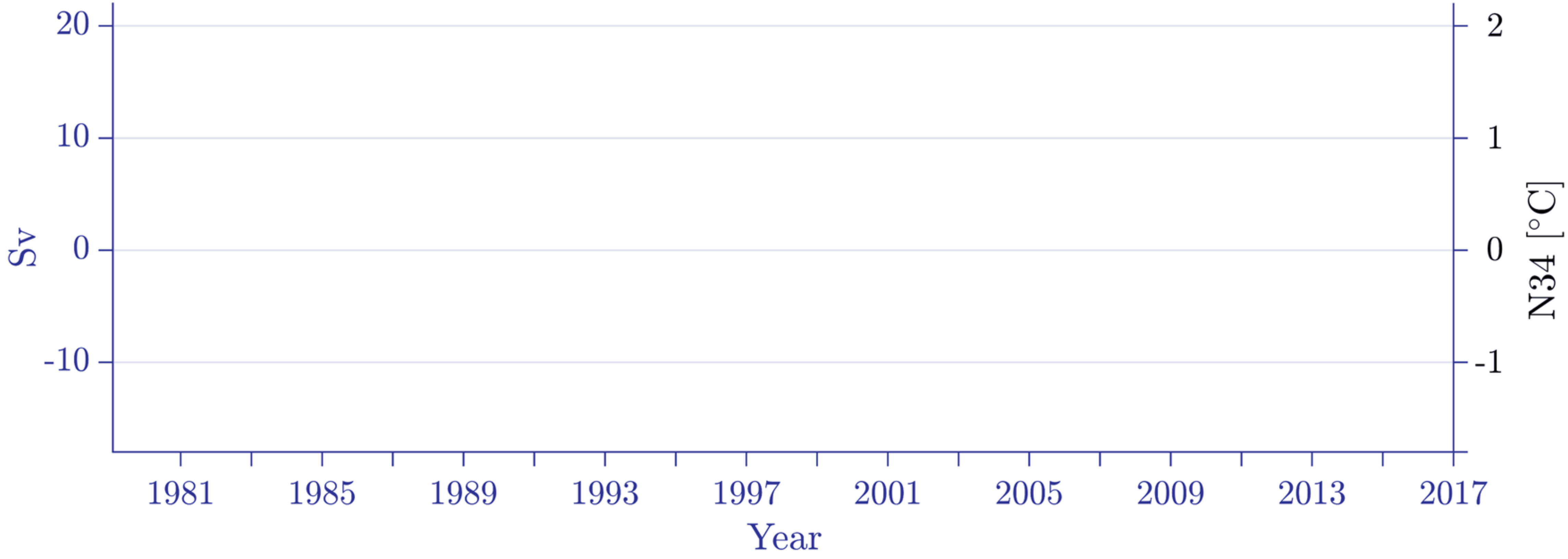
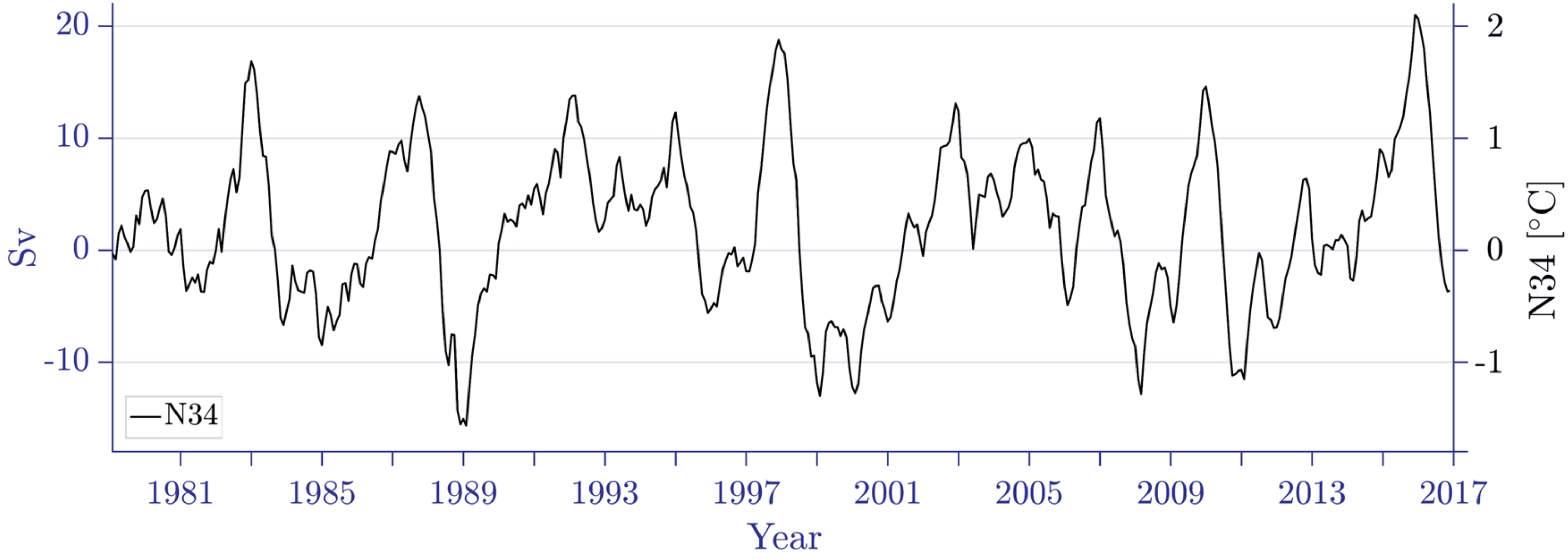
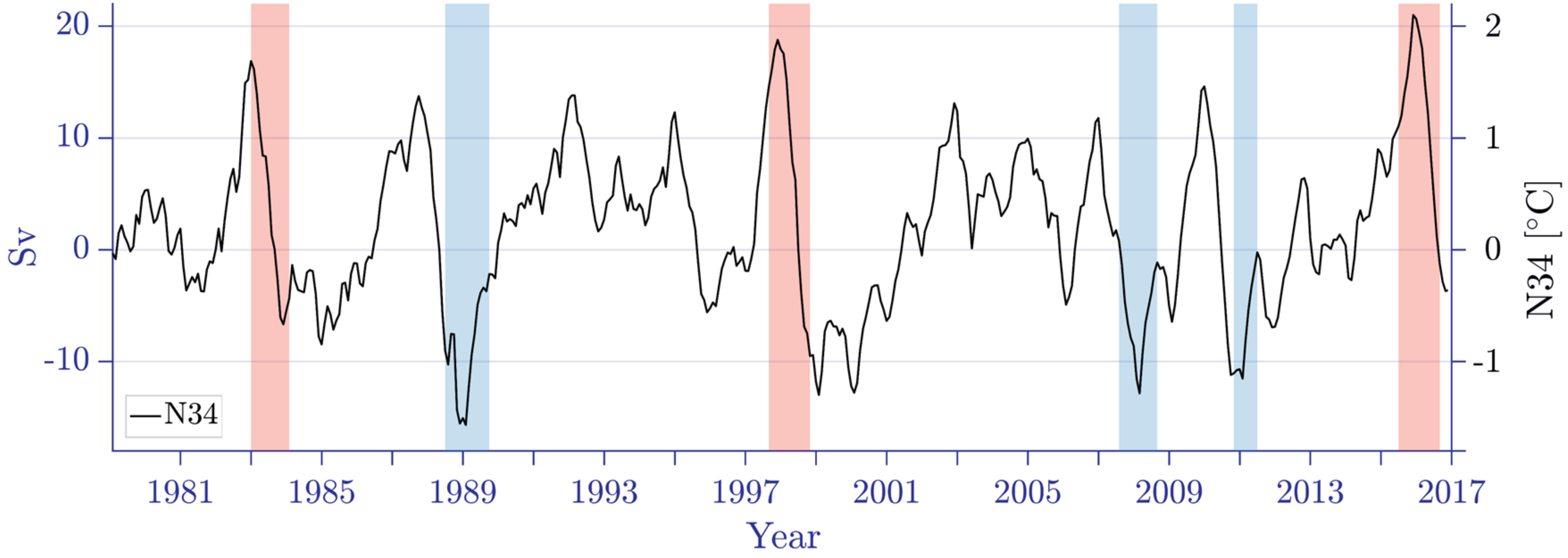
Interannual Variability of the Diabatic Fluxes



Interannual Variability of the Diabatic Fluxes



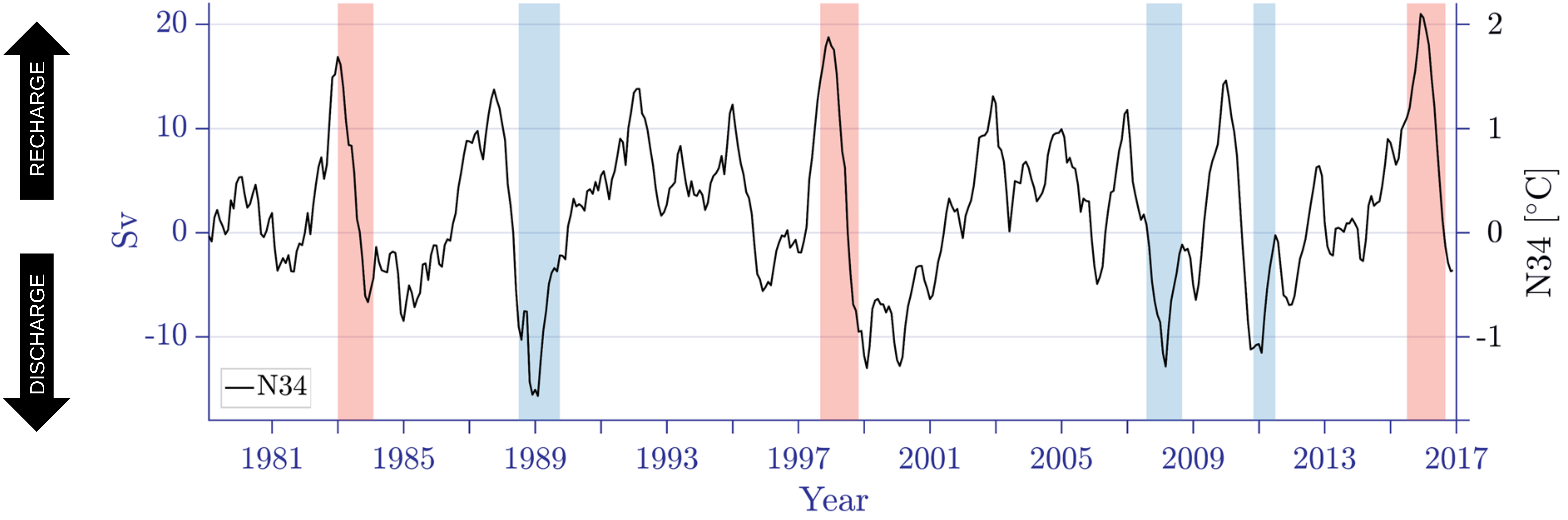
Interannual Variability of the Diabatic Fluxes



El Niño: discharge

La Niña: recharge

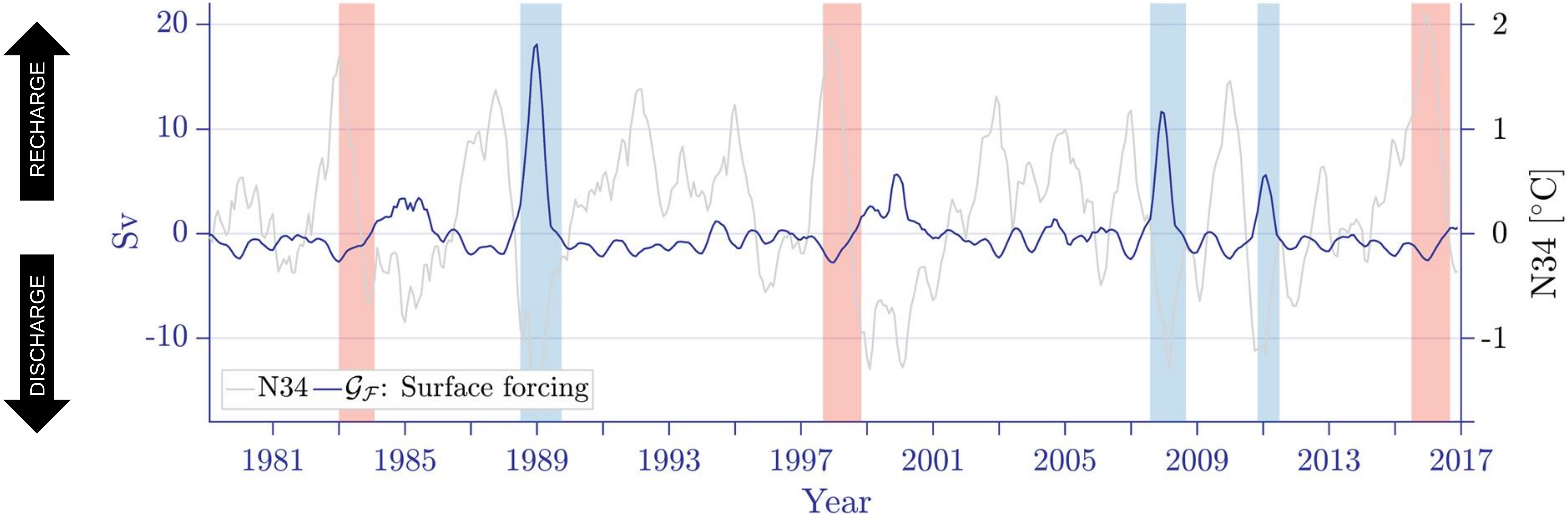
Interannual Variability of the Diabatic Fluxes



El Niño: discharge

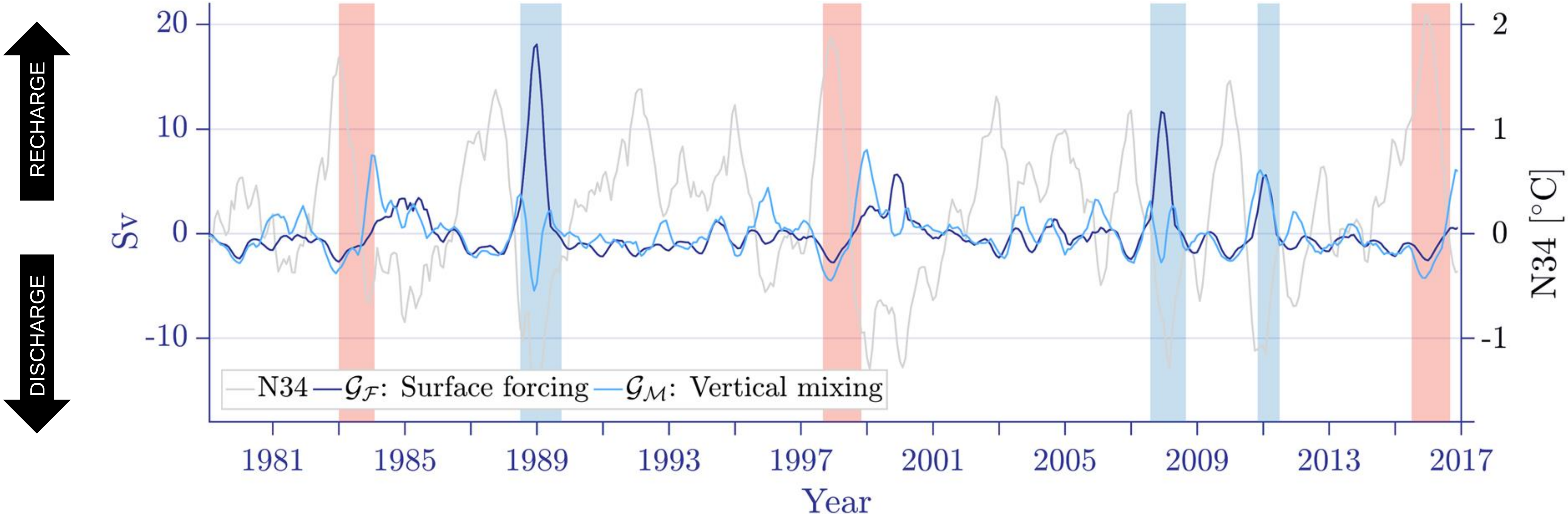
La Niña: recharge

Interannual Variability of the Diabatic Fluxes



<u>La Niña:</u> large positive contribution of surface forcing

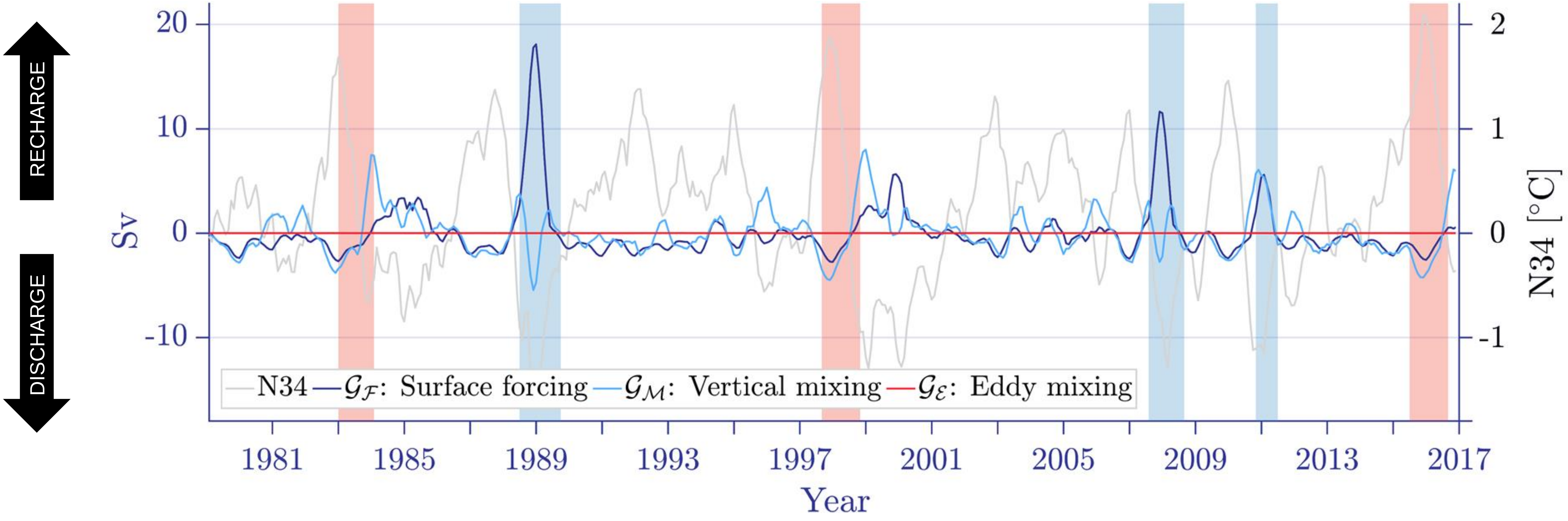
Interannual Variability of the Diabatic Fluxes



El Niño: both surface forcing & vertical mixing deplete WWV

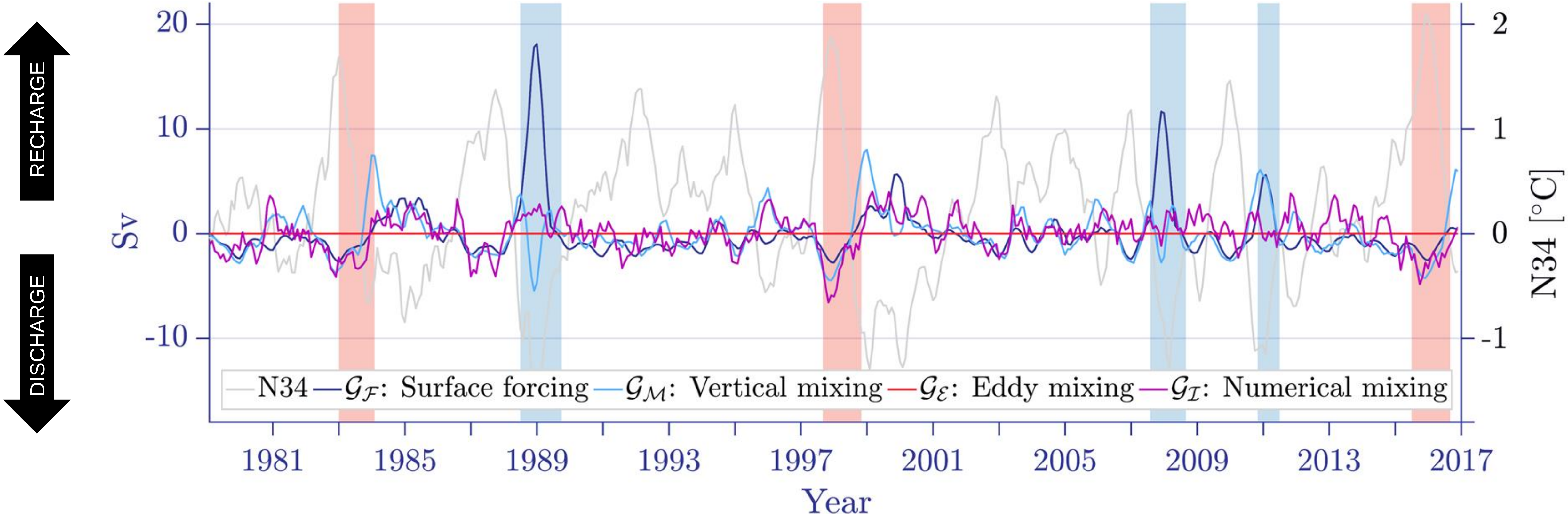
La Niña: large positive contribution of surface forcing

Interannual Variability of the Diabatic Fluxes



<u>El Niño:</u> both surface forcing & vertical mixing deplete WWV
<u>La Niña:</u> large positive contribution of surface forcing

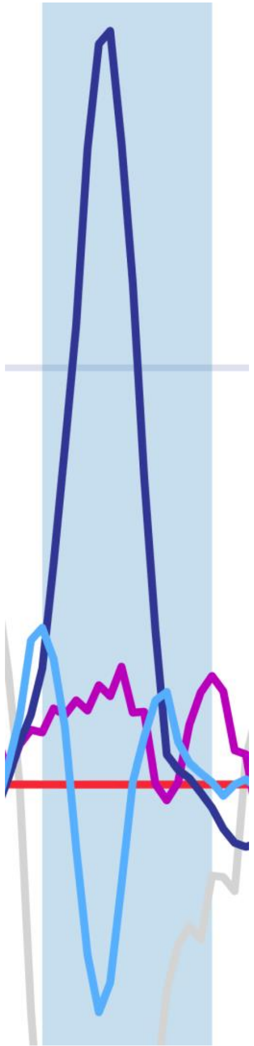
Interannual Variability of the Diabatic Fluxes



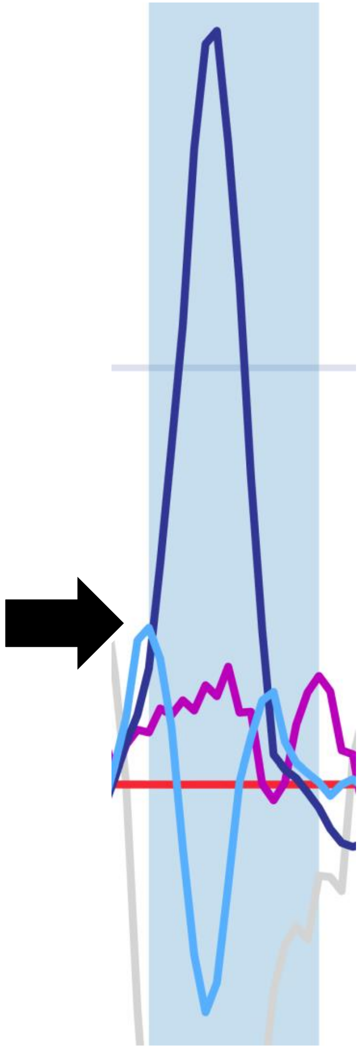
El Niño: both surface forcing & vertical mixing deplete WWV

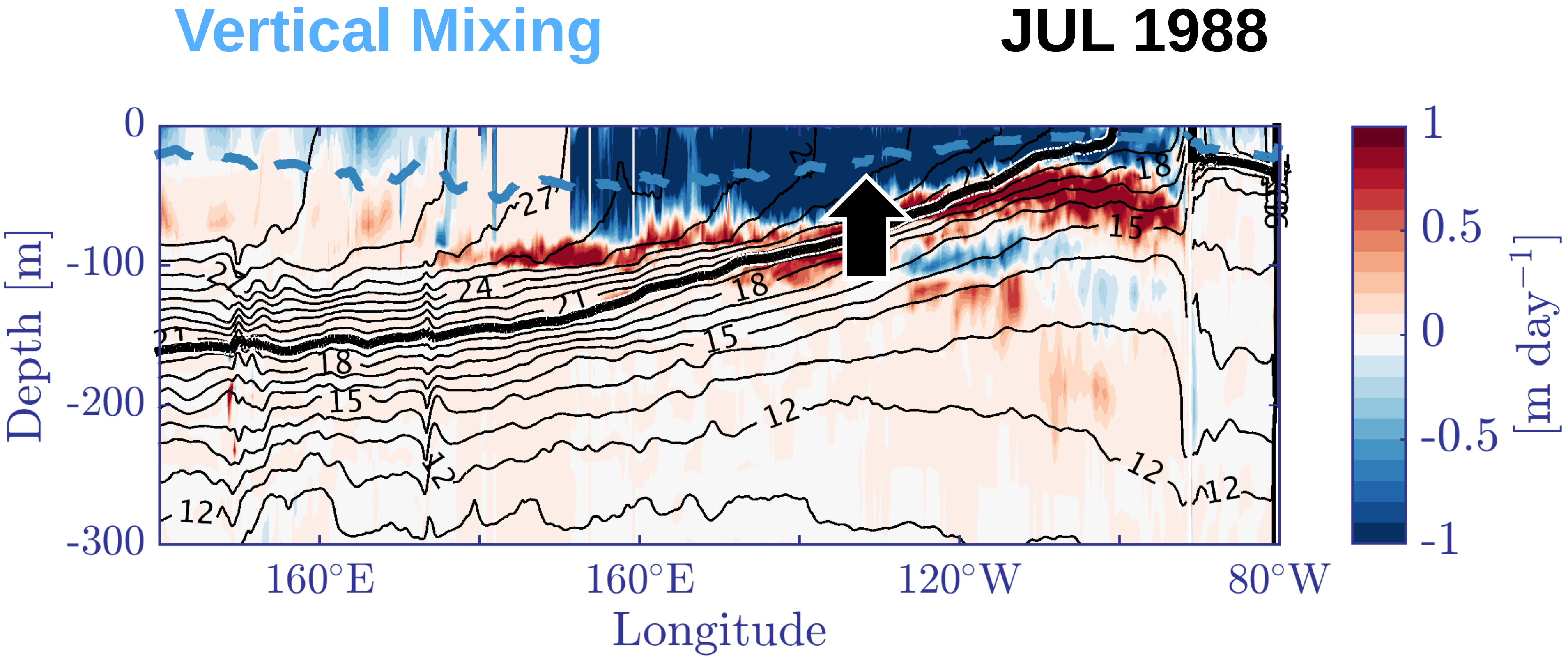
La Niña: large positive contribution of surface forcing

Diabatic Fluxes during La Niña 1988/89

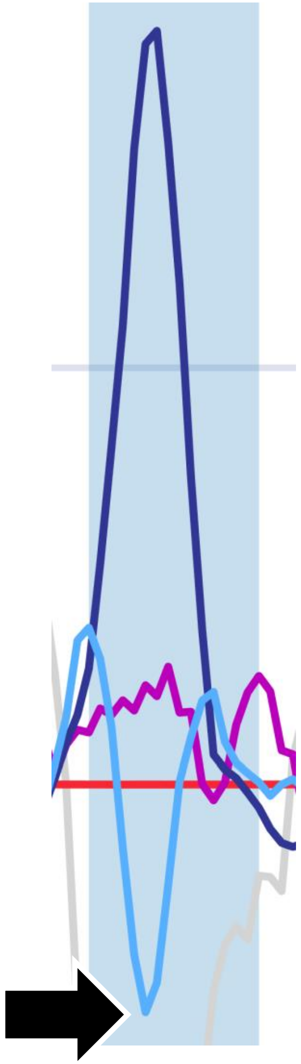


Diabatic Fluxes during La Niña 1988/89



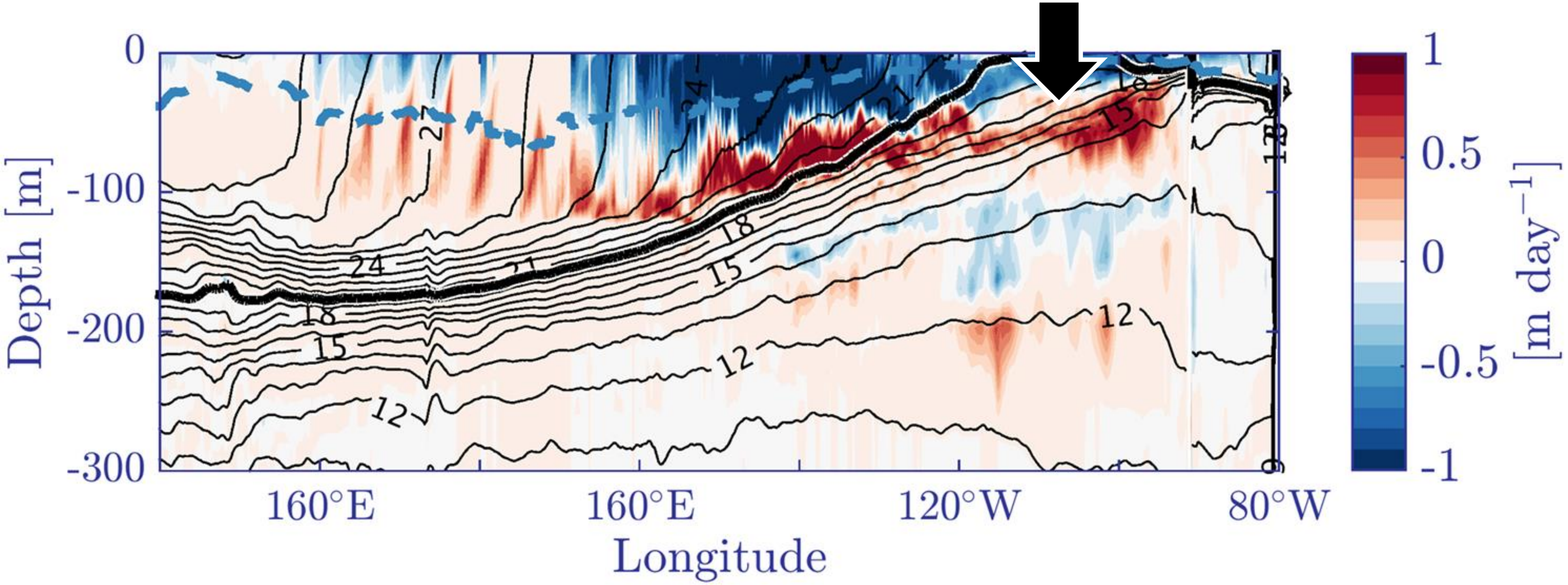


Diabatic Fluxes during La Niña 1988/89

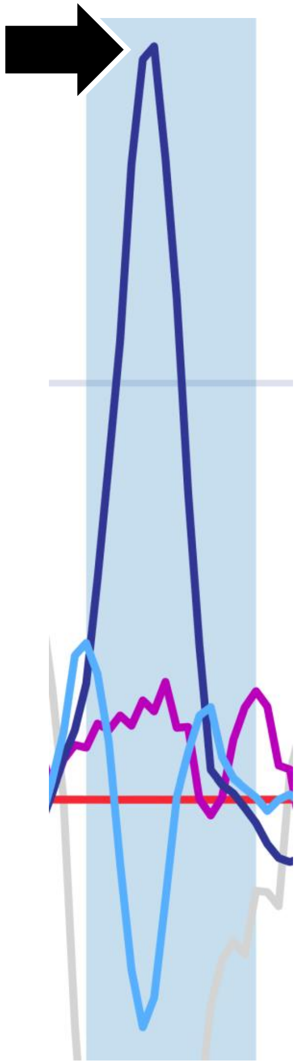


Vertical Mixing

DEC 1988

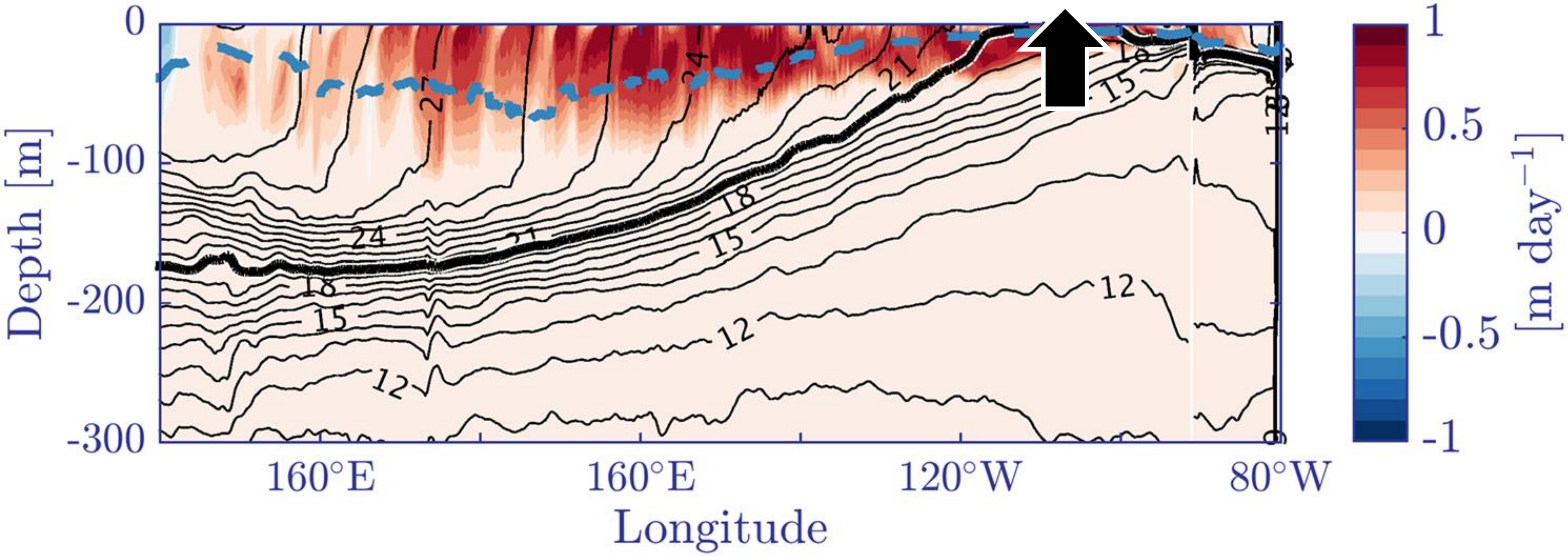


Diabatic Fluxes during La Niña 1988/89

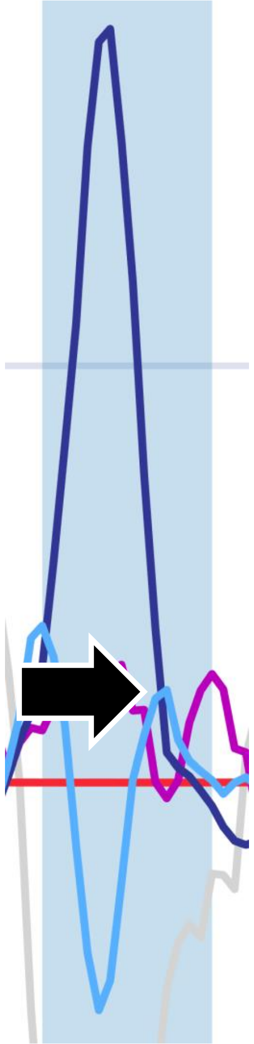


Surface Forcing

DEC 1988

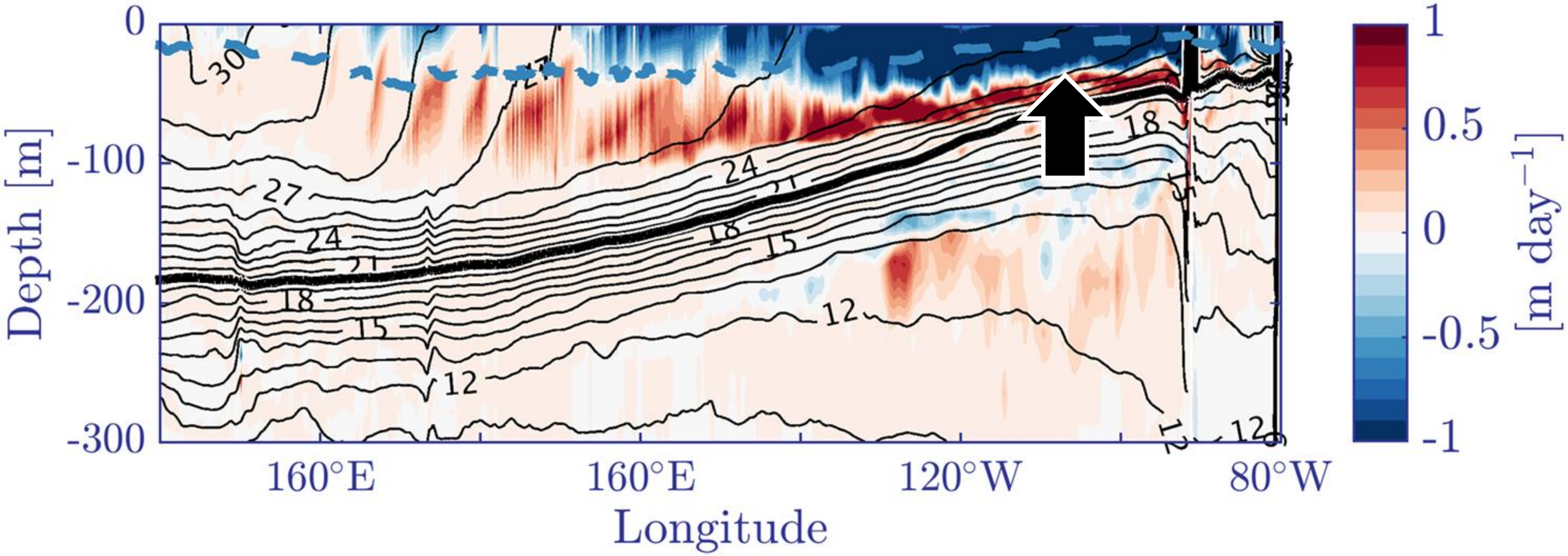


Diabatic Fluxes during La Niña 1988/89

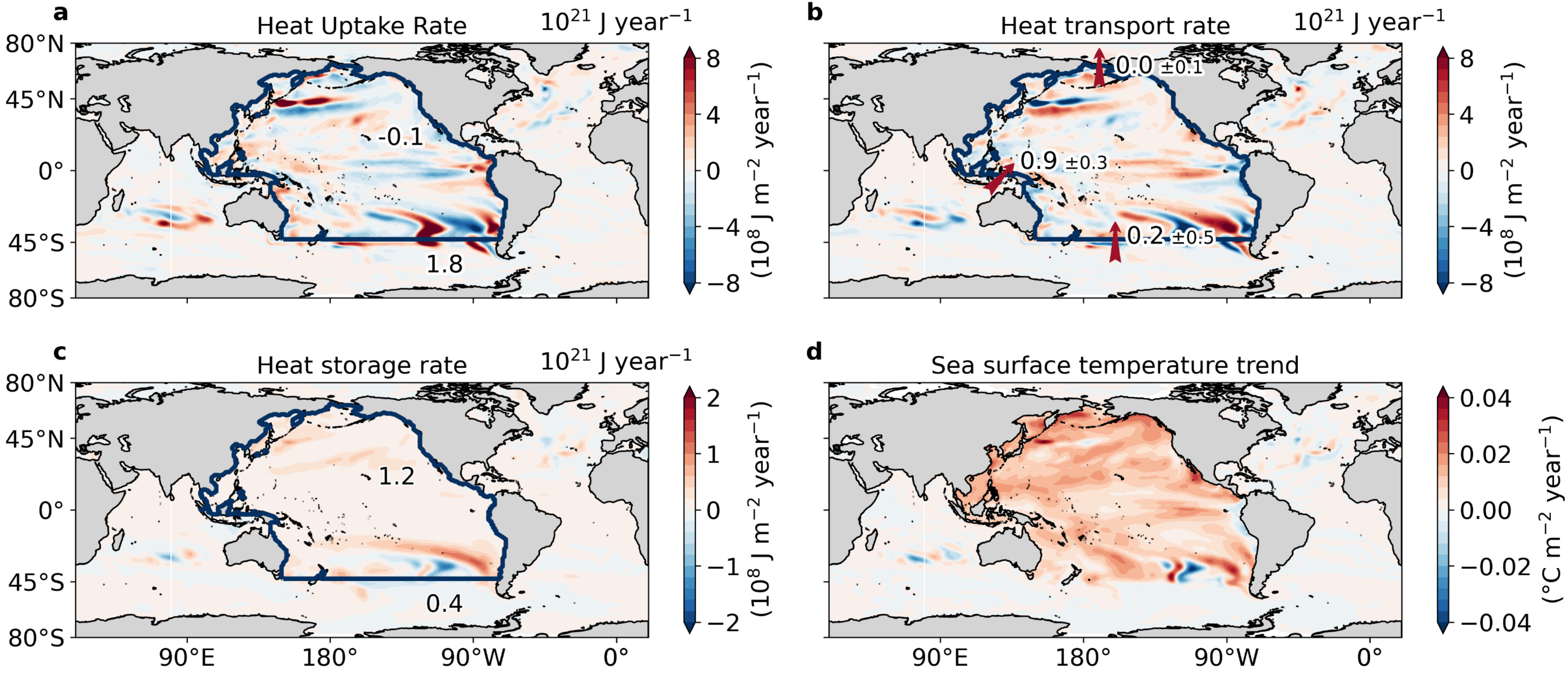


Vertical Mixing

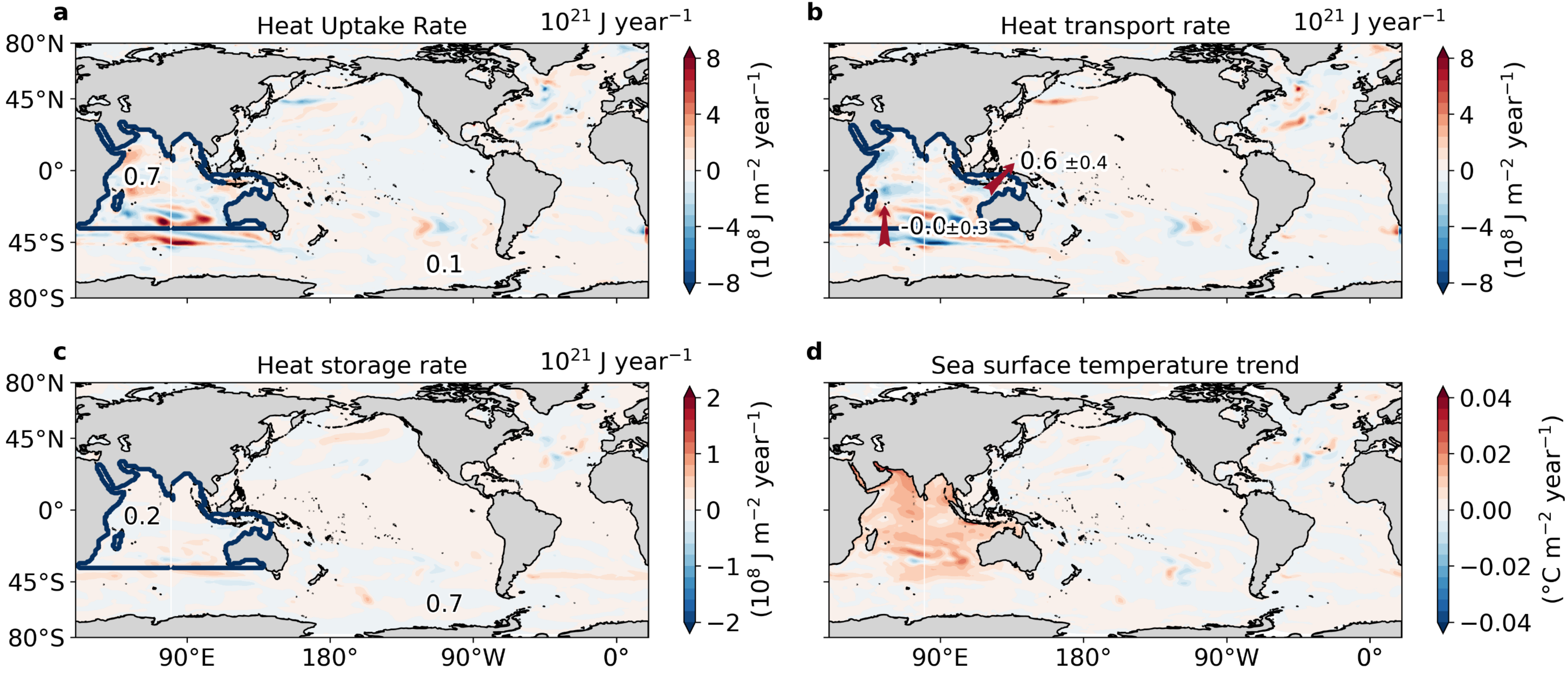
JUL 1989



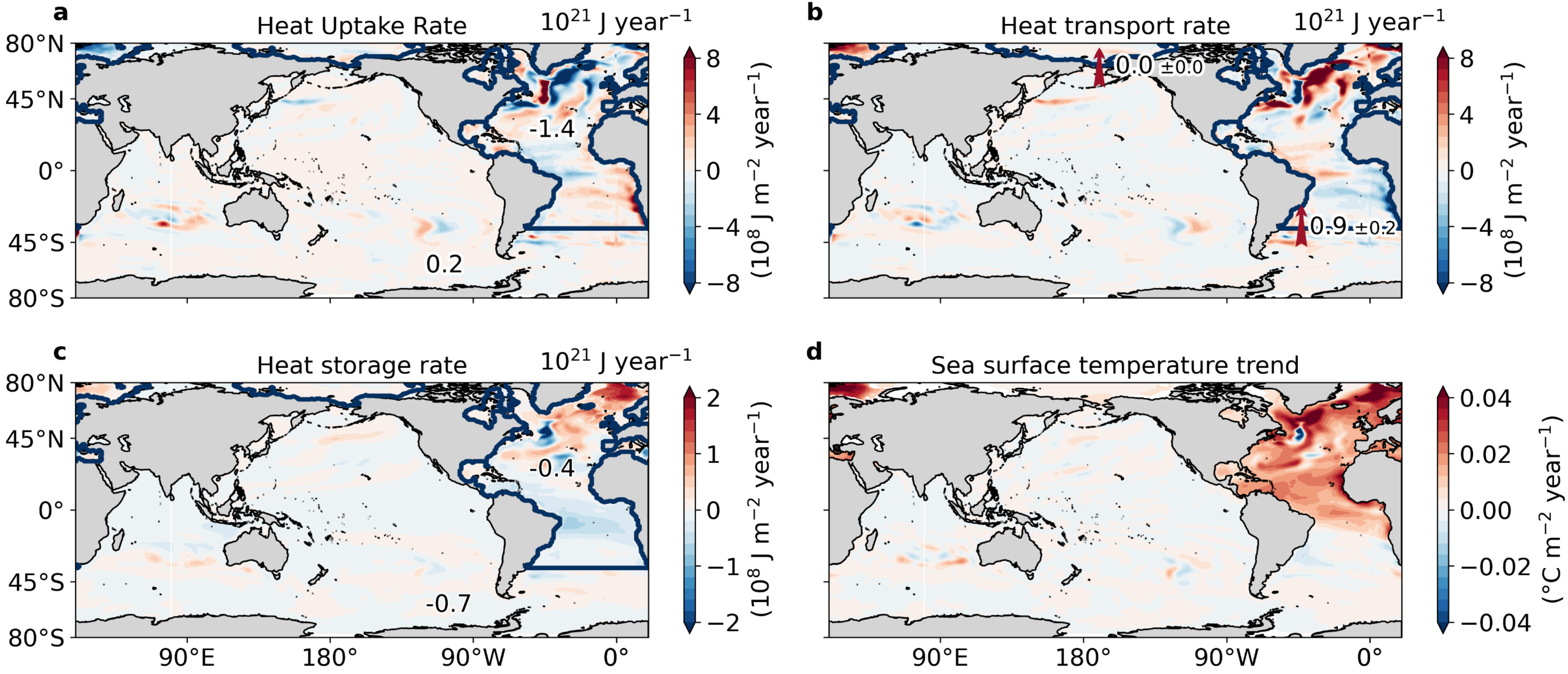
Pacific Ocean-only



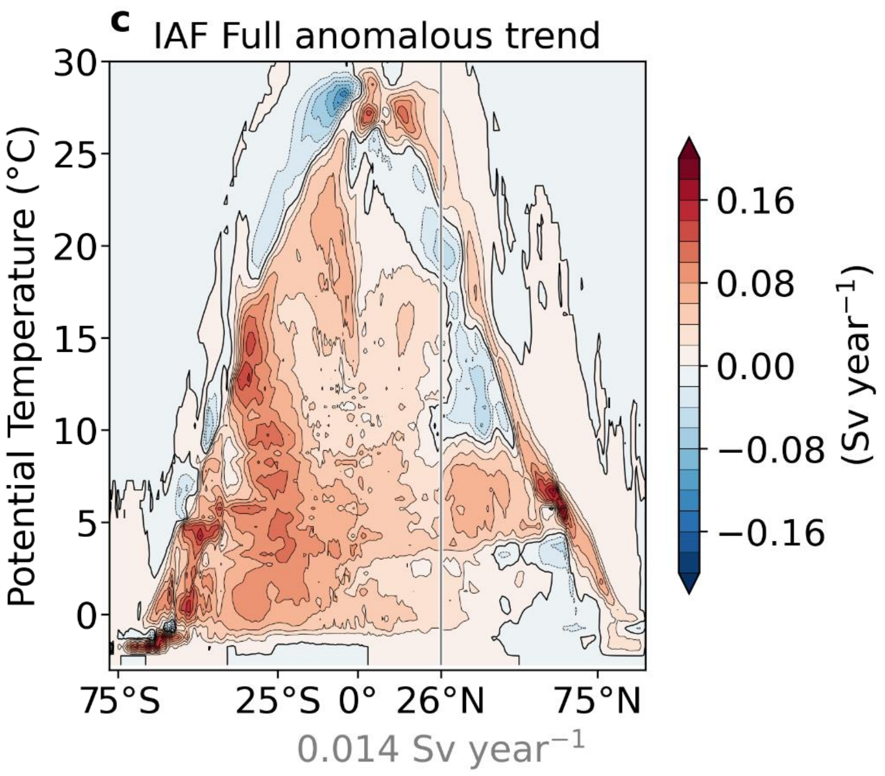
Indian Ocean-only

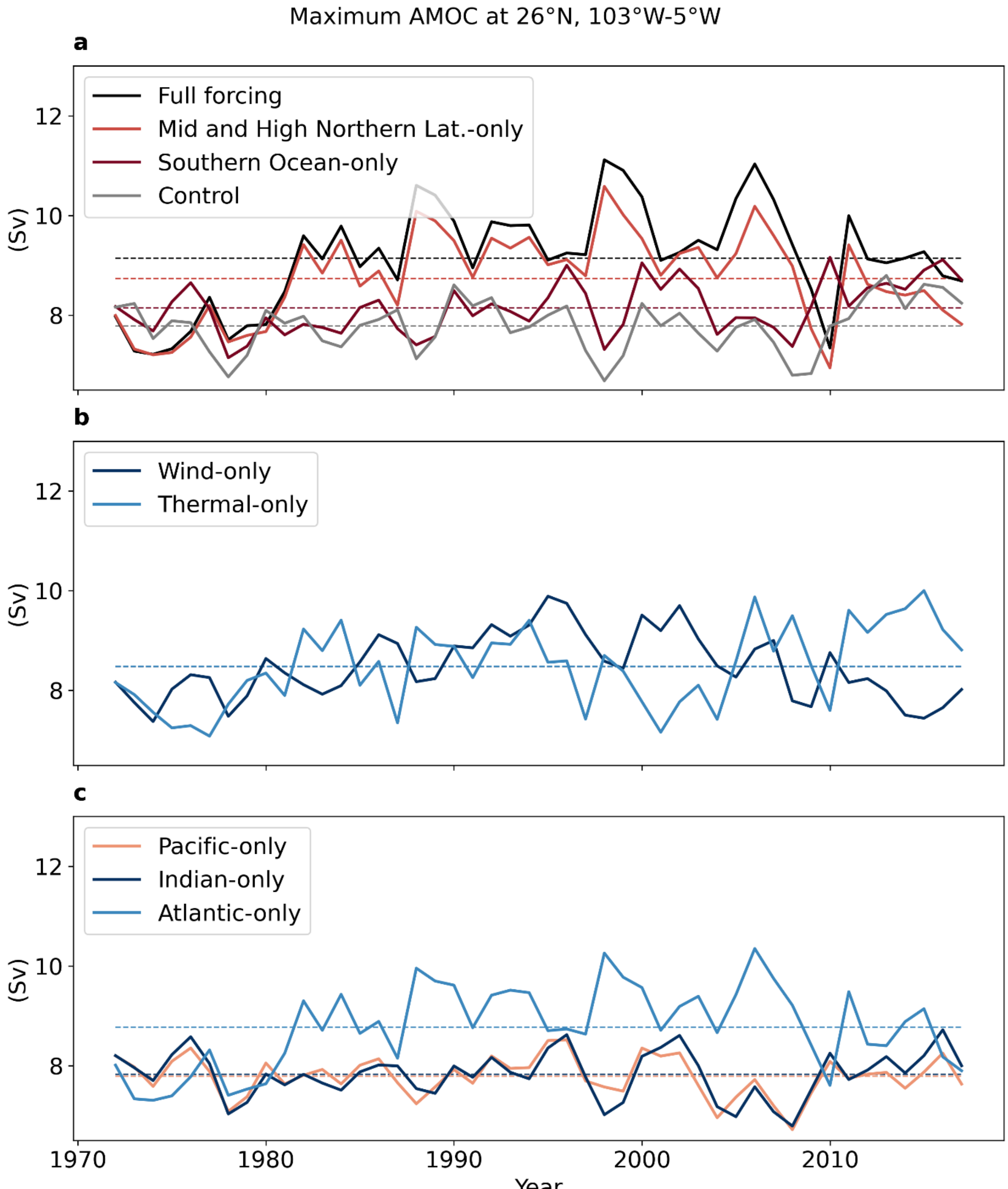


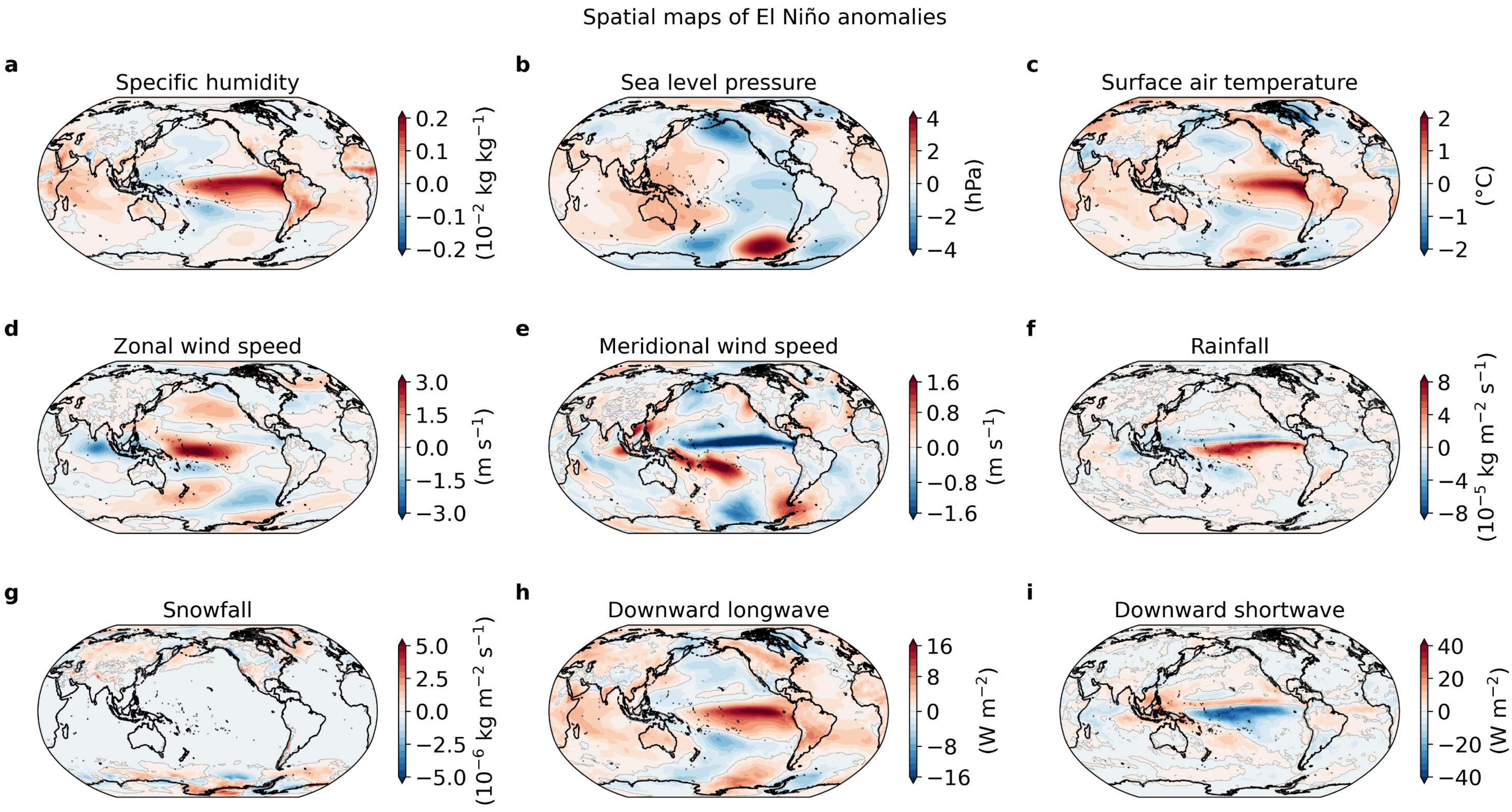
Atlantic Ocean-only



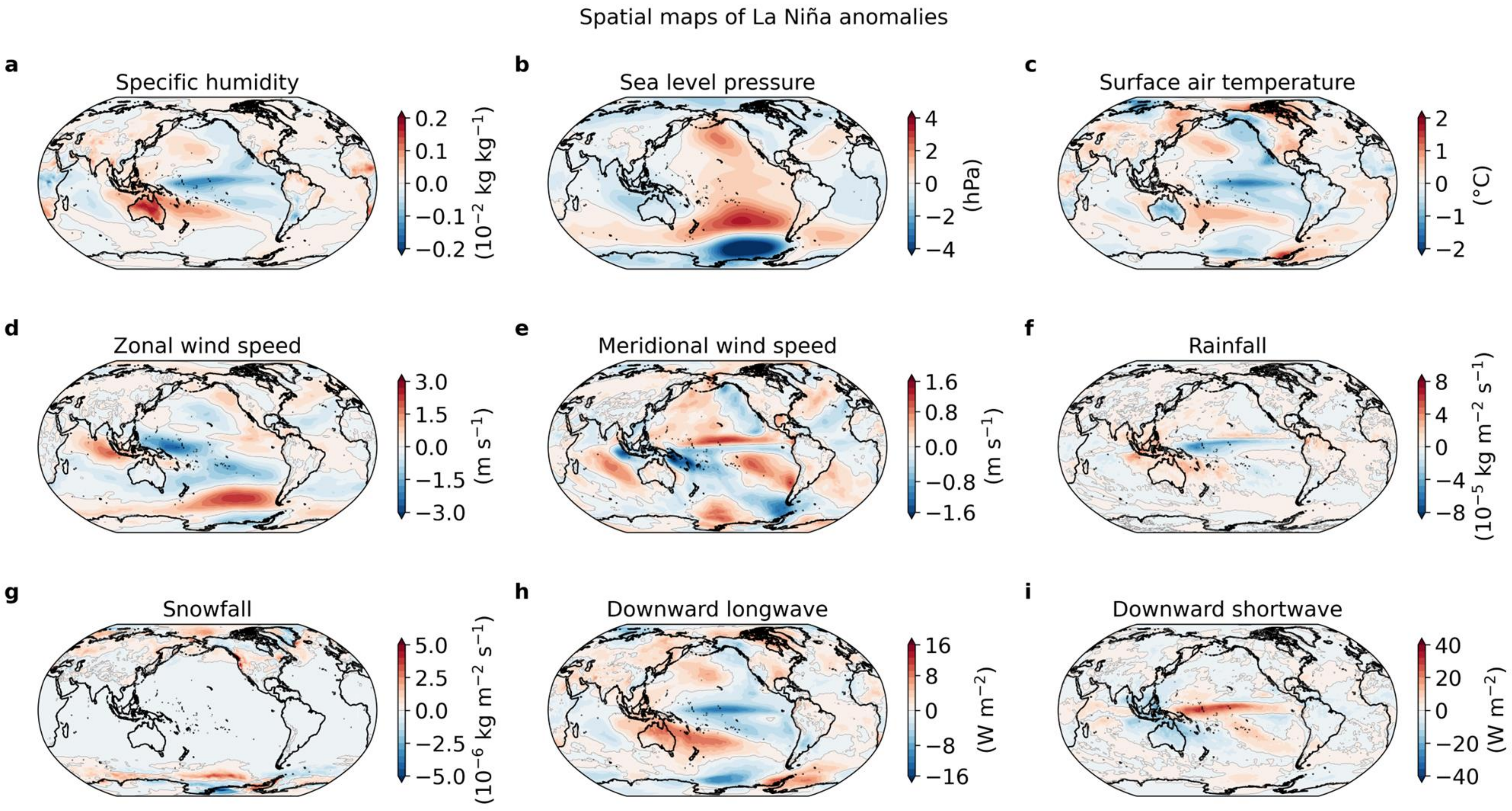
AMOC changes



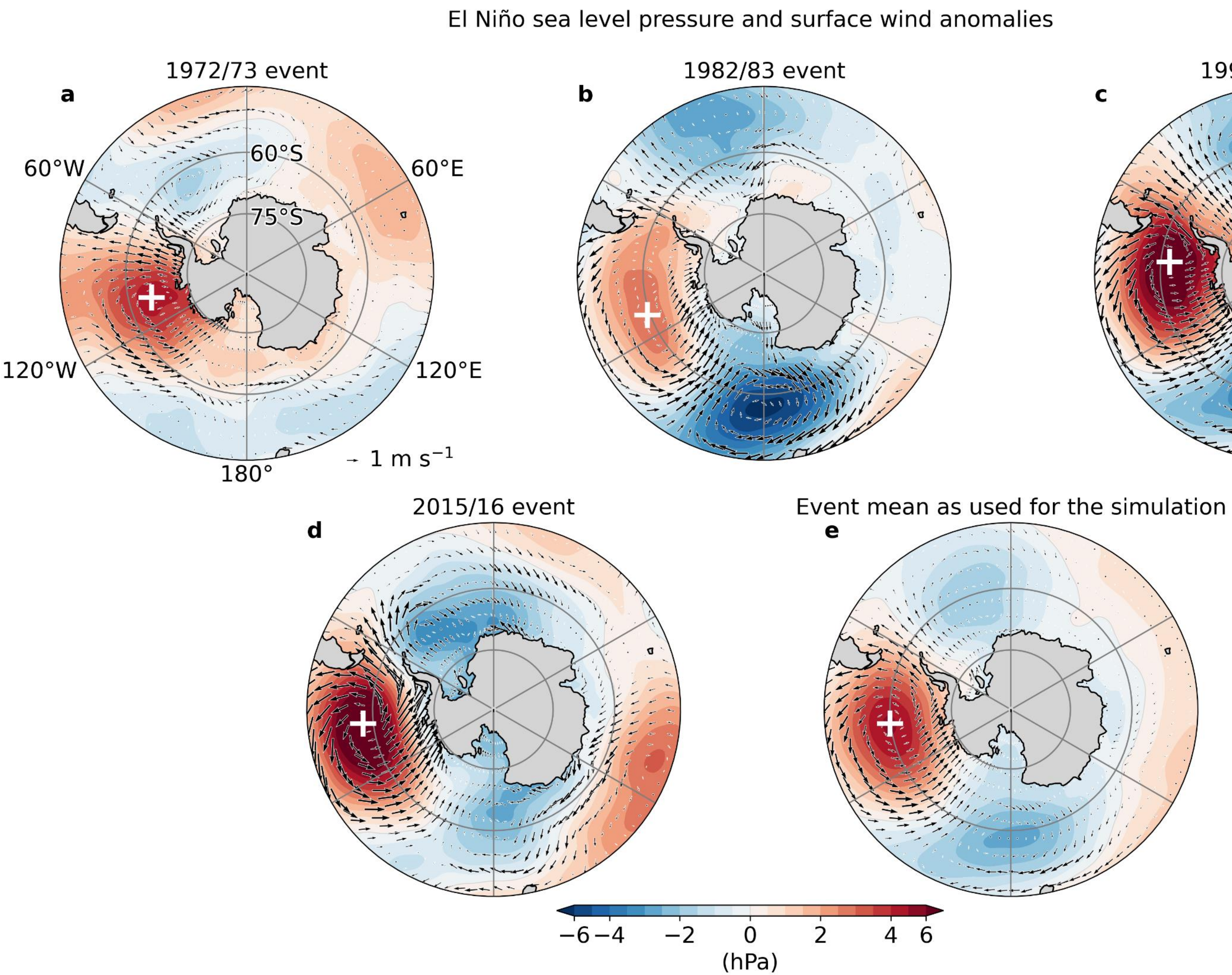




Spatial maps of El Niño anomalies
a
Specific humidity
$(10^{-2}$ kg kg$^{-1})$
0.2
0.1
0.0
−0.1
−0.2
b
Sea level pressure
(hPa)
4
2
0
−2
−4
c
Surface air temperature
(°C)
2
1
0
−1
−2
d
Zonal wind speed
(m s^{-1})
3.0
1.5
0.0
−1.5
−3.0
e
Meridional wind speed
(m s^{-1})
1.6
0.8
0.0
−0.8
−1.6
f
Rainfall
$(10^{-5}$ kg m^{-2} s$^{-1})$
8
4
0
−4
−8
g
Snowfall
$(10^{-6}$ kg m^{-2} s$^{-1})$
5.0
2.5
0.0
−2.5
−5.0
h
Downward longwave
(W m^{-2})
16
8
0
−8
−16
i
Downward shortwave
(W m^{-2})
40
20
0
−20
−40

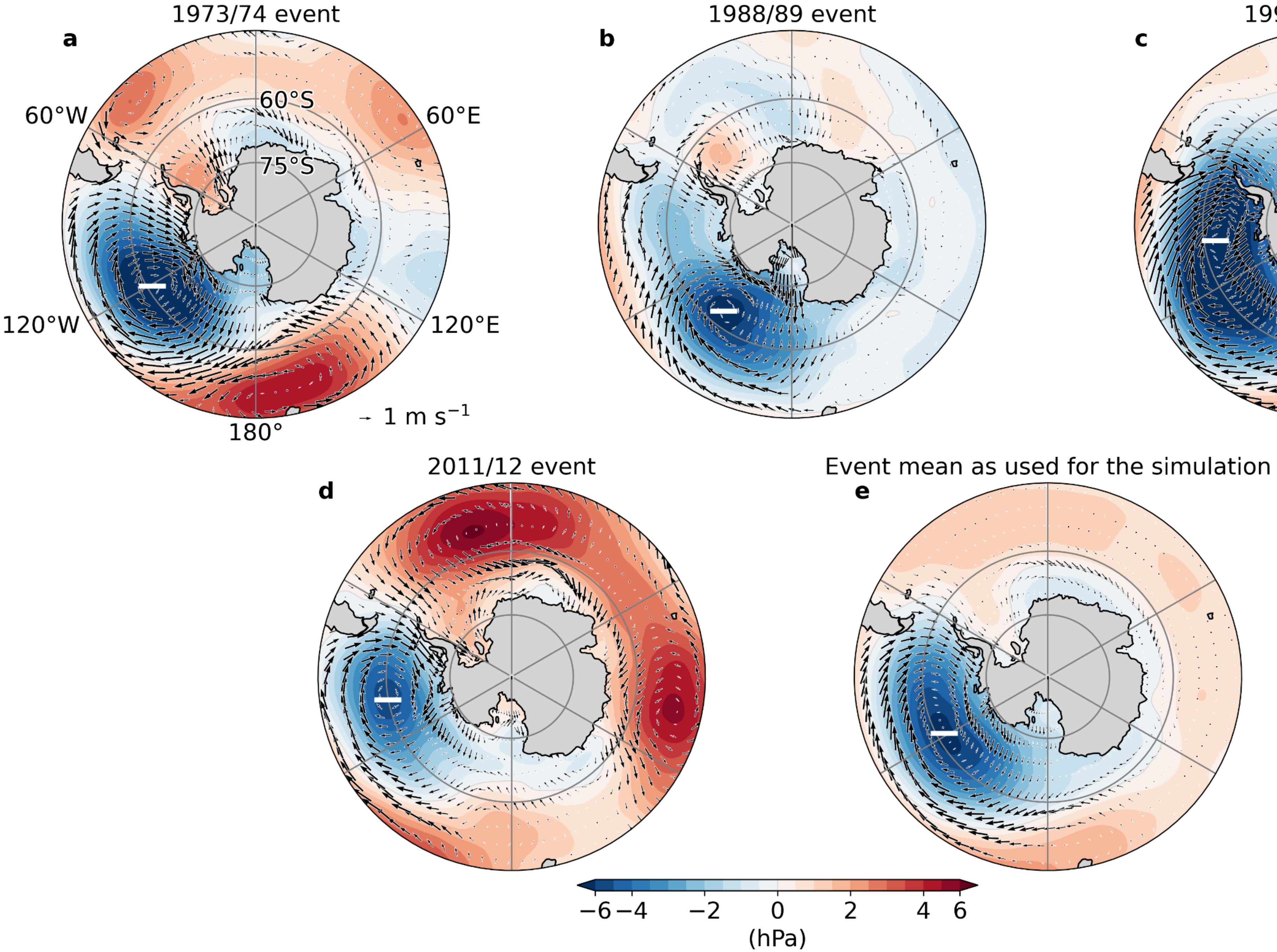


Spatial maps of La Niña anomalies
a
Specific humidity
(10^{-2} kg kg^{-1})
b
Sea level pressure
(hPa)
c
Surface air temperature
(°C)
d
Zonal wind speed
(m s^{-1})
e
Meridional wind speed
(m s^{-1})
f
Rainfall
(10^{-5} kg m^{-2} s^{-1})
g
Snowfall
(10^{-6} kg m^{-2} s^{-1})
h
Downward longwave
(W m^{-2})
i
Downward shortwave
(W m^{-2})

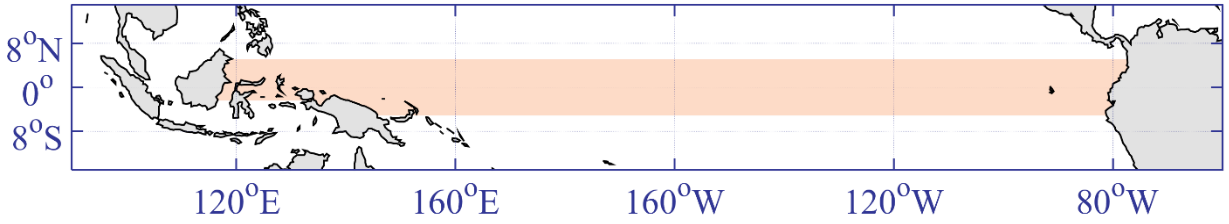


El Niño sea level pressure and surface wind anomalies
1972/73 event
a
60°S
75°S
60°W
60°E
120°W
120°E
180°
1 m s^{-1}
1982/83 event
b
1997/98 event
c
2015/16 event
d
Event mean as used for the simulation
e
−6 −4 −2 0 2 4 6
(hPa)

La Niña sea level pressure and surface wind anomalies



The warm water volume budget



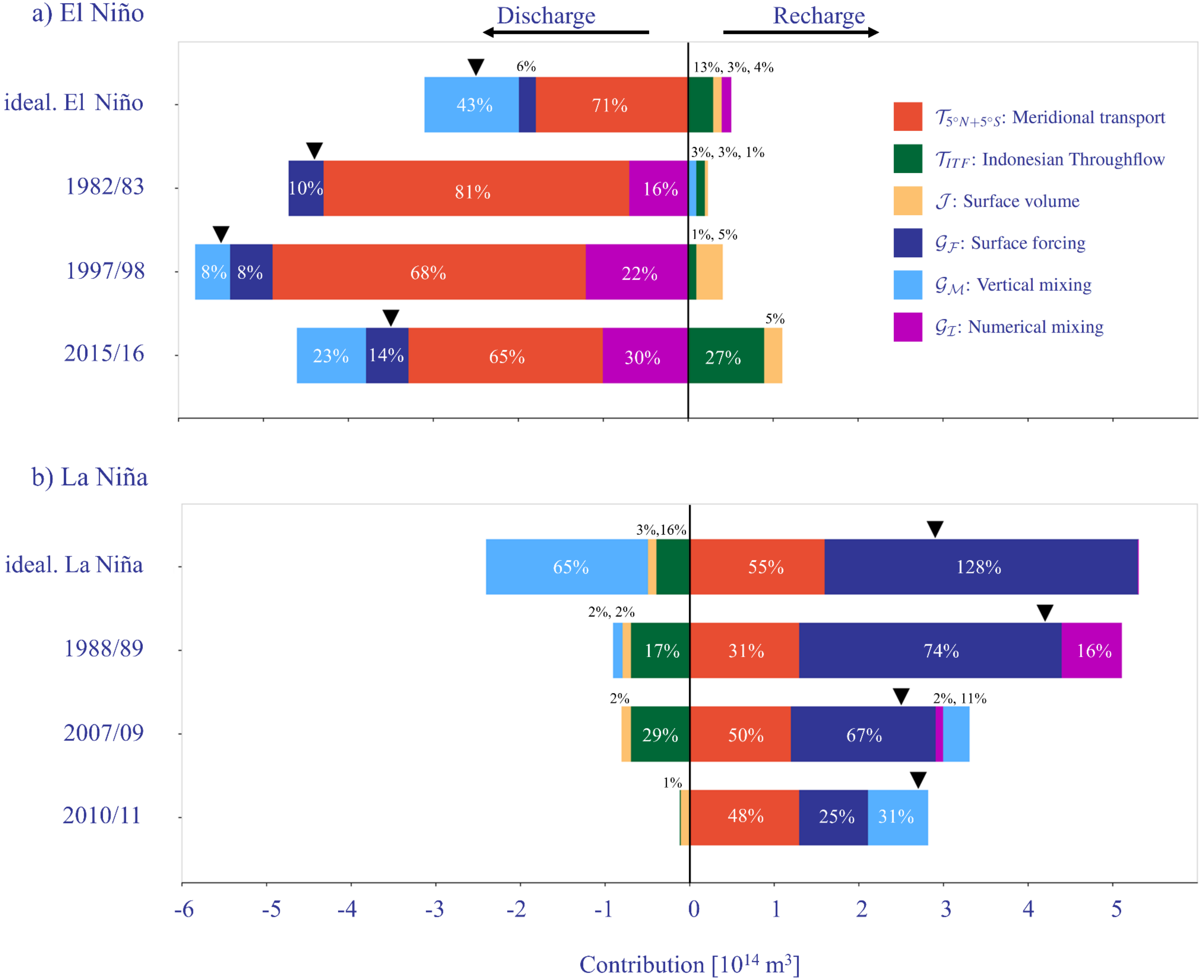
$$\frac{dWWV}{dt} = \underbrace{\mathcal{T}_{5^\circ N+5^\circ S} + \mathcal{T}_{ITF} + P - E + R}_{adiabatic\ fluxes} + \ \ldots$$

Eddy Mixing

Numerical Mixing

Surface Forcing **Vertical Mixing**

$$\underbrace{\boxed{\frac{1}{\rho_0 \cdot C_p} \cdot \int\int \frac{\partial \mathcal{F}}{\partial \Theta}\bigg|_{20^\circ C} dA} + \boxed{\frac{1}{\rho_0 \cdot C_p} \cdot \int\int \frac{\partial \mathcal{M}}{\partial \Theta}\bigg|_{20^\circ C} dA} + \boxed{\mathcal{G}_{\mathcal{E}}} + \boxed{\mathcal{G}_{\mathcal{I}}}}_{diabatic\ fluxes}$$



a) El Niño
Discharge
Recharge
ideal. El Niño
1982/83
1997/98
2015/16
43%
6%
71%
13%, 3%, 4%
10%
81%
16%
3%, 3%, 1%
8%
8%
68%
22%
1%, 5%
23%
14%
65%
30%
27%
5%
$\mathcal{T}_{5°N+5°S}$: Meridional transport
$\mathcal{T}_{ITF}$: Indonesian Throughflow
$\mathcal{J}$: Surface volume
$\mathcal{G}_{\mathcal{F}}$: Surface forcing
$\mathcal{G}_{\mathcal{M}}$: Vertical mixing
$\mathcal{G}_{\mathcal{I}}$: Numerical mixing
b) La Niña
ideal. La Niña
1988/89
2007/09
2010/11
65%
3%,16%
55%
128%
2%, 2%
17%
31%
74%
16%
2%
29%
50%
67%
2%, 11%
1%
48%
25%
31%
-6
-5
-4
-3
-2
-1
0
1
2
3
4
5
Contribution [10^{14} m^3]

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Take Home

1. Repeat decade **spin-up** → **better OHC evolution** than most OMIP-2 models

2. Recent surface **wind** and **thermal** property **trends**: **~50%** of global OHC → **almost 100%** when applied only over **Southern Ocean**

3. Heat uptake facilitated by **cool SSTs** & dominant …

   … **sensible heat fluxes** with **thermal forcing** held **fixed**

   … downward **longwave radiation** when **winds** are **fixed** & thermal properties evolve over time

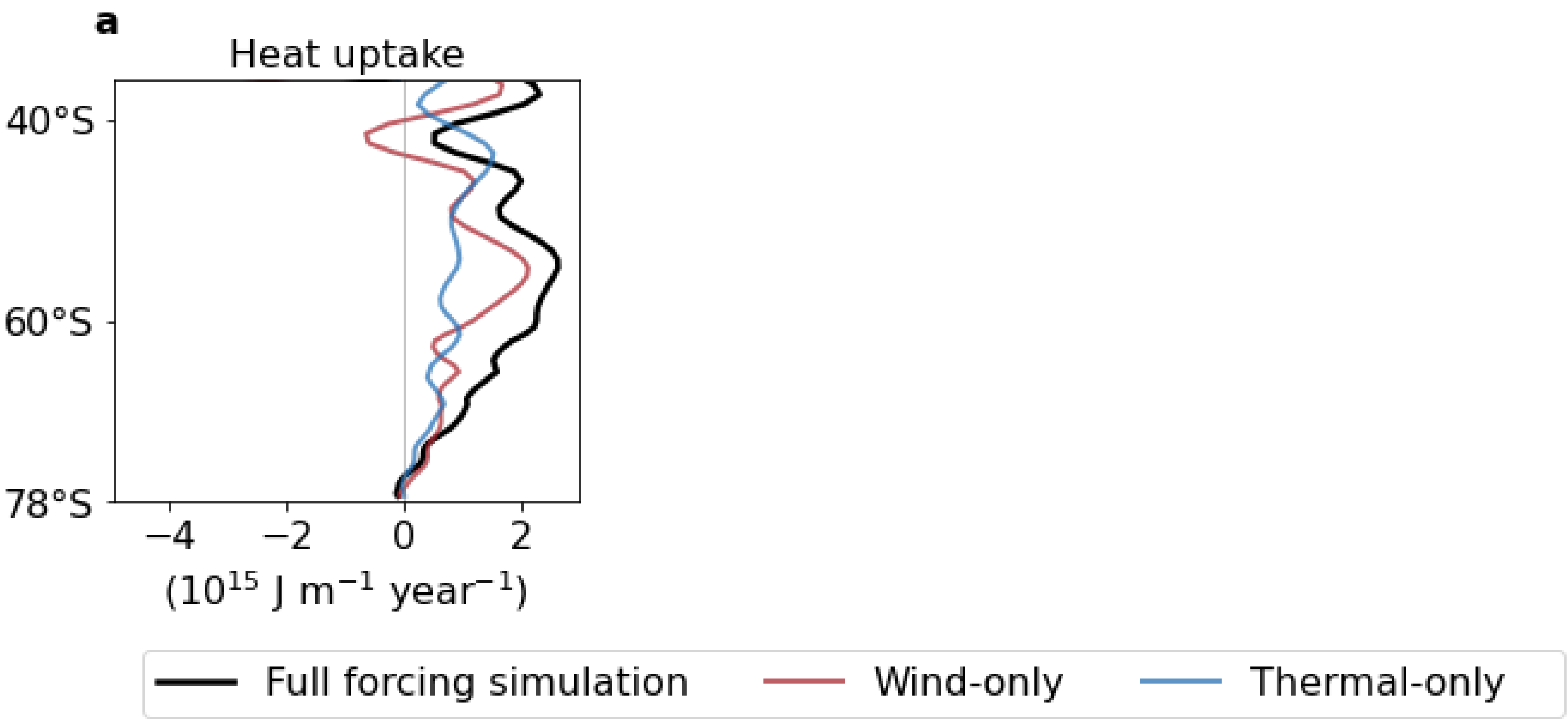
Project I: Take Home Messages

- In-depth analysis of individually calculated upper ocean heat/volume fluxes during ENSO in ACCESS-OM2

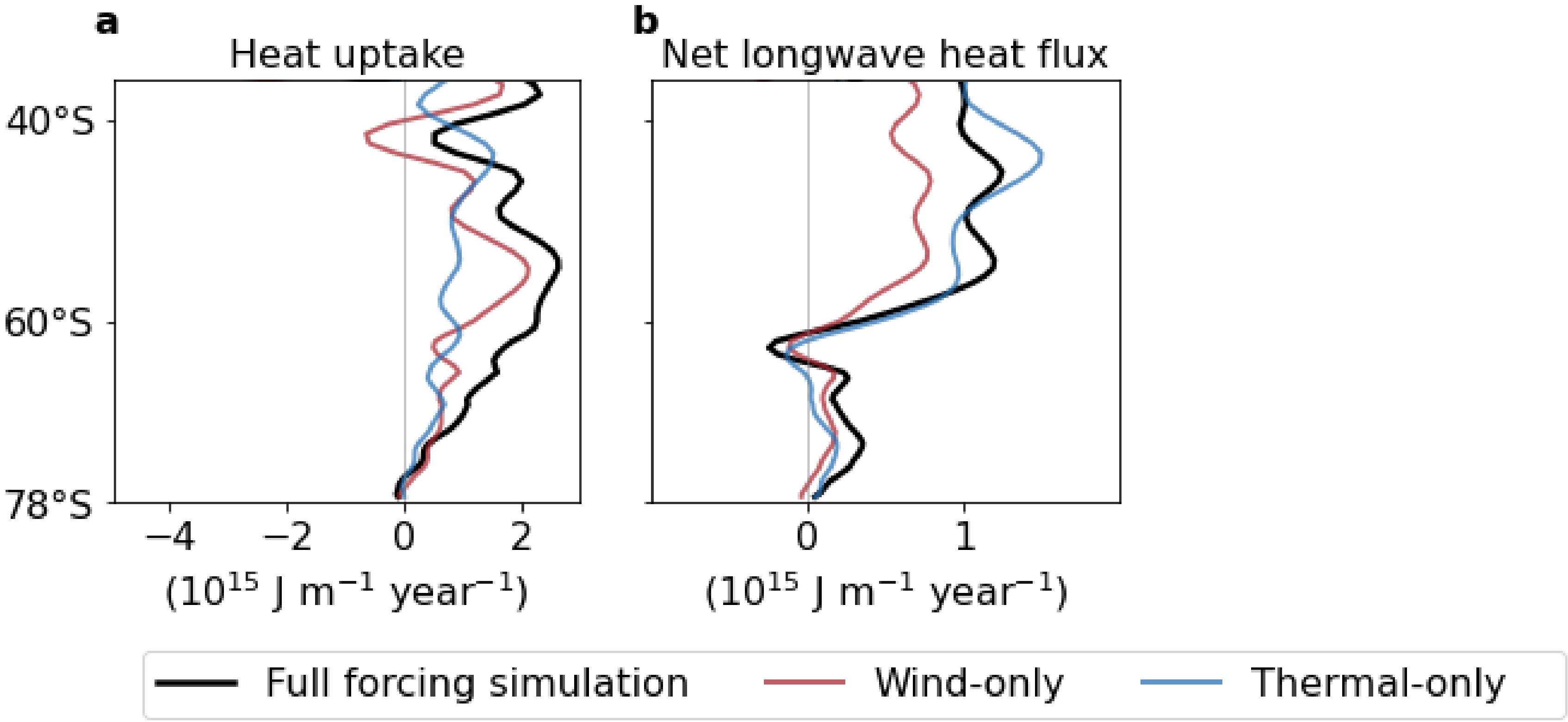
- Adiabatic volume fluxes mostly symmetric, diabatic fluxes show a strong asymmetry and peak three to six months earlier

- The large event-to-event variability in the surface forcing flux is linked to the shoaling of the 20°C isotherm in the eastern equatorial Pacific

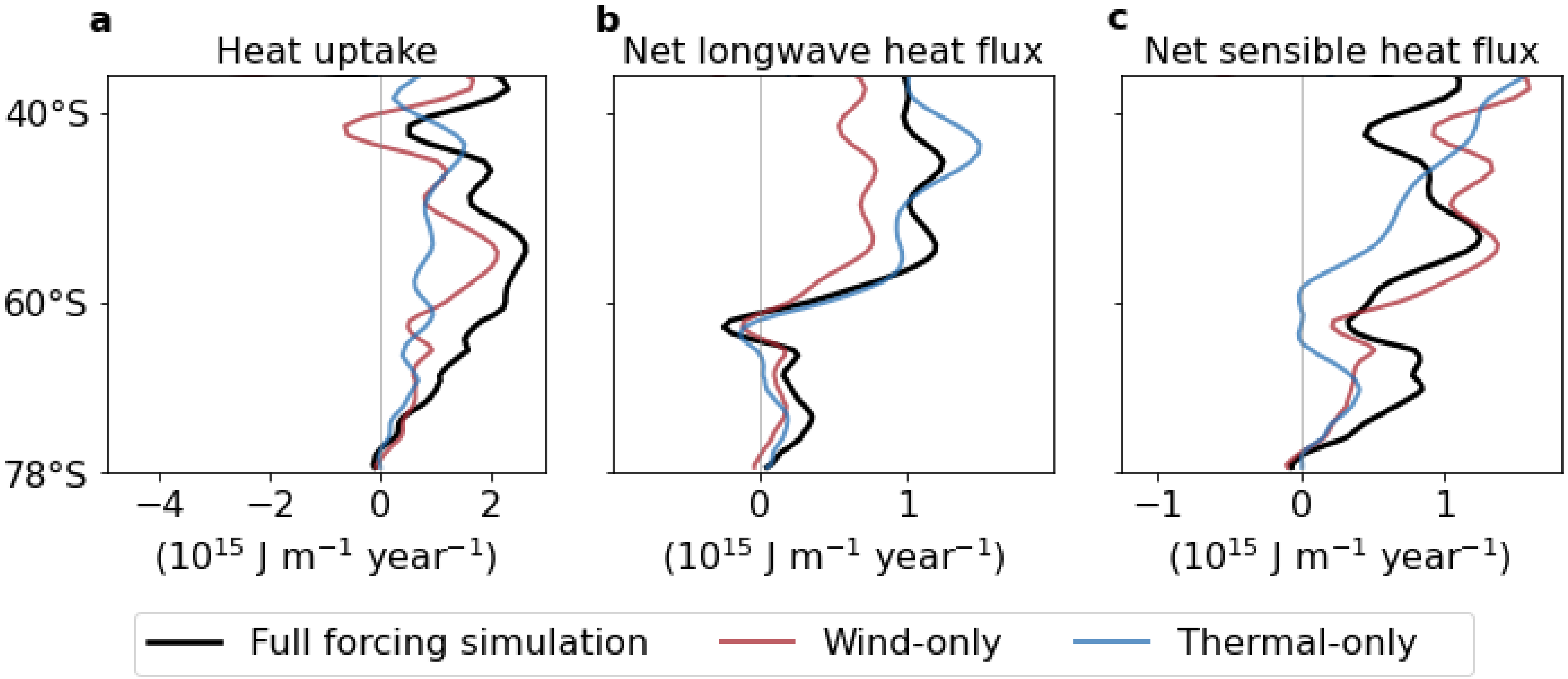
Zonally integrated heat fluxes



Zonally integrated heat fluxes



Zonally integrated heat fluxes



ENSOAnt

UNSW SYDNEY

Climate Change Research Centre

School of Biological, Earth and Environmental Sciences

Processes and Dynamics of Global to Regional Ocean Heat Uptake and Variability

A thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy

Maurice F. Huguenin

supervised by

Prof. Dr. Matthew H. England and Dr. Ryan M. Holmes

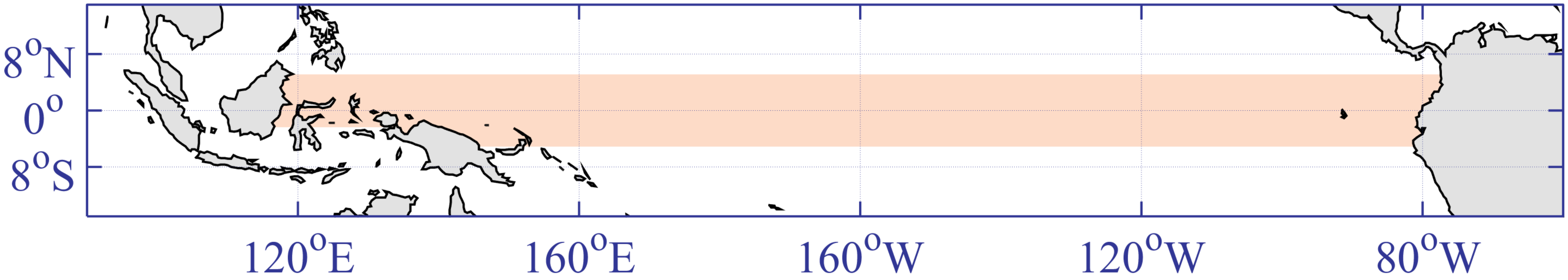
23rd May 2023

1. Drivers and distribution of global ocean heat uptake over the last half century *(Huguenin et al. 2022)*

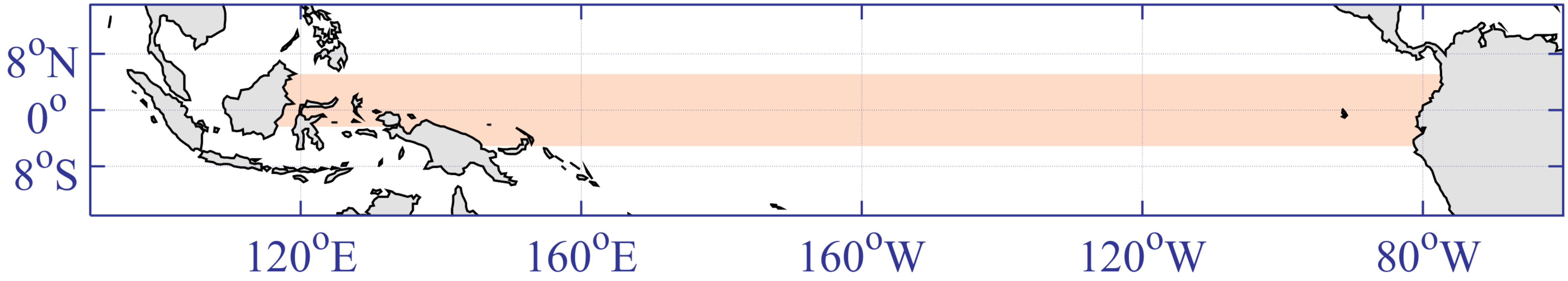
2. Key role of surface forcing and vertical mixing in changing warm water volume during ENSO *(Huguenin et al. 2020b)*

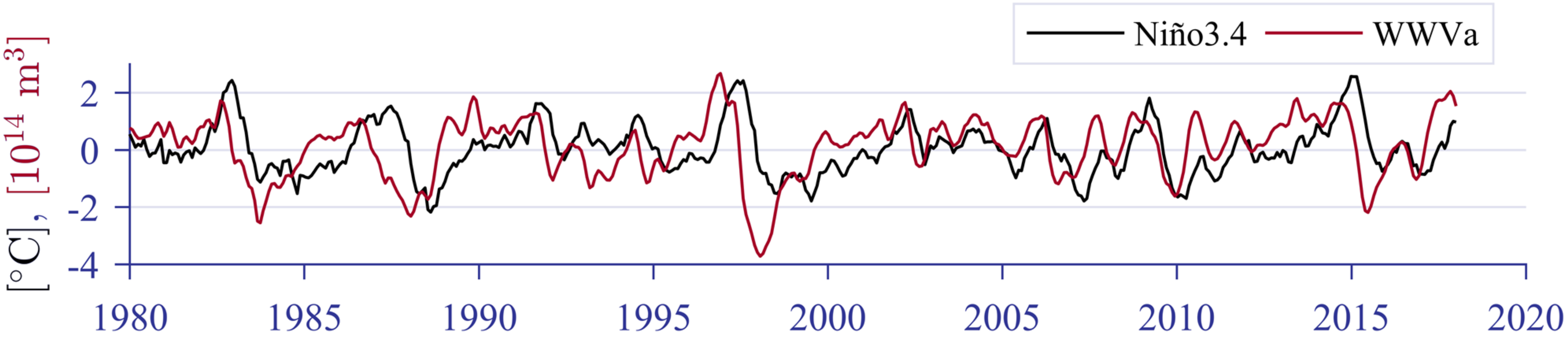
Motivation

Motivation



Motivation





Reynolds et al. (2007); Meinen & McPhaden (2000)

Motivation

- Focus on adiabatic exchange (Ekman, Sverdrup dynamics)
  → e.g. Jin (1997), McGregor et al. (2013, 2014), Neske and McGregor (2018), Izumo et al. (2018), …

Motivation

- Focus on adiabatic exchange (Ekman, Sverdrup dynamics)
  → e.g. Jin (1997), McGregor et al. (2013, 2014), Neske and McGregor (2018), Izumo et al. (2018), …

- Diabatic fluxes account for ~50% of warm water volume discharge in 1997/98
  Meinen and McPhaden (2001)

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- Diabatic fluxes account for ~50% of warm water volume discharge in 1997/98
  Meinen and McPhaden (2001)

- Diabatic contribution to warm water volume changes varies
  Lengaigne et al. (2012) model study

- Disagreement amongst studies: Brown and Fedorov (2010)

Part 2: Goals

1. Revisit the warm water volume budget using online calculated fluxes

2. Simulate ENSO variability over 1979-2016

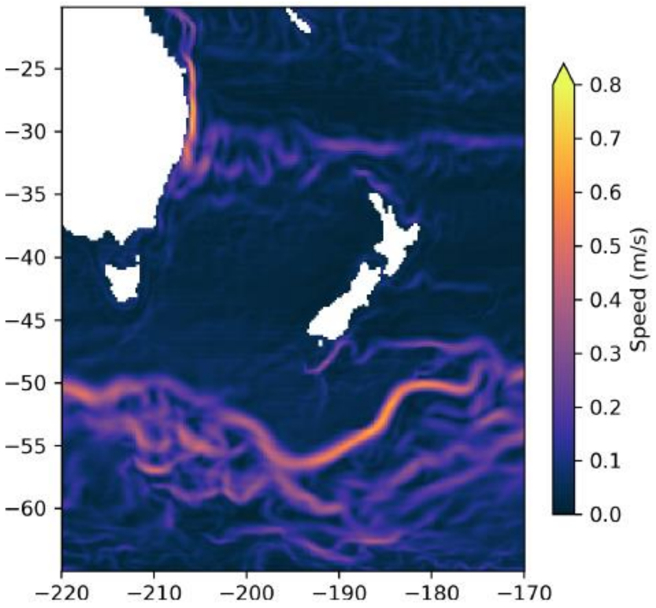
3. Examine extreme El Niño/La Niña events and asymmetries

More ocean-sea ice modelling!

- 1/4° ACCESS-OM2 with 50 z* levels

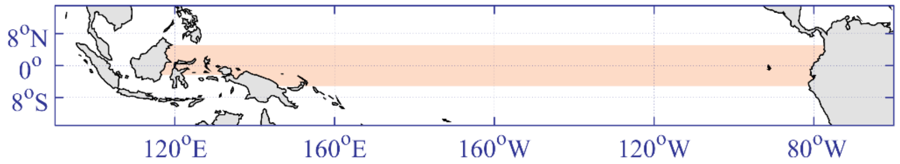
- Precise temperature-space water mass transformation diagnostics (Holmes et al., 2019a)

1/4°



Kiss et al. (2019)

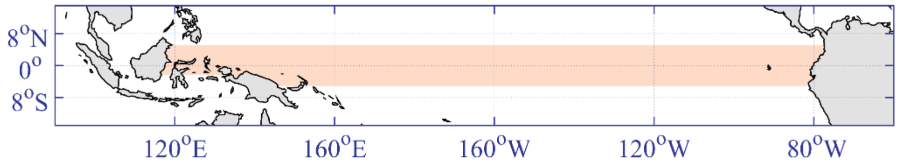
The warm water volume budget



$$\frac{dWWV}{dt} = \underbrace{\qquad\qquad\qquad\qquad}_{adiabatic\ fluxes} + \ \ldots$$

$$\underbrace{\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad}_{diabatic\ fluxes}$$

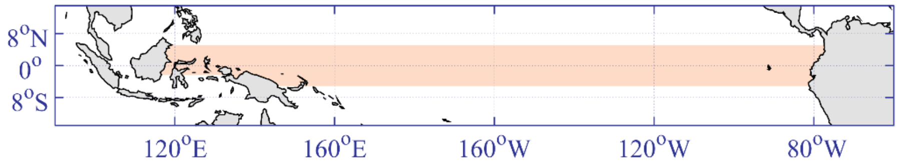
The warm water volume budget



$$\frac{dWWV}{dt} = \underbrace{\mathcal{T}_{5^\circ N+5^\circ S} + \mathcal{T}_{ITF} + P - E + R}_{adiabatic\ fluxes} + \ \ldots$$

$$\underbrace{\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad}_{diabatic\ fluxes}$$

The warm water volume budget

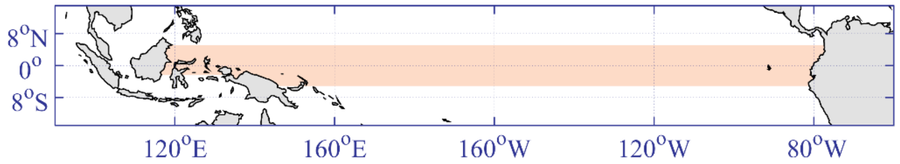


$$\frac{dWWV}{dt} = \underbrace{\mathcal{T}_{5^\circ N+5^\circ S} + \mathcal{T}_{ITF} + P - E + R}_{adiabatic\ fluxes} + \quad \ldots$$

Surface Forcing

$$\underbrace{\boxed{\frac{1}{\rho_0 \cdot C_p} \cdot \int\int \left.\frac{\partial \mathcal{F}}{\partial \Theta}\right|_{20^\circ C} dA} + \qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad}_{diabatic\ fluxes}$$

The warm water volume budget

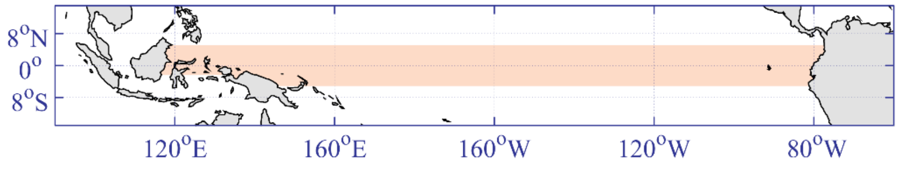


$$\frac{dWWV}{dt} = \underbrace{\mathcal{T}_{5^\circ N+5^\circ S} + \mathcal{T}_{ITF} + P - E + R}_{adiabatic\ fluxes} + \ \ldots$$

Surface Forcing **Vertical Mixing**

$$\underbrace{\boxed{\frac{1}{\rho_0 \cdot C_p} \cdot \int\int \frac{\partial \mathcal{F}}{\partial \Theta}\bigg|_{20^\circ C} dA} + \boxed{\frac{1}{\rho_0 \cdot C_p} \cdot \int\int \frac{\partial \mathcal{M}}{\partial \Theta}\bigg|_{20^\circ C} dA} +}_{diabatic\ fluxes}$$

The warm water volume budget



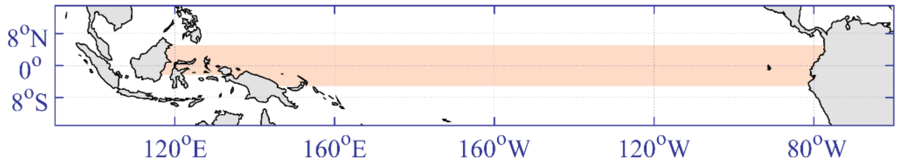
$$\frac{dWWV}{dt} = \underbrace{\mathcal{T}_{5^\circ N + 5^\circ S} + \mathcal{T}_{ITF} + P - E + R}_{adiabatic\ fluxes} + \quad \ldots$$

Eddy Mixing

Surface Forcing **Vertical Mixing**

$$\underbrace{\boxed{\frac{1}{\rho_0 \cdot C_p} \cdot \int \int \frac{\partial \mathcal{F}}{\partial \Theta}\bigg|_{20^\circ C} dA} + \boxed{\frac{1}{\rho_0 \cdot C_p} \cdot \int \int \frac{\partial \mathcal{M}}{\partial \Theta}\bigg|_{20^\circ C} dA} + \boxed{\mathcal{G}_{\mathcal{E}}} +}_{diabatic\ fluxes}$$

The warm water volume budget



$$\frac{dWWV}{dt} = \underbrace{\mathcal{T}_{5^\circ N+5^\circ S} + \mathcal{T}_{ITF} + P - E + R}_{adiabatic\ fluxes} + \quad \ldots$$

Eddy Mixing

Surface Forcing **Vertical Mixing** **Numerical Mixing**

$$\underbrace{\boxed{\frac{1}{\rho_0 \cdot C_p} \cdot \int\int \frac{\partial \mathcal{F}}{\partial \Theta}\Big|_{20^\circ C} dA} + \boxed{\frac{1}{\rho_0 \cdot C_p} \cdot \int\int \frac{\partial \mathcal{M}}{\partial \Theta}\Big|_{20^\circ C} dA} + \boxed{\mathcal{G}_{\mathcal{E}}} + \boxed{\mathcal{G}_{\mathcal{I}}}}_{diabatic\ fluxes}$$

The diabatic volume fluxes: September-November

Vertical Mixing

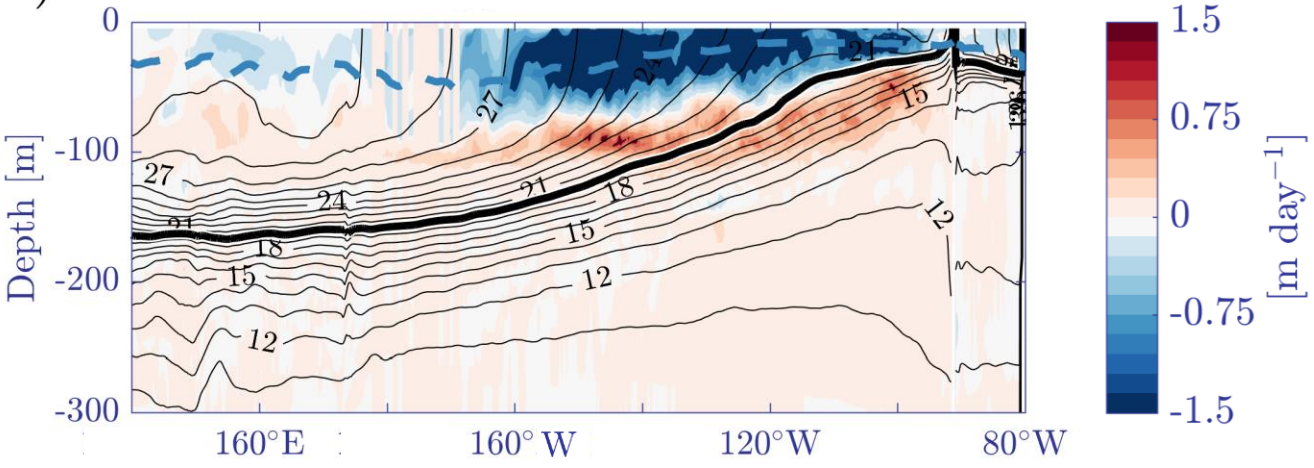
Surface Forcing

The diabatic volume fluxes: September-November

Vertical Mixing

Surface Forcing

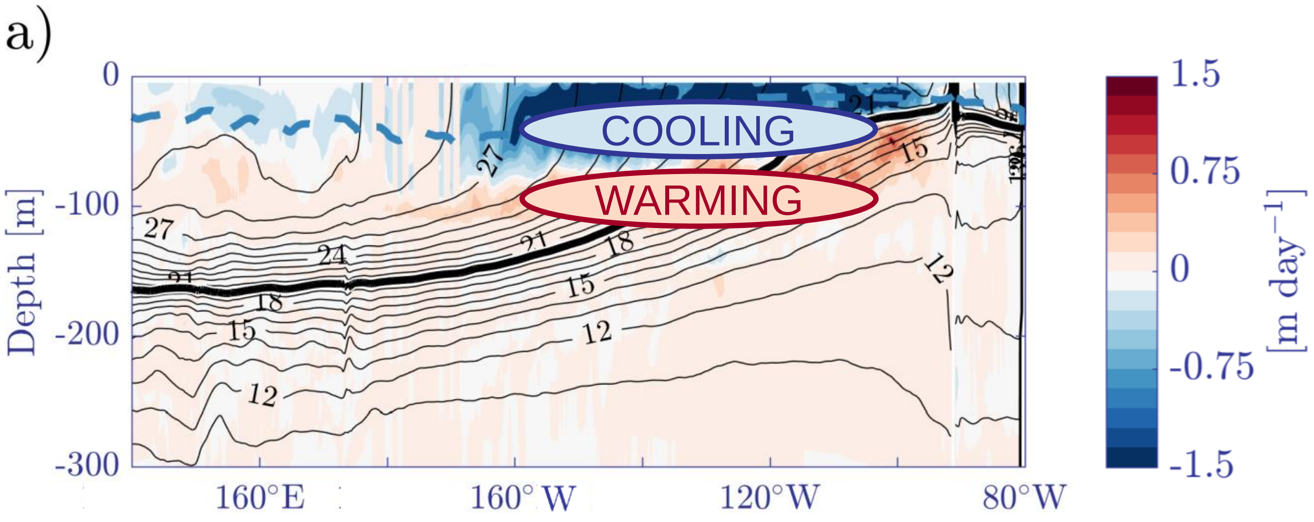
a)



The diabatic volume fluxes: September-November

Vertical Mixing

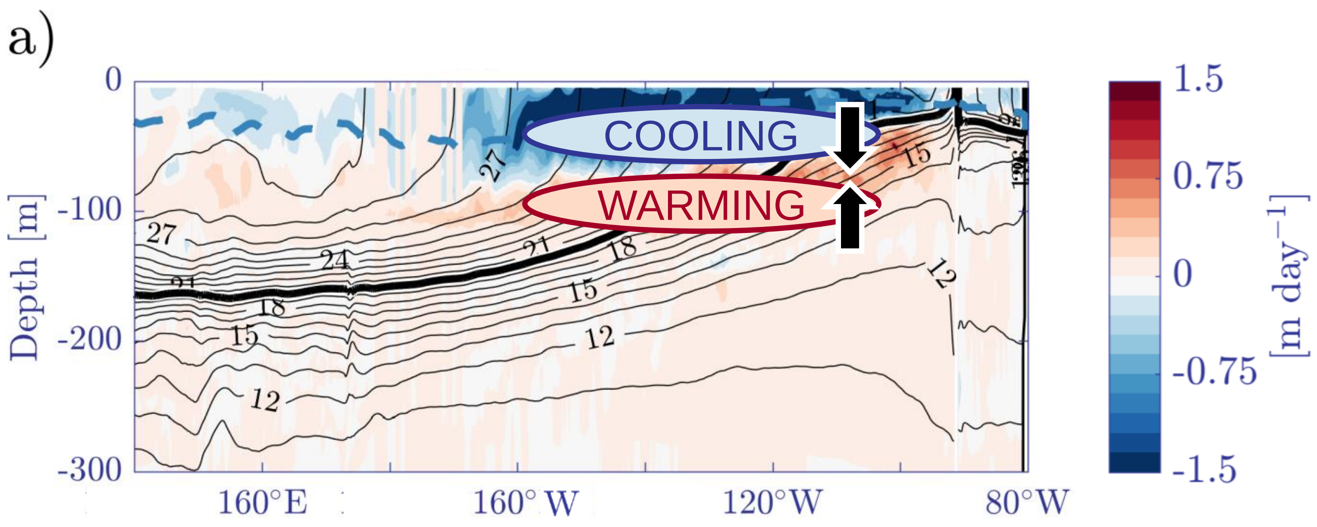
Surface Forcing



The diabatic volume fluxes: September-November

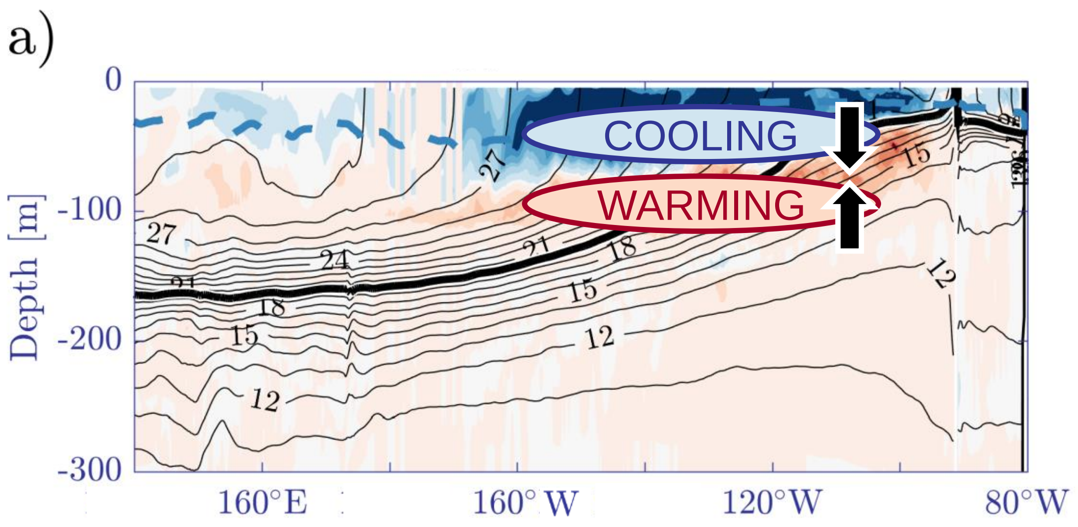
Vertical Mixing

Surface Forcing

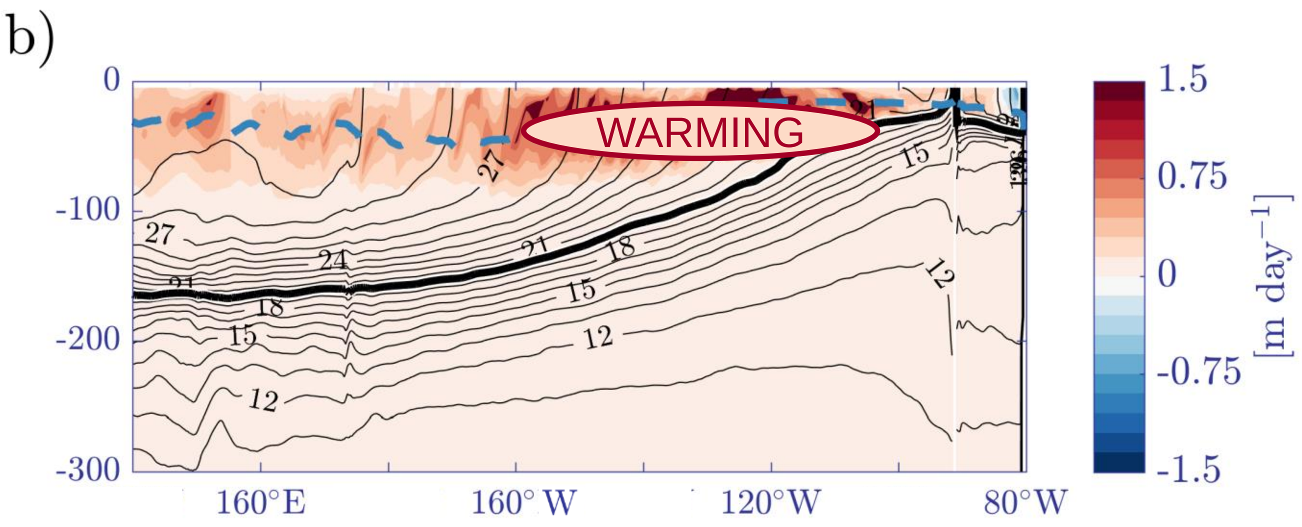


The diabatic volume fluxes: September-November

Vertical Mixing

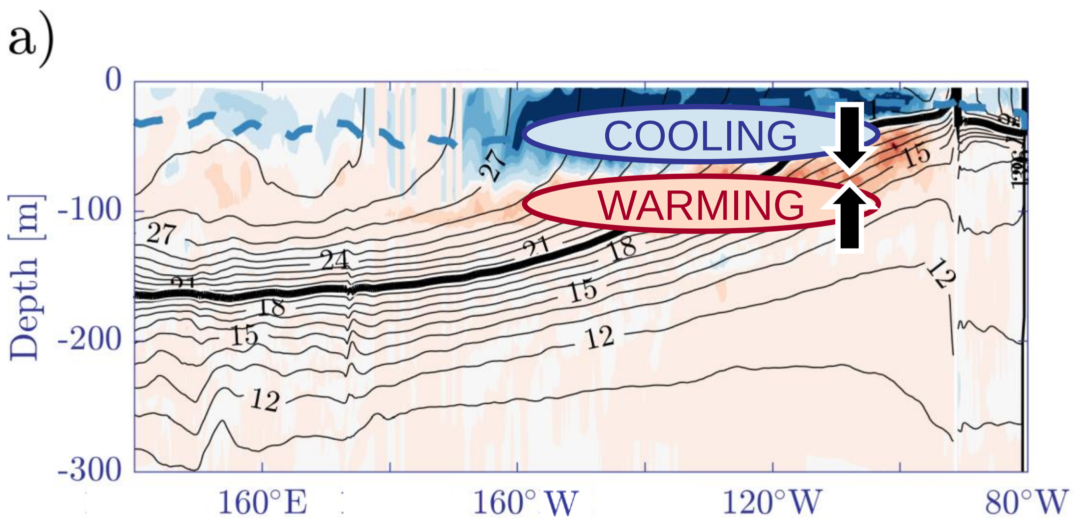


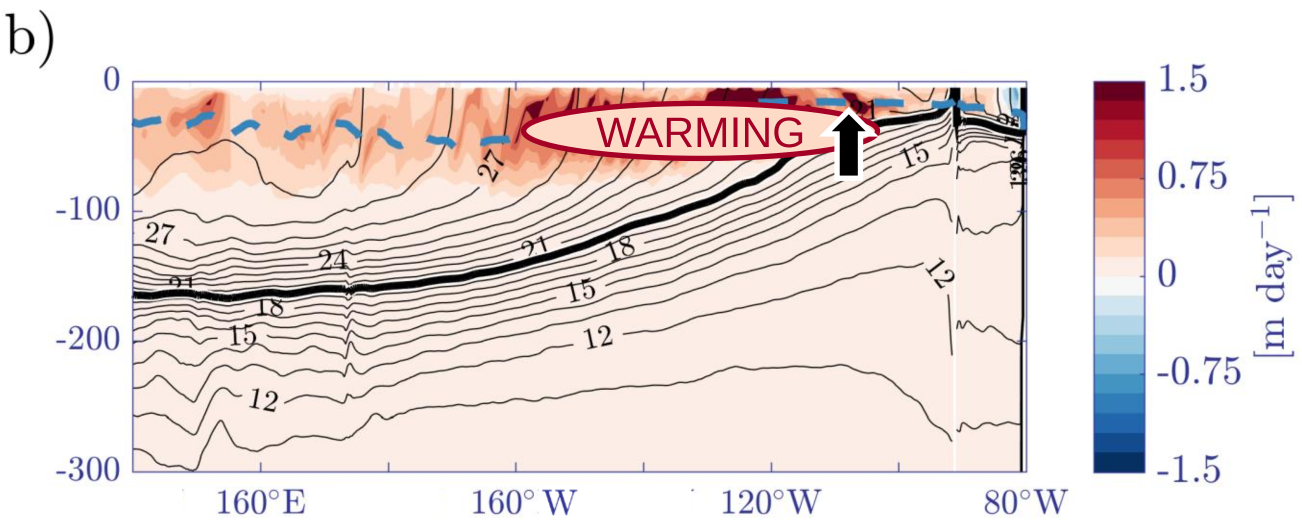
Surface Forcing



The diabatic volume fluxes: September-November

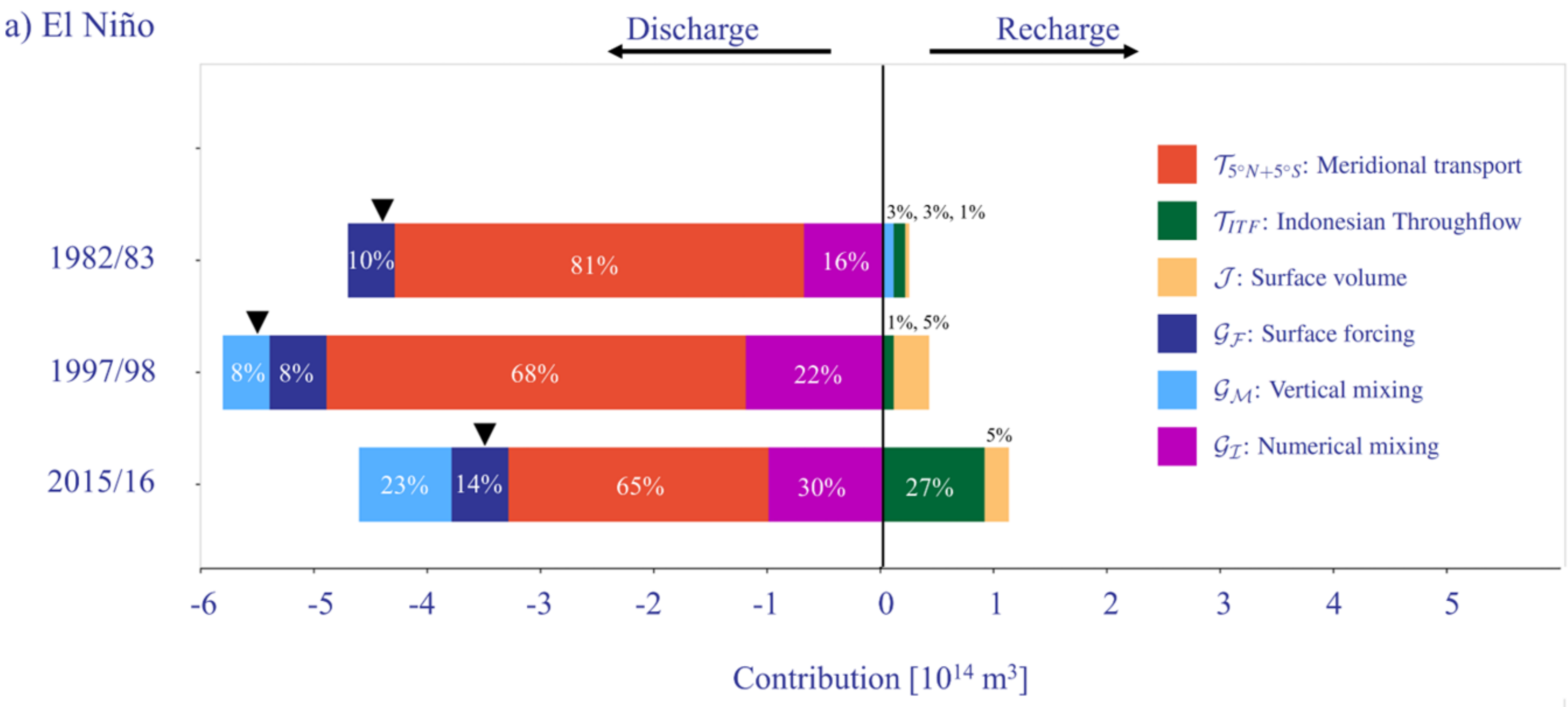
Vertical Mixing | **Surface Forcing**



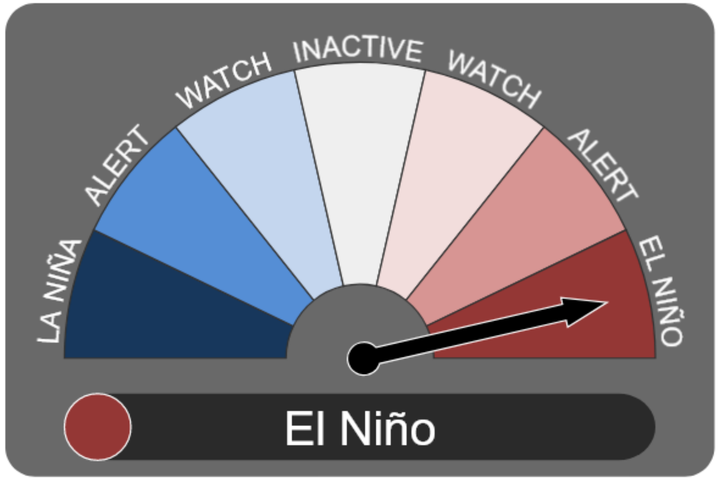


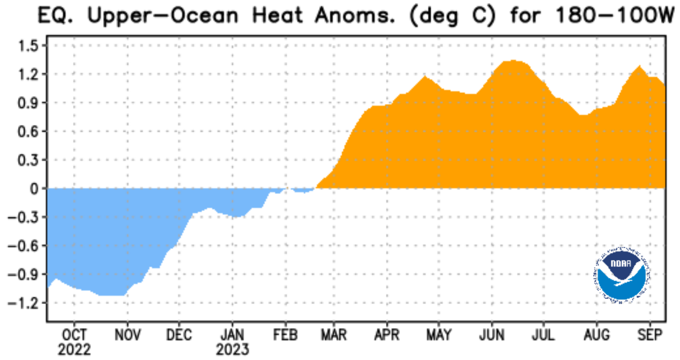
Summary figure

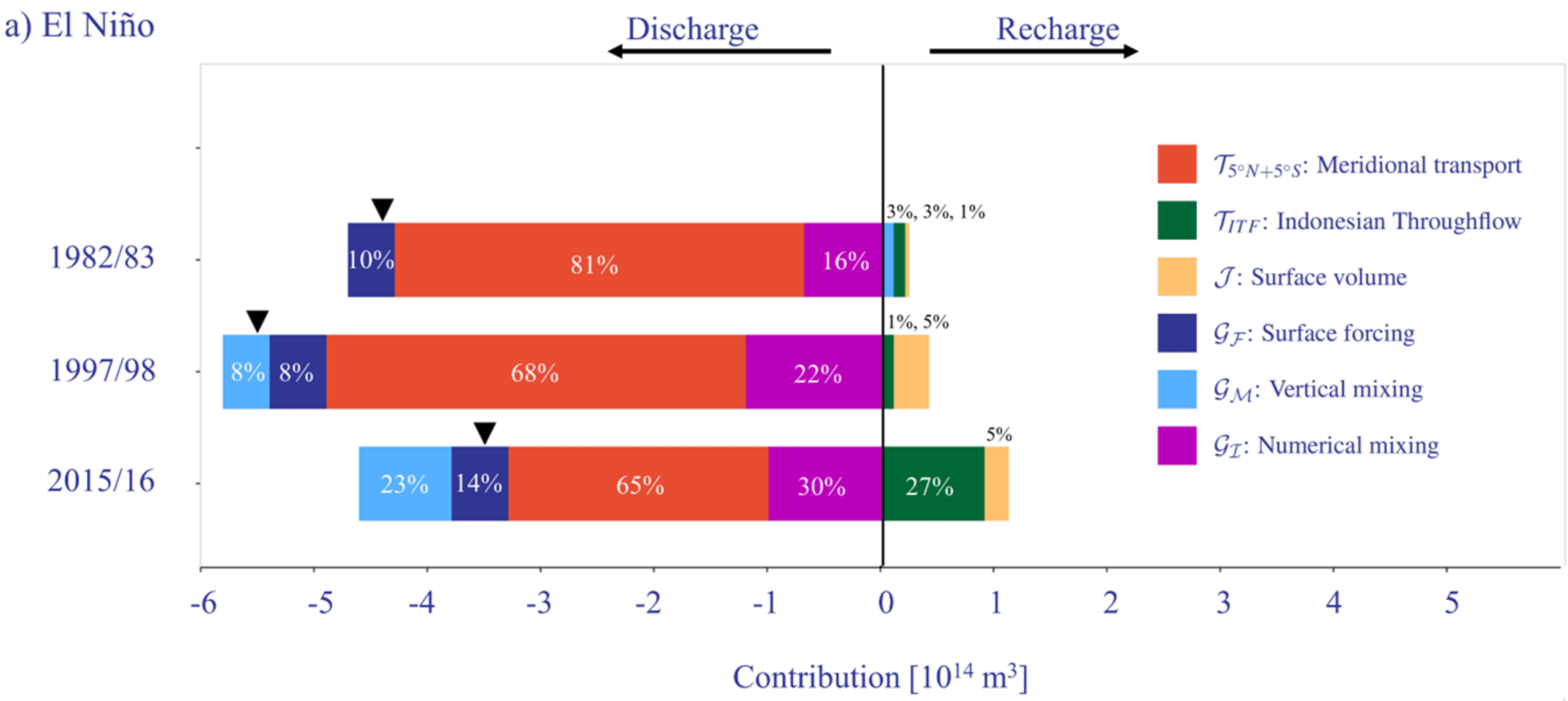
Summary figure



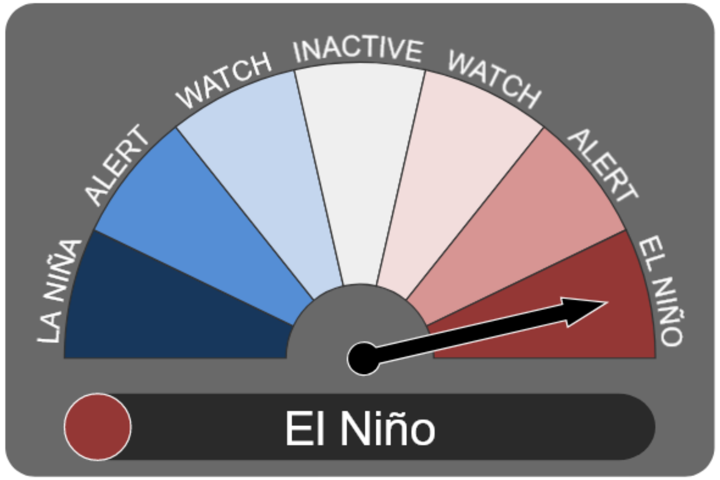
Summary figure

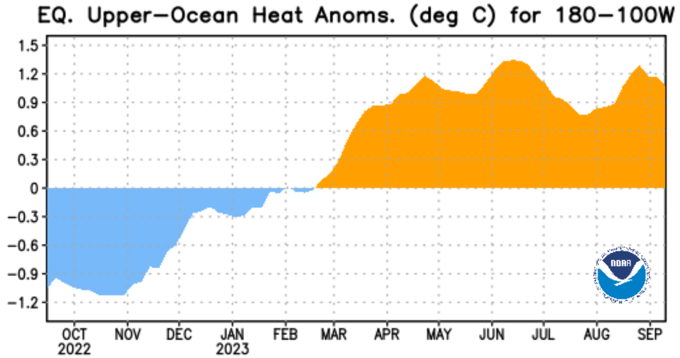


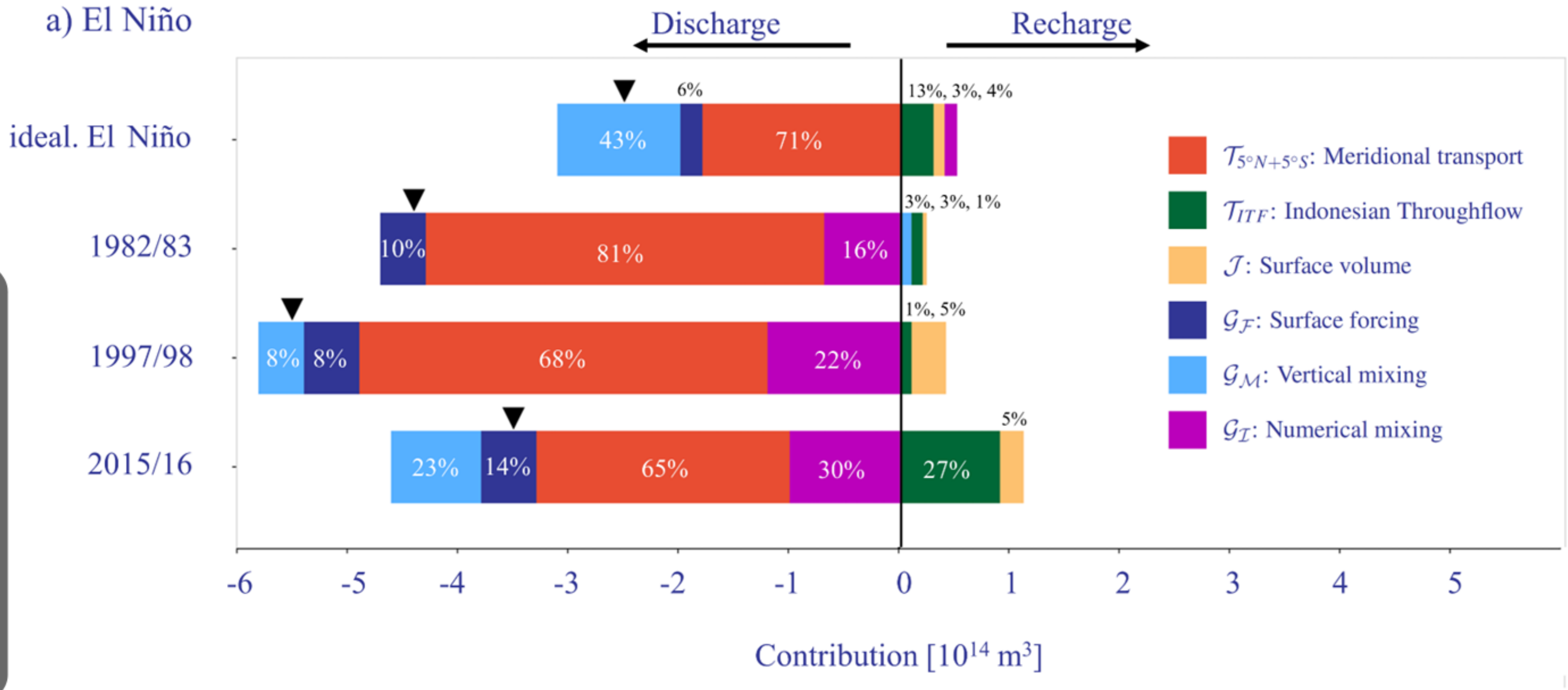




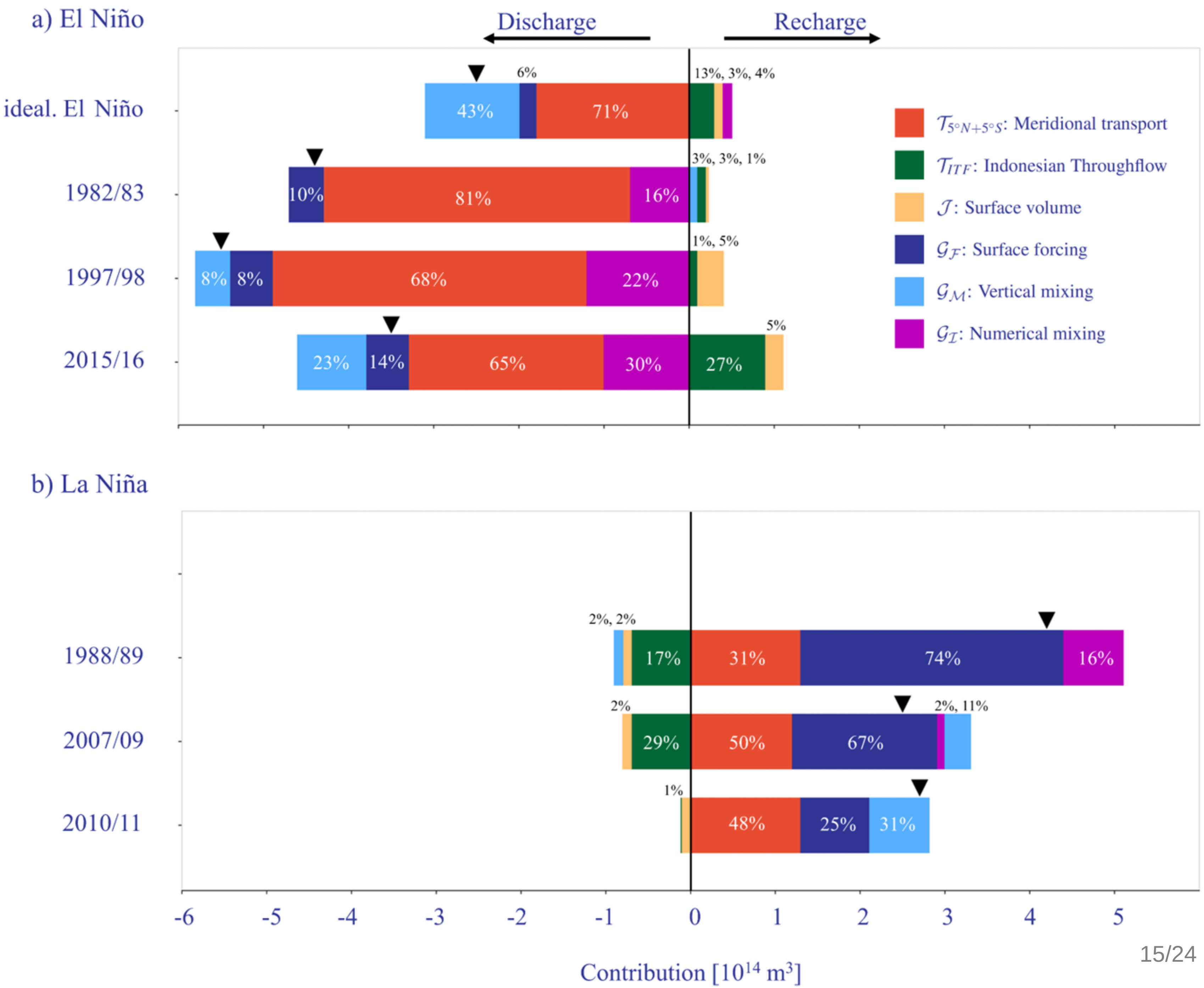
Summary figure



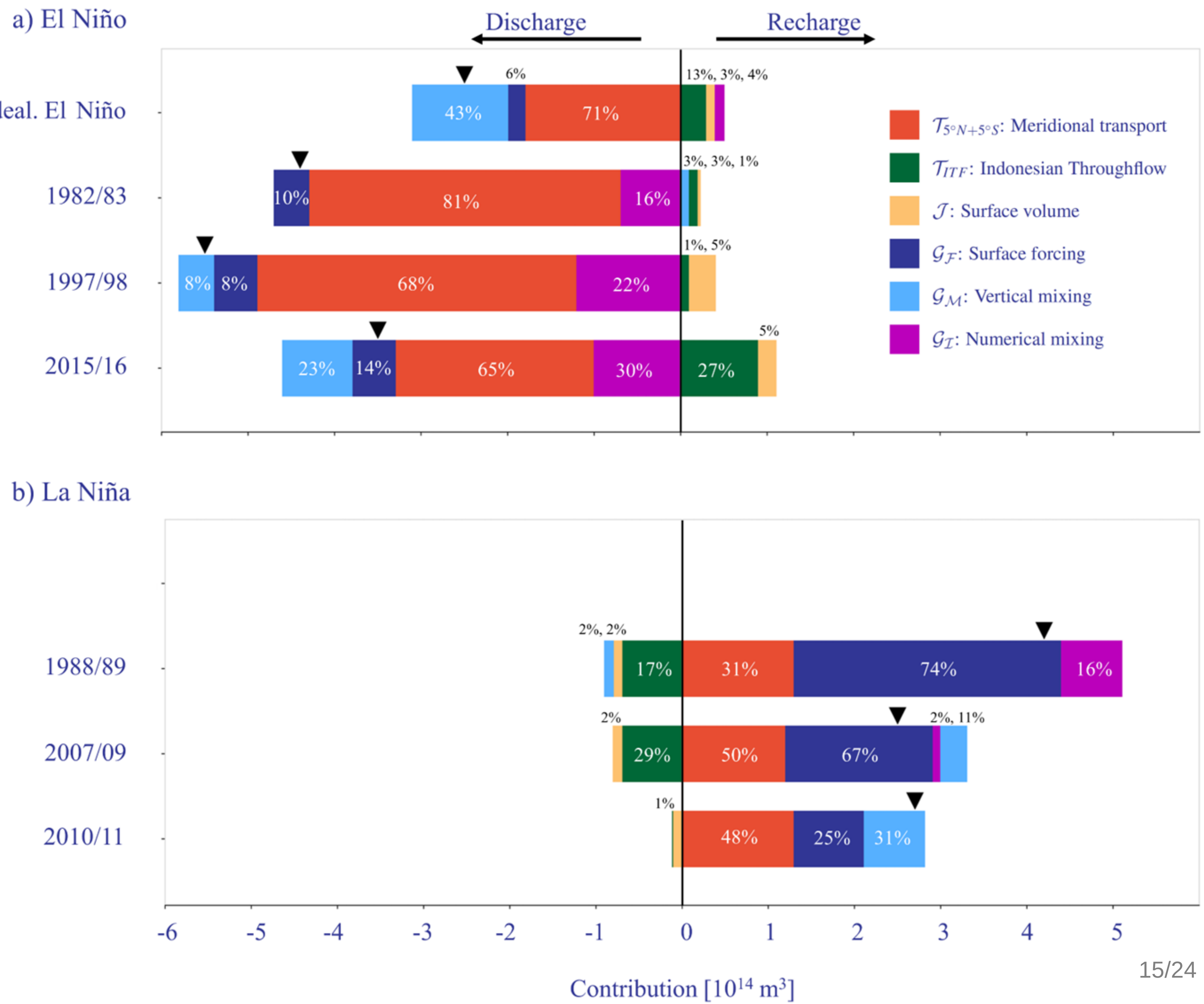




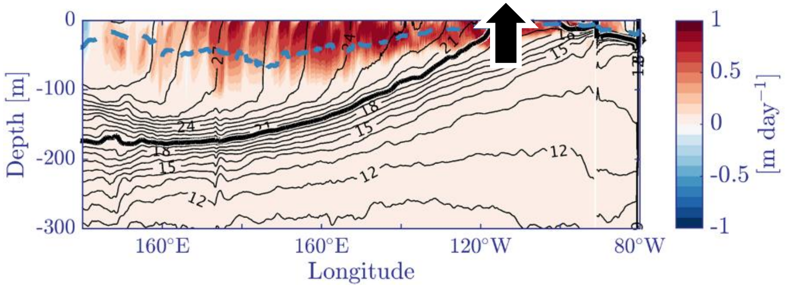
Summary figure



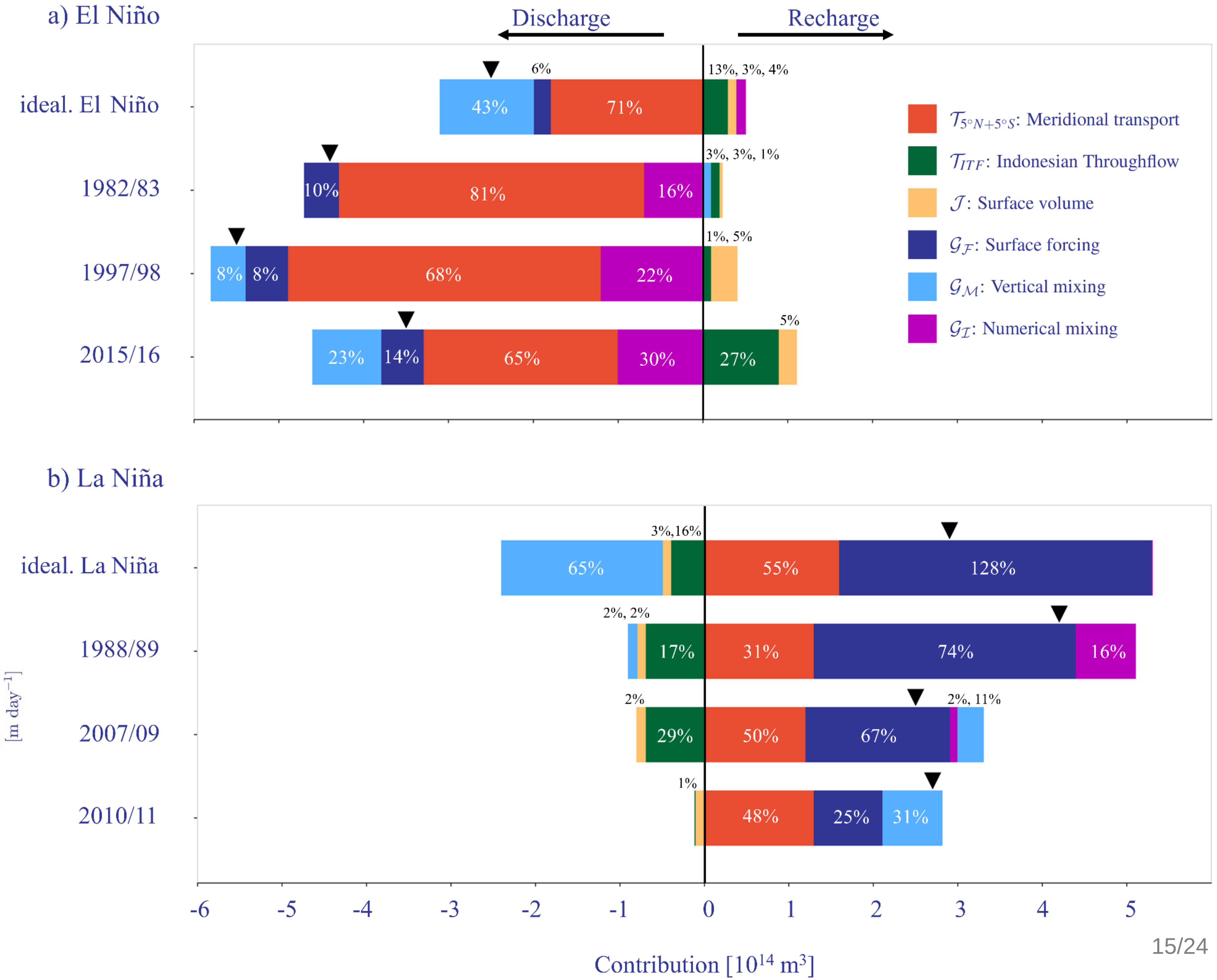
Summary figure



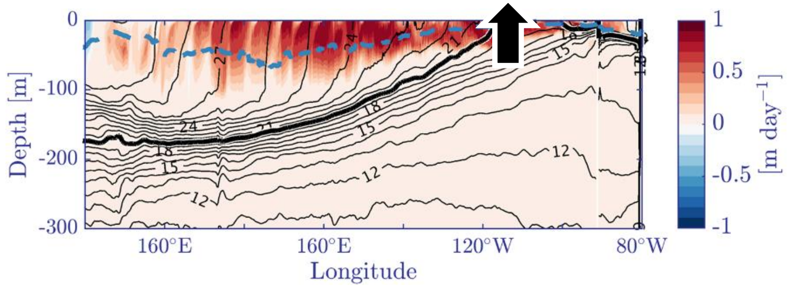
Surface Forcing **DEC 1988**



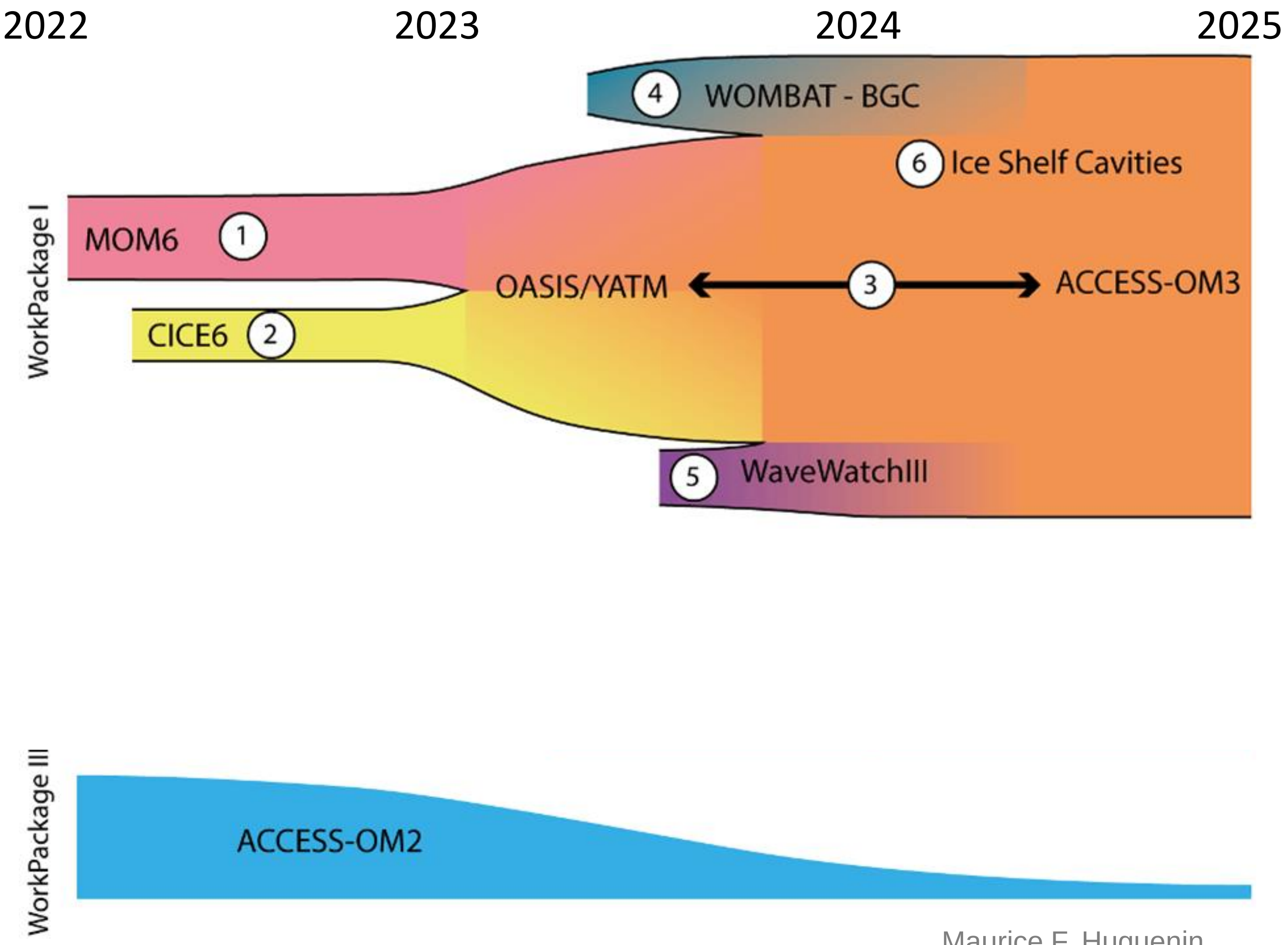
Summary figure



Surface Forcing DEC 1988

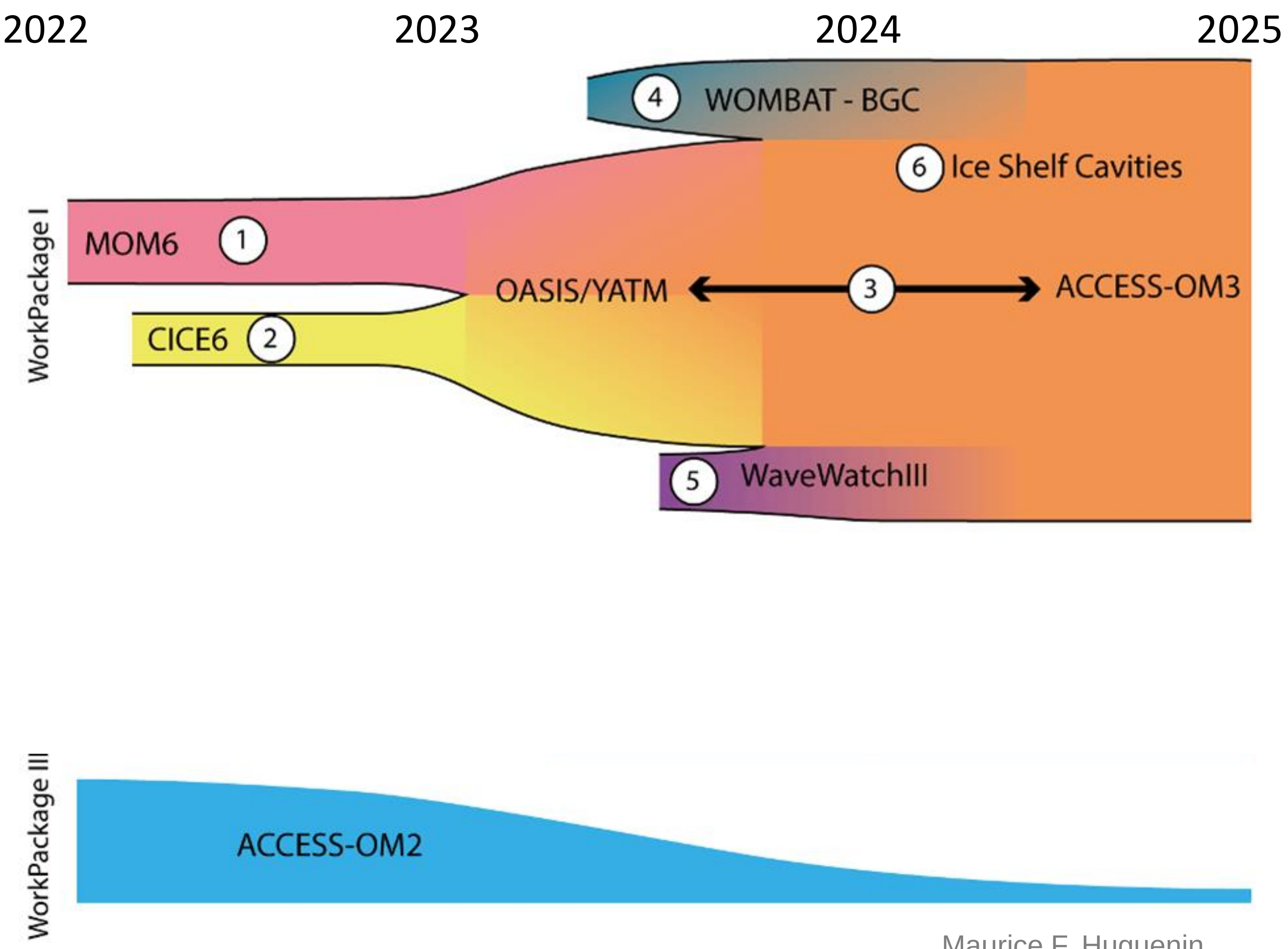


Global ocean-sea ice model



Global ocean-sea ice model

COSIMA



Pan-Antarctic 1/20° & 1/40° model