# *Check it out!* Examining western boundary currents using global ocean observations

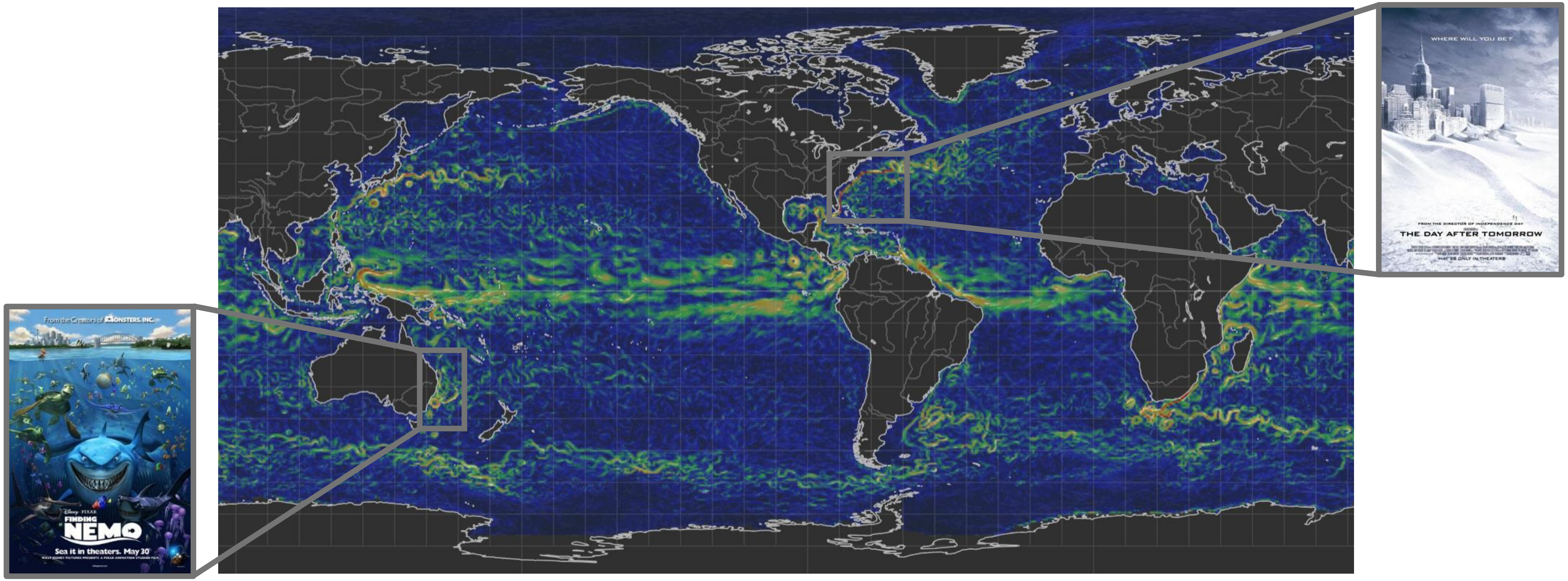
**Mitchell Chandler PhD Defence**
**April 2025**

Advised by Nathalie Zilberman and Janet Sprintall

Ocean currents are the arteries and veins of the climate system

# Western Boundary Currents (WBCs)

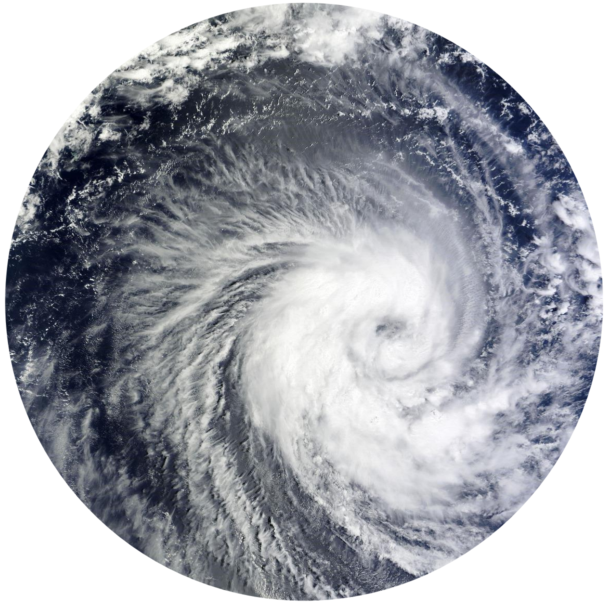
The subtropical western boundary currents (WBCs) and deep western boundary currents (DWBCs) are strong ocean currents located on the western side of the major ocean basins.




earth.nullschool.net

# WBCs have cultural, climatic, and economic importance

Redistribute water and heat and influence weather, sea level, fisheries, and more.



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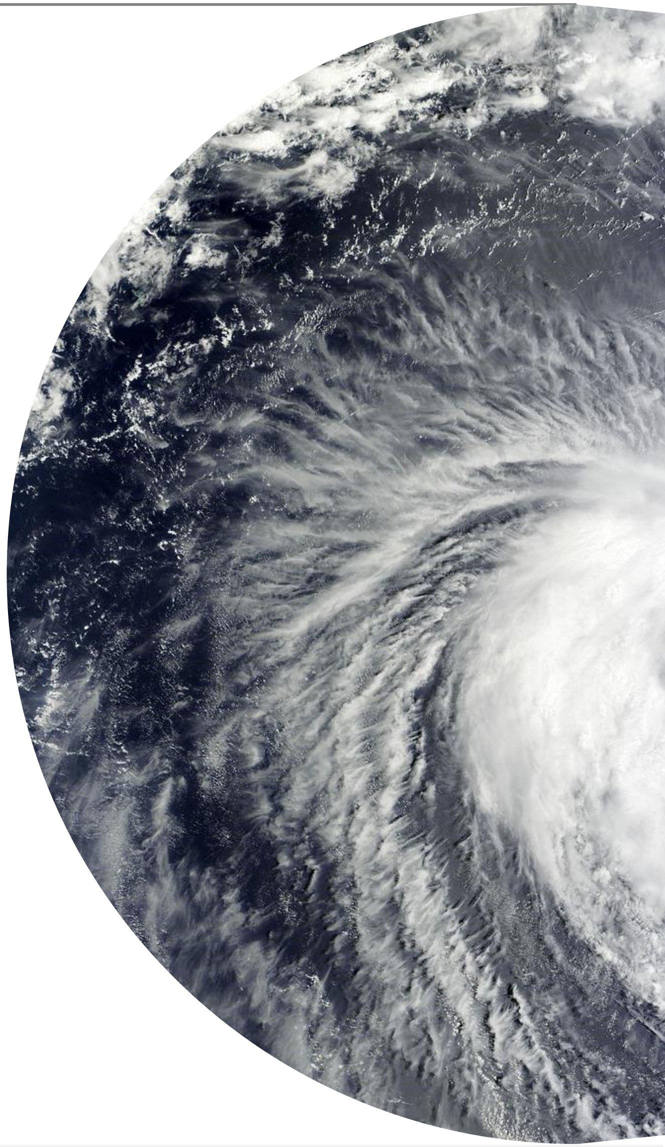
# e.g. Weather

- A large meander in the path of the Kuroshio causes warming of coastal waters and uncomfortably humid conditions around Tokyo.
- The Gulf Stream influences sea level along the US mid-Atlantic coast on time scales from months to decades.
- Changes in the path of the Kuroshio along the coast of Japan control the habitat range of juvenile Pacific Bluefin Tuna.



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# e.g. Sea level

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# e.g. Fisheries

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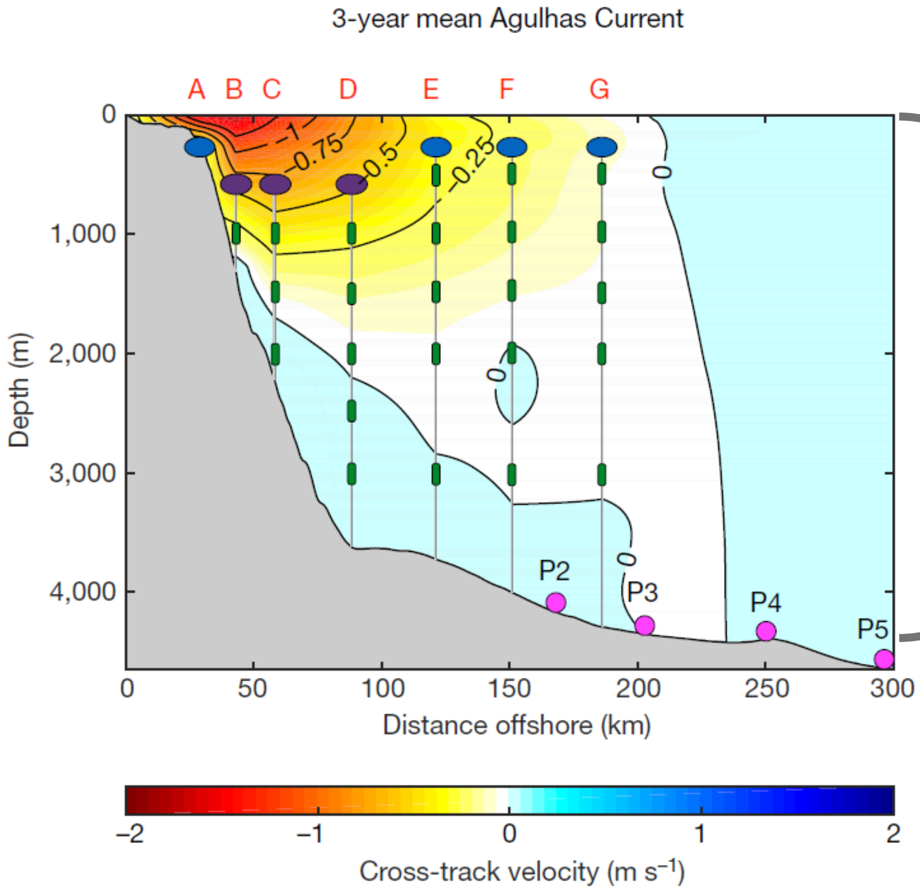
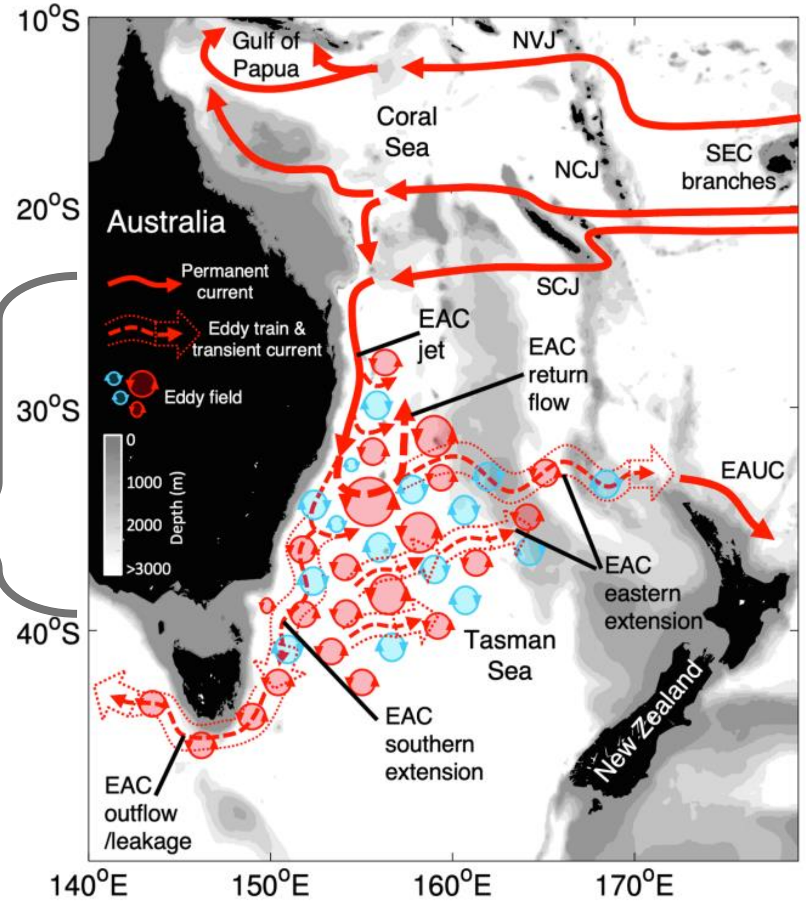
# Observing WBCs presents unique challenges

Therefore still unknowns in present-day conditions and projected changes under a warming climate.




WBC

WBC and Extension region

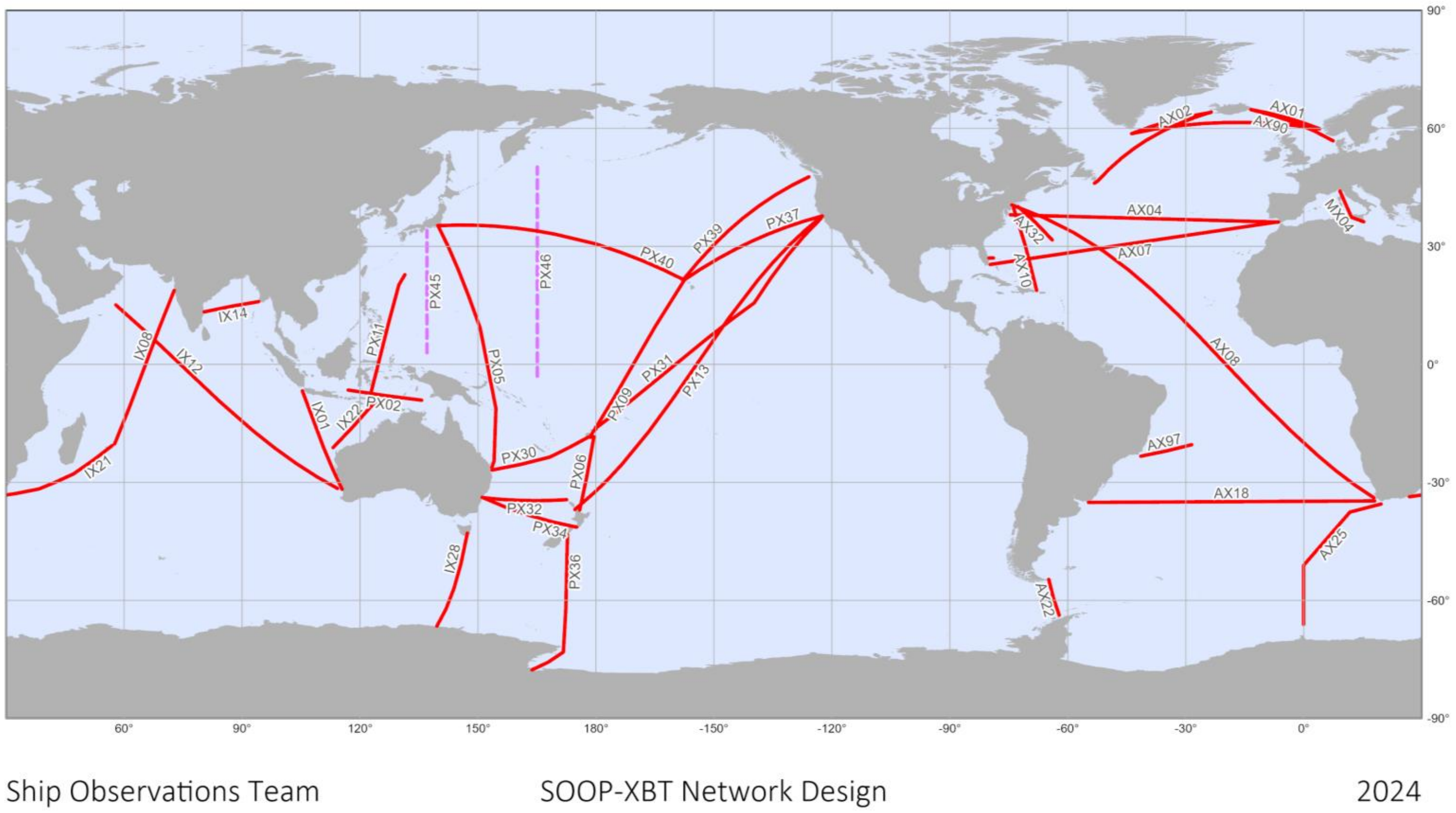



Beal and Elipot 2016

Oke et al. 2019

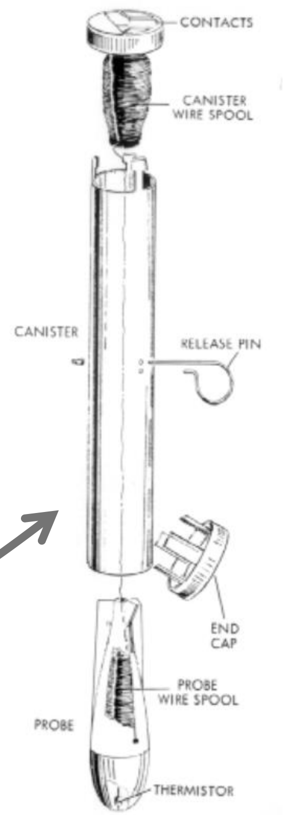
# HR-XBT transects measure subsurface temperature

High-Resolution eXpendable BathyThermograph (**HR-XBT**) transects provide measurements of ocean temperature between the surface and 800-m along fixed transects occupied nominally 4x a year.




ocean-ops.org

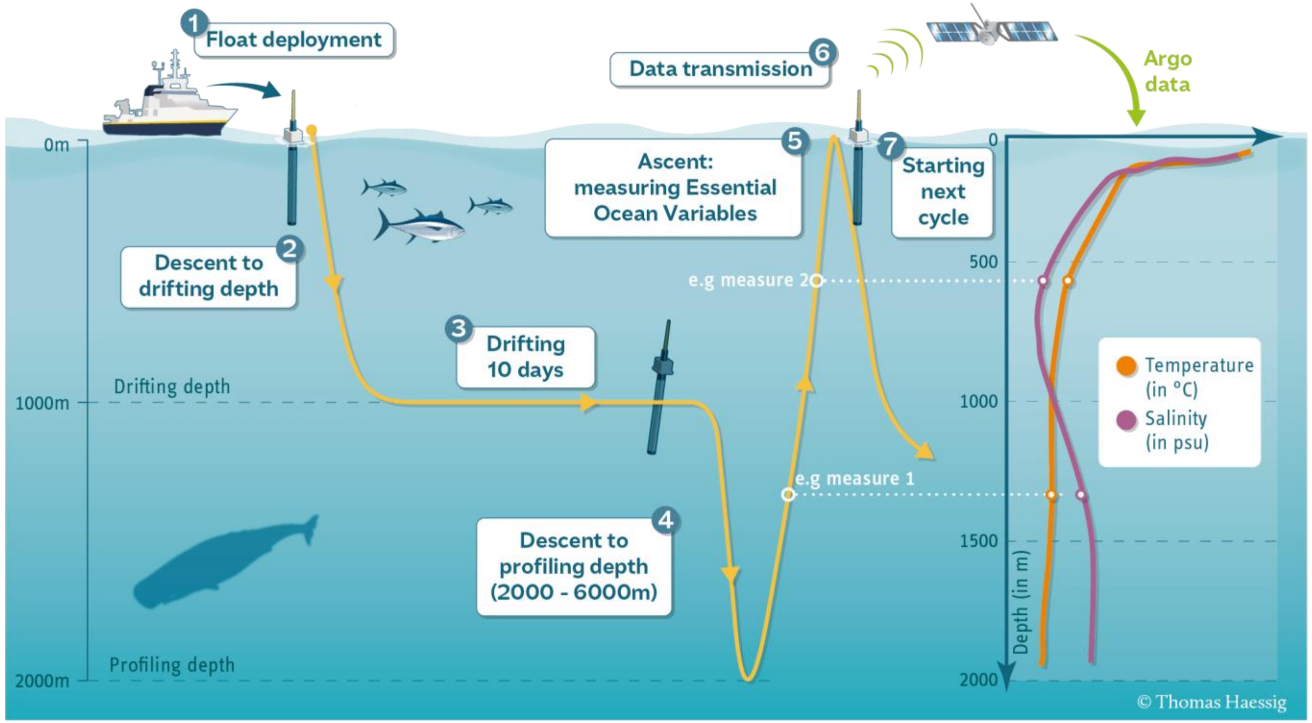
Diagram of
an XBT probe

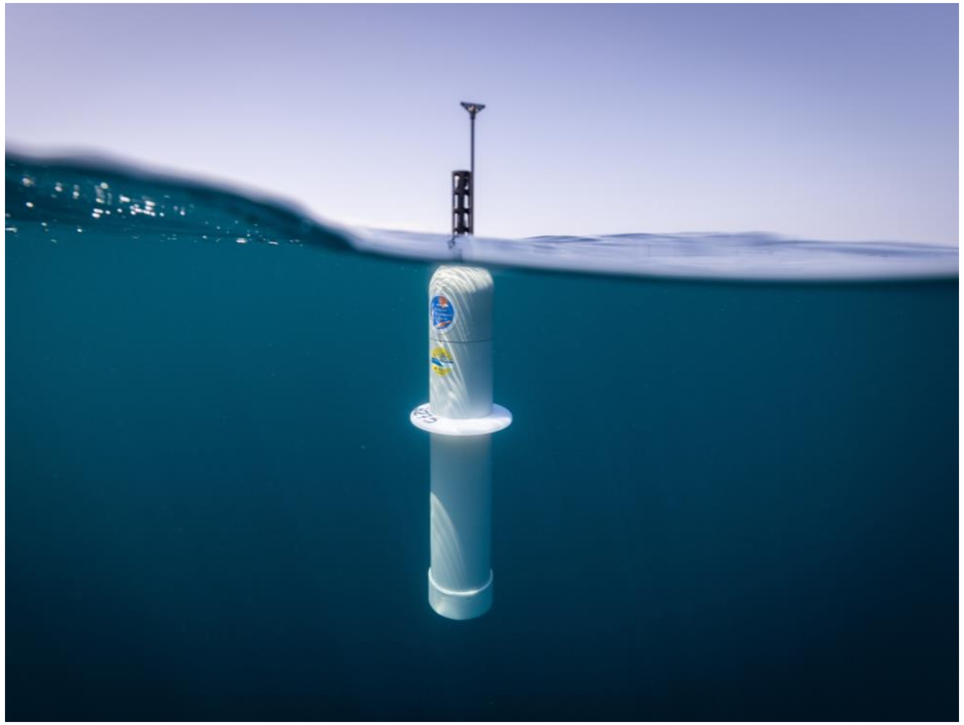



https://www-hrx.ucsd.edu

# Argo floats provide subsurface profiles and velocities

**Core Argo** floats measure temperature, salinity, and pressure as they profile to as deep as 2000-m.

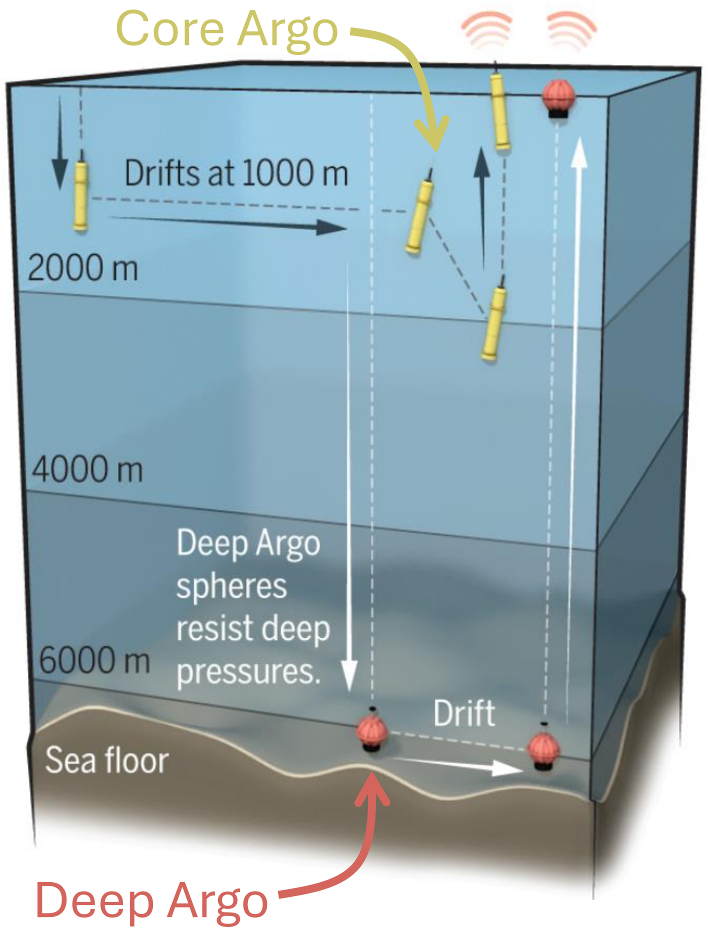


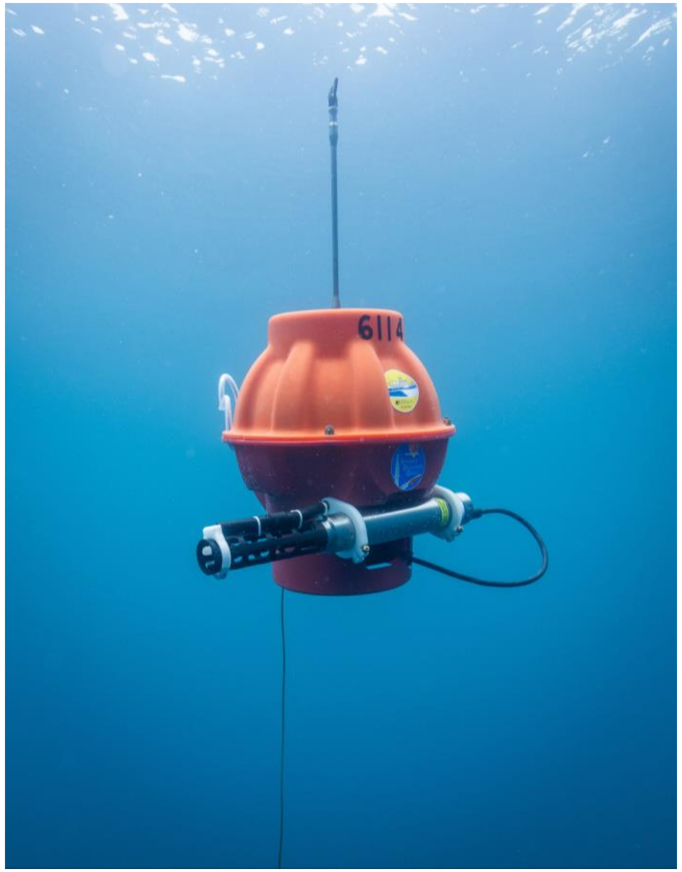



https://argo.ucsd.edu

# Argo floats provide subsurface profiles and velocities

**Deep Argo** floats measure temperature, salinity, and pressure as they profile to as deep as 6000-m.

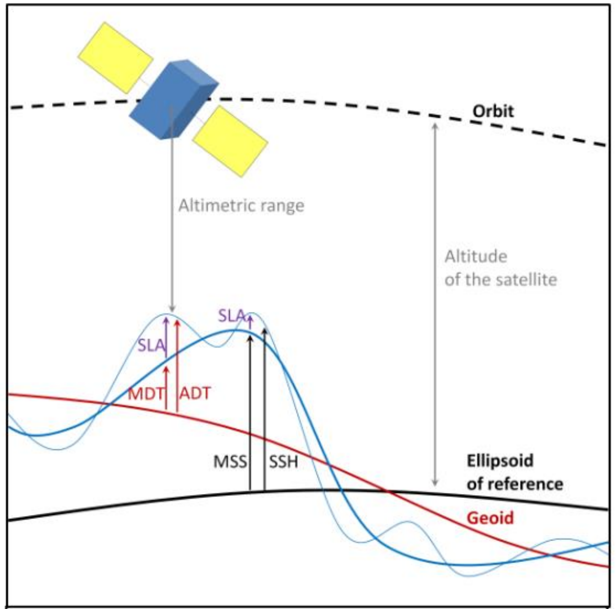



Voosen 2017

# Satellites provide long-term measurements of the surface

**Satellite altimetry** reference missions provide near-global sea level anomaly (SLA) measurements.




- SSH: Sea Surface Height
- SLA: Sea Level Anomaly
- MSS: Mean Sea Surface
- ADT: Absolute Dynamic Topography
- MDT: Mean Dynamic Topography

CMEMS


NASA

- Introduction
- *Chapter 1:* Transport in the subtropical western boundary currents
- *Chapter 2:* Subsurface marine heatwaves in the Kuroshio
- *Chapter 3:* The deep western boundary current of the Southwest Pacific Basin
- Acknowledgements
- Questions

BW
Best Western®
Boundary Currents

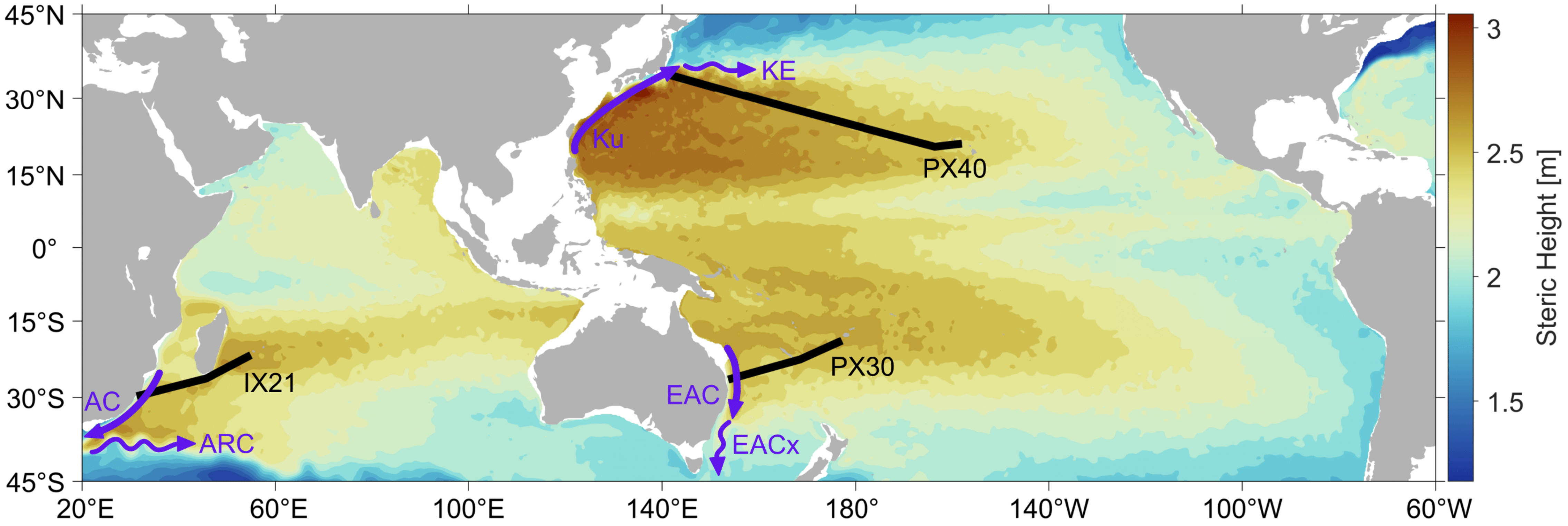
## Chapter 1

Seasonal To Decadal Western Boundary Current Variability From Sustained Ocean Observations

Chandler M, Zilberman NV, Sprintall J. (2022). Seasonal to decadal western boundary current variability from sustained ocean observations. *Geophysical Research Letters*.

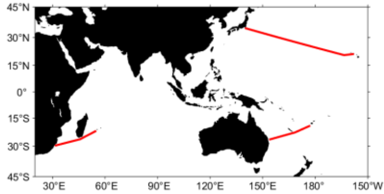
# Observations can be combined to estimate subsurface velocity

Combined HR-XBT, Argo, and satellite altimetry observations over 2004 to 2019 to produce monthly estimates of cross-transect velocity between the surface and 1975-m.

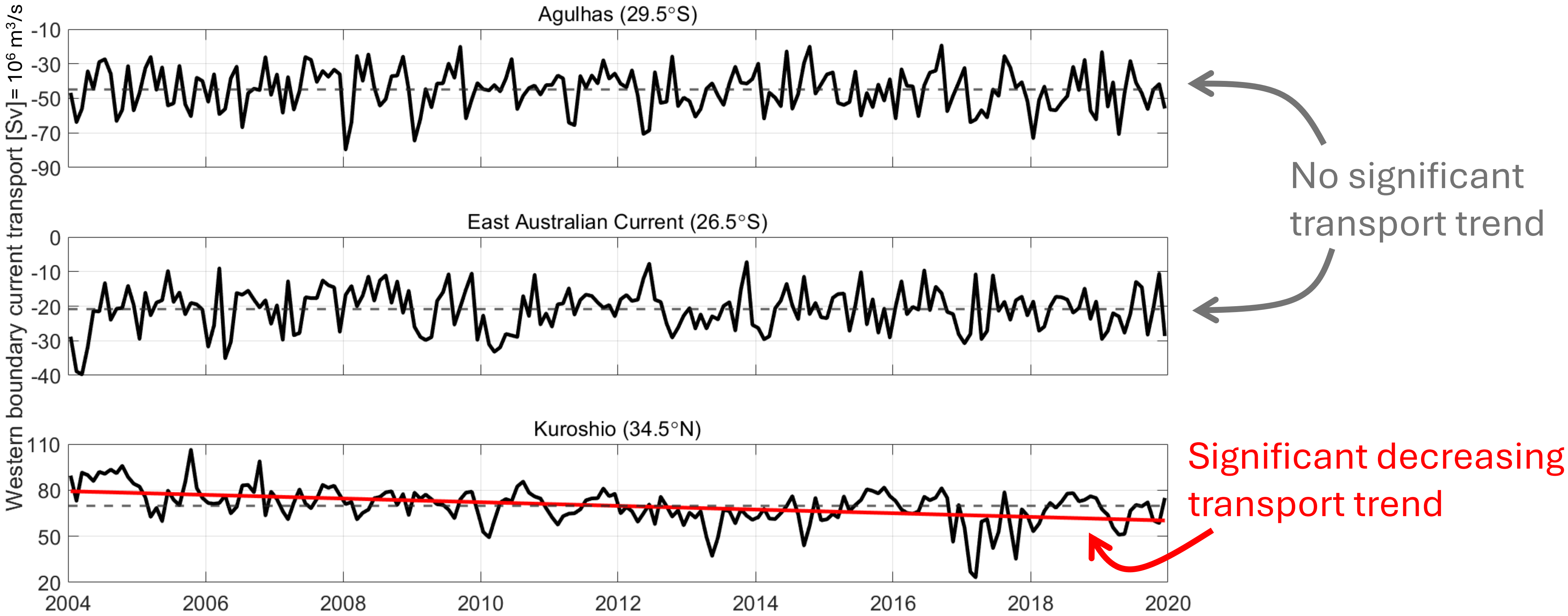



AC – Agulhas Current; EAC – East Australian Current; Ku – Kuroshio

# Decrease in Kuroshio transport between 2004 and 2019



But no significant change in East Australian Current or Agulhas Current transport.
(transport = the volume of water crossing the transect each second)

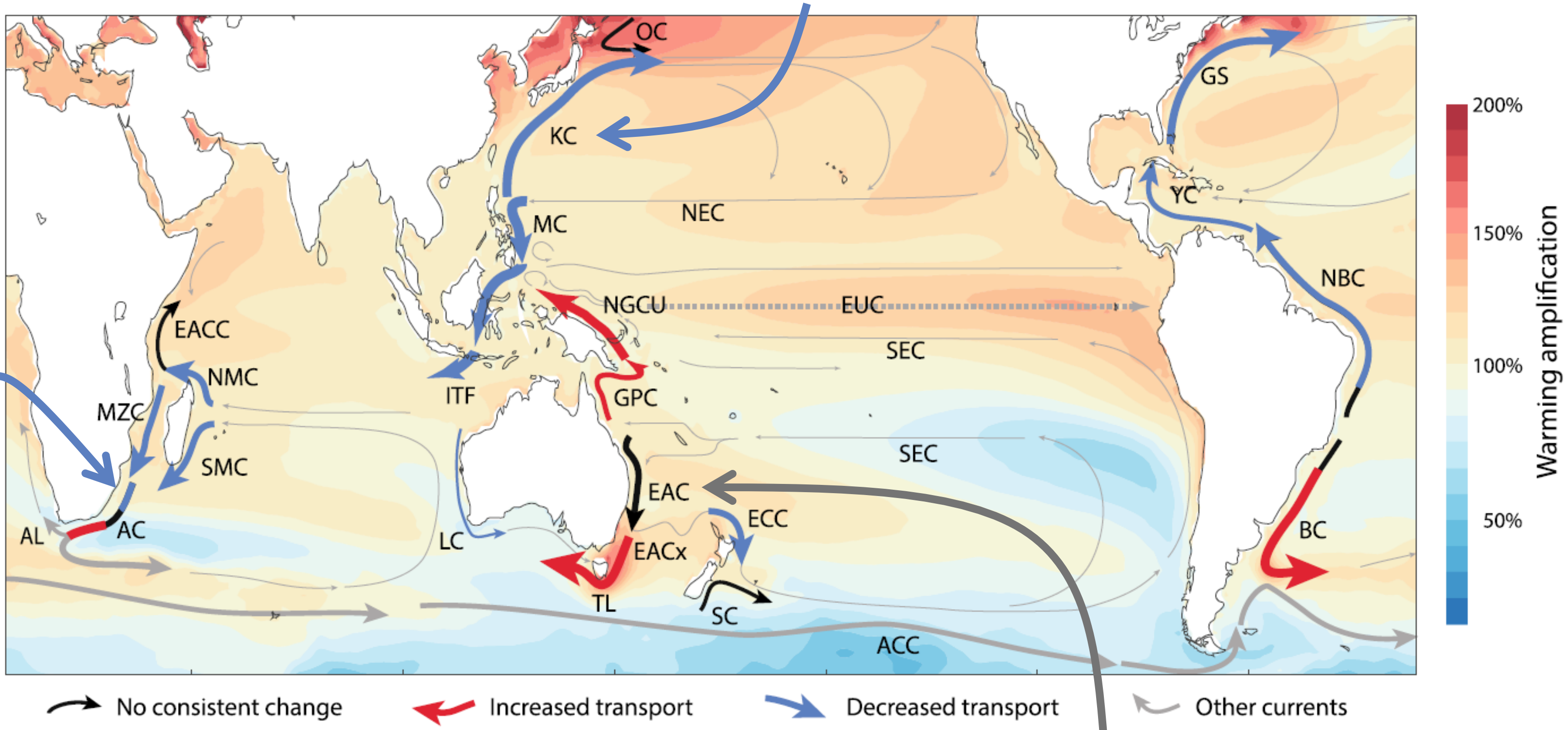


# Projected future changes largely resemble observed trends

Projected changes in WBC transport between the 1900—2000 historical mean and 2050—2100 mean from CMIP5 and CMIP6 models.

Decrease observed and projected in Kuroshio

No change observed, decrease projected in Agulhas

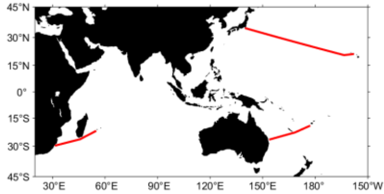


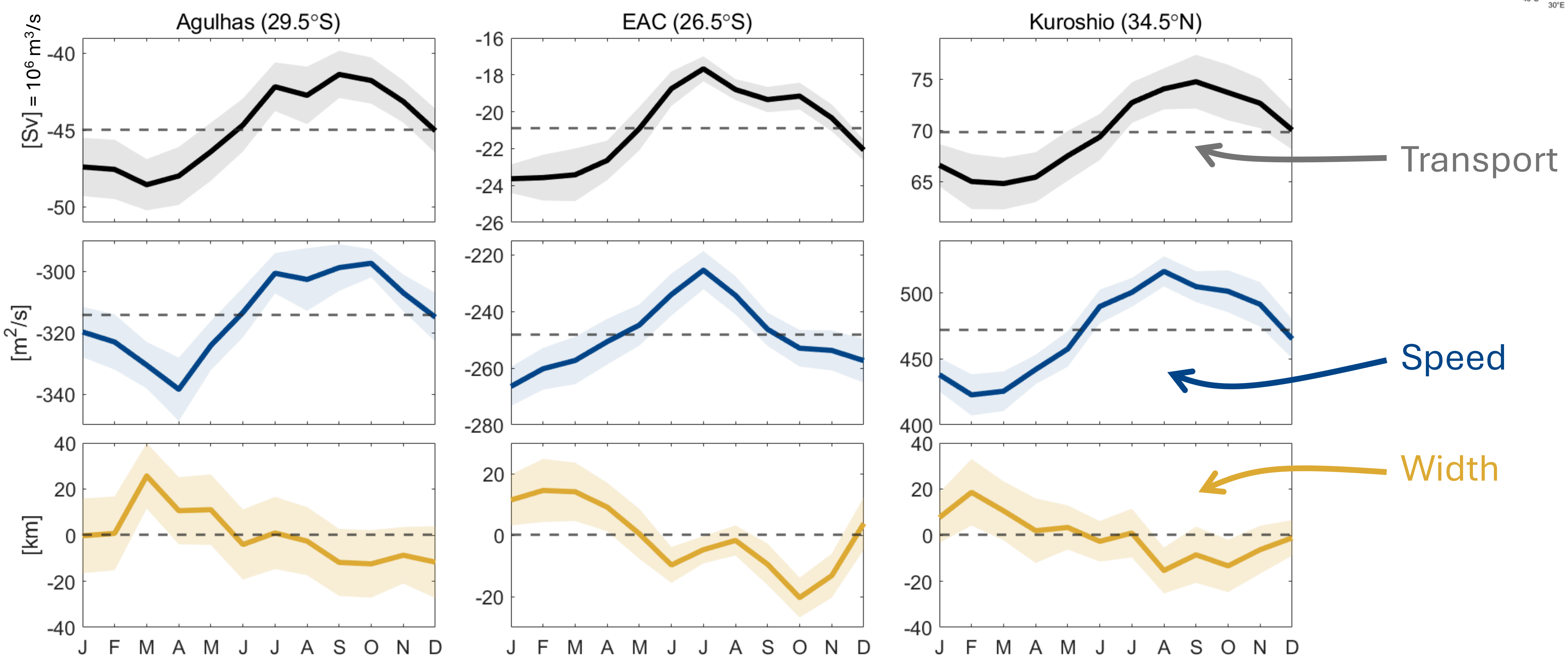

No change observed and projected in EAC

Sen Gupta et al. 2021

# All three WBCs demonstrate similar transport seasonal cycles

With poleward transport stronger in the summer and weaker in the winter.





# Key Takeaways

Chandler M, Zilberman NV, Sprintall J. (2022). Seasonal to decadal western boundary current variability from sustained ocean observations. *Geophysical Research Letters*.

- **Complementary HR-XBT, Argo, and satellite altimetry observations can be combined to produce estimates of cross-transect absolute geostrophic velocity in the upper 2000-m.**
- **Observed a decrease in Kuroshio transport, and no significant change in Agulhas Current transport or EAC transport.**
- **Transport in all three WBCs (Agulhas Current, EAC, Kuroshio) is greatest in summer and related to coincident changes in the speed of the current, rather than changes in the width of the current.**


# Chapter 2

ENSO Influences Subsurface Marine Heatwave Occurrence In The Kuroshio Extension

Chandler M, Sprintall J, Zilberman NV. (in prep). ENSO influences subsurface marine heatwave occurrence in the Kuroshio Extension.

# MHWs are prolonged periods of anomalously warm water

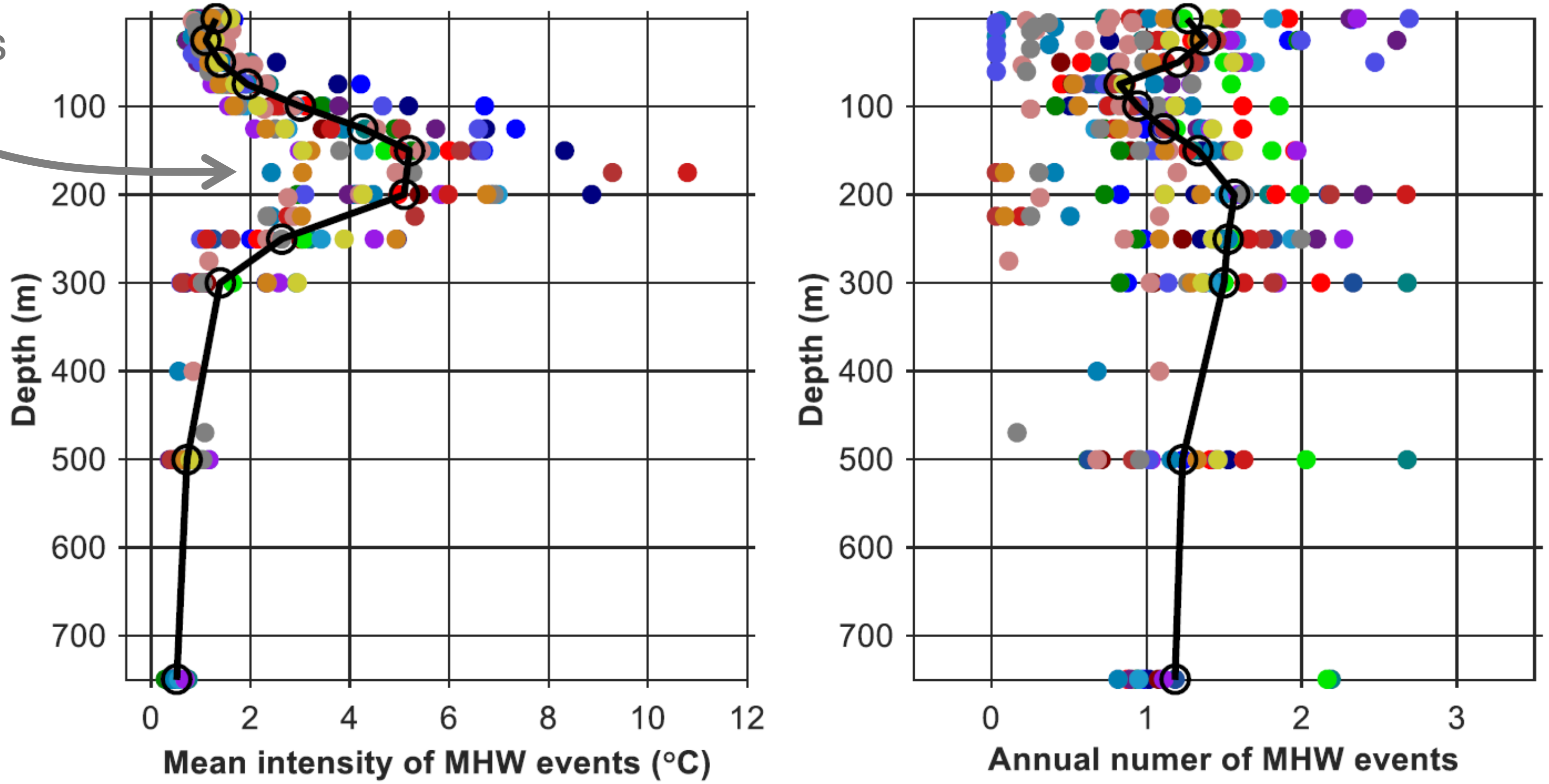
Marine heatwaves (MHWs) can have devastating impacts on marine ecosystems and communities.

Pixabay

# Most MHW studies focus only on the sea surface

However MHWs are not restricted solely to the sea surface, and neither is marine life, so we need to observe these events in the subsurface.

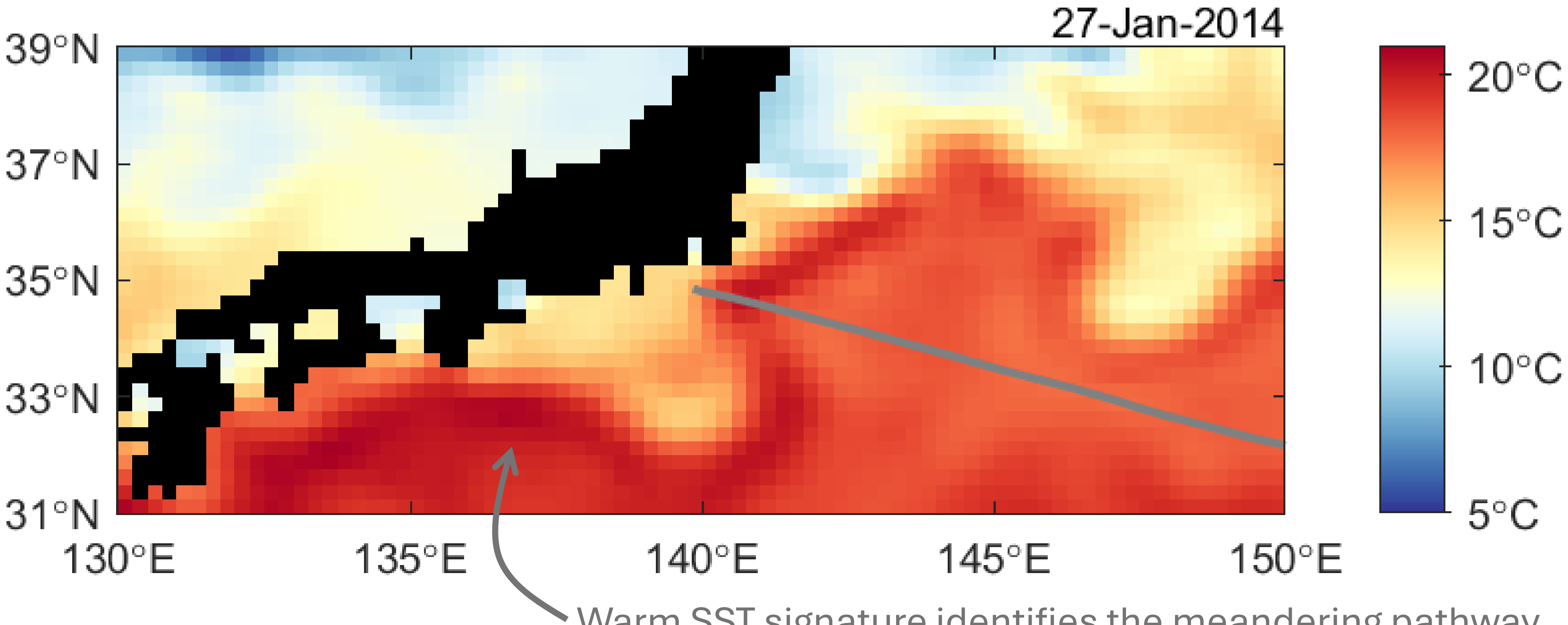
Peak MHW intensities observed at depth




Hu et al. 2021

# HR-XBT transect intersects the Kuroshio and Kuroshio Extension

Which make up the subtropical western boundary current system of the North Pacific Ocean.




Warm SST signature identifies the meandering pathway of the Kuroshio and Kuroshio Extension along Japan

OISSTv2.1: Huang et al. 2021

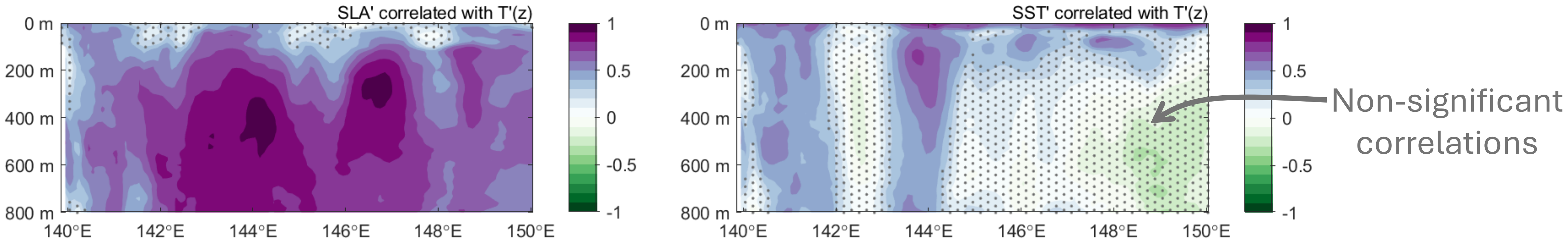
# Producing a synthetic subsurface temperature time series

1. Temperature climatology corrects for path differences between individual HR-XBT transects

2. Seasonal cycle removed to obtain sea level anomalies (SLA’), sea surface temperature anomalies (SST’), and temperature anomalies (T’)

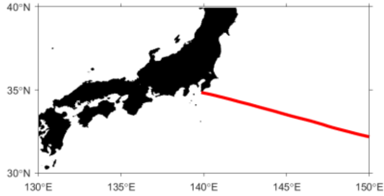
3. 10-day averaged SLA’ and SST’ fit to HR-XBT T’: $T'(x,z,t) = \alpha(x,z) \cdot SLA'(x,t) + \beta(x,z) \cdot SST'(x,t)$

4. Regression coefficients applied to obtain synthetic time series of 10-day averaged T’ between 0-m and 800-m deep over the 1993 to 2022 time period

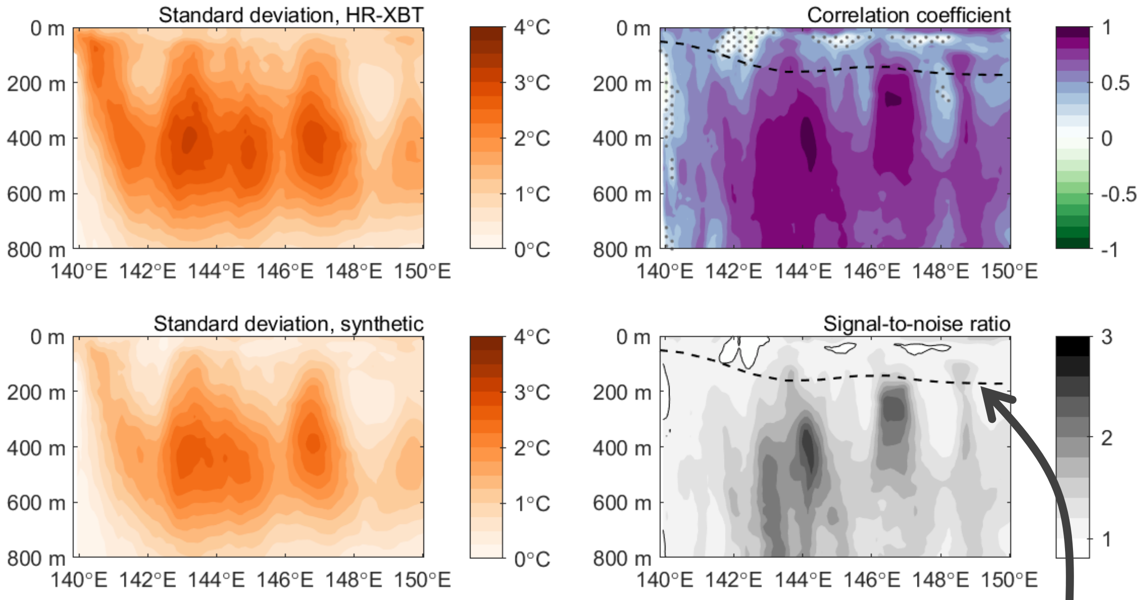


# Validation of synthetic subsurface temperature anomalies

Synthetic temperature anomalies compared favourably with observations (although with some discrepancies in the surface mixed-layer).

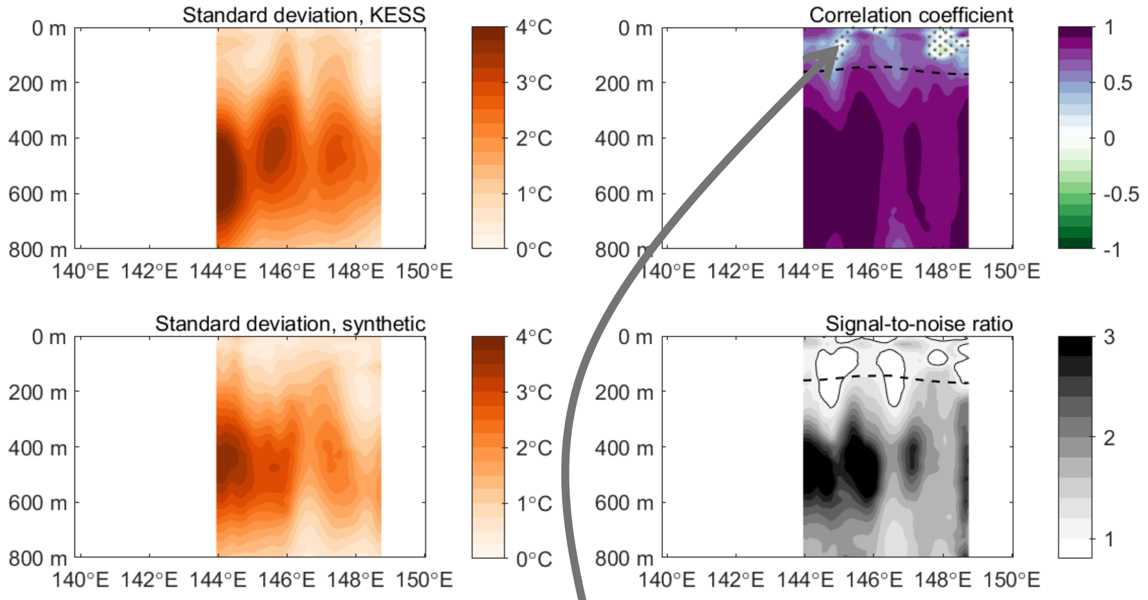



## Leave-one-out validation:




Maximum climatological mixed layer depth

## Co-located mooring array (2004—2005):



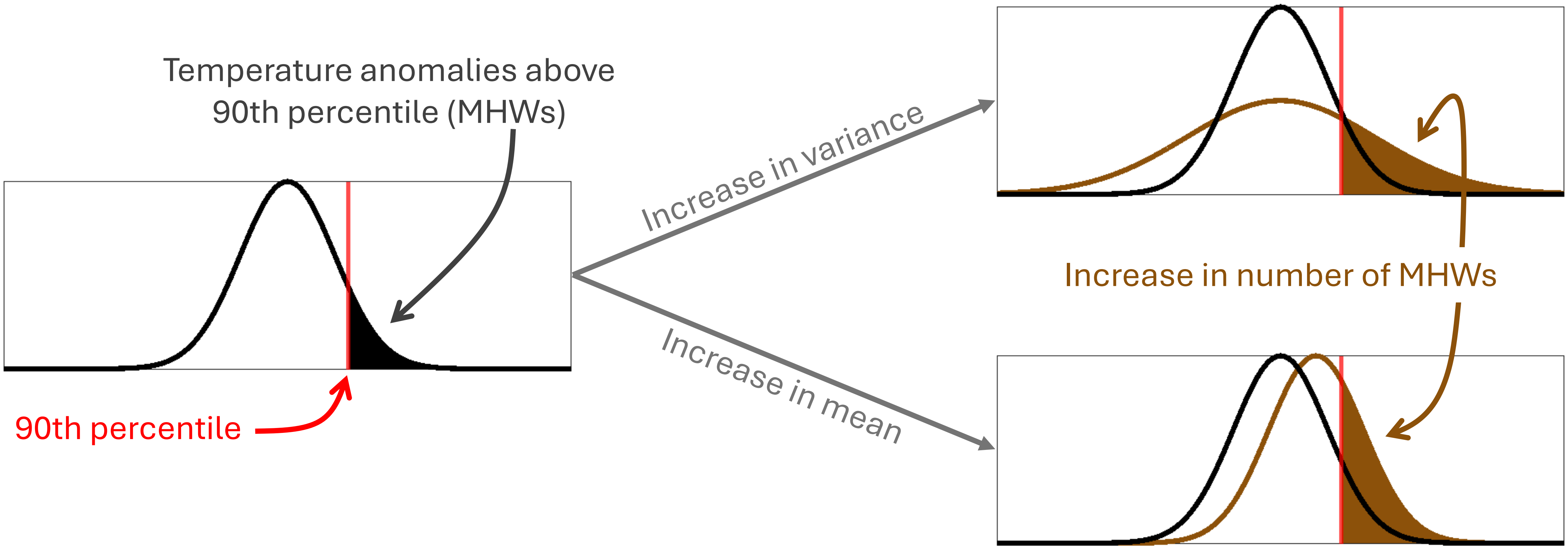

Non-significant correlations

MLD: de Boyer Montégut et al. 2004

Donohue et al. 2010

# Defining a MHW

In this study MHWs are defined as periods when the temperature anomaly is above the 90th percentile. All MHW events are at least 10 days long due to the 10-day resolution of the time series.

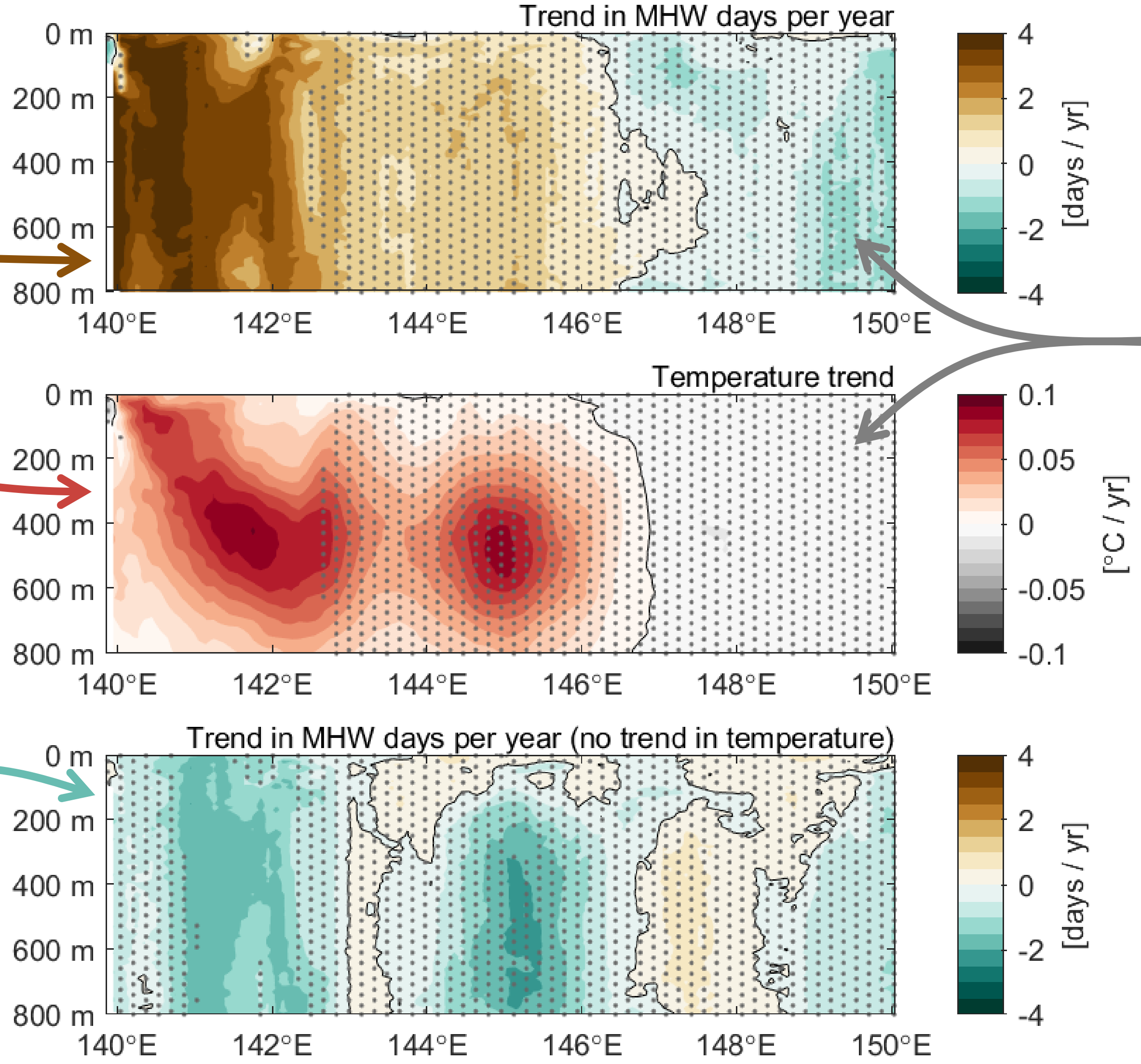


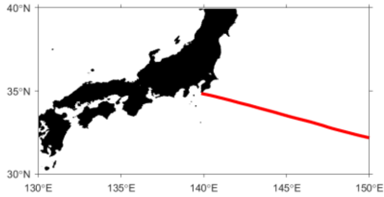
# Kuroshio MHW days have increased due to warming

Significant increase in Kuroshio MHW days per year

Significant Kuroshio warming trend

No increase in MHW days when temperature trend is removed

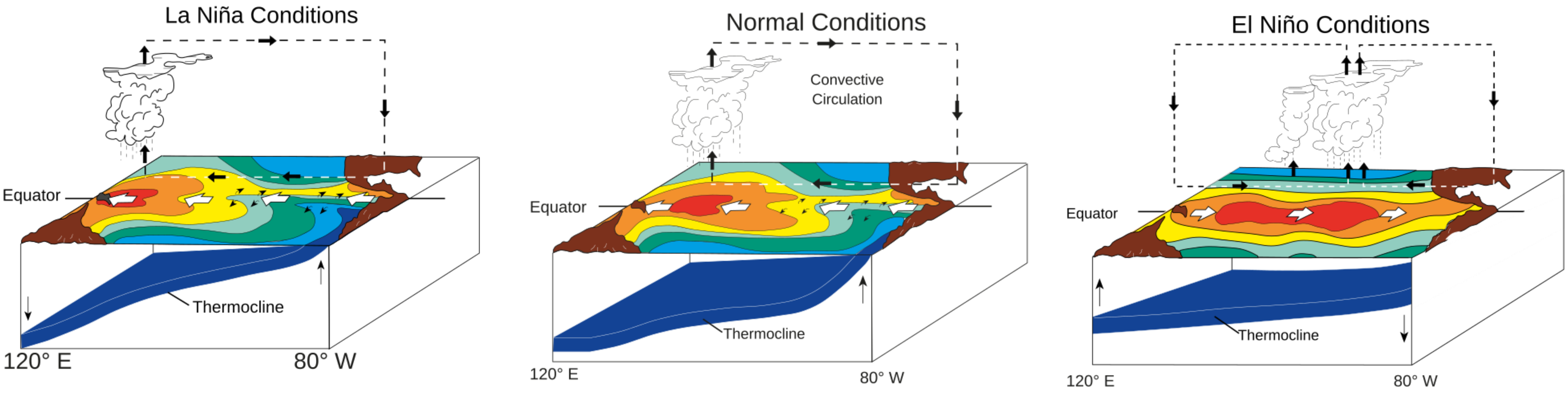


No significant trend further offshore

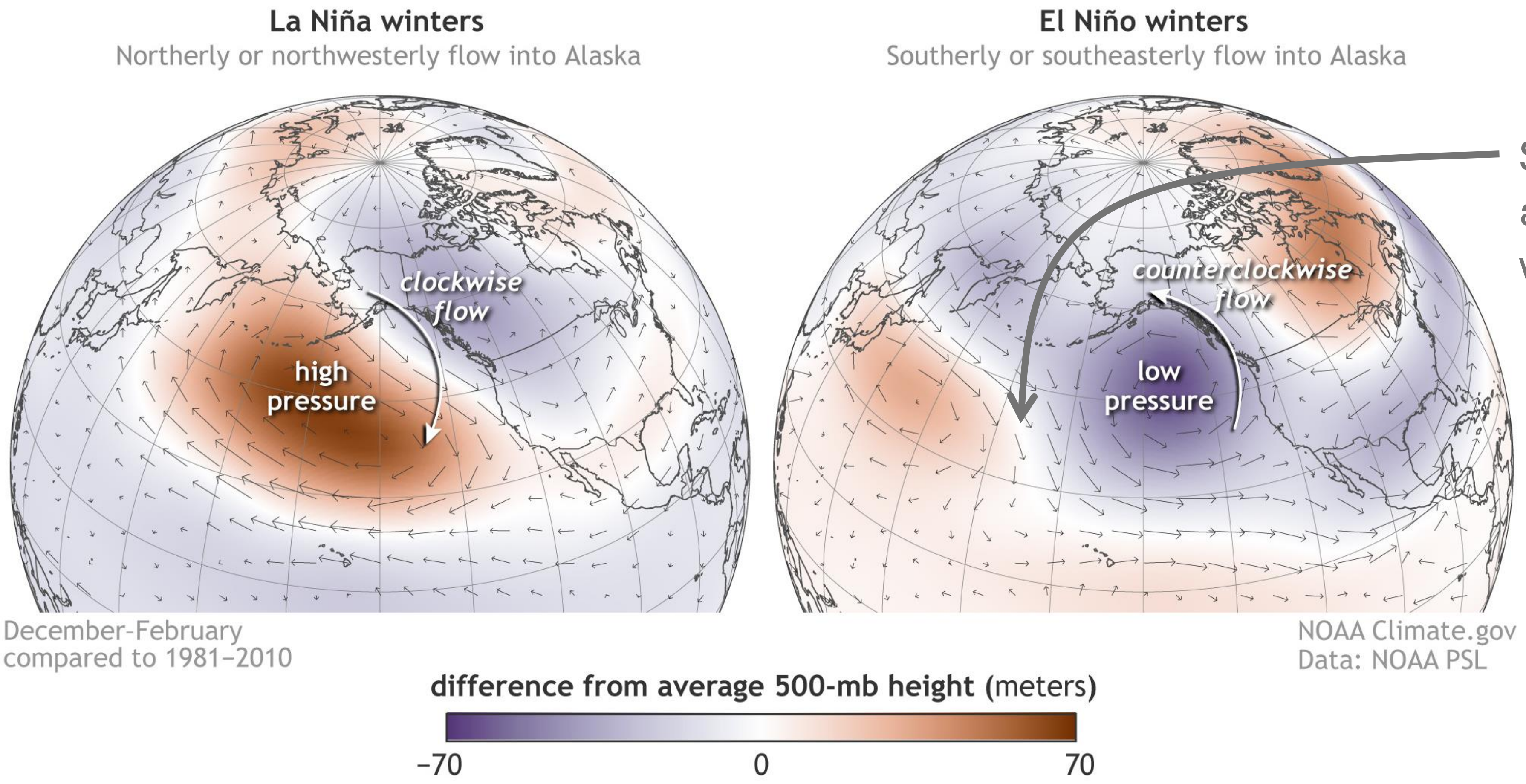
# The El Niño-Southern Oscillation (ENSO)

ENSO impacts atmospheric circulation all over the Earth.




Talley et al. 2011

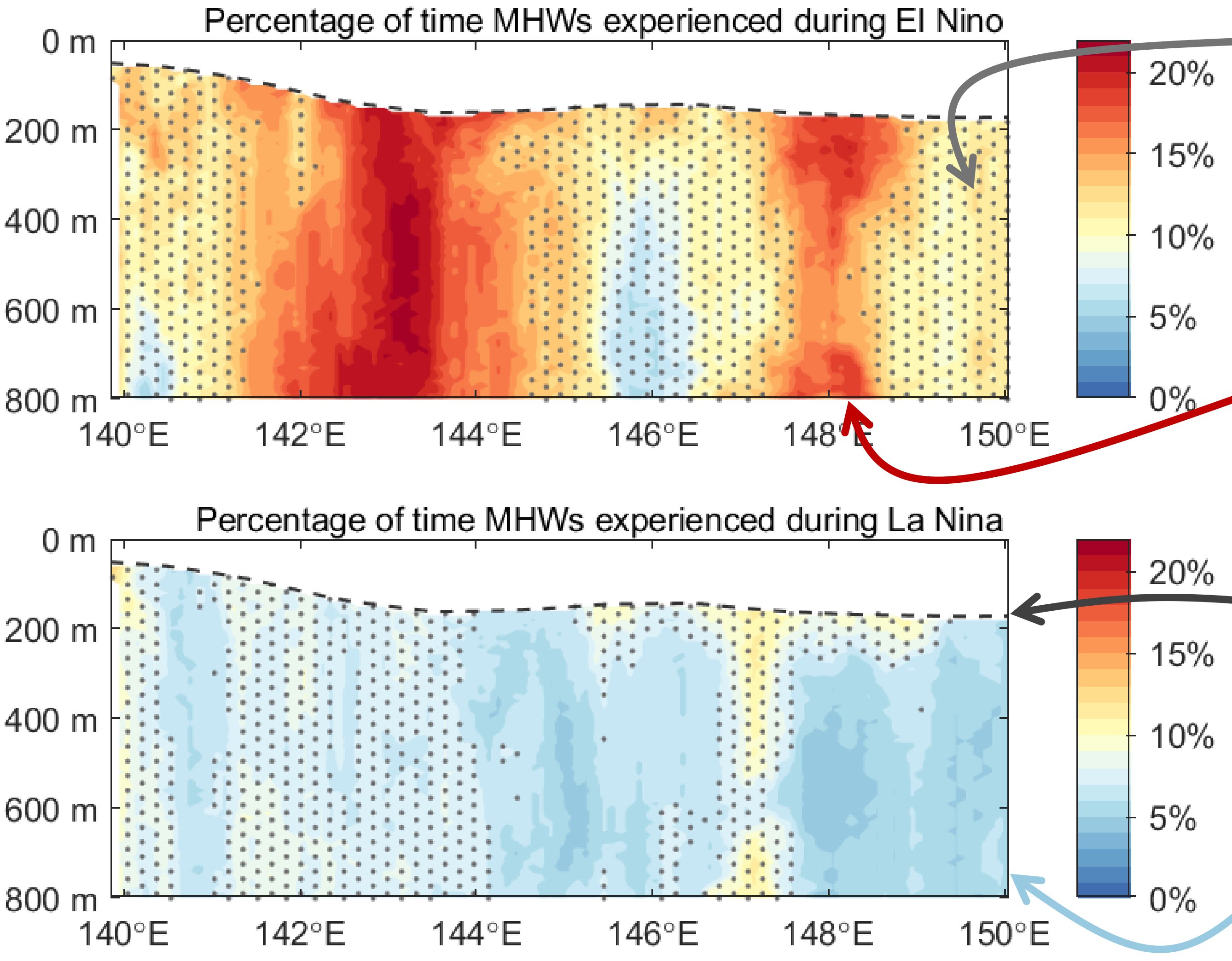
# ENSO in the North Pacific

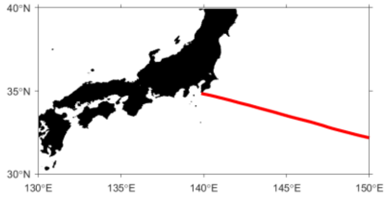



Stronger westerlies and more negative wind stress curl

NOAA

# Subsurface MHWs are more common during El Niño periods



MHW occurrence not significantly different from 10% of the time

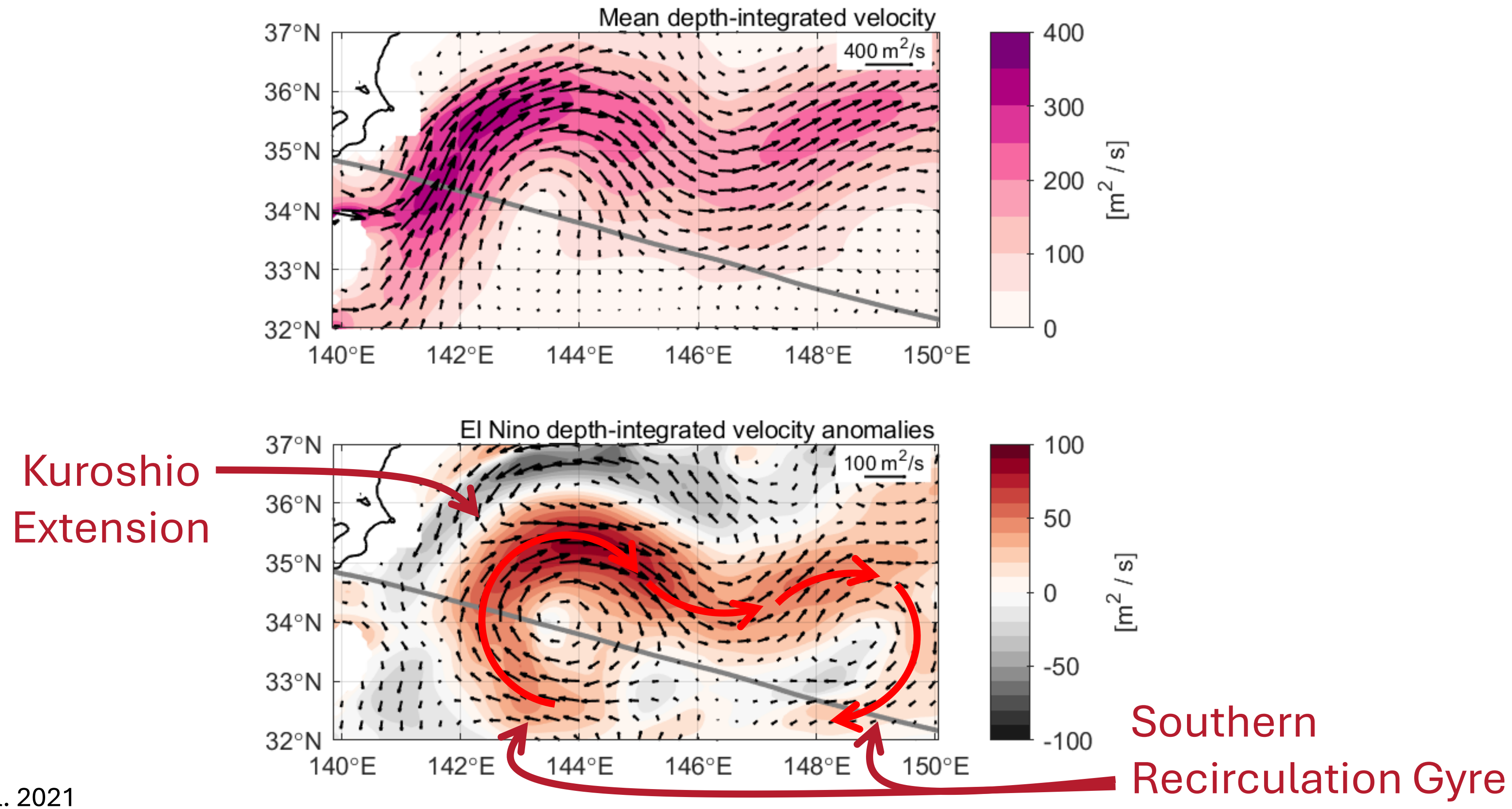
Subsurface MHWs occur more often

Maximum climatological mixed layer depth

Subsurface MHWs occur less often

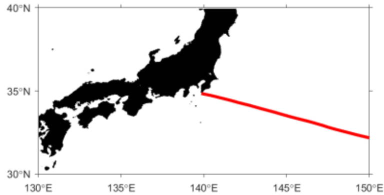
# Increase in El Niño MHWs due to a stronger Kuroshio Extension

Stronger Kuroshio Extension and stronger Southern Recirculation Gyre during El Niño transport more warm subtropical water across the transect.

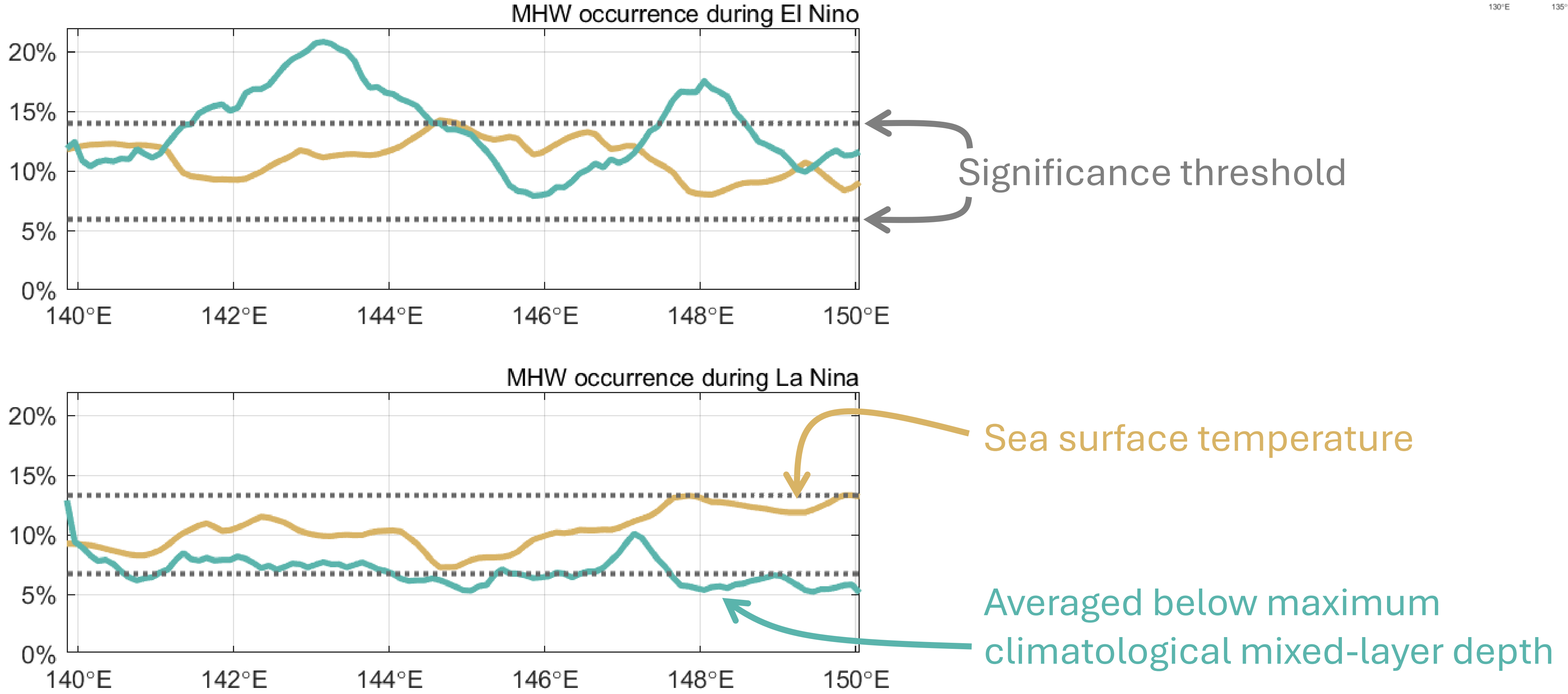



GLORYS12V1: Lellouche et al. 2021

# Surface MHW occurrence differed from subsurface occurrence

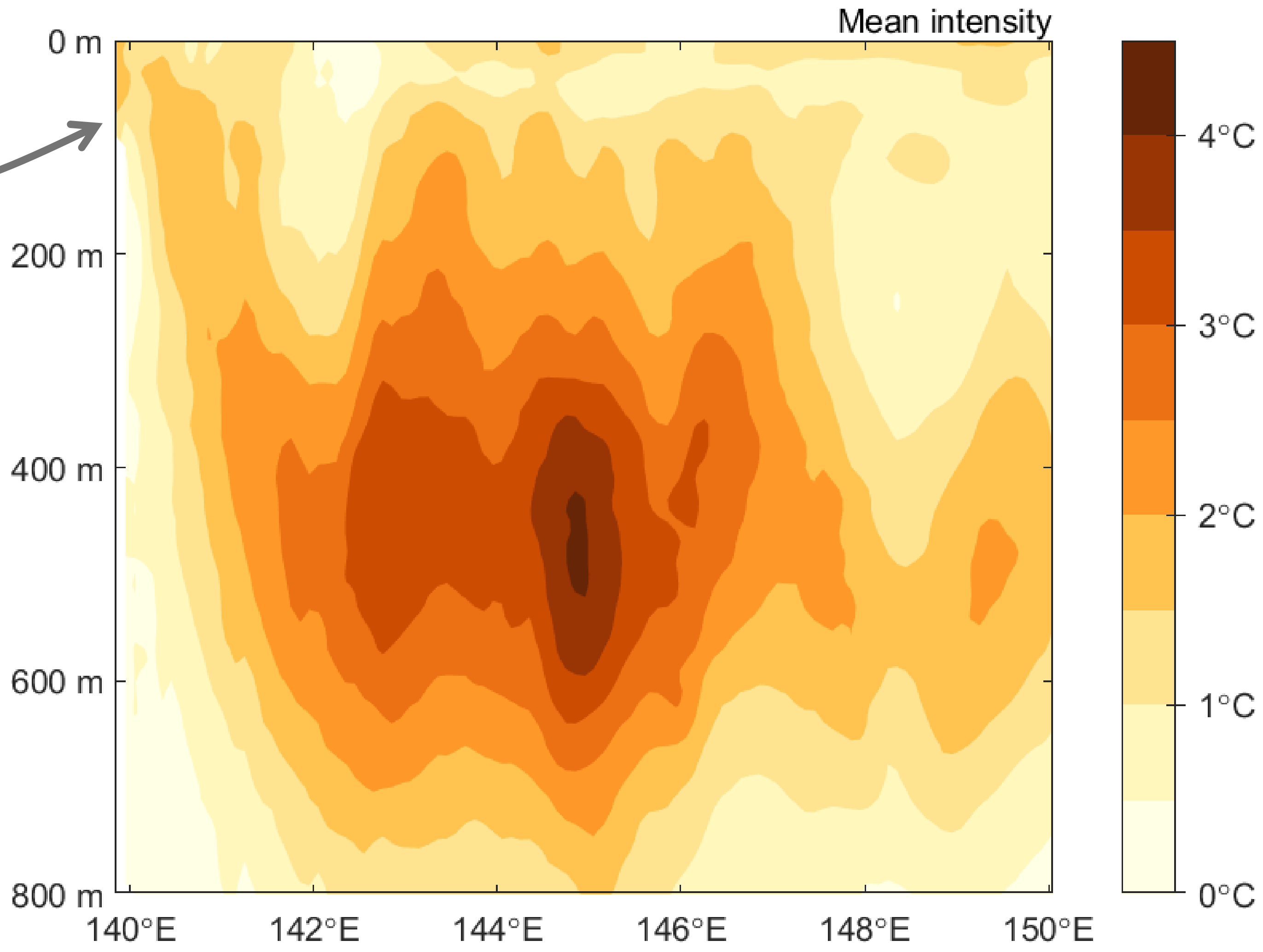


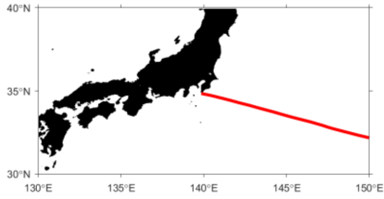

ENSO does not influence surface MHW occurrence along the transect.



# MHWs are more intense in the subsurface than at the surface

Temperature anomaly relative to the 1993 to 2022 mean



# Key Takeaways

- Subsurface temperature observations from HR-XBTs can be combined with satellite observations of sea surface height and sea surface temperature to produce multi-decadal subsurface temperature time series.
- A significant warming trend in the Kuroshio drove a significant increase in Kuroshio MHW days per year.
- The largest mean MHW intensities occur in the subsurface rather than at the sea surface at every location along the transect.
- Subsurface marine heatwaves are more common during El Niño where a stronger Kuroshio Extension and its Southern Recirculation Gyre intersect the transect.


Illustration by Alphonse de Neuville (Twenty thousand leagues under the sea)

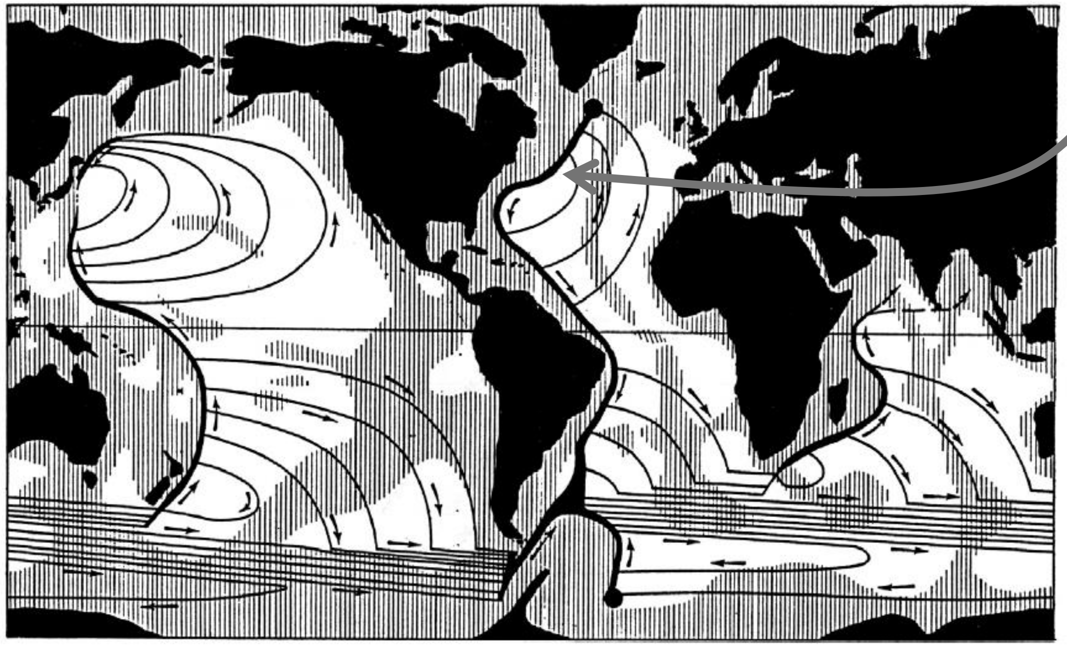
# Chapter 3

## The Deep Western Boundary Current Of The Southwest Pacific Basin: Insights From Deep Argo

*(20 000 feet under the sea)*

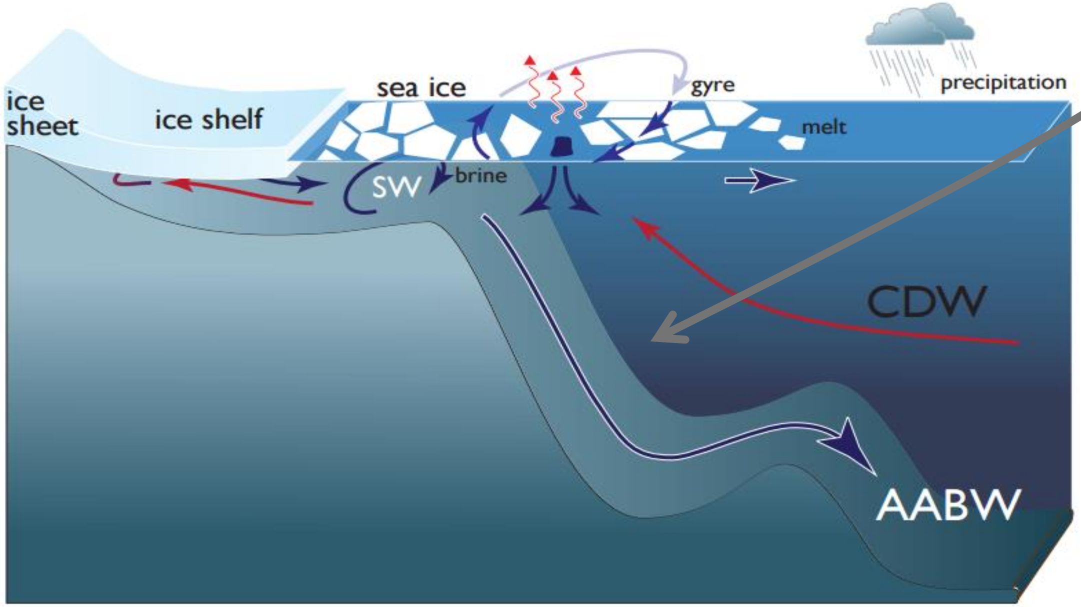
Chandler M, Zilberman NV, Sprintall J. (2024). The deep western boundary current of the Southwest Pacific Basin: insights from Deep Argo. *Journal of Geophysical Research: Oceans.*

# Deep Western Boundary Currents (DWBCs)



DWBCs transport cold, dense waters away from high-latitude formation regions

In the Southern Hemisphere these deep waters are formed near the surface around Antarctica




DWBCs therefore carry surface changes into the deep-ocean, impacting dissolved oxygen content, sea level, and carbon storage.

Stommel 1958

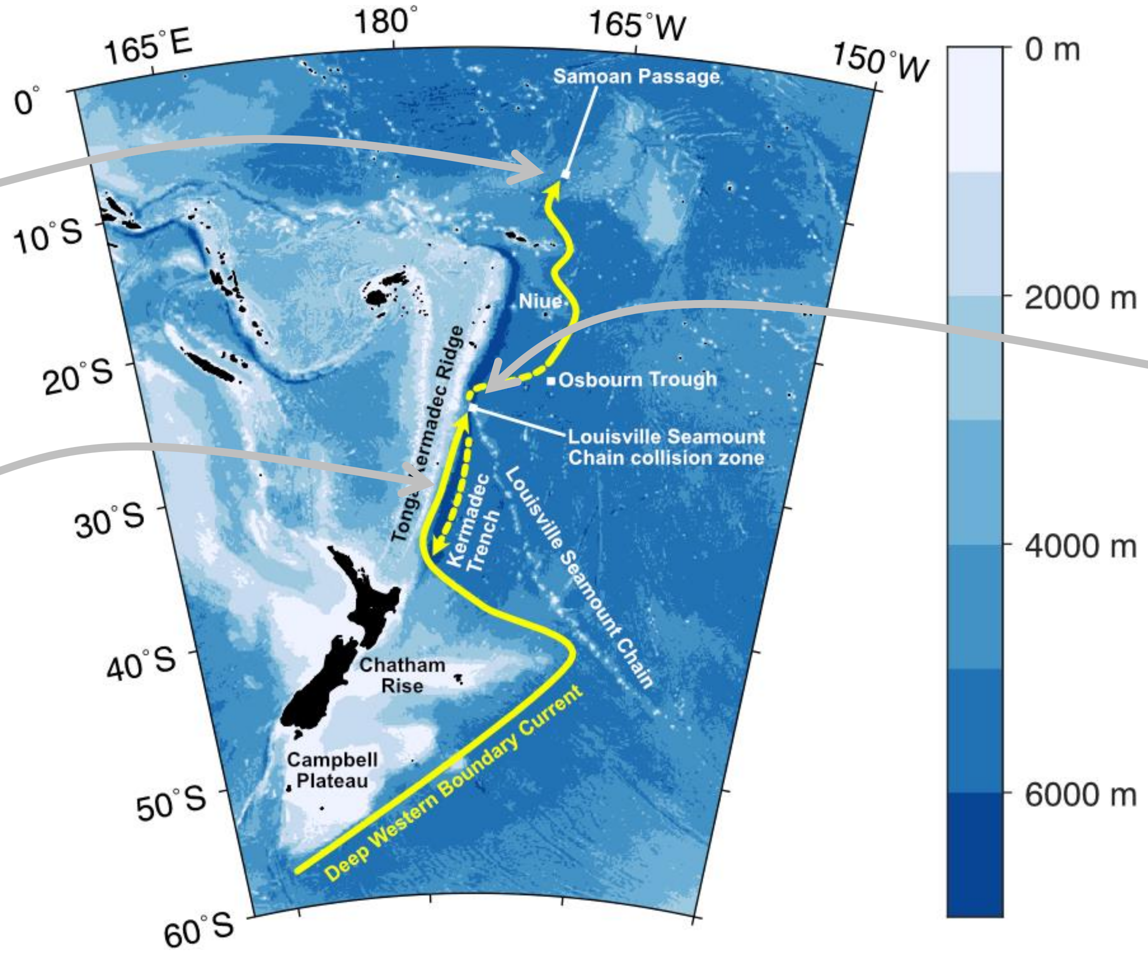
Figure provided by Christina Hulbe

# The DWBC of the Southwest Pacific Basin

The main pathway for transport of deep waters away from Antarctica into the South and North Pacific.

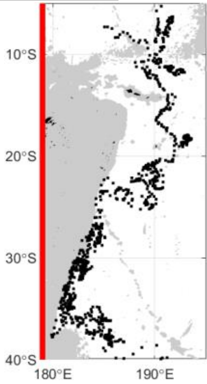
Samoan Passage

Kermadec Trench

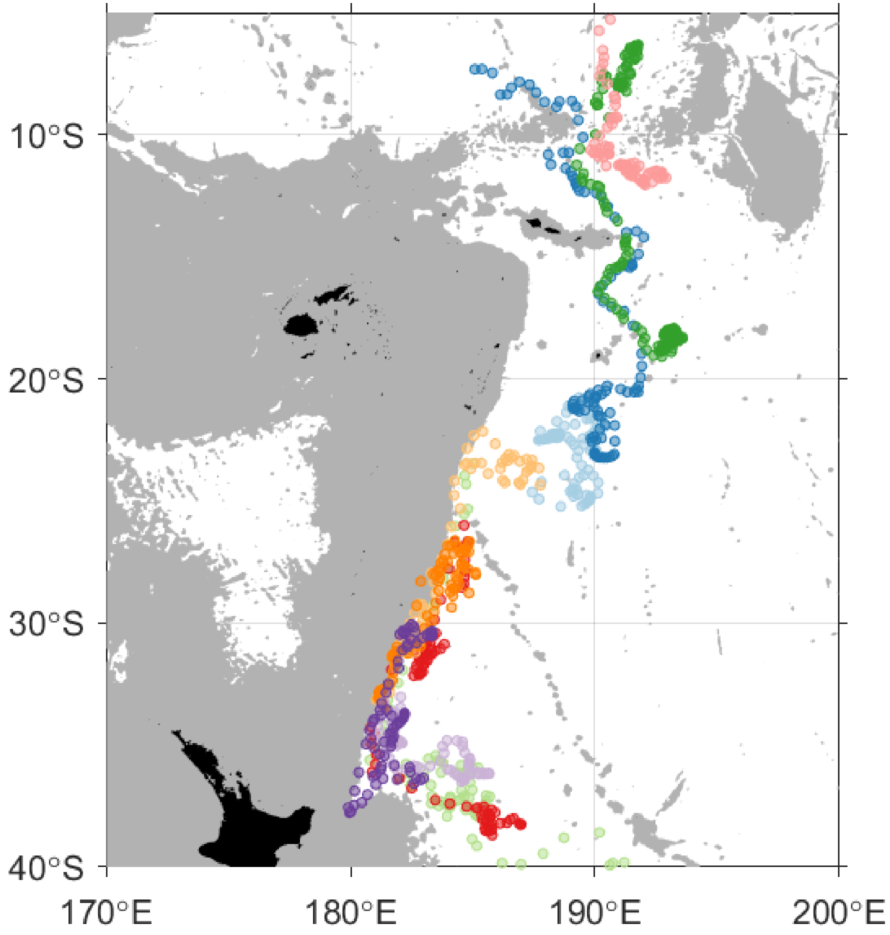


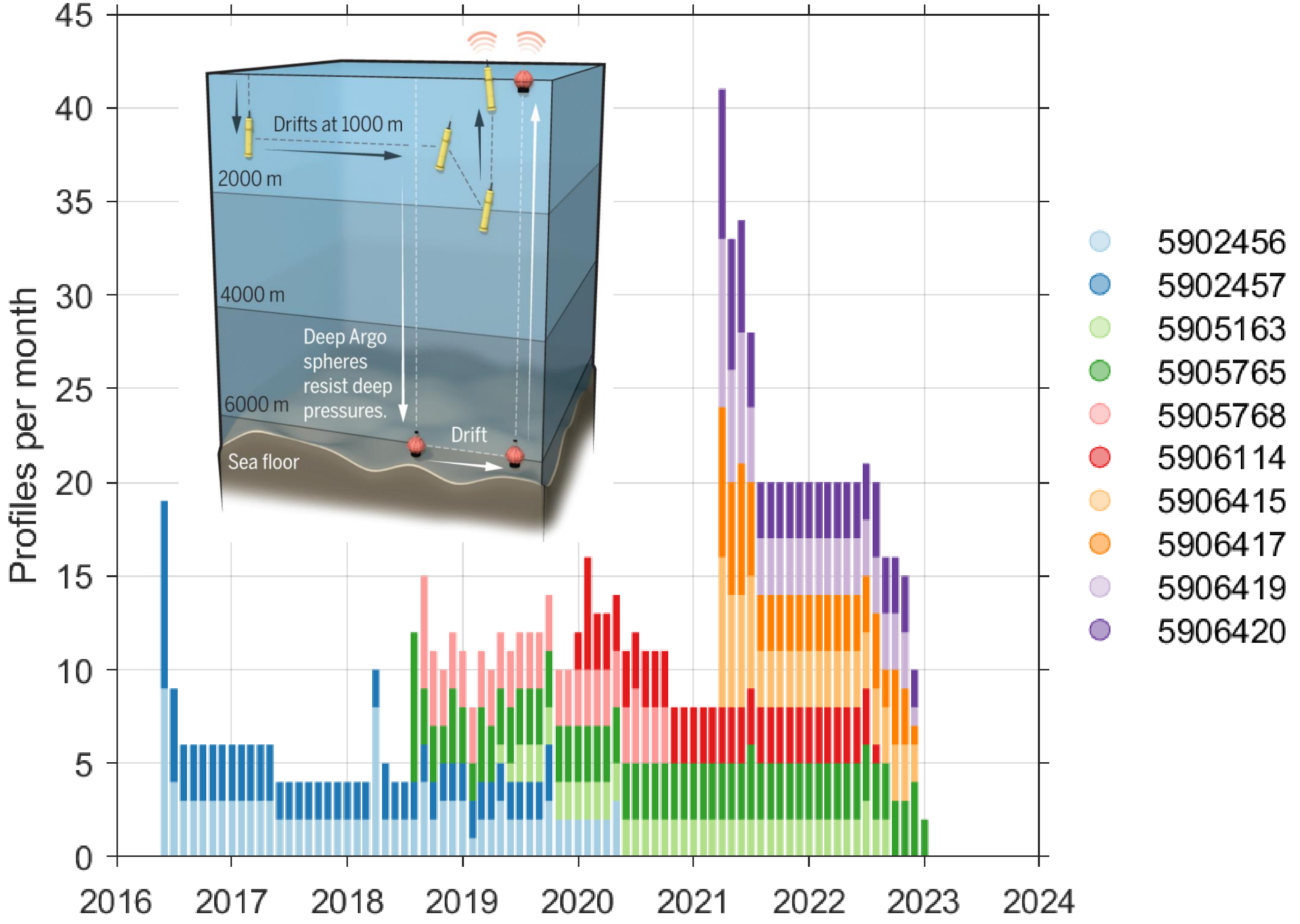

Louisville Seamount Chain collision zone

# Deep Argo observations in this DWBC

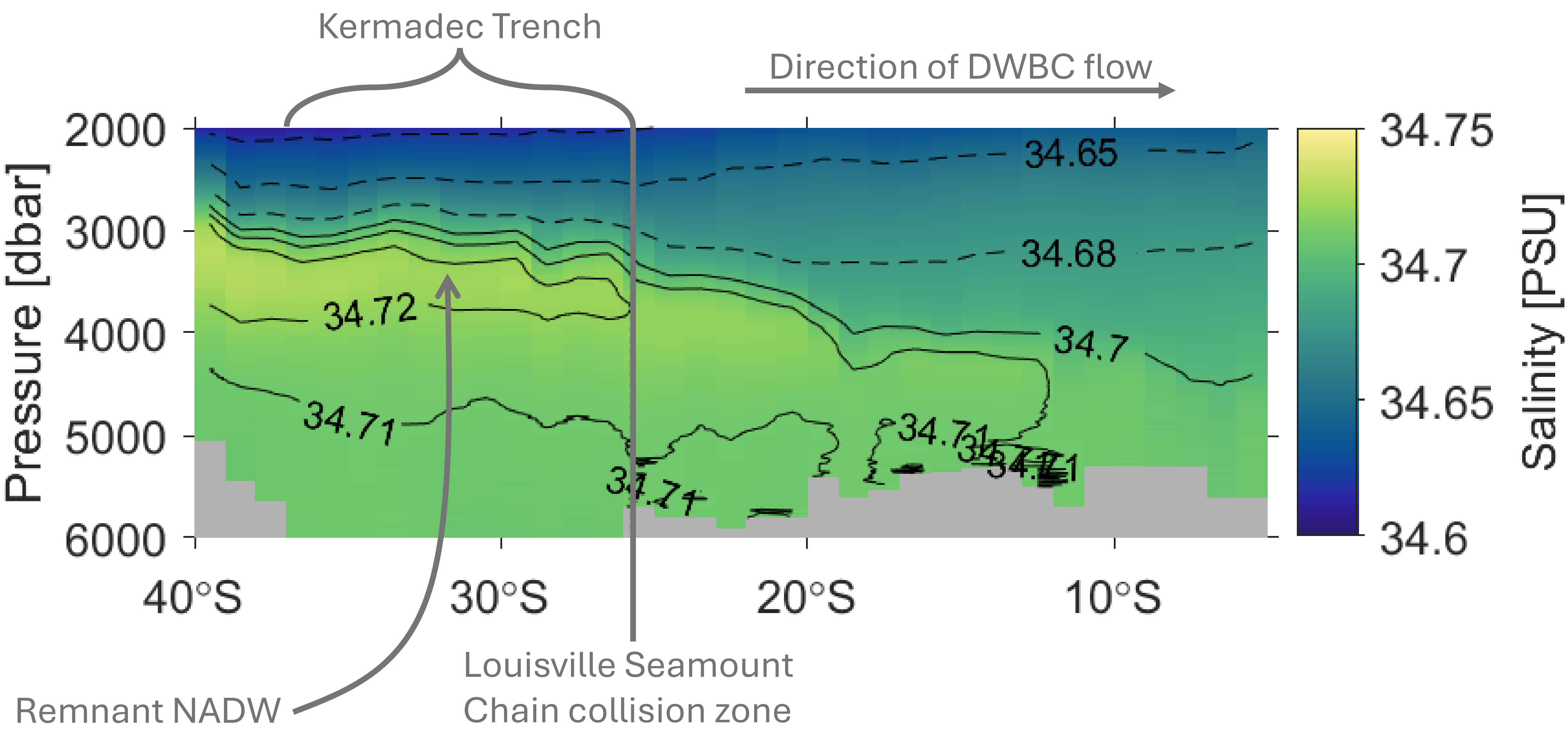


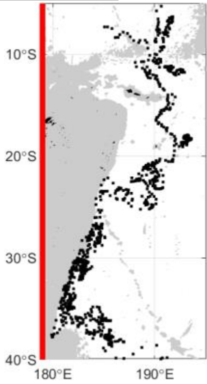

964 delayed-mode profiles from 10 Deep Argo floats profiling within the DWBC.



# Salinity maximum eroded as DWBC exits Kermadec Trench



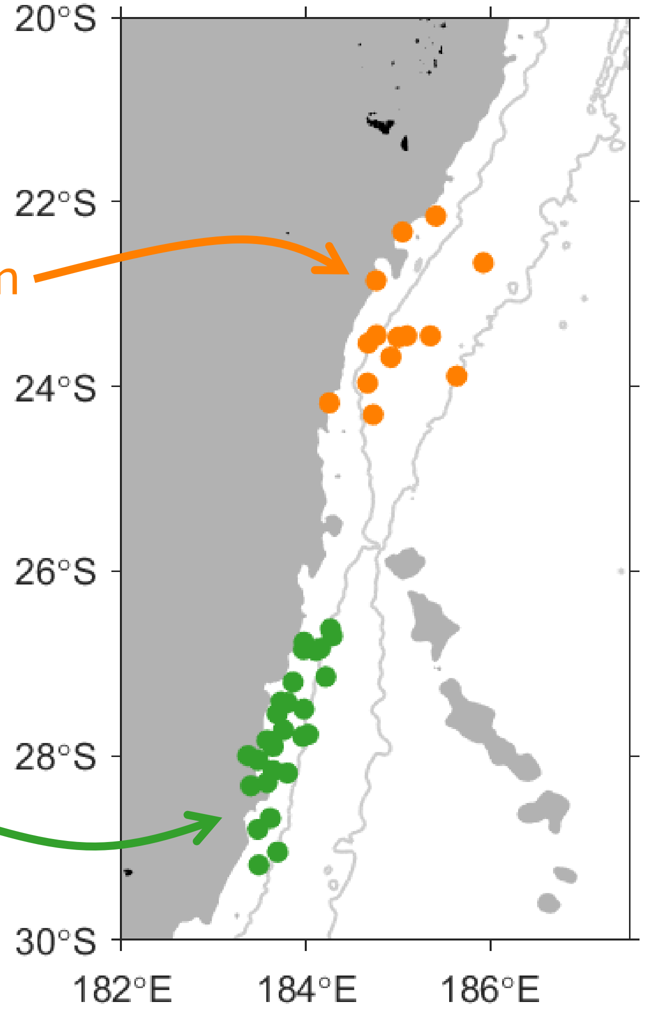



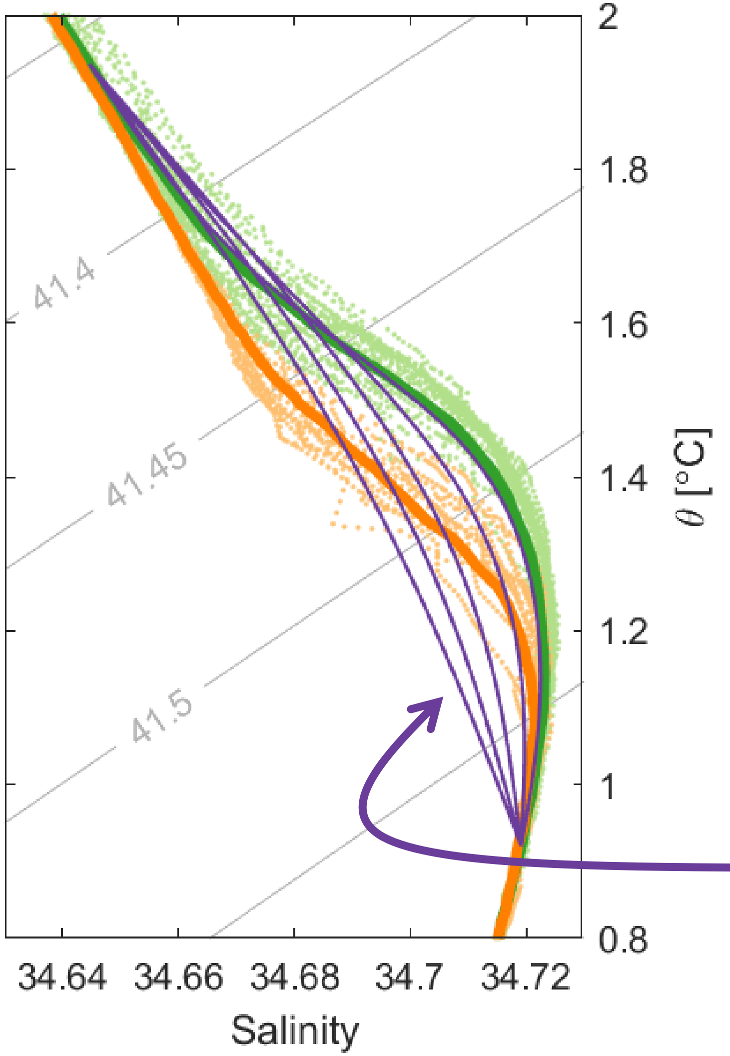
# Mixing cannot be attributed solely to vertical turbulent diffusivity

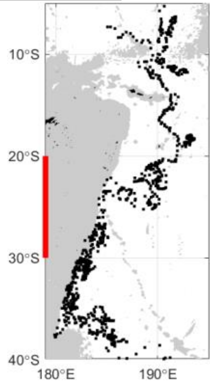
Direction of DWBC flow

Downstream profiles

Upstream profiles



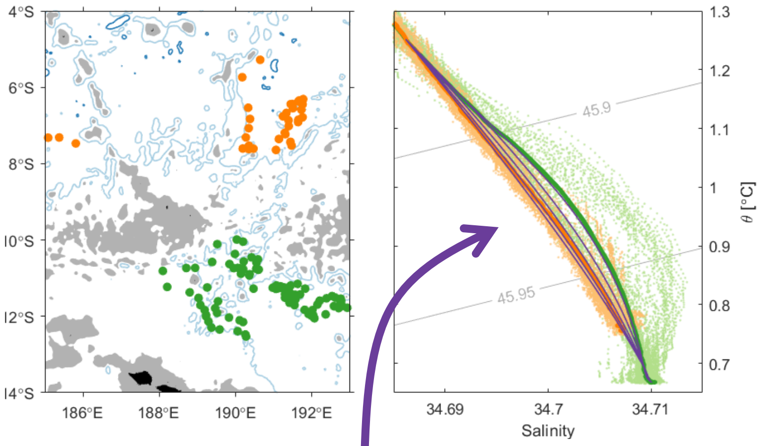




Modelled profile evolution due to vertical turbulent diffusivity

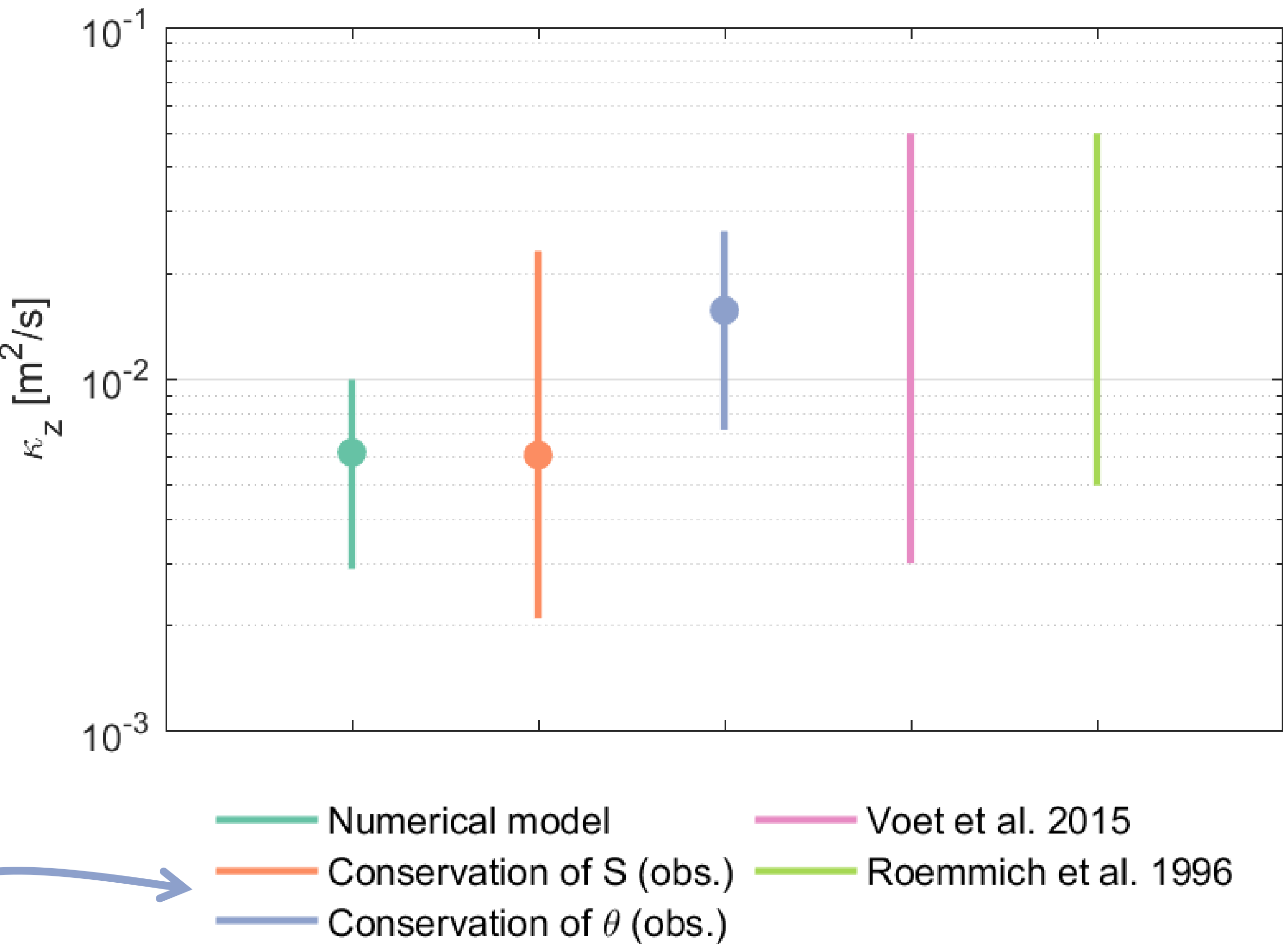
$$\frac{\partial C}{\partial T} = \kappa_z \frac{\partial^2 C}{\partial z^2}$$

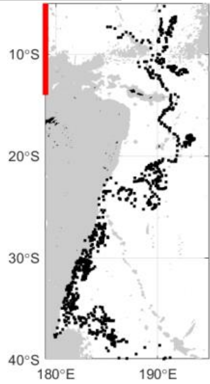
Voet et al. 2015

# Deep Argo can resolve vertical diffusivity in Samoan Passage




Modelled profile changes due to vertical turbulent diffusivity match observed changes through the Samoan Passage

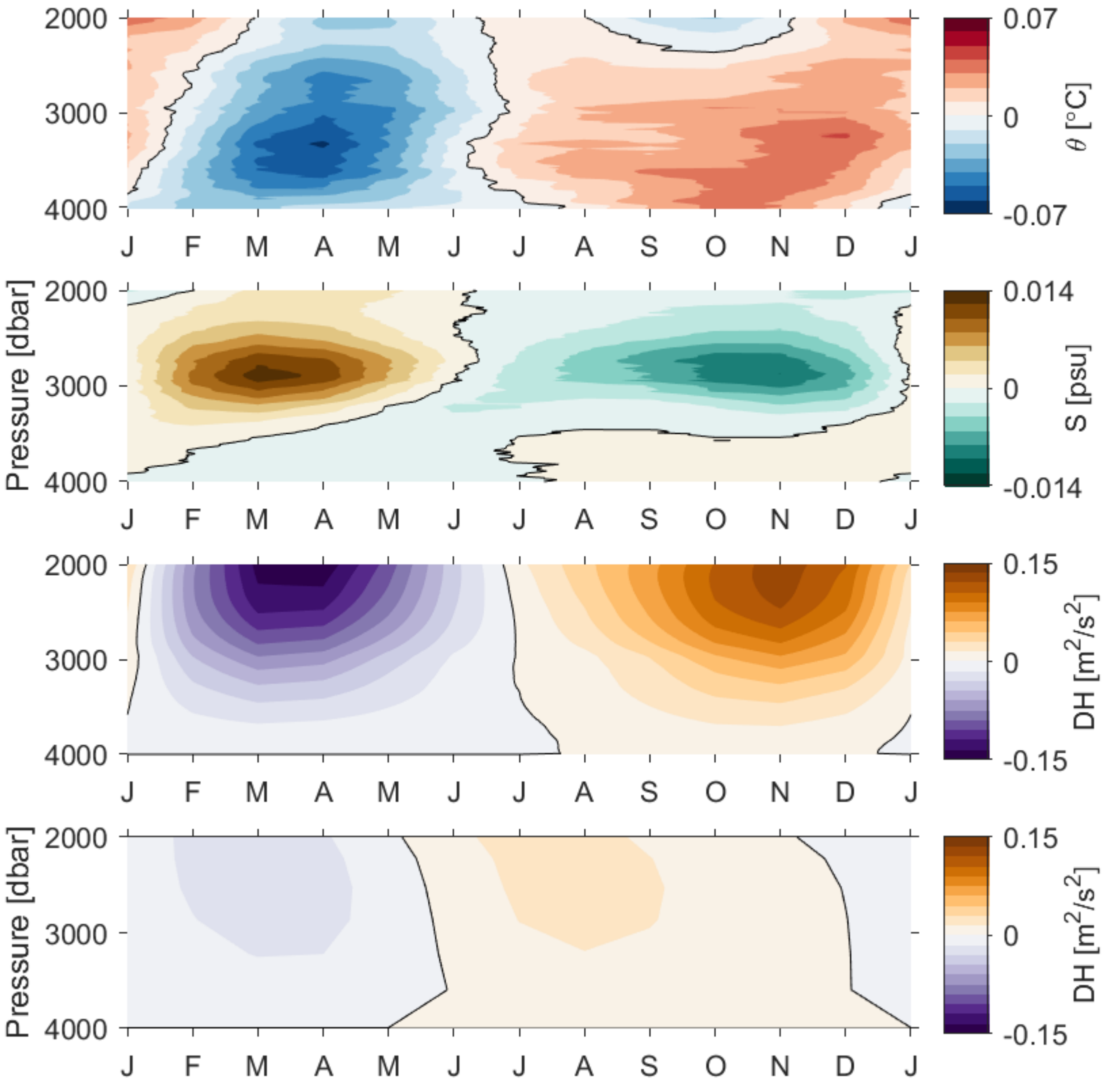


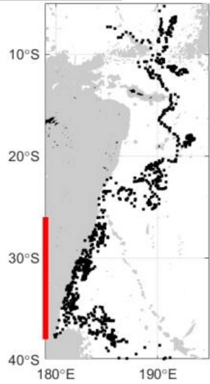




$$v\frac{\partial C}{\partial y} = \kappa_z \frac{\partial^2 C}{\partial z^2}$$

(direct observations)

# Seasonal cycle identified in DWBC within Kermadec Trench



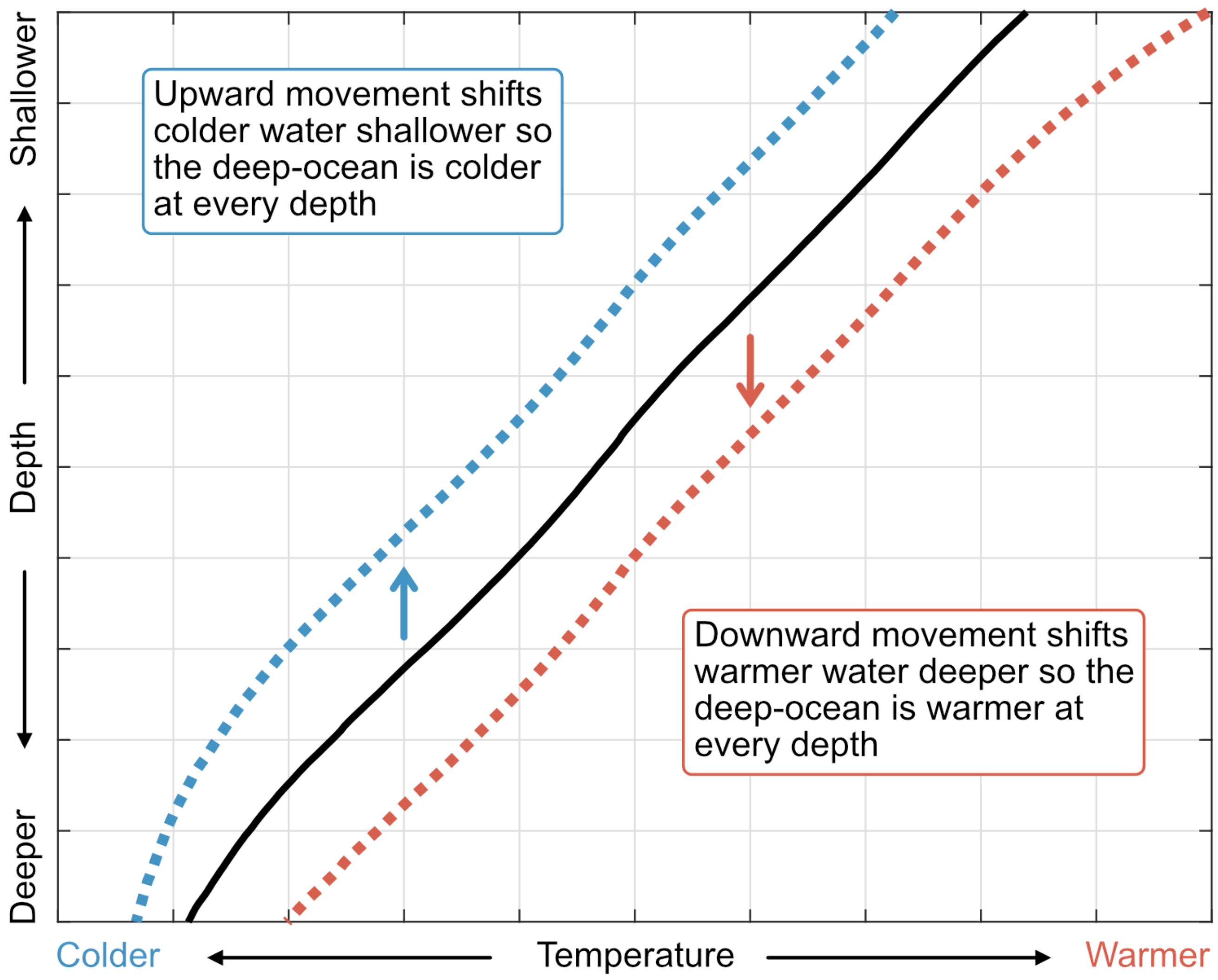




Deep Argo observations

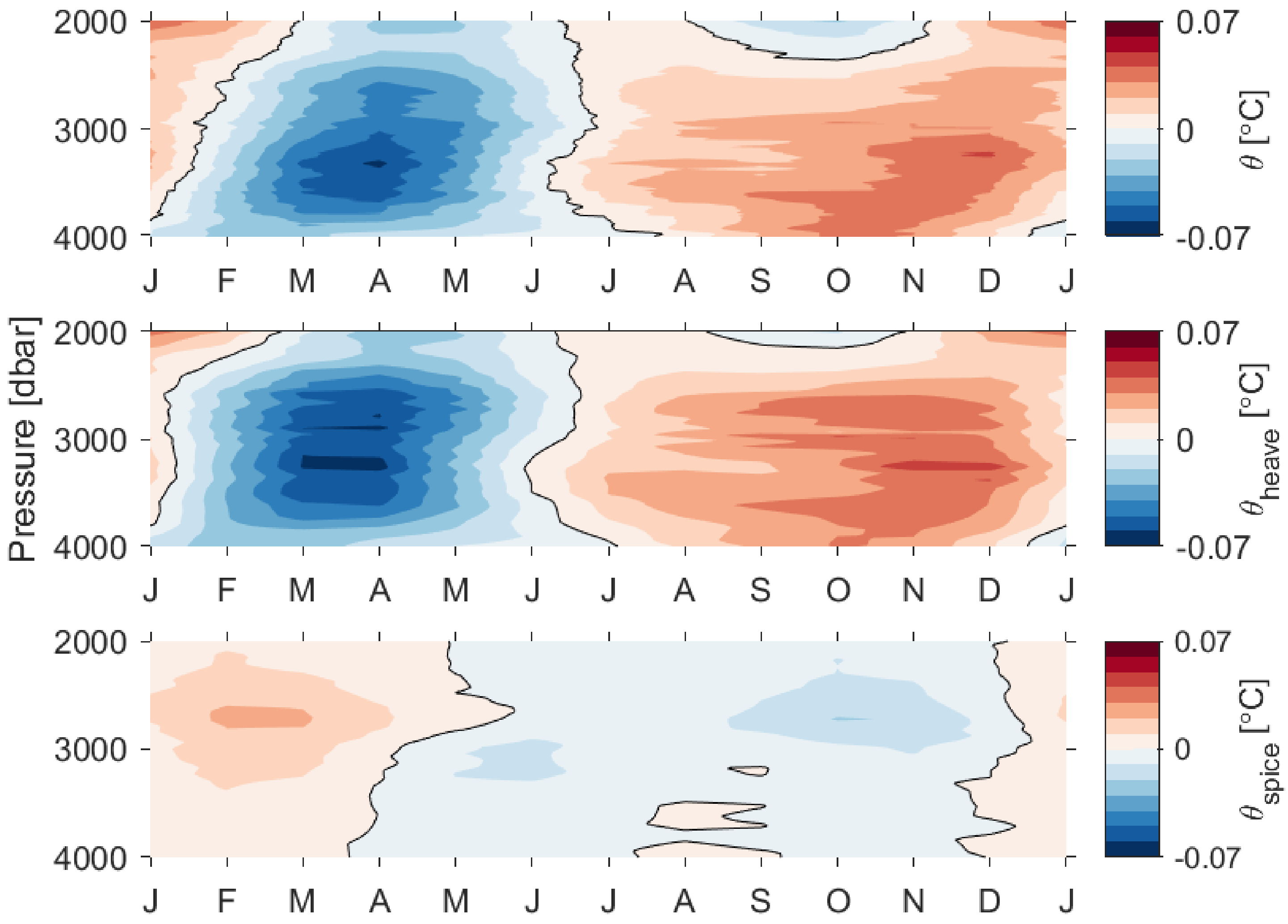
Similar phase but weaker magnitude in ocean reanalysis

GLORYS12V1: Lellouche et al. 2021

# Heaving is the vertical displacement of isotherms



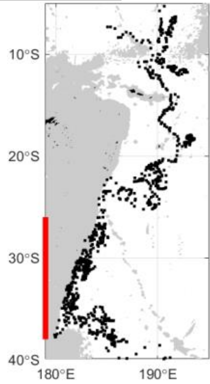
# Deep-ocean seasonal cycle predominantly due to heave




Observed seasonal cycle

Heave (vertical movement of isopycnals) dominates the seasonal changes

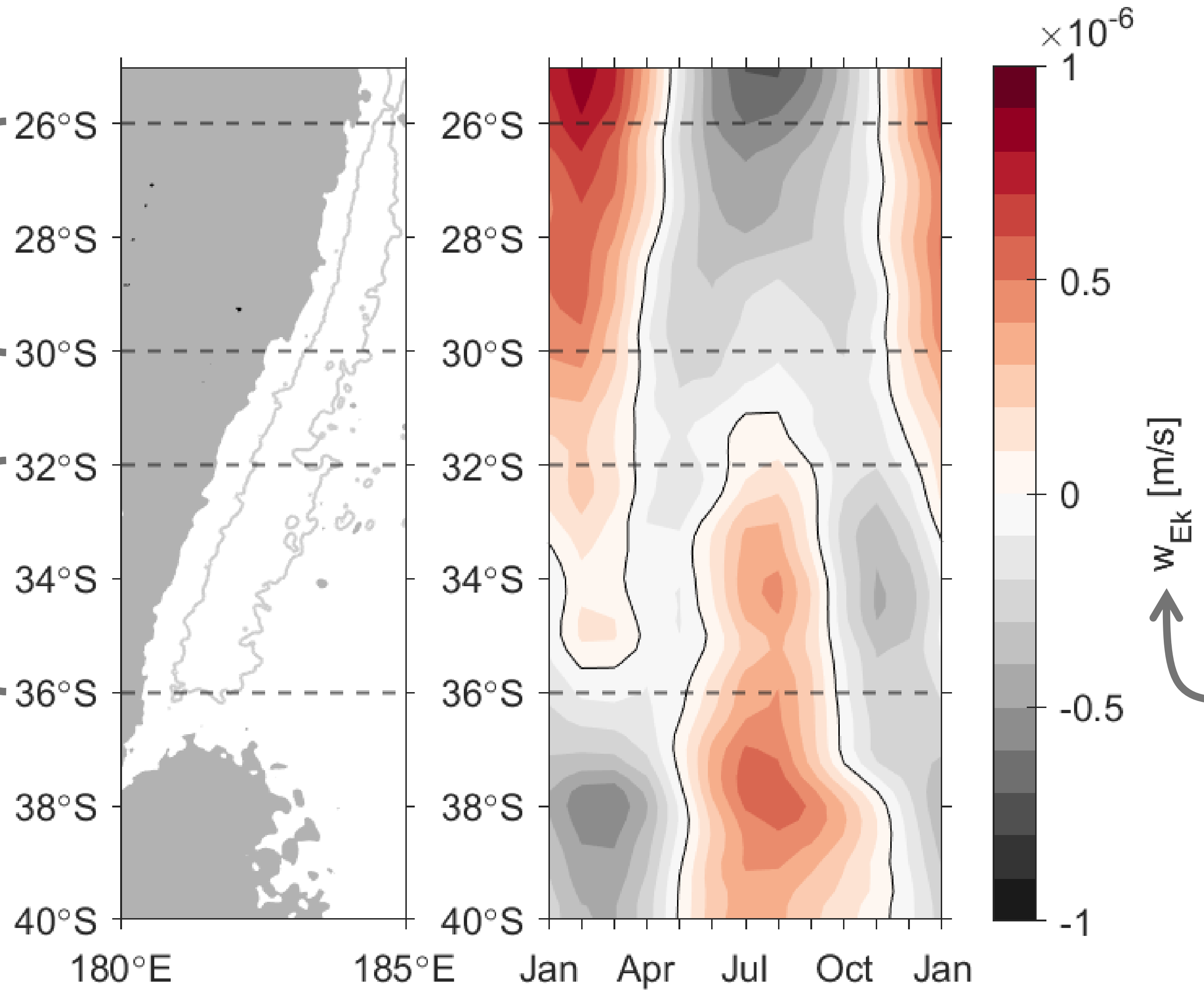
Contribution from spice (change in water mass properties) is minimal



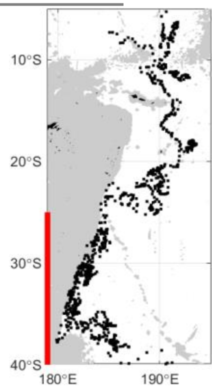
# Wind seasonal cycle changes over latitude of Kermadec Trench

northern Kermadec Trench

southern Kermadec Trench



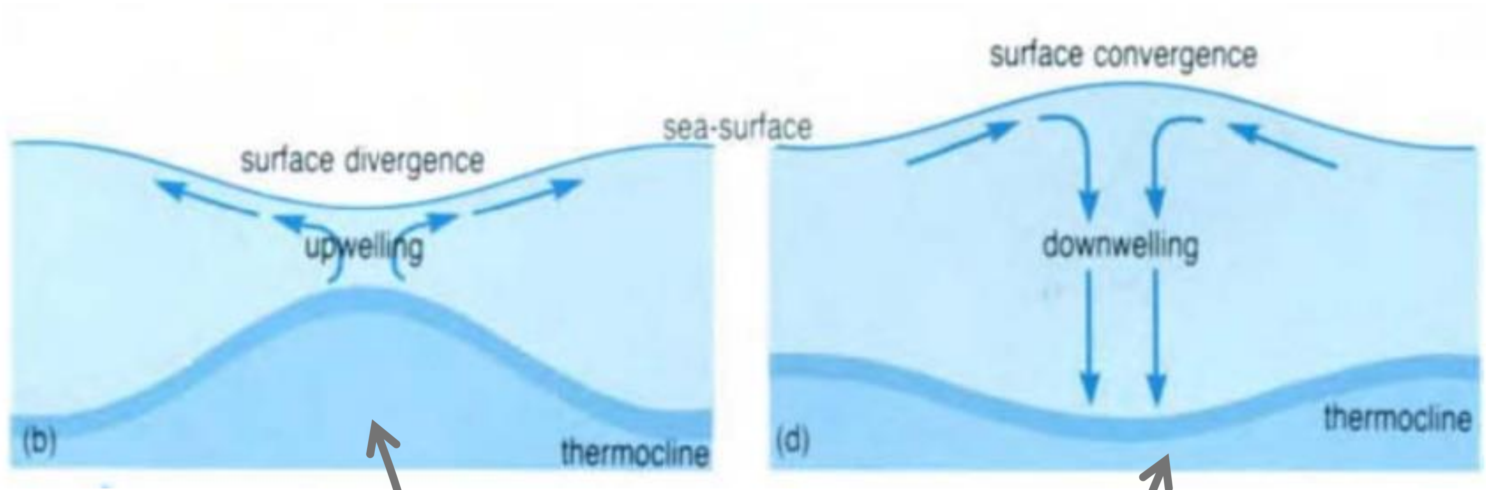

Wind seasonal cycle (Ekman pumping)




ERA5: Hersbach et al. 2020

# Ekman pumping

TLDL: Ekman pumping is a wind-driven process that drives upwelling and downwelling of water.

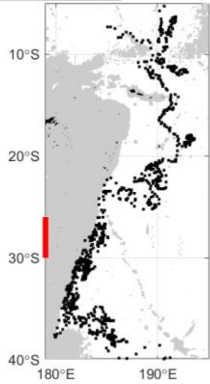



Positive Ekman pumping drives upward movement

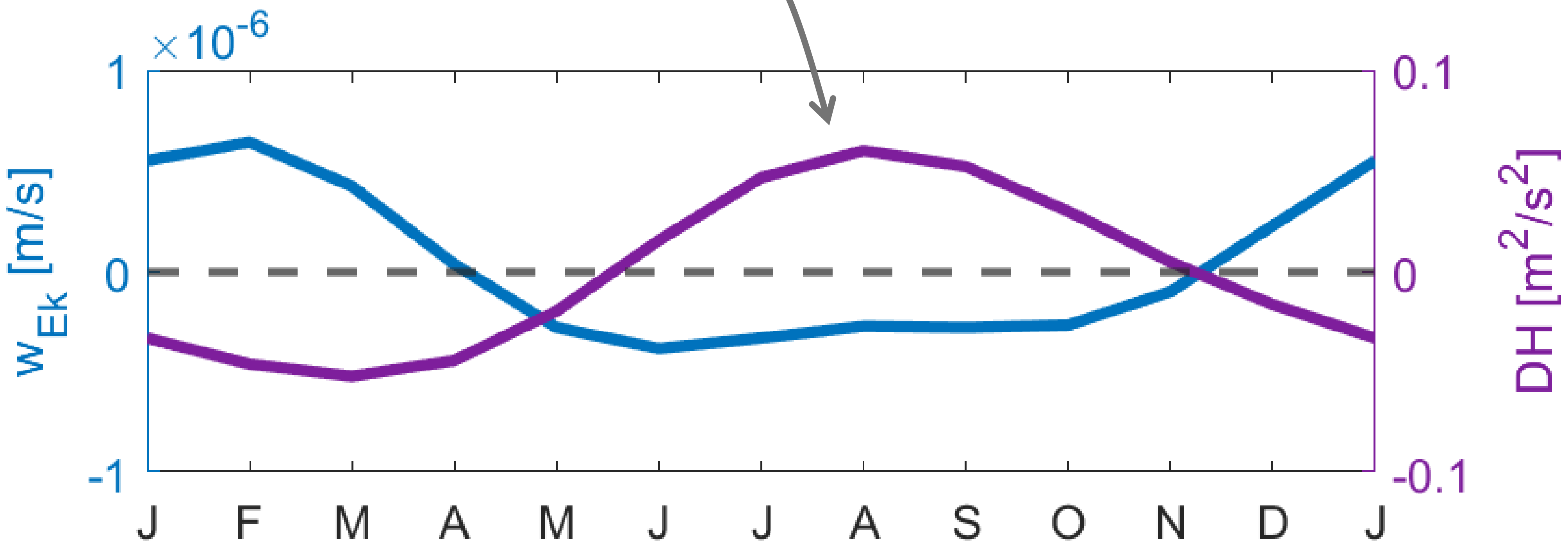
Negative Ekman pumping drives downward movement

Open University 2001

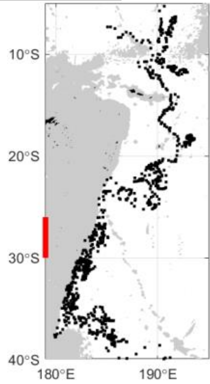
# Local winds drive northern Kermadec Trench seasonal heaving



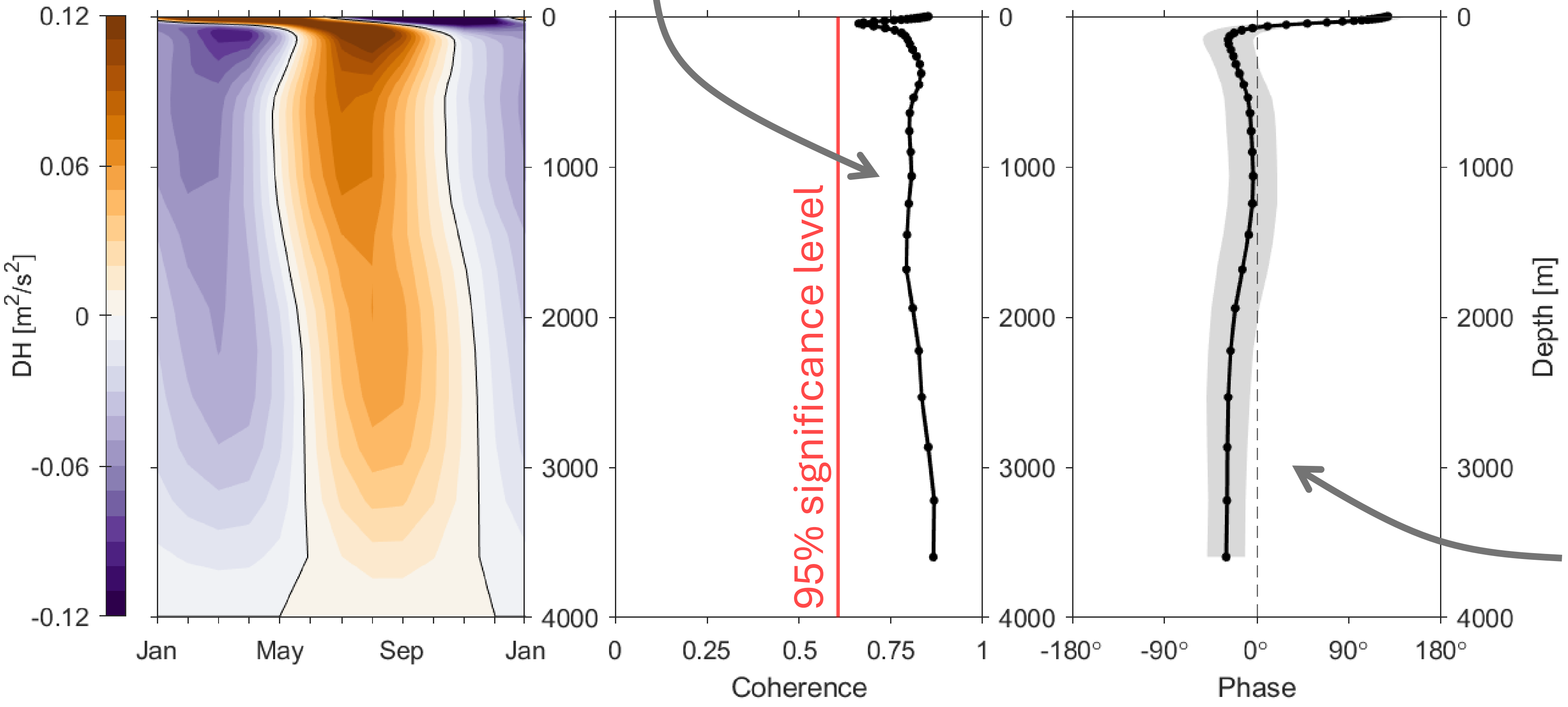

Downward motion (–ve Ekman pumping anomaly, blue) lowers isopycnals resulting in steric expansion (+ve dynamic height anomaly, purple)



# Local winds drive northern Kermadec Trench seasonal heaving



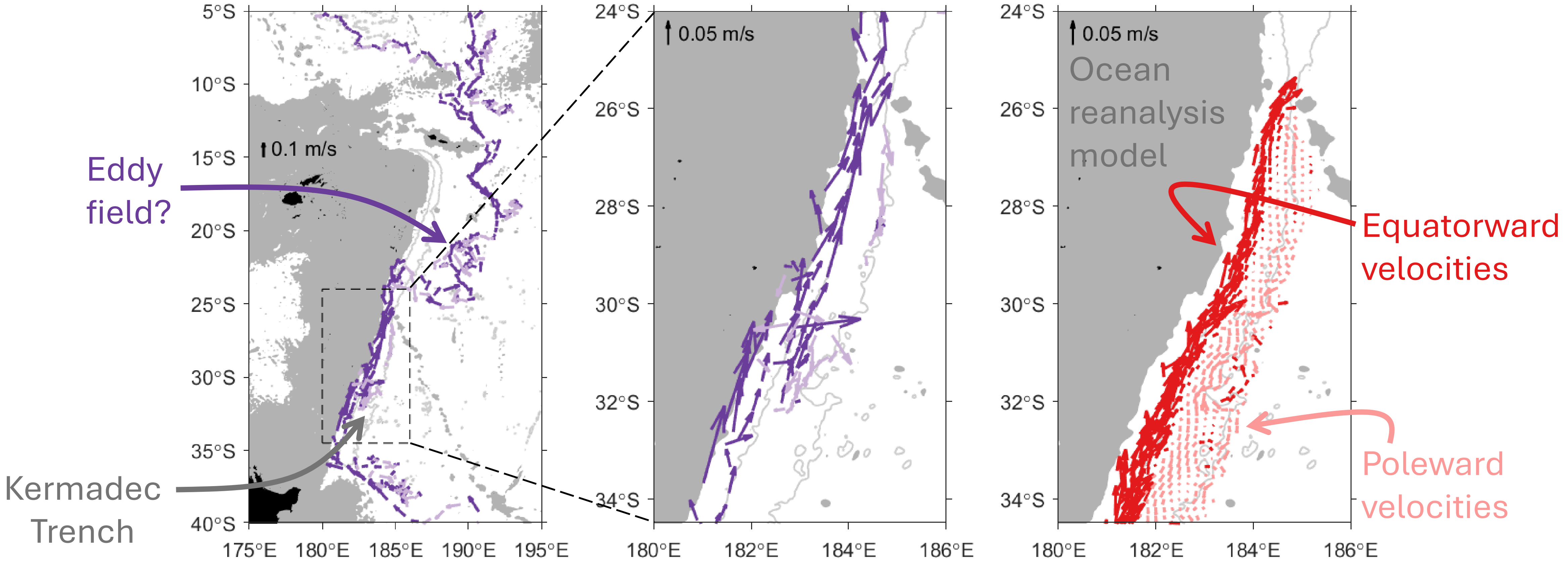

Significant coherence between monthly dynamic height and Ekman pumping anomalies at annual period




Ekman pumping leads dynamic height by <1-month at annual period

# Deep Argo trajectories map the path of the DWBC

Existence of a previously hypothesised cyclonic recirculation over the Kermadec Trench is confirmed.



# Seasonal heaving could influence seasonal DWBC transport

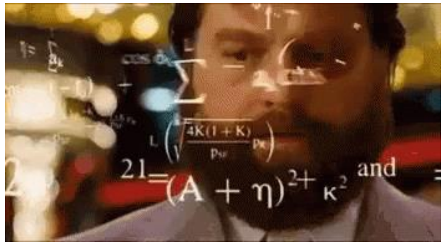
Anomalously positive Ekman pumping ⟶ enhanced poleward transport in the interior ⟶ enhanced equatorward transport at the western boundary.

–ve in Southern Hemisphere

$$V = \frac{f}{\beta} w_{ek}$$

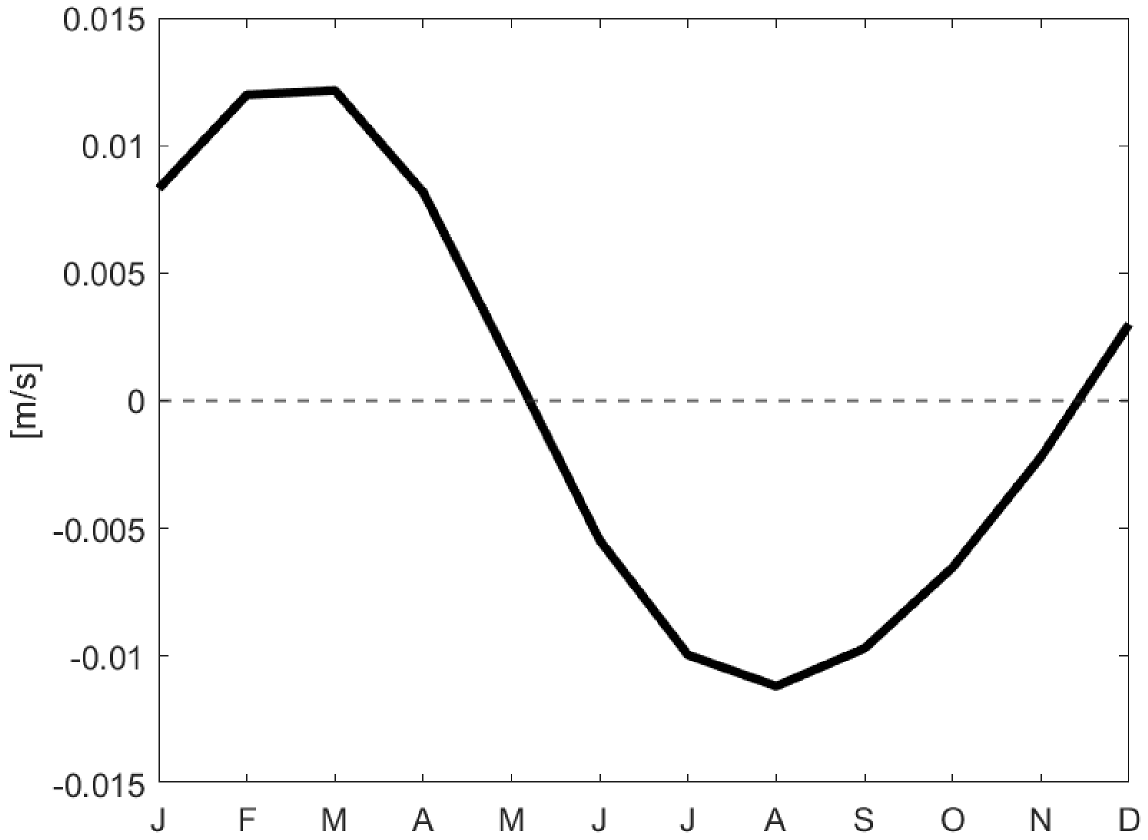
Ekman pumping

Interior (Sverdrup) transport



# Reanalysis model suggests a DWBC velocity seasonal cycle

However, velocity temporal variability in eddy-resolving ocean reanalysis model has not yet been validated against observations in this DWBC.



# Key Takeaways

Chandler M, Zilberman NV, Sprintall J. (2024). The deep western boundary current of the Southwest Pacific Basin: insights from Deep Argo. *Journal of Geophysical Research: Oceans*.

- **Deep Argo floats provide measurements of temperature, salinity, and pressure between the sea surface down to as deep as 6000-dbar.**
- **The remnant NADW salinity maximum is eroded as the DWBC exits the Kermadec Trench to the north through the Louisville Seamount Chain collision zone.**
- **Deep Argo measurements accurately estimated vertical turbulent diffusivity through the Samoan Passage.**
- **There is a deep-ocean seasonal cycle in the northern Kermadec Trench that is predominantly due to seasonal heaving and is driven by local Ekman pumping at the surface.**
- **Deep Argo subsurface trajectories have confirmed the existence of a cyclonic (clockwise) circulation over the Kermadec Trench.**

The ability to observe WBCs beneath the sea surface and over long time periods is invaluable for understanding WBC variability

Sustaining the global ocean observing system is critical for understanding our oceanic arteries and veins – the WBCs

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NOPP National Oceanographic Partnership Program
FULBRIGHT New Zealand TE TŪĀPAPA MĀTAURANGA O AOTEAROA ME AMERIKA

Scan for a copy of the slides

**Chapter 1:**
Chandler et al. (2022). Seasonal to decadal western boundary current variability from sustained ocean observations. *Geophysical Research Letters*. doi: 10.1029/2022GL097834

**Chapter 2:**
Chandler et al. (in prep). ENSO influences subsurface marine heatwave occurrence in the Kuroshio Extension.

**Chapter 3:**
Chandler et al. (2024). The deep western boundary current of the Southwest Pacific Basin: insights from Deep Argo. *Journal of Geophysical Research: Oceans*. doi: 10.1029/2024JC021098