ACC Meanders Enhance Air-Sea Heat Flux and Water Subduction

Felipe Vilela-Silva Nathan L. Bindoff Helen E. Phillips Steve R. Rintoul Max Nikurashin

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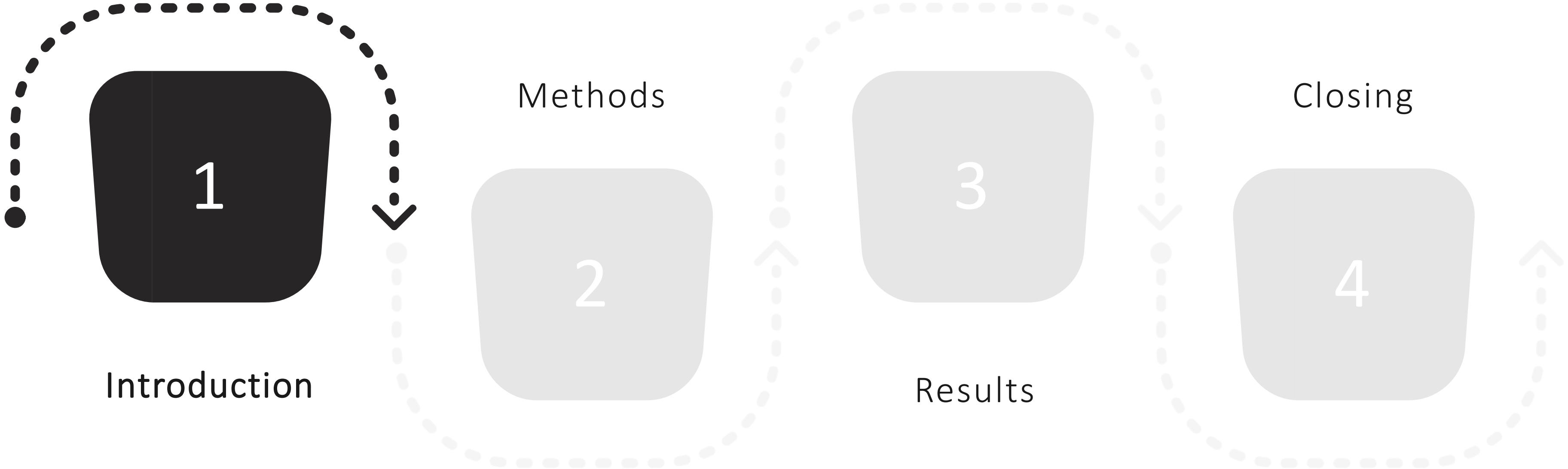

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Why Air-Sea Heat Fluxes Matter?

Climate Regulation

Air-sea heat fluxes play a key role in regulating the earth's climate by transporting heat from the equator to the poles.

Weather Prediction

Accurate prediction of air-sea heat fluxes is essential for reliable weather forecasts and storm alerts.

Ocean Circulation

Changes in air-sea heat fluxes can impact ocean circulation, which affects global climate and marine ecosystems.

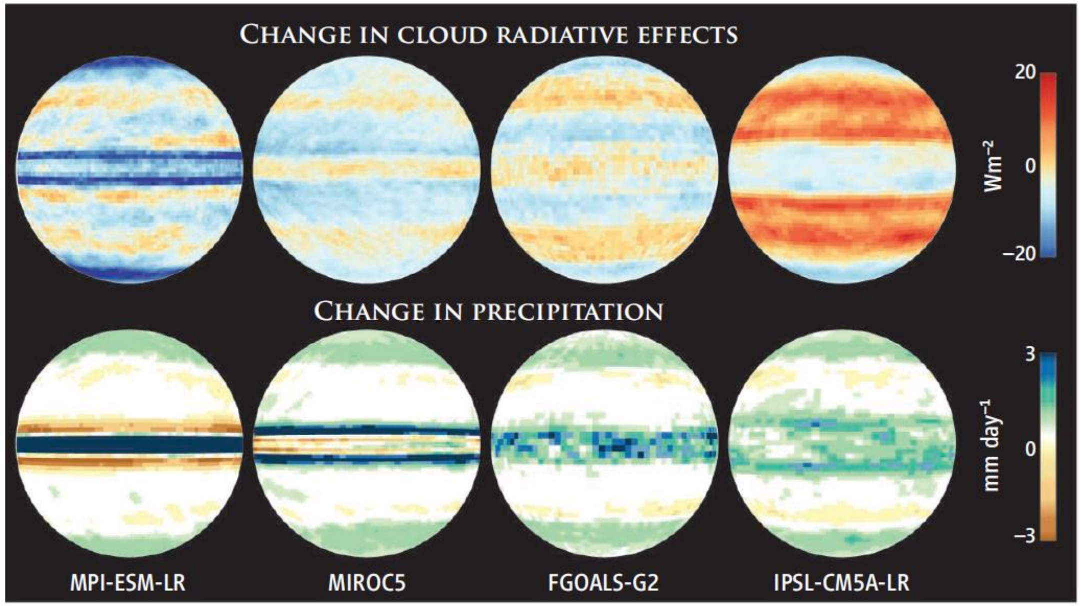


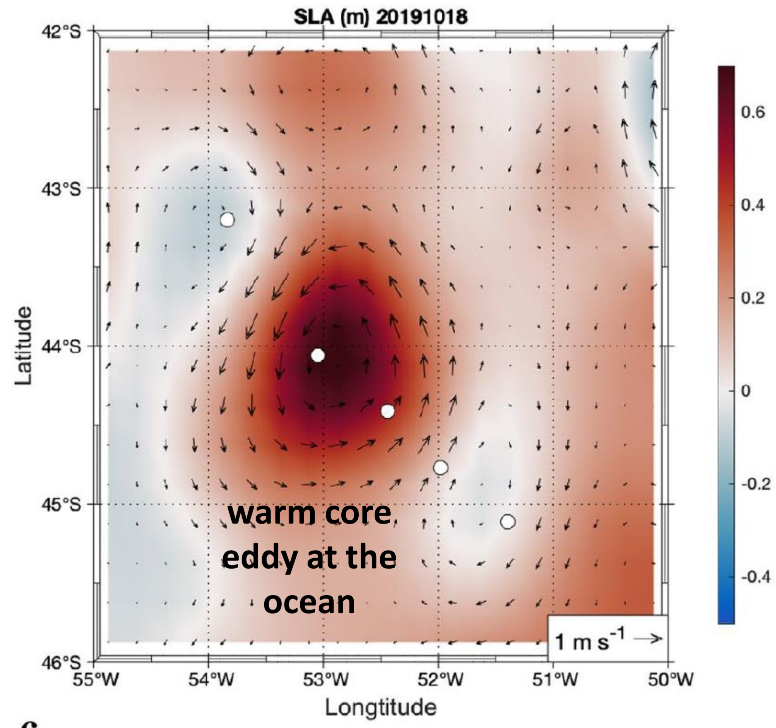
Figure extracted from Stevens and Bony (2013), Science.

- Stevens and Bony (2013) found **different precipitation rates** in CMIP5 models after simulating a **waterworld**.
- The **vertical transport of heat** between the **ocean** and the **atmosphere** is one of the key uncertainties driving the different scenarios in the waterworld (Stevens and Bony, 2013).

What Are the Oceanic Factors Affecting Air-Sea Heat Fluxes?

Eddies!

- Pezzi et al. (2021) observed a **warm core eddy at the ocean** and **marine atmospheric boundary layer** in the **Brazil-Malvinas Confluence region**.
- The sea surface temperature anomaly caused by **the warm ocean eddy**
    - increase the **surface winds** and **heat fluxes** from the ocean to the atmosphere (Pezzi et al., 2021); and
    - produce a **warm**, **mixed**, and **unstable** marine **atmospheric boundary layer** (Pezzi et al., 2021).



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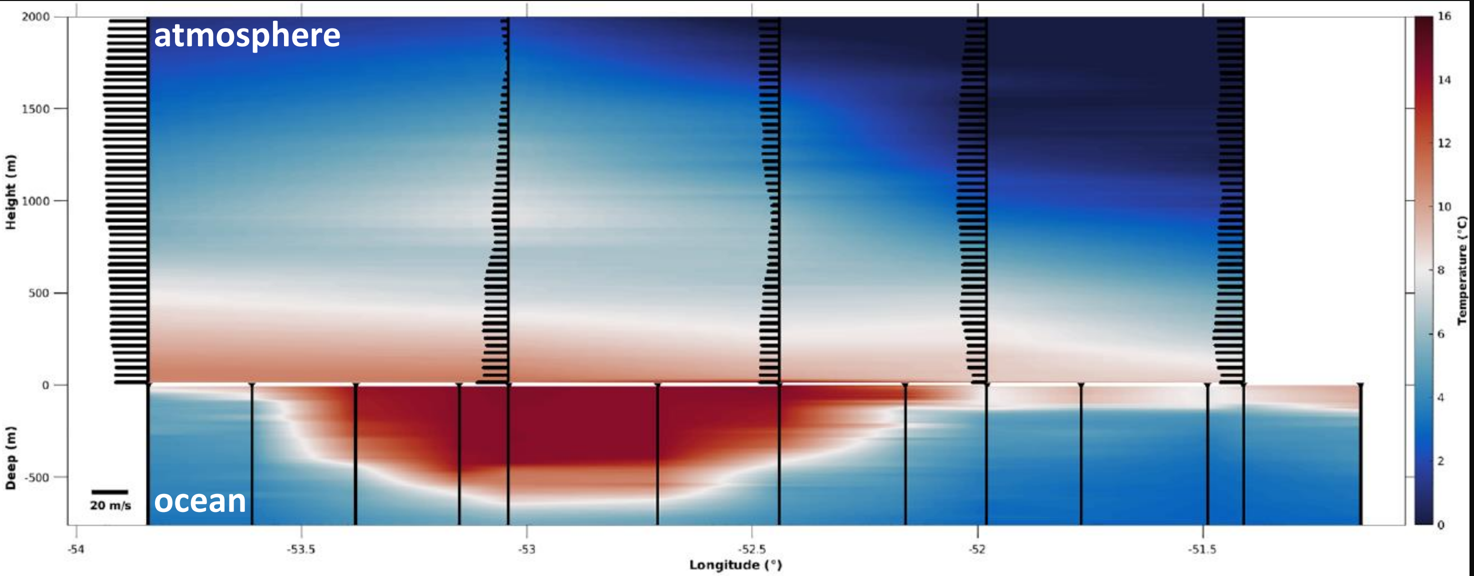


Figure 3. Temperature profiles (°C) of the atmosphere and ocean (colors) taken simultaneously by radiosondes and XBTs along the Brazilian Navy Polar Vessel (Po/V) Almirante Maximiano (H-41) route while crossing the eddy during 18th October 2019. The lower part of this figure also displays the oceanic sounding positions. Wind magnitude (m s^{-1}) in vectors is also displayed, superimposed on the air temperature. The vector size reflects the wind magnitude. MATLAB, Version 9.1.0.441655 (R2016b). https://www.mathworks.com.

Figures extracted from Pezzi et al. (2021), Scientific Reports, Nature.

Eddies!

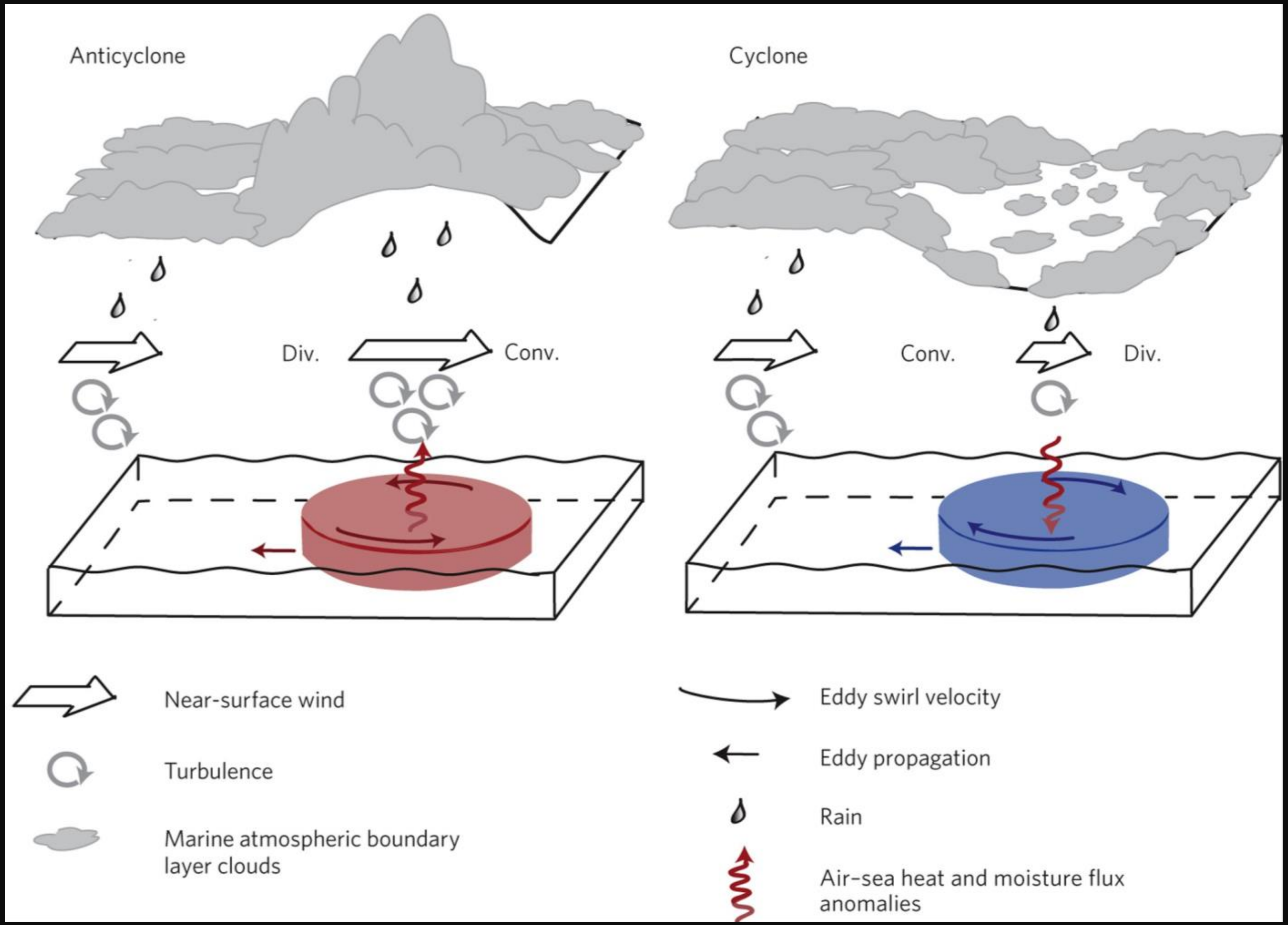


Figure extracted from Frenger et al. (2013), Nature Geoscience.

- The **oceanic eddies in the Southern Ocean** (Frenger et al., 2013) modulate the:
  - **cloud cover** and **water content**,
  - **precipitation**,
  - **wind circulation**.
- The warm core eddies accelerate the winds and increase the precipitation;
- The cold core decelerate the winds and decrease the precipitation (Frenger et al., 2013).

Meanders?

- Foppert et al. (2017) highlight **strong eddy heat fluxes** at locations of ACC **standing meanders**.
- Meanders along the Antarctic Circumpolar Current funnel heat towards the Antarctica (Phillips and Rintoul, 2000) and sea ice zone;
- What is the impact of standing meanders in air-sea interaction once meanders hold enhanced eddy heat fluxes?
    - Is the impact of meanders like eddies because the **crests and troughs of meanders** concentrate warm and cold waters, respectively?

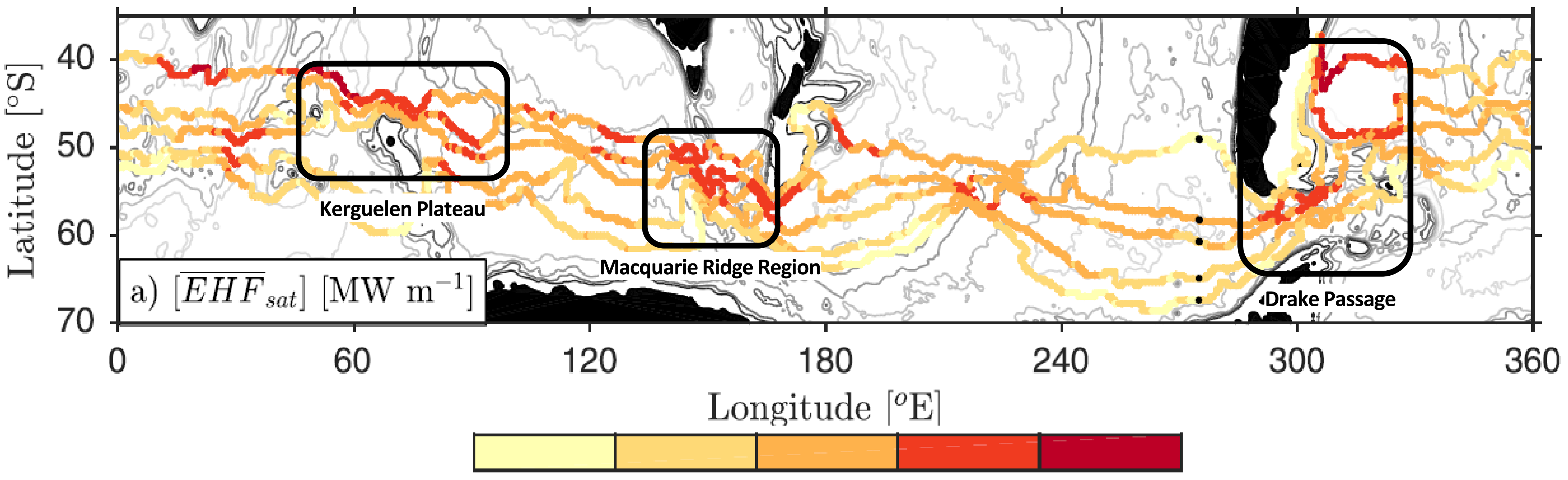


Figure extracted from Foppert et al. (2017), JGR: Oceans.

Equilibration of the ACC transport by meanders

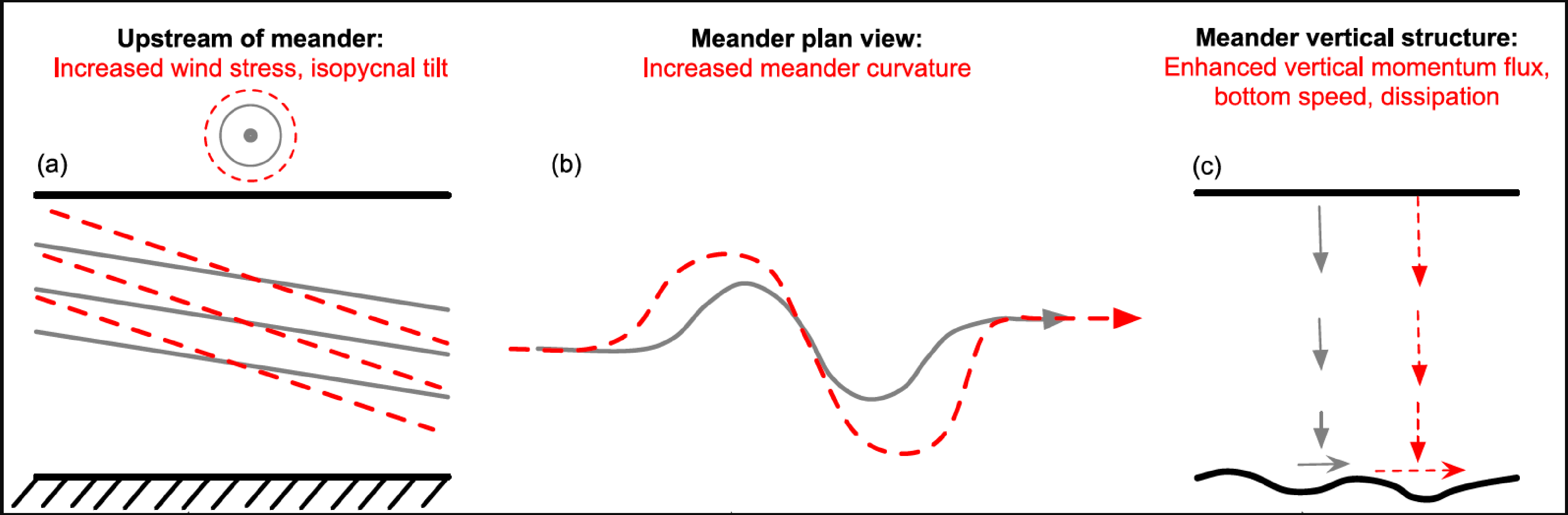
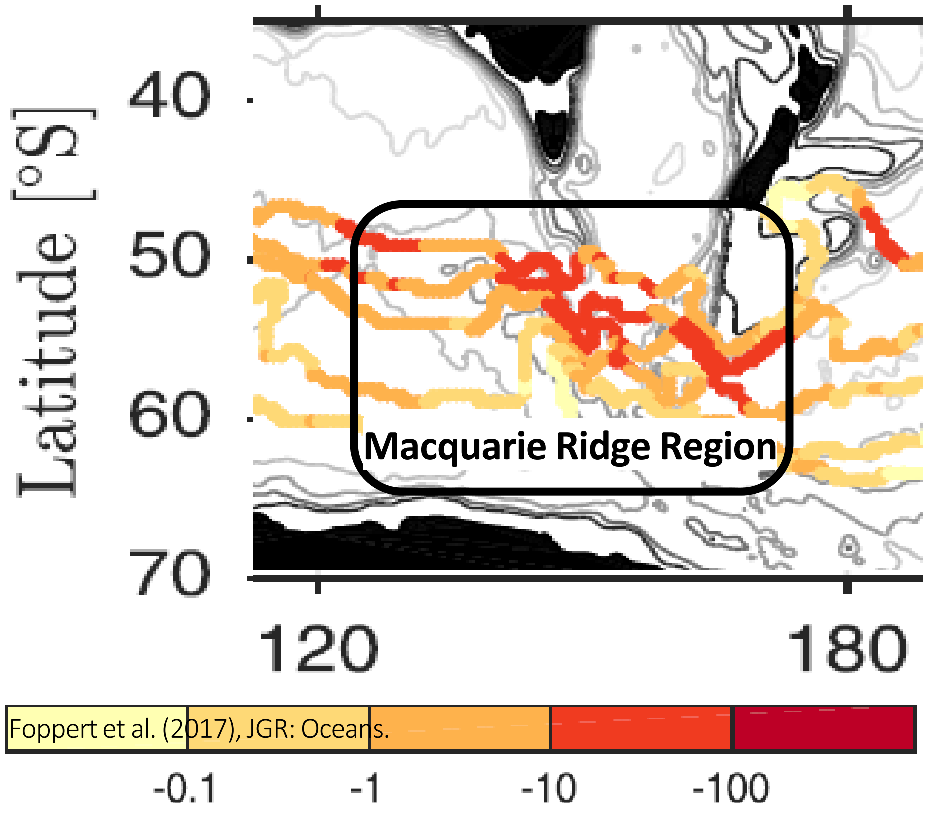
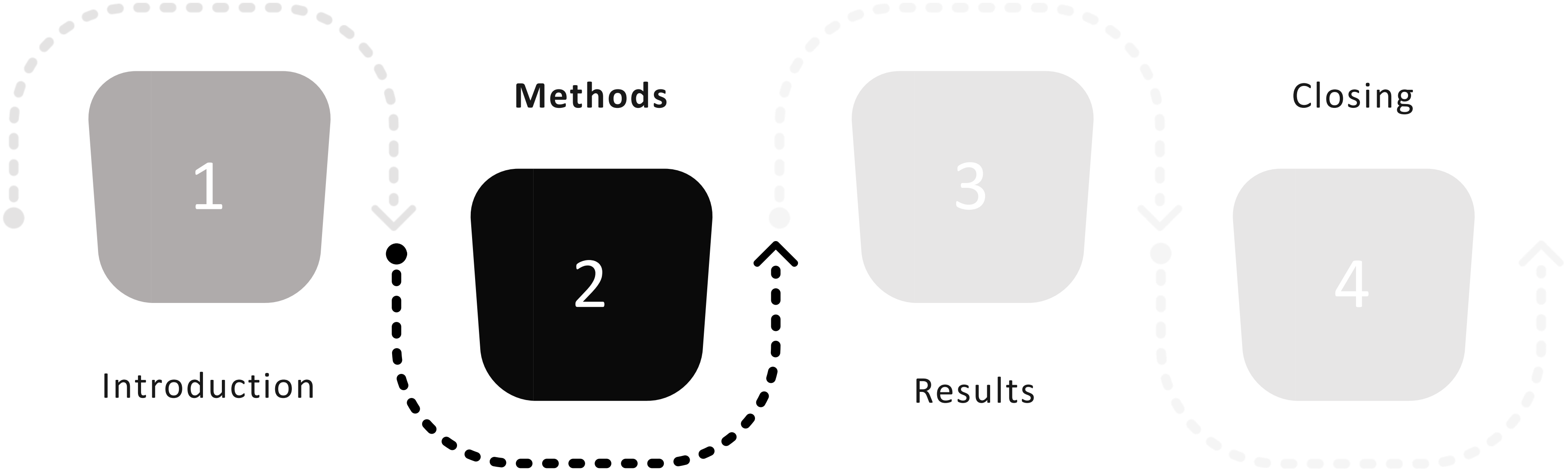


Figure extracted from Thompson and Naveira Garabato (2014), JPO.

Goal

- Motivated by the increase in Eddy Heat Flux at the Macquarie Ridge region (Foppert et al., 2017) and subsurface impact of meanders (Thompson and Naveira Garabato, 2014) , we explore:
- What is the impact of the Macquarie Meander on
  - the regional air-sea heat fluxes and water subduction?
  - subsurface dynamics?
  - We explore this question using the monthly output from the **ACCESS-OM2** global model (Kiss et al., 2020);
  - 0.1° resolution ocean-sea ice model;
  - forced by the JRA55 atmospheric reanalysis (Tsujino et al., 2018).

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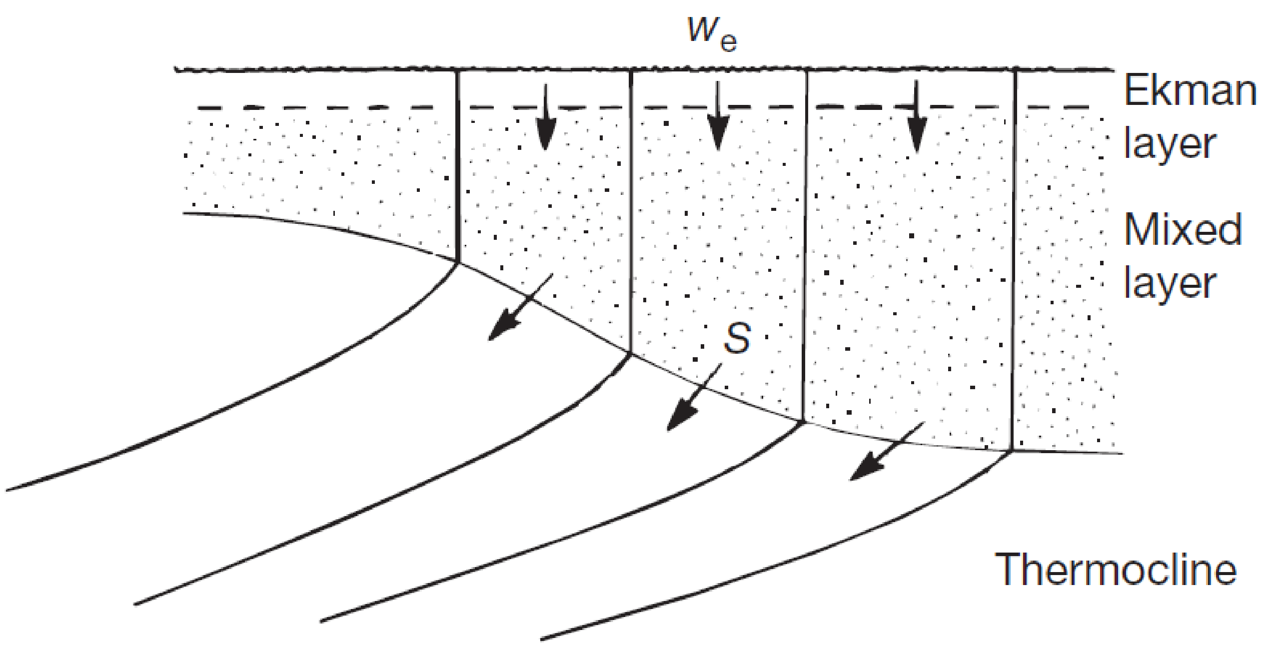
1 Water Subduction

- The **subduction (S) of water** below the permanent thermocline is obtained with the lateral induction of fluid through the sloping base of the mixed layer and the vertical velocity at the same level (Marshall et al., 1993; Downes et al., 2010; Langlais et al., 2017).

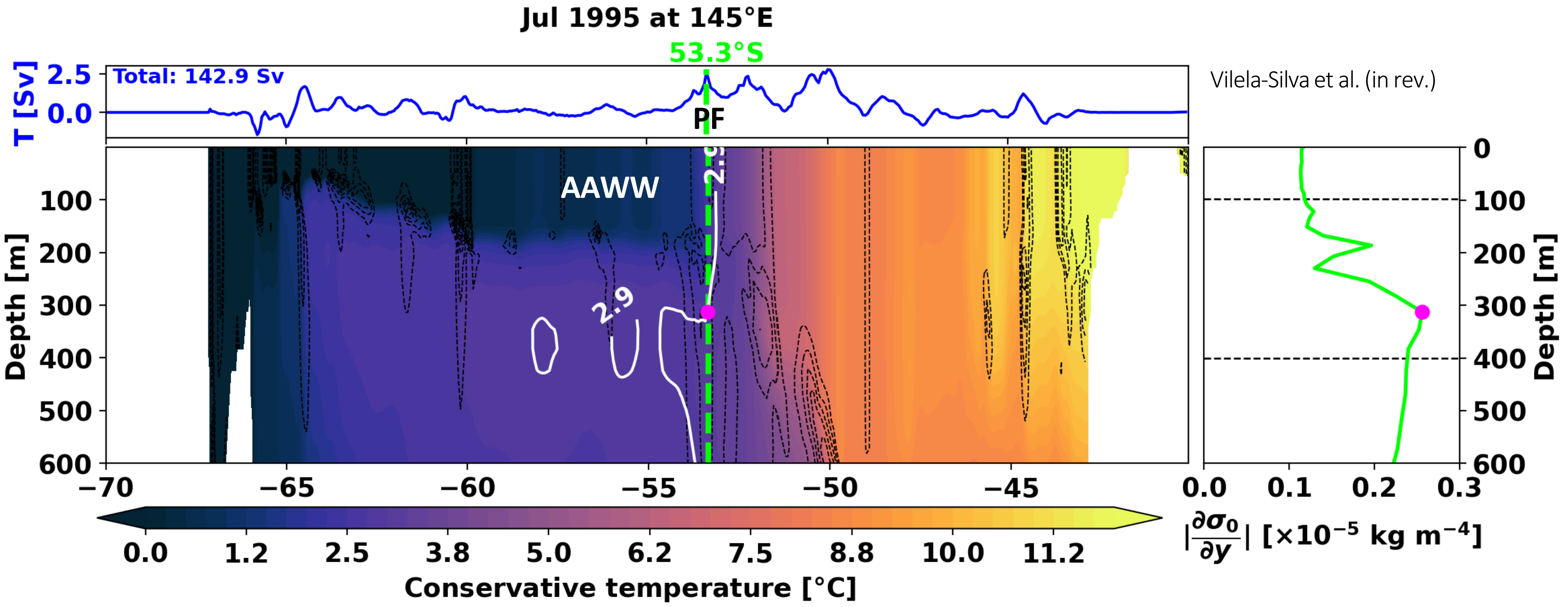
$$S = \underbrace{-\vec{U}_{MLD} \cdot \nabla(\mathrm{MLD})}_{\text{lateral induction}} - \underbrace{\vec{w}_{MLD}}_{\text{vertical velocities}}$$



Schematic extracted from Marshall et al. (1993), JPO.

2 Frontal Tracking Algorithm

- We **track the fronts** by following the isotherms related to local transport maximum (as in Langlais et al., 2011) and the meridional density gradient.
- We ran the frontal tracking algorithm over a 26-year period (1993--2018) covering 46 longitudes (120°E--165°E);
  - It returned two most frequent temperature values **in the ACCESS-OM2** outputs: 2.9°C at 300 m and 5.3°C at 383 m.
  - These values are characteristic for the **PF and sSAF** when compared to observations (Sokolov and Rintoul, 2002) and model outputs (Langlais et al., 2011).



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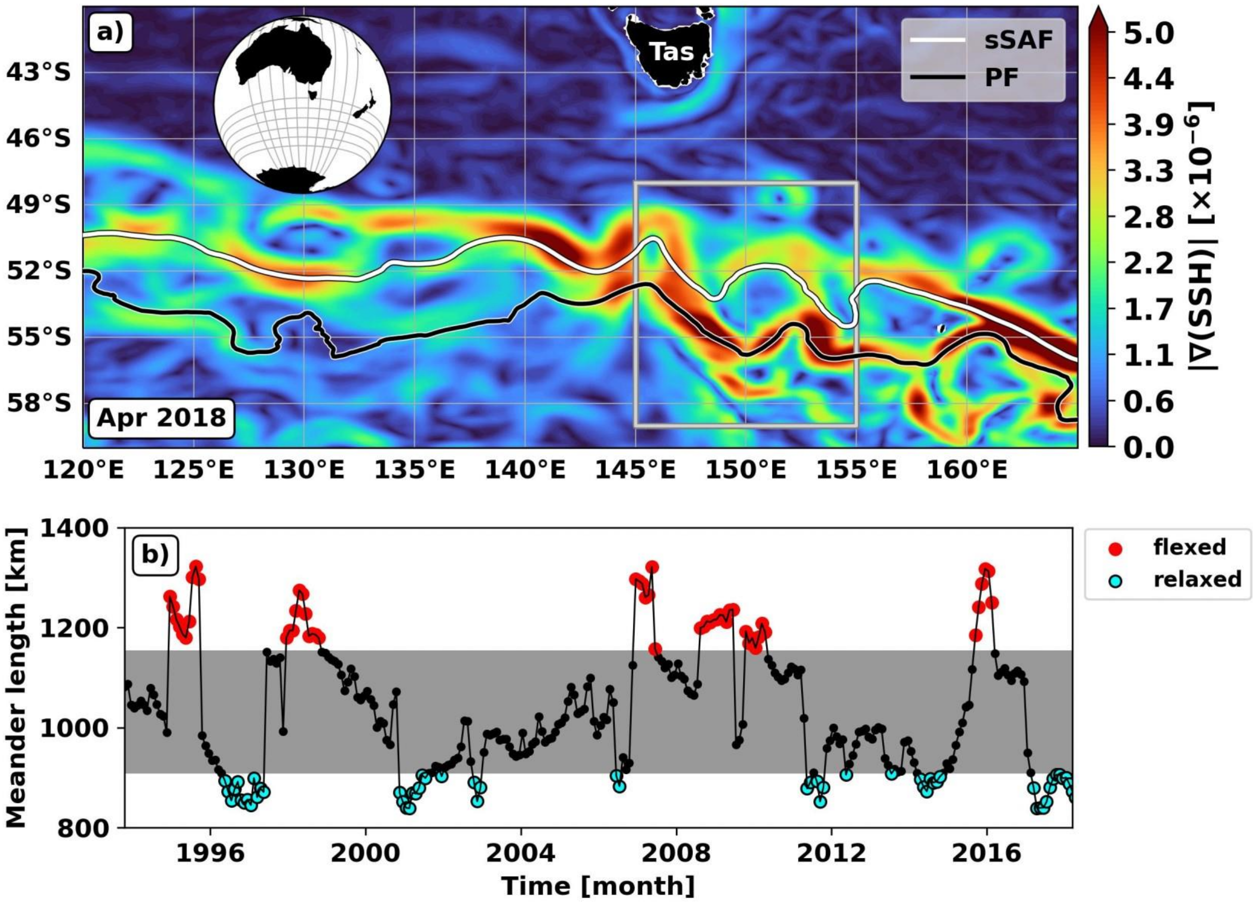
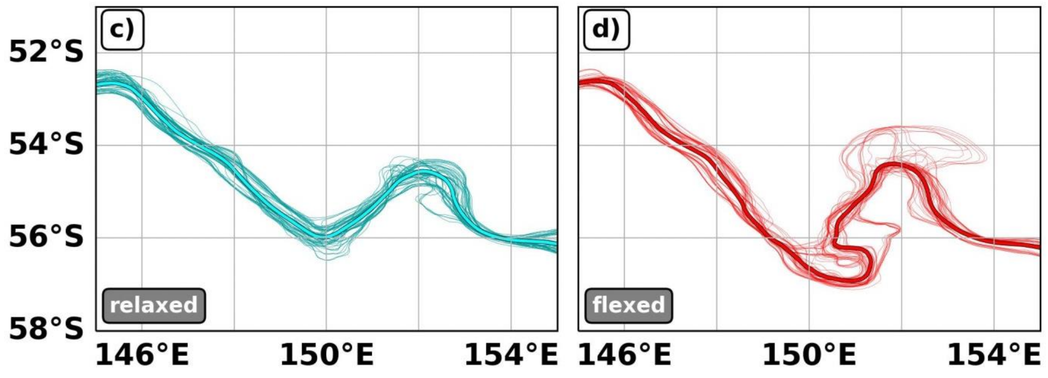
3 Extracting Signals of Variability: Composites



- We extract the **signal of the standing meander** by reducing the noise from higher-frequency variability by compositing the **relaxed and flexed events**.

- We build **composites of the meander structure** based on the length variability of **the PF contour between 145°E and 155°E**.



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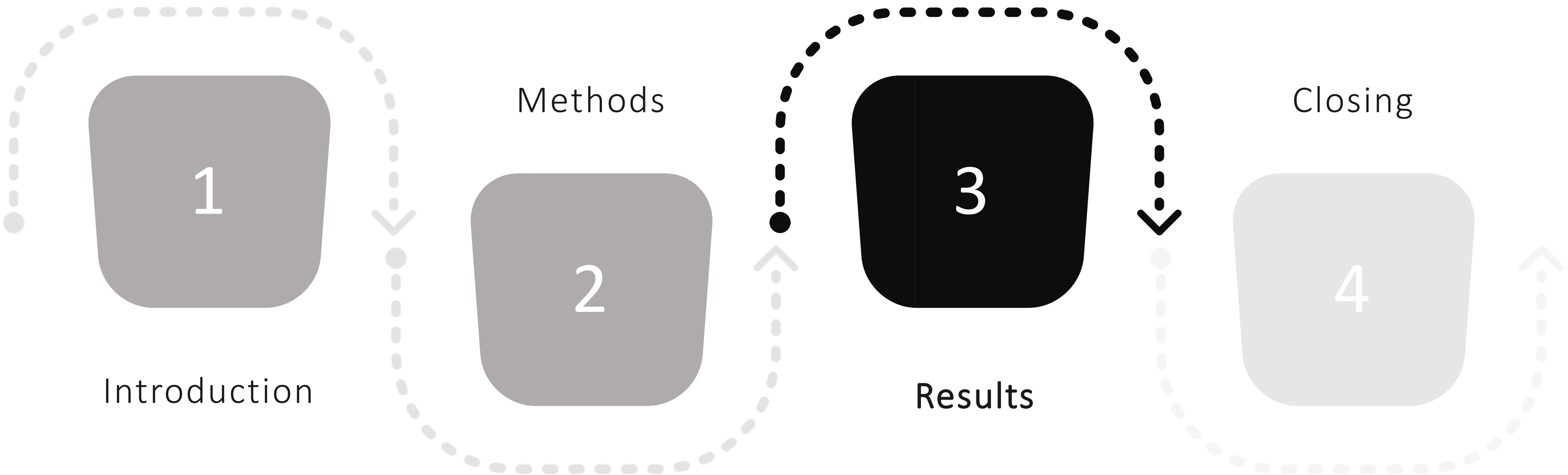
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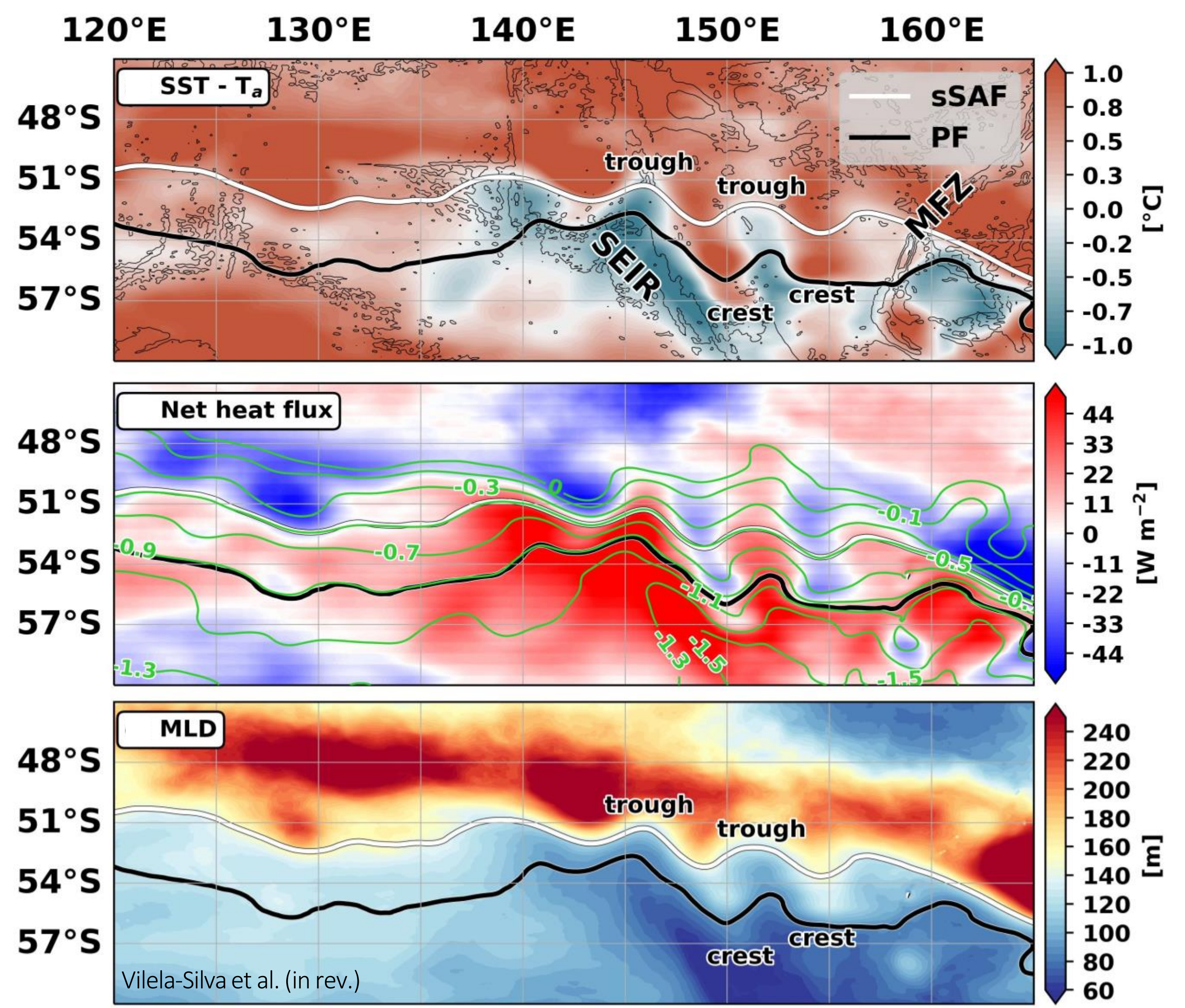
The Impact of the Macquarie Meander on

Thermodynamics



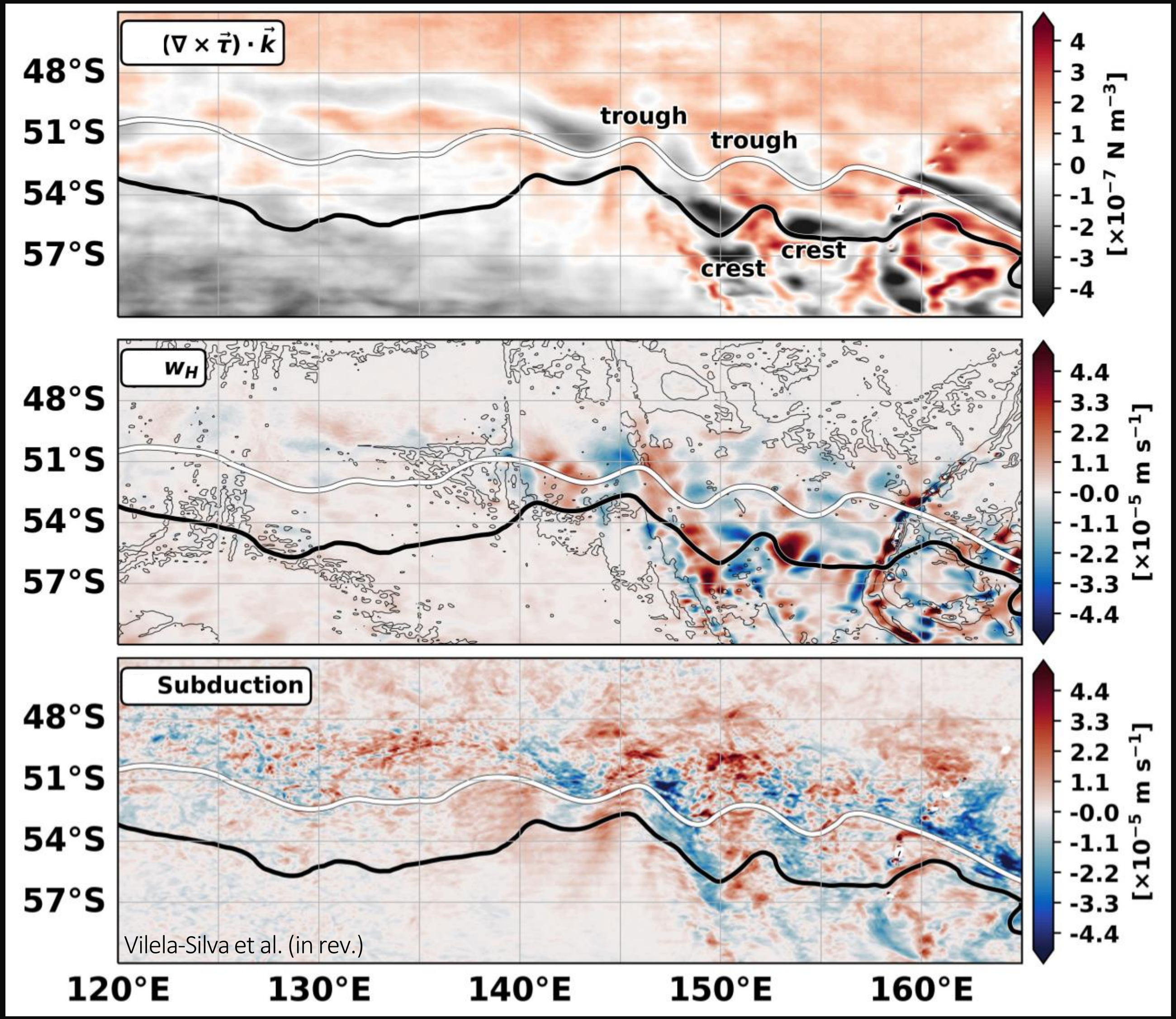
- Wave-like signal of **trough-crest-trough-crest** for the **air-sea temperature anomaly**, **surface net heat flux**, and **mixed layer depth** at the Macquarie Meander region;

- Positive and negative air-sea temperature anomaly at the crests and troughs, respectively;

- **Heat loss by the ocean at the crests** and heat gain by the ocean at the troughs;
  - Poleward displacement of warm sSAF waters at the crests to a region of cold atmosphere → heat loss by the ocean.

- Heat loss leads to buoyancy loss (or density gain) which causes the deepening of the MLD;
  - The **MLD is deeper at the crests** where the ocean loses heat and **shallower at the troughs** where the ocean gains heat.

Circulation



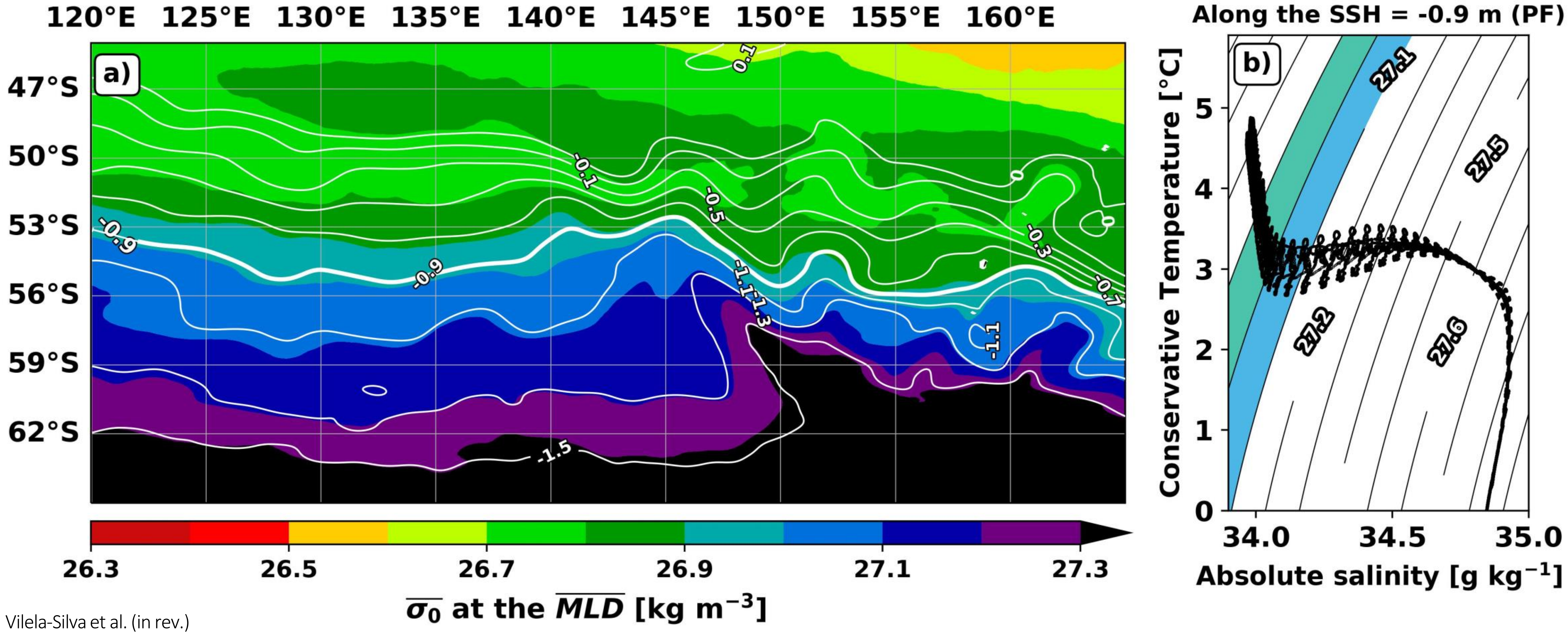
- Wave-like signal of **trough-crest-trough-crest** for the **wind-stress curl**, **vertical velocities at the MLD**, and **water subduction** at the Macquarie Meander region;

- The rotation of the flow at the crests and troughs returns **strong wind stress curl** at the crests and troughs of the meander;

- The centre of the meander's troughs and crests splits into regions of **upwelling** (w>0) and **downwelling**.
  - W is much higher at the Macquarie Meander than upstream.

- The Macquarie Meander is a place where a significant rate of water obduction and **water subduction (S > 0) extend to the PF waters**.

Along-stream variability of air-sea heat fluxes and subduction



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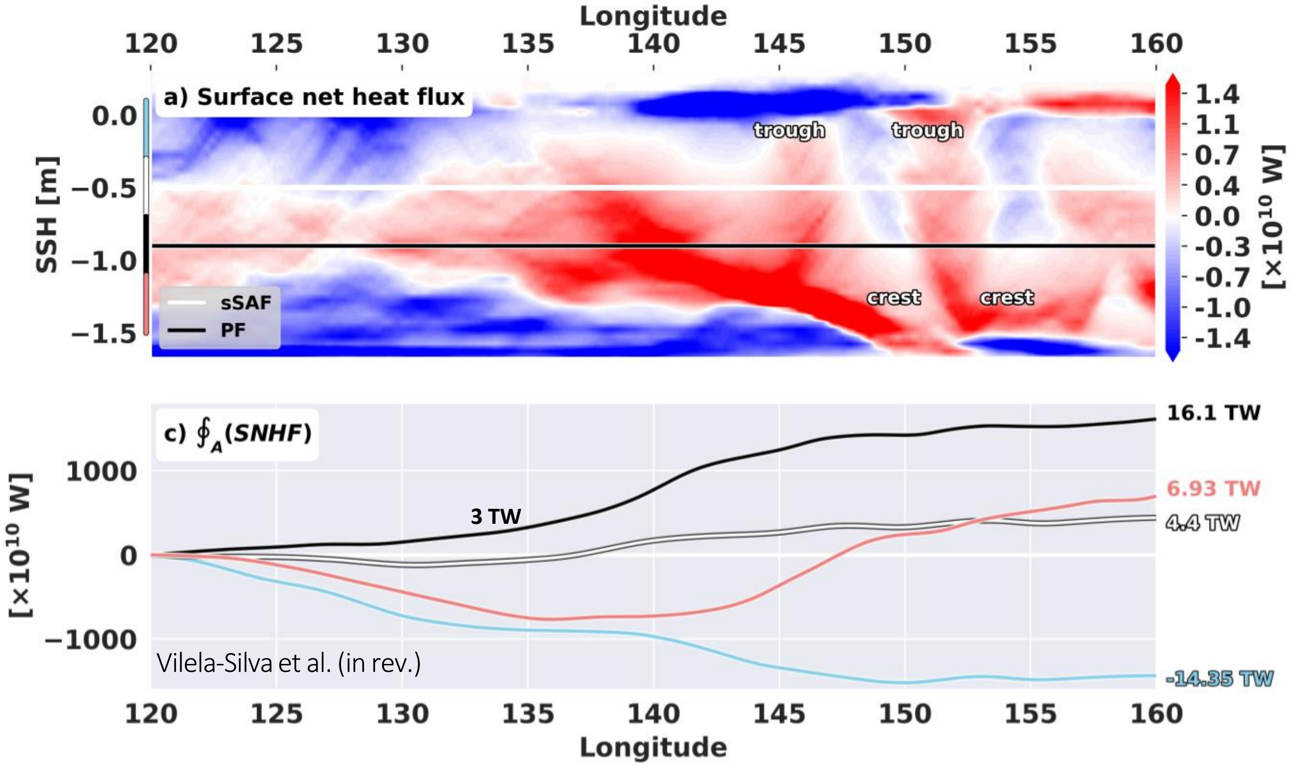
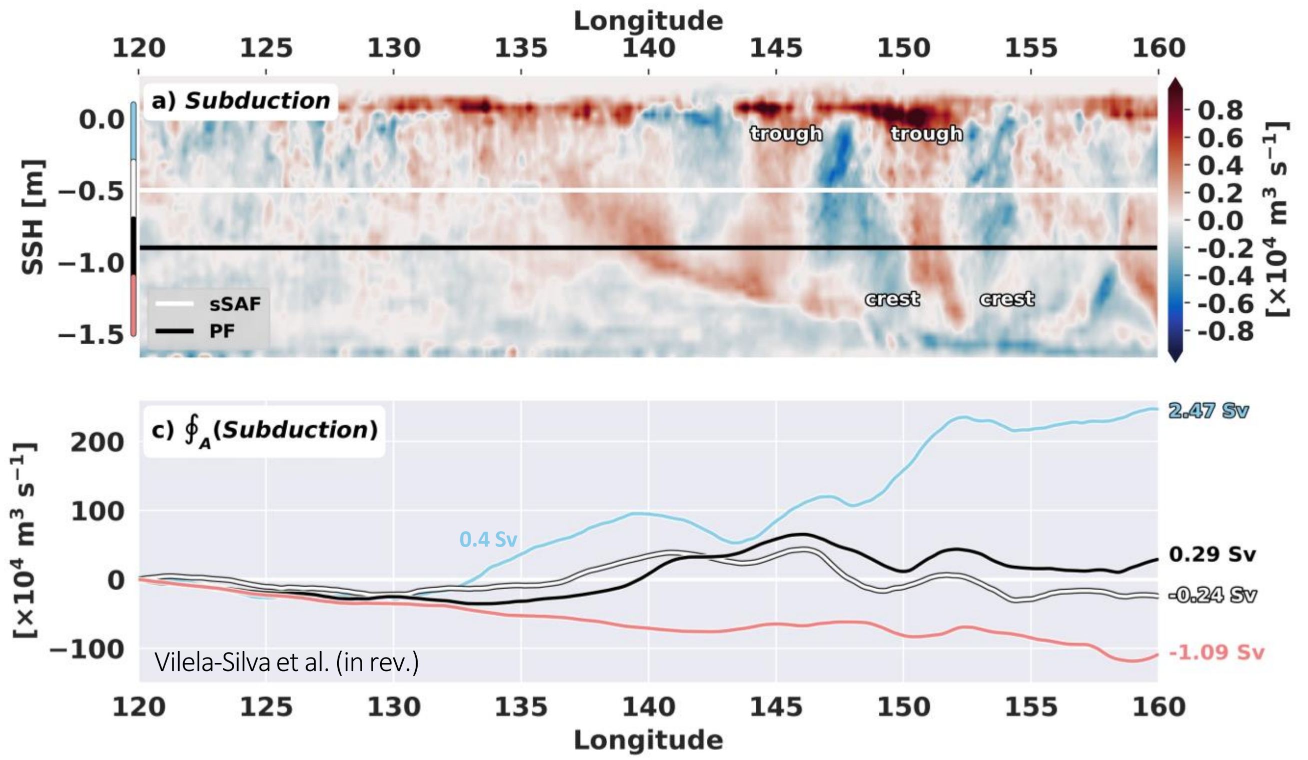
Air-Sea Heat Fluxes



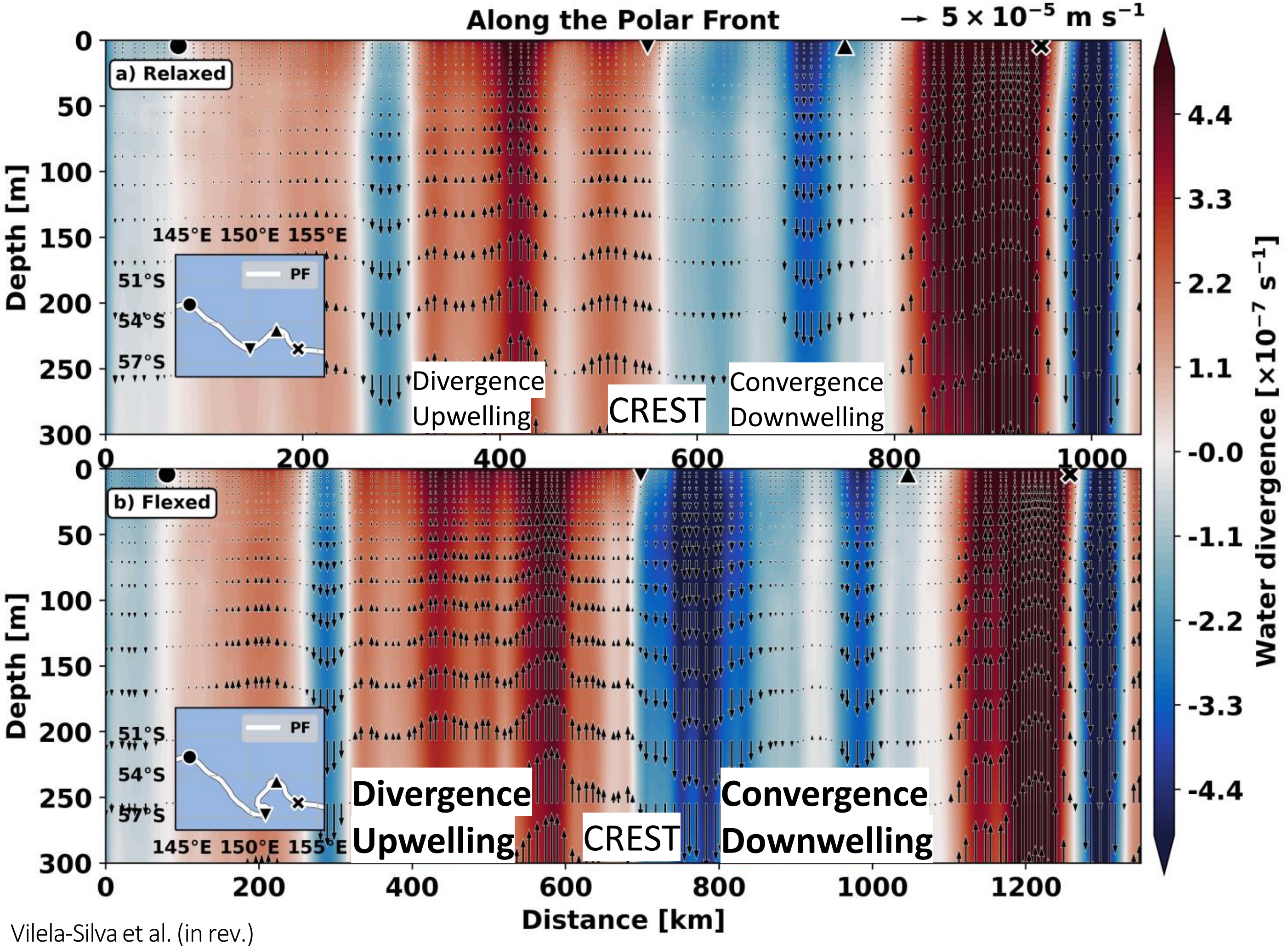
- We present the **surface net heat fluxes along SSH contours** to diagnose along the stream coordinates. The SSH contours approximate to water mass boundaries and fronts since SSH values are related to density classes (Sokolov & Rintoul, 2007).
- The **heat gain by the ocean extends from the denser to lighter density classes** at the centre of the meander's troughs. Conversely, the heat loss by the ocean extends from lighter to denser density classes at the crests.
- The integrated **heat flux along the PF increases in 13 TW** from the upstream to the downstream of the meander;

Water Subduction



- Subduction crosses more SSH contours (or density classes) downstream of 135°E where the fronts meander.
- The accumulated **subduction at the SAF region increases in 2 Sv** when comparing the subduction upstream (at 135E) and downstream of the meander (160E).
- The **PF region** changes the regime of accumulated obduction upstream of the meander to accumulated subduction downstream of the meander.

The Subsurface Impact of Flexing the PF Meander



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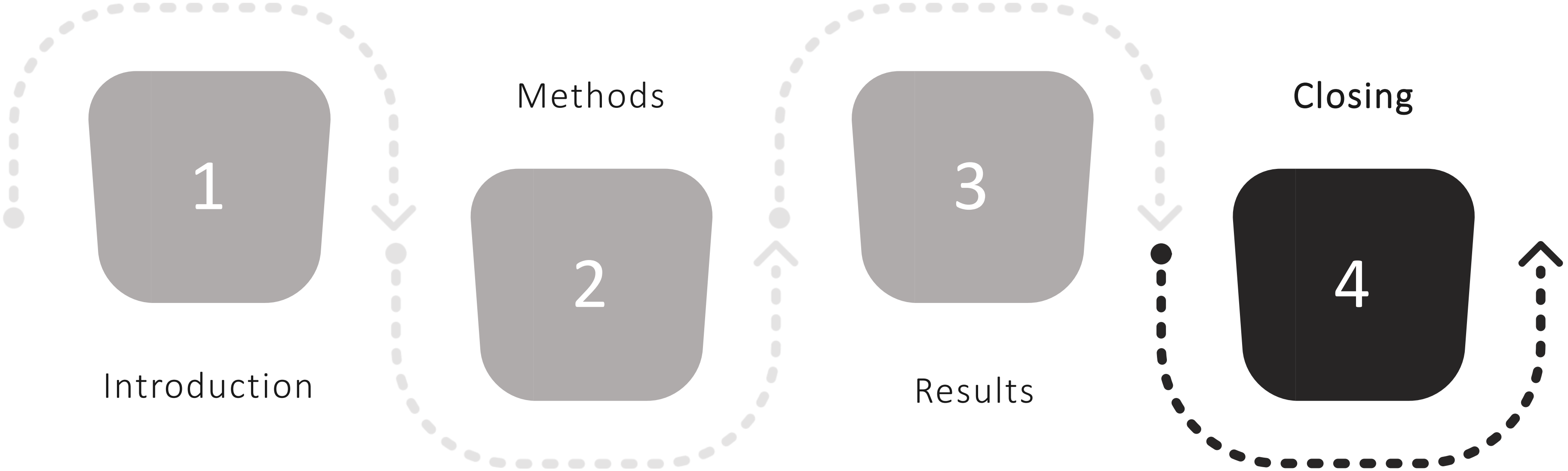
- The **meander's curvature** leads to **more water divergence** and upwelling at the entering of crests along the PF meander as well as reported for the SAF meander (Meijer et al., 2022);

- The comparison between the relaxed (top) and flexed (bottom) meander composites shows the link between the **meander flexing** with the **water divergence** and **vertical velocities**.

- As a consequence for the enhanced water divergence, the **vertical velocities are faster** at the **flexed meander** (as hypothesized by Thompson and Naveira Garabato, 2014).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Conclusions

1 **Meanders Enhance Air-Sea Heat Fluxes**

The crest of the meander hosts surface heat loss

by the ocean and deep mixed layers.

The opposite occurs at the trough.

2 **Meanders Extend Water Subduction from the SAF zone to high latitudes**

Water subducted along SSH contours of

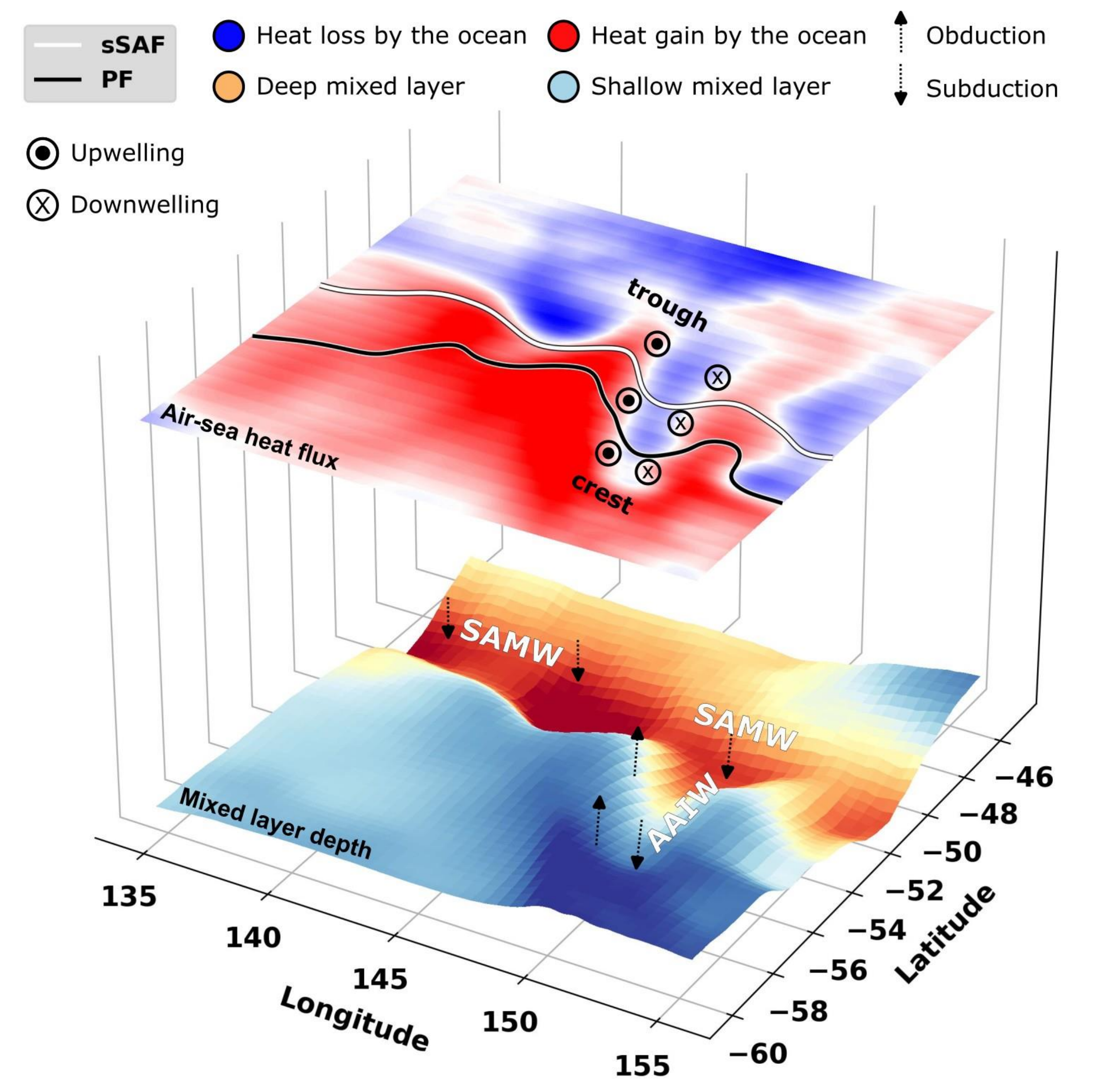
denser waters might be related to the AAIW formation.

3 **Meander Flexing Leads to Enhanced W**

The increase in the meander's curvature enhance the

water divergence leading to faster vertical velocities

in meanders (as hypothesized by Thompson and Naveira Garabato, 2014).



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Conclusions

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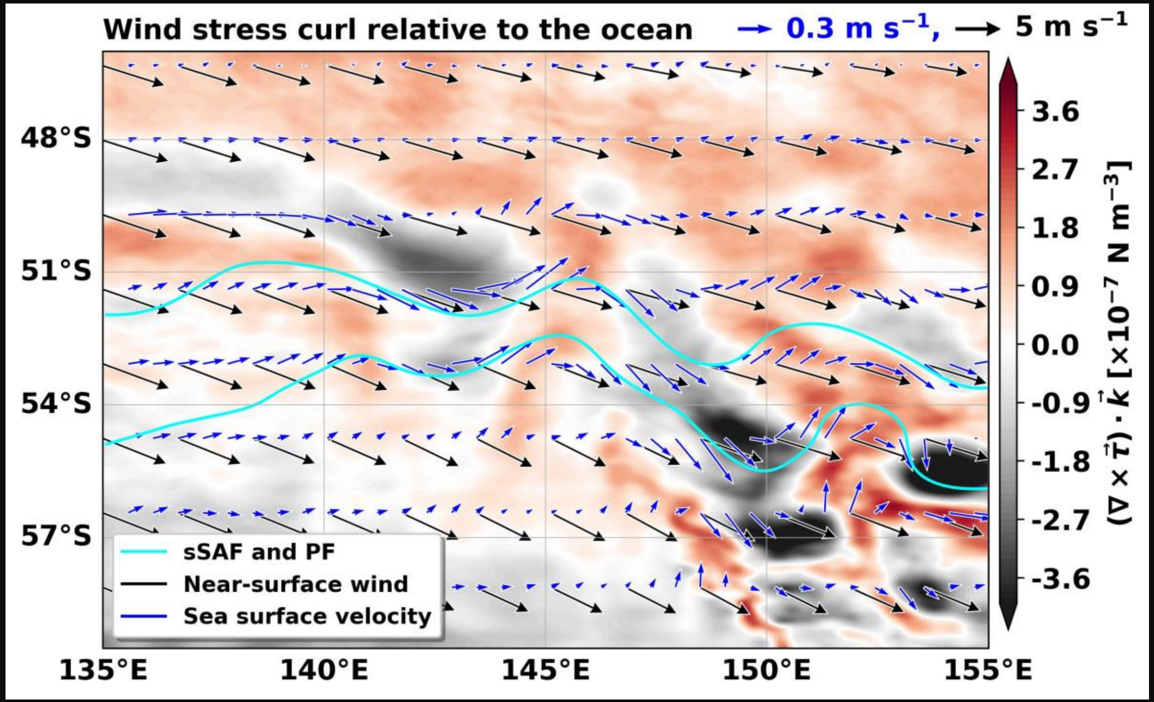
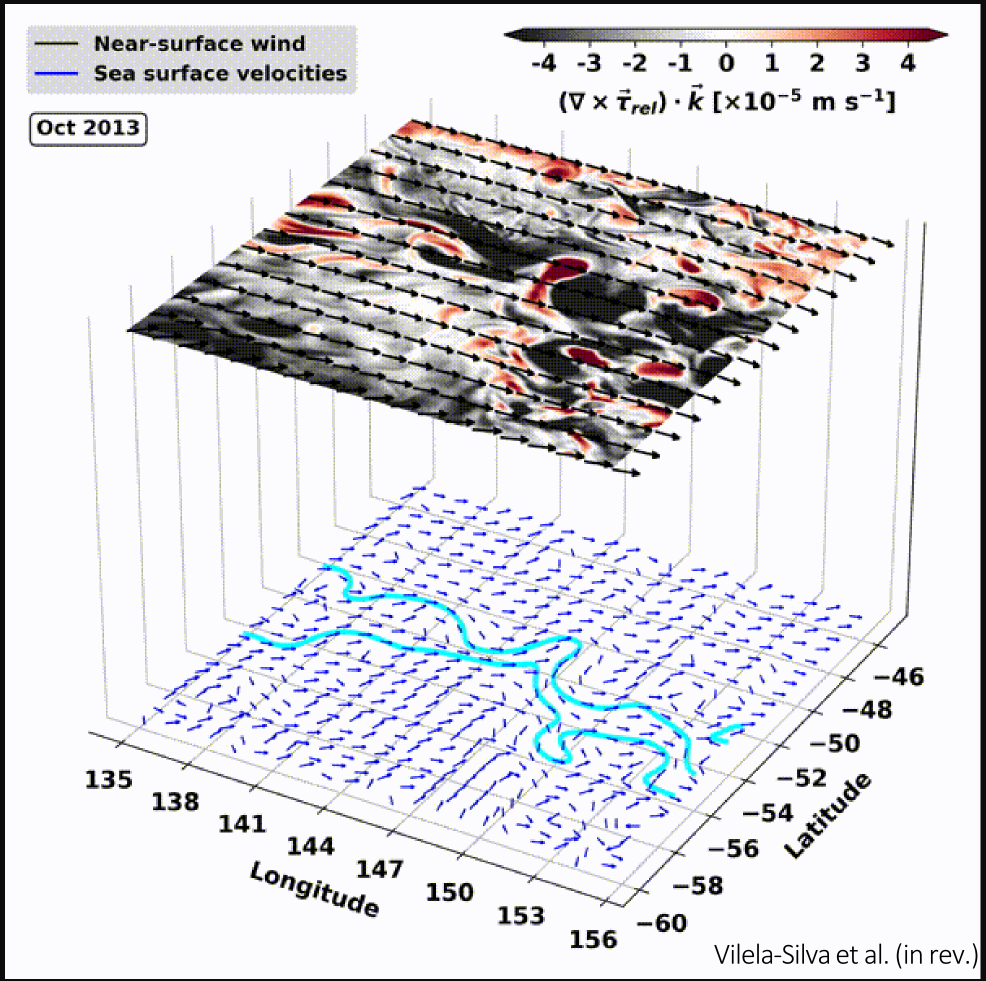
Meanders can locally force the atmosphere

➢ The meander also imprints its signal in the wind stress curl relative to the ocean.





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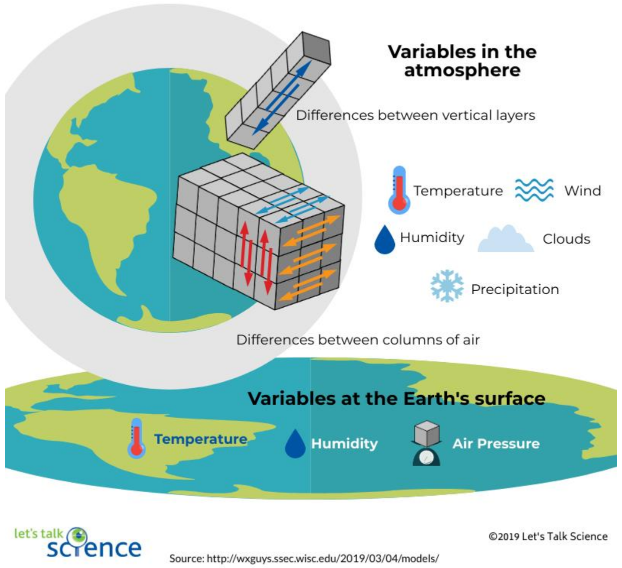
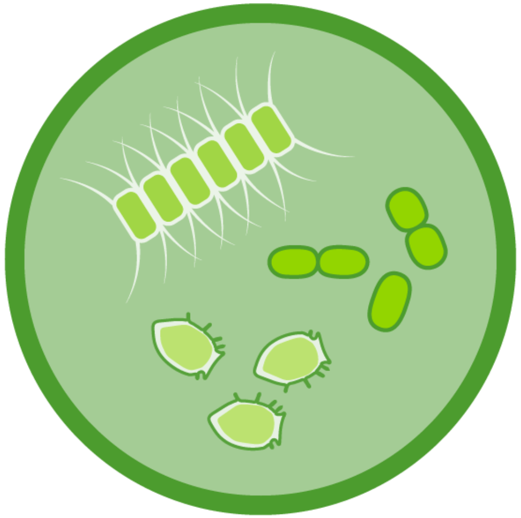
Potential Consequences of the SO meanders

Weather Forecast Models



Resolving meander patterns (or fine scale) in weather forecast models could increase the weather predictability downstream.

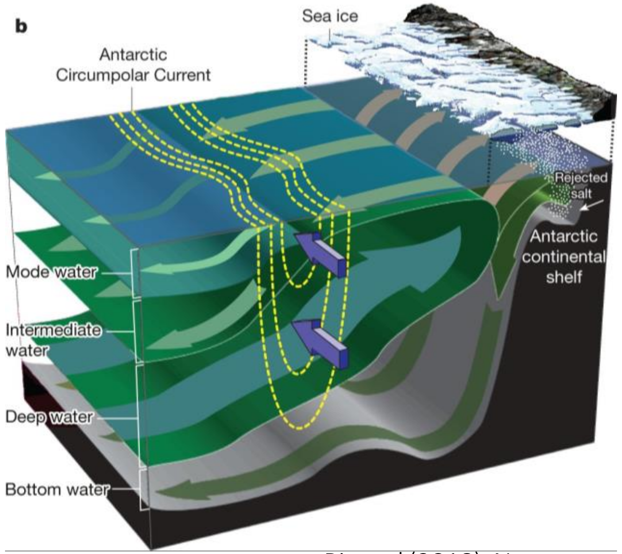
Chl-a distribution



ecowatch.noaa

The meandering of the fronts deform the MLD and enhance vert vel. Biological production increases where nutrients are fluxed from the thermocline into the mixed layer.

Water Mass Formation



Rintoul (2018), Nature

Implications of meanders for water mass formation (e.g., SAMW and AAIW), carbon sequestration, and ventilation of the ocean interior.

Let’s talk about meanders!

Email: felipe.dasilva@utas.edu.au


Felipe Vilela-Silva

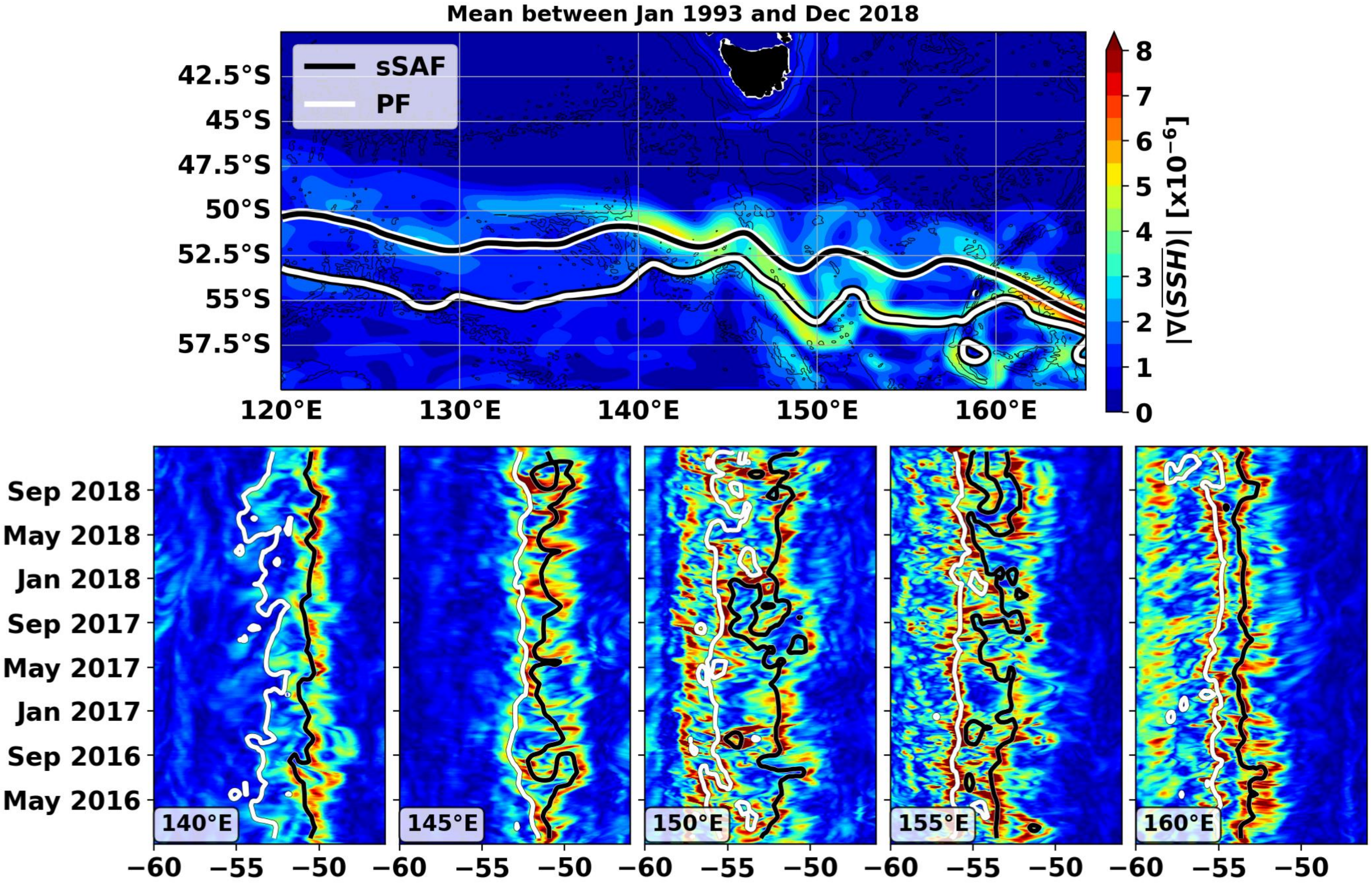

Nathan L. Bindoff


Helen E. Phillips


Steve R. Rintoul


Max Nikurashin

Extras



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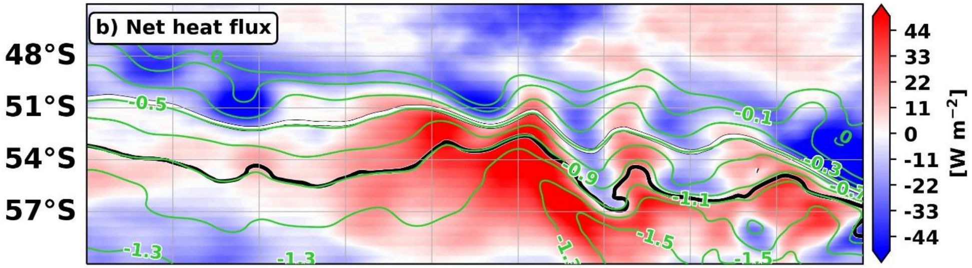
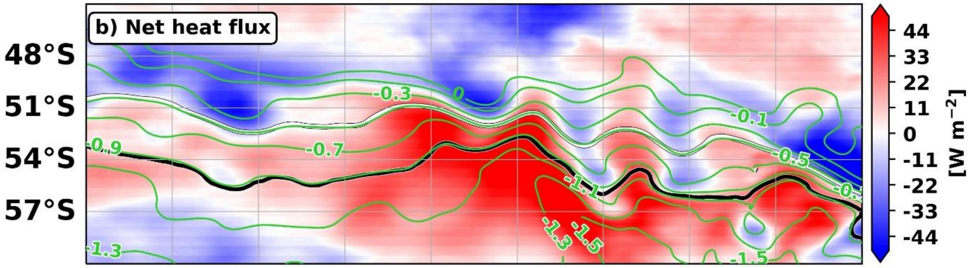
Extras

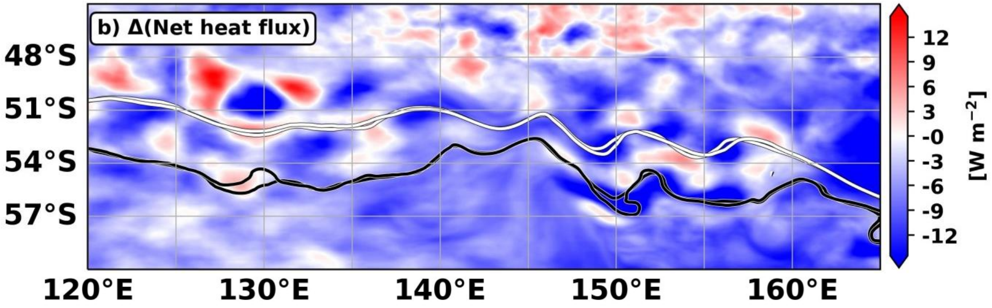
Flexed composite



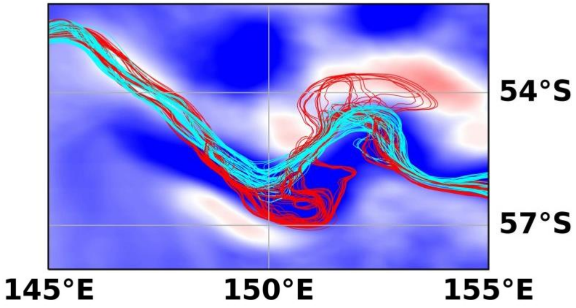
Relaxed composite



Flexed - Relaxed



Zoom at the Macquarie Meander



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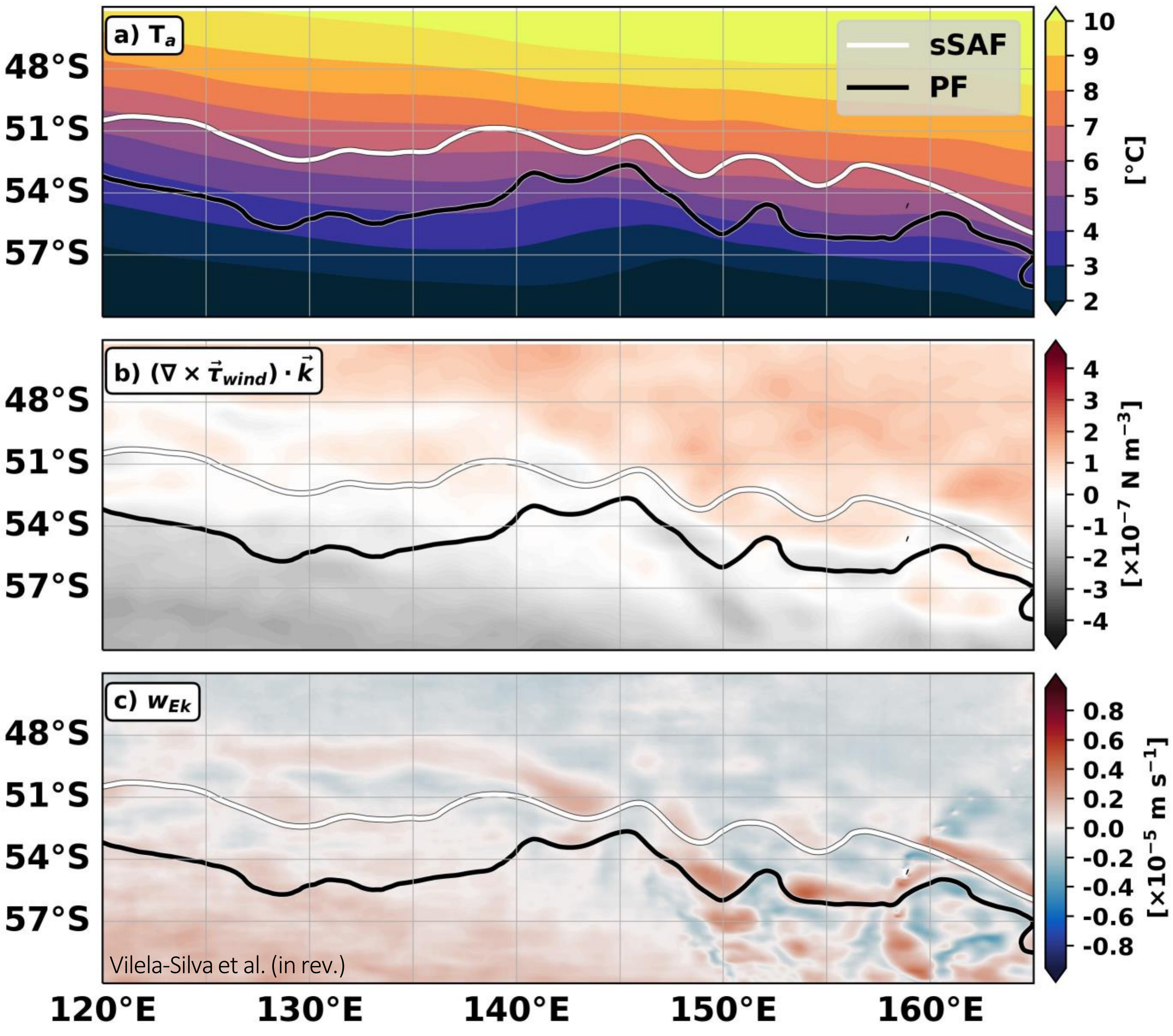

a) T_a
sSAF
PF
[°C]
b) $(\nabla \times \vec{\tau}_{wind}) \cdot \vec{k}$
[$\times 10^{-7}$ N m^{-3}]
c) w_{Ek}
[$\times 10^{-5}$ m s^{-1}]
48°S
51°S
54°S
57°S
120°E
130°E
140°E
150°E
160°E
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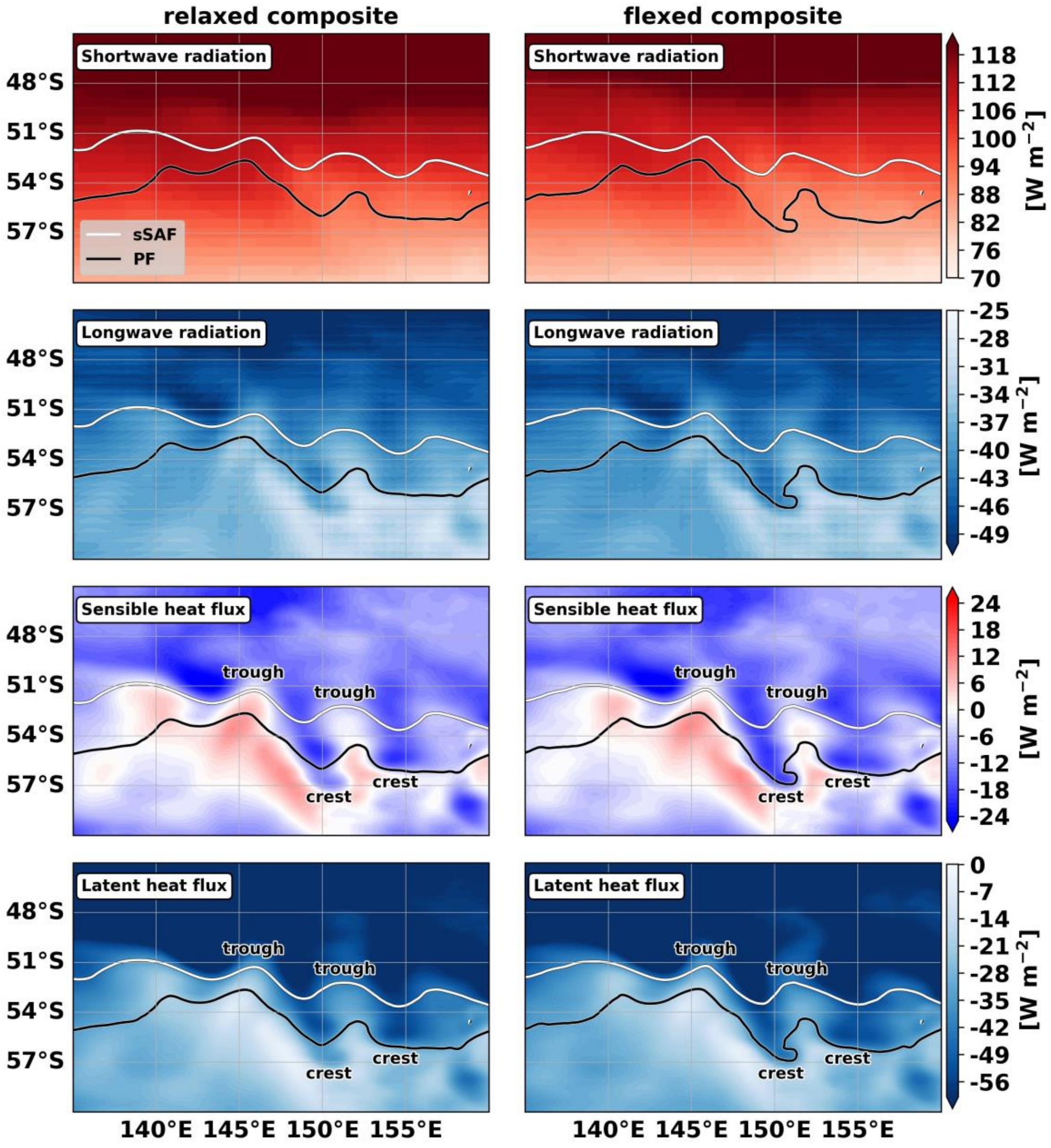
Extras



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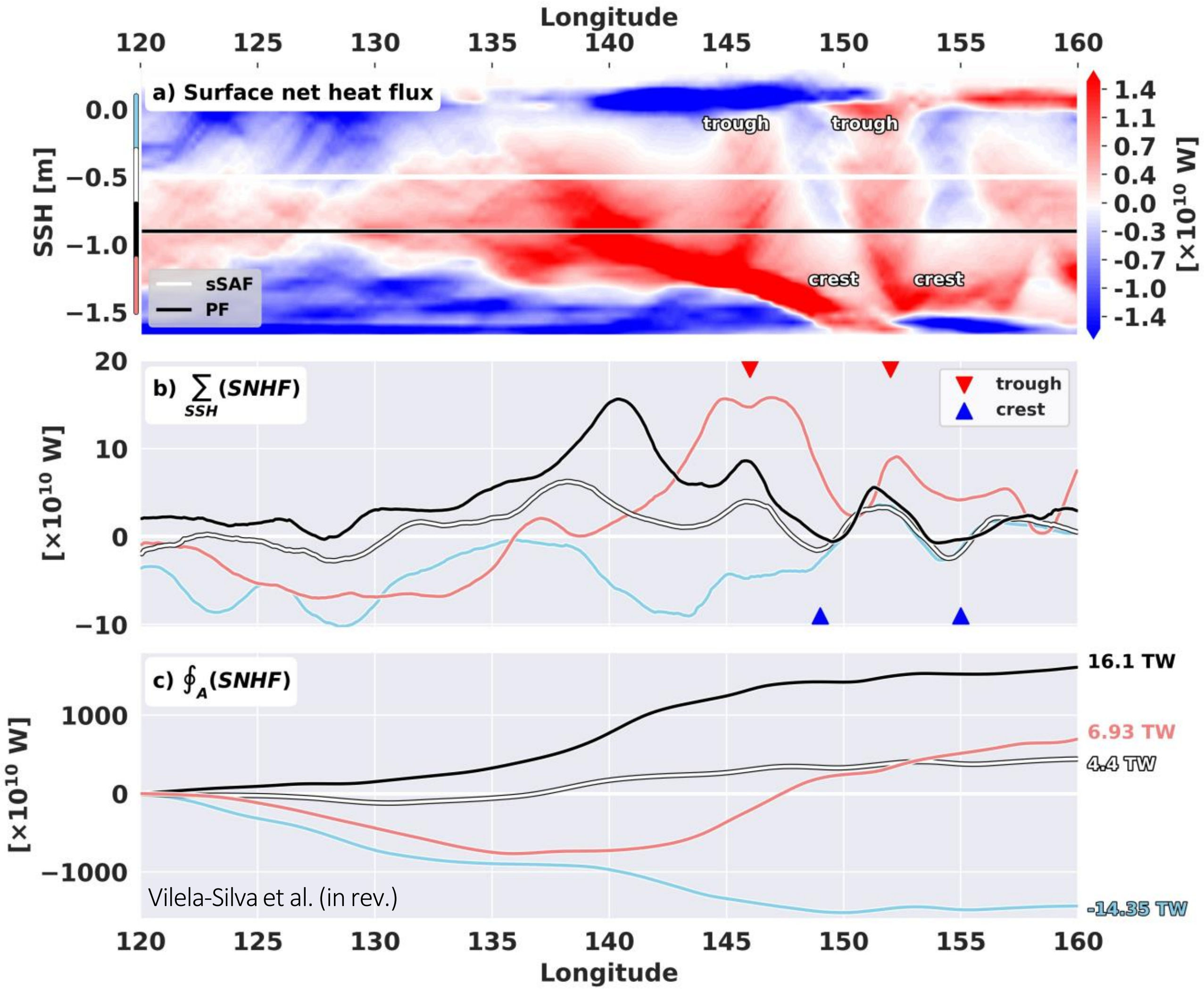

Longitude
a) Surface net heat flux
trough
trough
crest
crest
sSAF
PF
SSH [m]
[×10¹⁰ W]
b) $\sum_{SSH}(SNHF)$
trough
crest
c) $\oint_A(SNHF)$
16.1 TW
6.93 TW
4.4 TW
-14.35 TW
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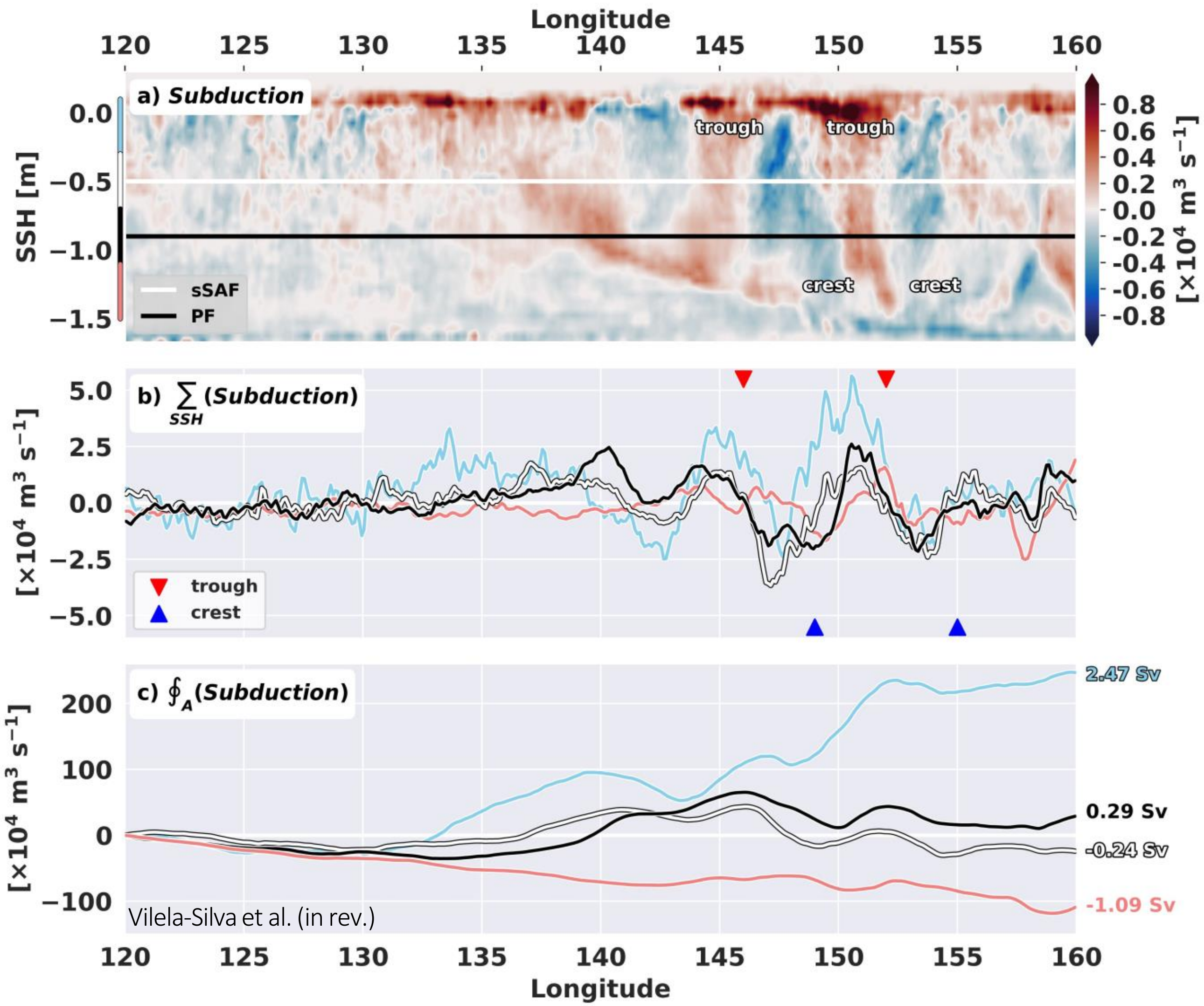
Extras



Longitude
120
125
130
135
140
145
150
155
160
a) Subduction
trough
trough
crest
crest
sSAF
PF
SSH [m]
0.0
−0.5
−1.0
−1.5
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
[×10⁴ m³ s⁻¹]
b) ∑SSH (Subduction)
5.0
2.5
0.0
−2.5
−5.0
trough
crest
c) ∮A (Subduction)
200
100
0
−100
2.47 Sv
0.29 Sv
-0.24 Sv
-1.09 Sv
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