

How does heat flux affect large scale stratification?

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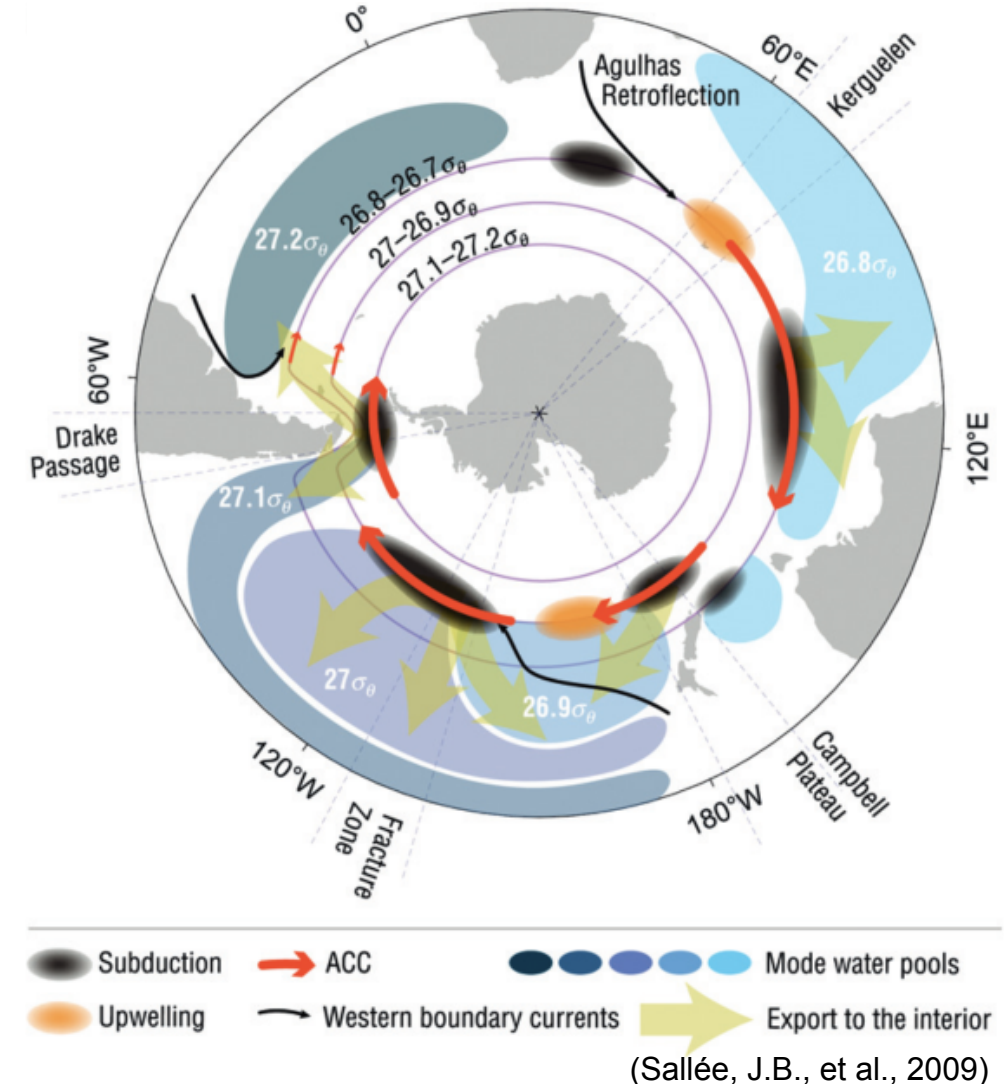


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1. Mode water formation regions are important areas for the uptake of heat and carbon.

- The motivation behind this work is to understand what controls the ventilation and subduction of mode water formation sites.
- Potential vorticity (PV) in these regions affects the subduction and ventilation rate, with consequences for the uptake of heat and carbon.



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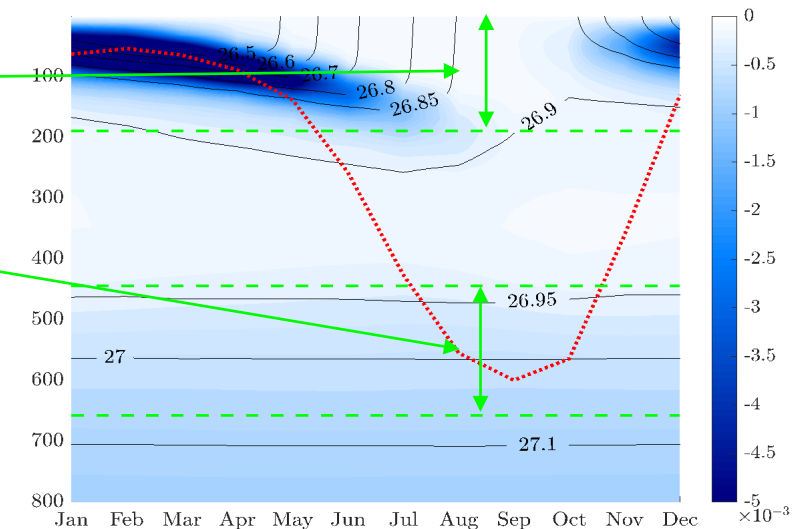
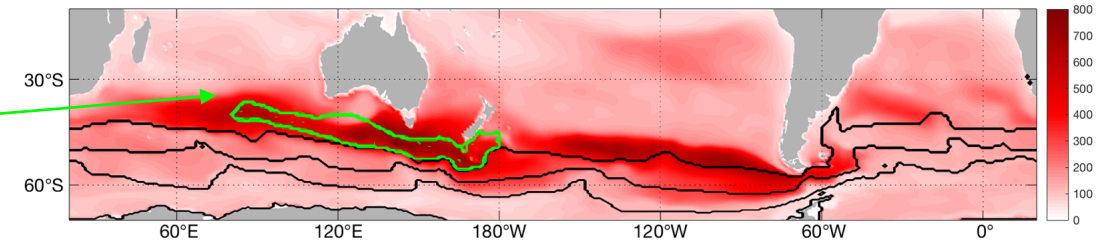


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2. Adjoint sensitivity experiments were used to understand large scale stratification in the South Indian Ocean.

- Firstly a known mode water formation site in the south Indian Ocean was identified using the characteristics of low absolute PV/stratification and deep winter mixed layers.
- Next two depth horizons were found using mixed layer depth, stratification, and neutral density. The upper depth covers the area from the surface to the depth where low absolute stratification is in the water column. The lower depth captures the seasonal ventilation cycle.



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3. The results from four separate adjoint sensitivity experiments are put together for the overall sensitivity of PV to heat flux.

- Adjoint sensitivity experiments were conducted in ECCOv4r2.
- Four separate adjoint experiments were completed using different objective functions:
 1. Mean annual potential temperature integrated over the upper depth and South Indian Ocean horizontal area.
 2. Mean annual potential temperature integrated over the lower depth and South Indian Ocean horizontal area.
 3. Mean annual salinity integrated over the upper depth and South Indian Ocean horizontal area.
 4. Mean annual salinity integrated over the lower depth and South Indian Ocean horizontal area.
- The results, called sensitivities or partial derivatives, from these four adjoint experiments were then put together to find the overall sensitivity of large scale PV to heat flux.

$$\frac{\partial(PV)}{\partial \mathcal{H}} = \frac{f}{d_2 - d_1} \left(-\alpha \left(\frac{\partial \theta_1}{\partial \mathcal{H}} - \frac{\partial \theta_2}{\partial \mathcal{H}} \right) + \beta \left(\frac{\partial S_1}{\partial \mathcal{H}} - \frac{\partial S_2}{\partial \mathcal{H}} \right) \right)$$

1. 2. 3. 4.

Lower depth Upper depth

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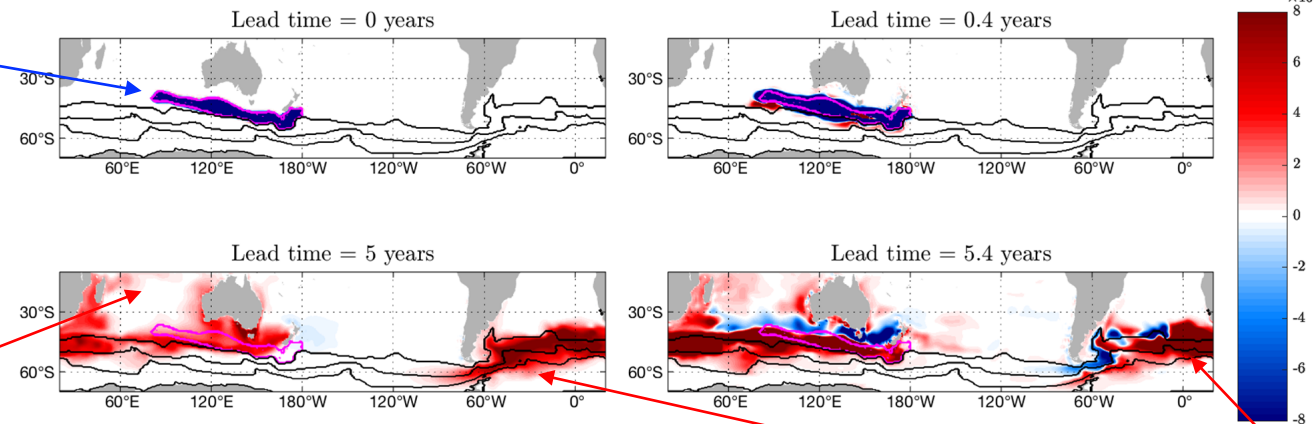


4. Snapshots of the sensitivity of PV to heat flux reveal a sign flip in the sensitivities.

If there is heat loss from the ocean (a **positive anomaly**) then;

- Areas of **negative sensitivity** indicate a **decrease** in PV.
- Areas of **positive sensitivity** indicate an **increase** in PV.

Negative local sensitivity consistent with local convection.



Positive remote northern sensitivity consistent with an atmospheric response.

Positive local and remote sensitivity consistent with advection.

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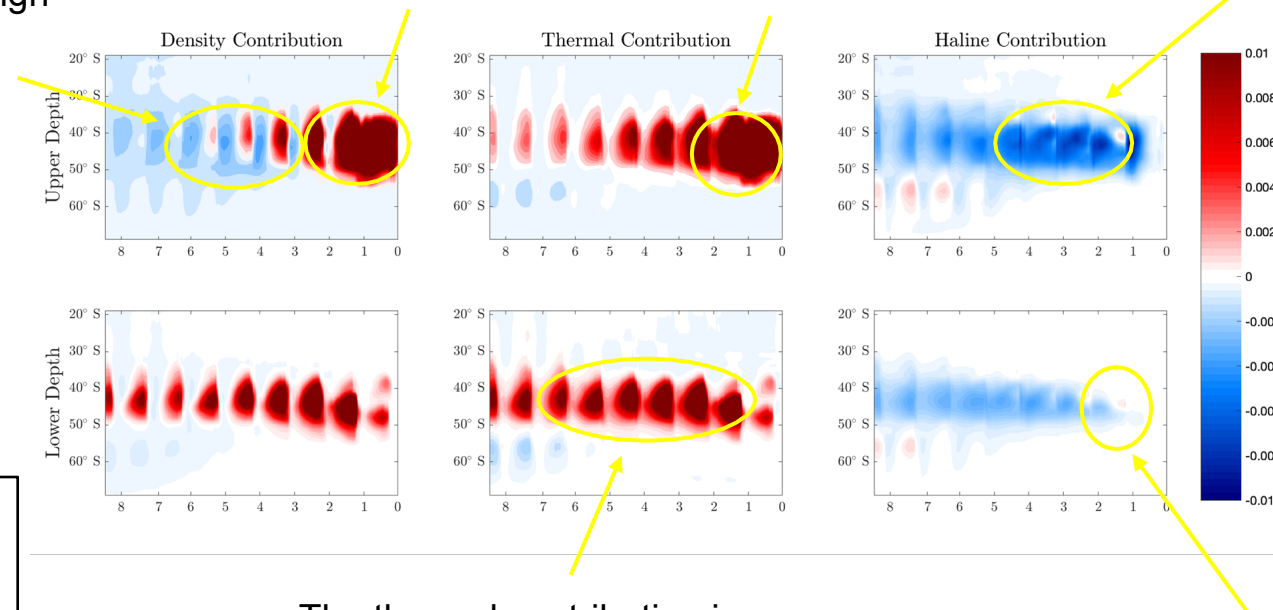
5. Splitting the sensitivities into the separate contributions; density, thermal, and haline, helps to explain why a sign flip takes place over time.

At 0 - 2 years lag density at the upper depth is dominant.

Over the first 2 years the thermal contribution is strongest.

After 2 years the haline contribution compensates and exceeds thermal contribution.

After 3 years lag there is a sign flip in the sensitivities.



- Over the first two years local surface heat loss acts to reduce stratification.
- After 2 years entrainment of cold, fresh water leads to the damping out of the potential temperature anomaly.

The thermal contribution is dominant at most times at the lower depth.

The haline contribution is very weak from 0 – 2 years lag.

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5. Confirmation of adjoint theory with forward perturbation experiments.

- Forward perturbation experiments were conducted in areas of strong adjoint sensitivity before and after the sign flip in adjoint sensitivities to try to confirm the results of the adjoint sensitivity experiments.
- Over 1 year it can be seen that salinity has more affect later in time and also this effect is deeper.
- After June 2008 in the years following the initial perturbation, it can be seen that fresher saltier water is entrained into the upper levels of the water column.
- These results help to confirm the linear theory from the adjoint sensitivity experiments.

