ORCHESTRA
OCEAN • CLIMATE • CARBON

British Antarctic Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

EGU European Geosciences Union

The sensitivity of Southeast Pacific heat content to changes in ocean structure



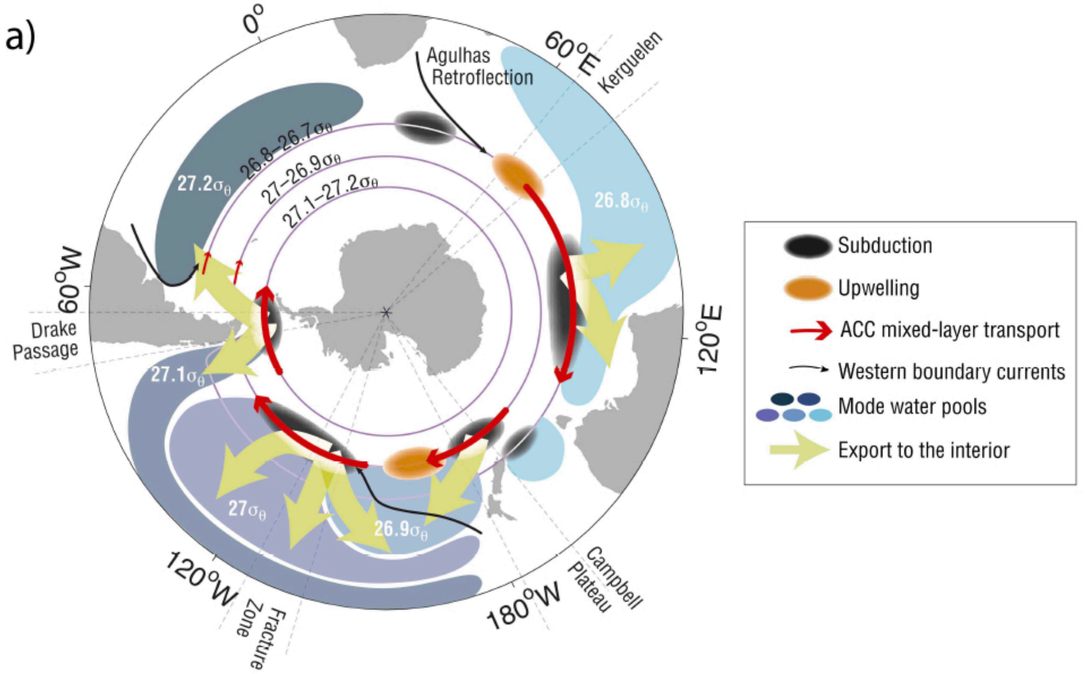
Dan Jones
UKRI Future Leaders Fellow
British Antarctic Survey (BAS)

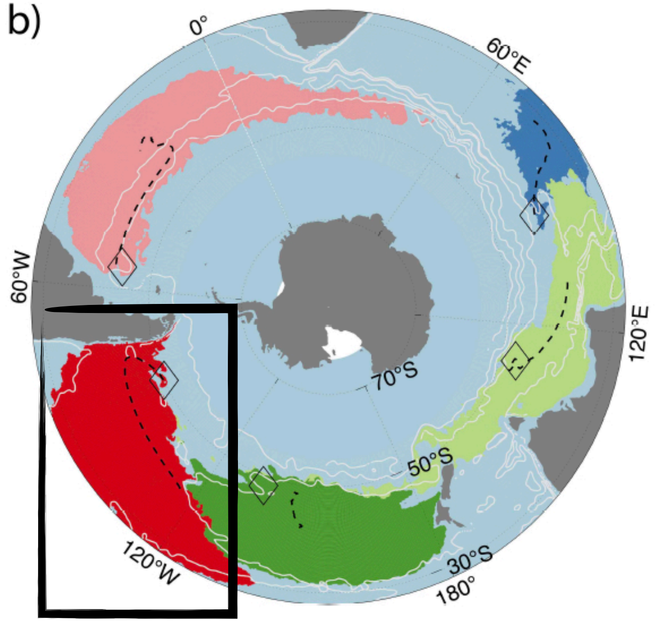
DanJonesOcean.com
@DanJonesOcean
github.com/DanJonesOcean

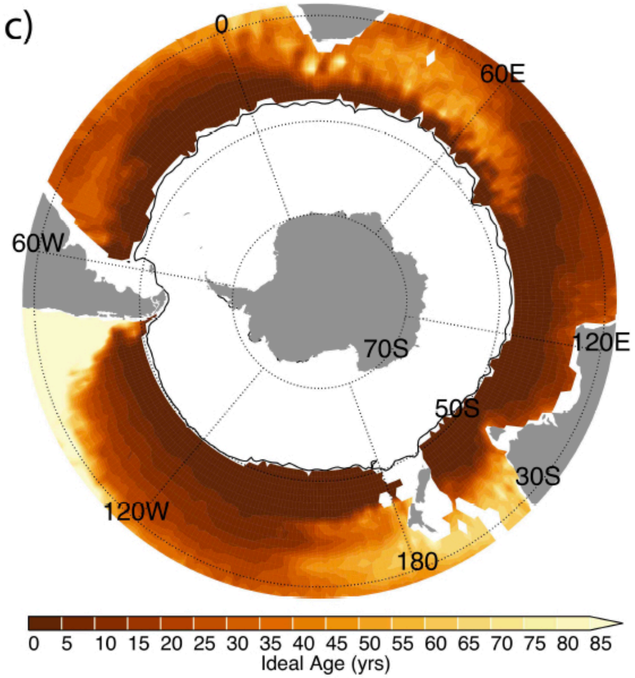
Collaborators: Emma Boland (BAS), Andrew Meijers (BAS), Gael Forget (MIT), Simon Josey (NOC), Ciara Pimm (U. Liverpool), J.-B. Sallée (L'OCEAN), Emily Shuckburgh (Cambridge Zero)

The Southern Ocean features localised subduction hotspots and a variety of ventilation pathways

The Southeast Pacific pathway is an especially rapid ventilation pathway, as measured by numerical tracer release experiments







Sallee et al. (JPO, 2010)

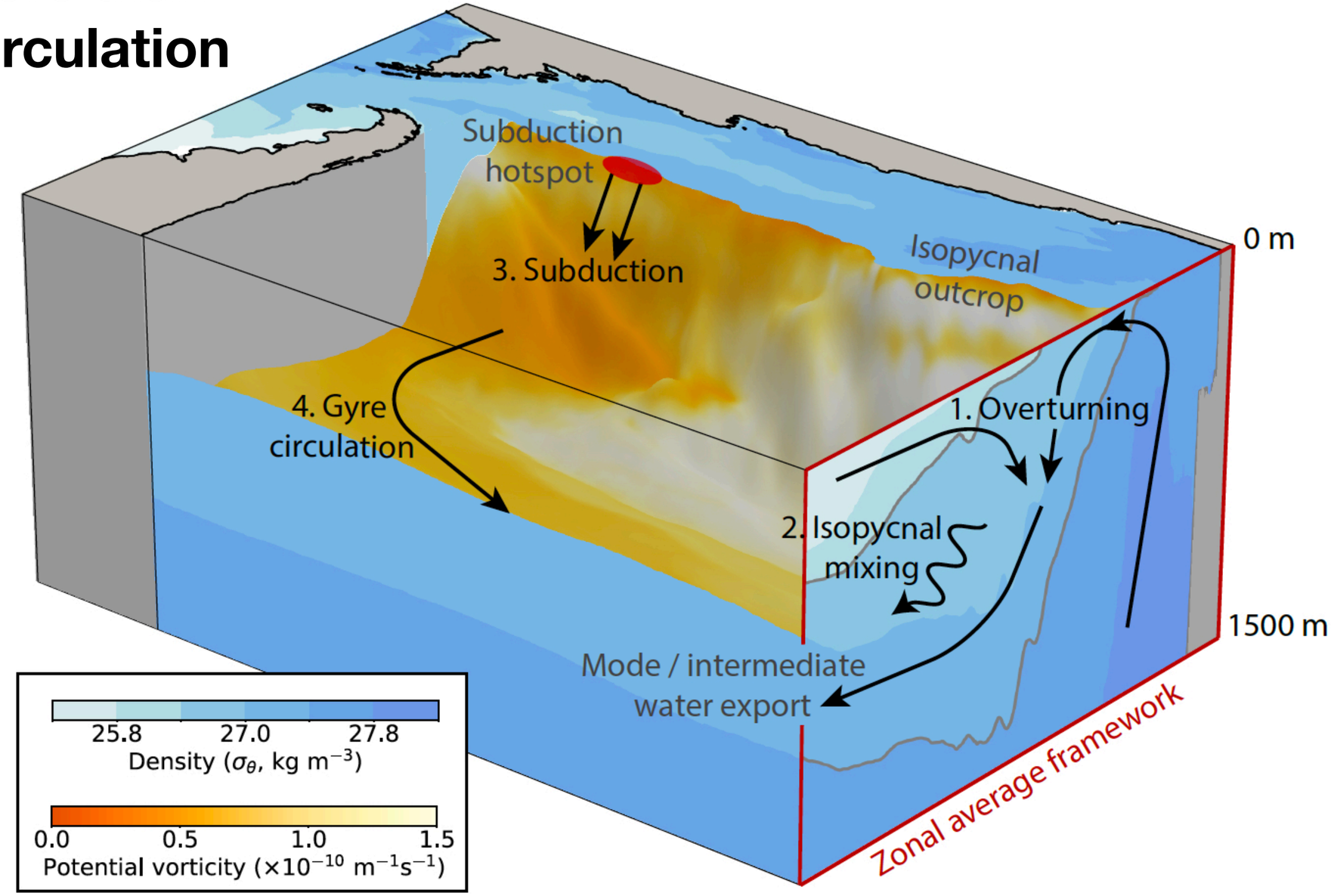
Jones et al. (JGR-Oceans, 2016)

Morrison et al. (submitted)

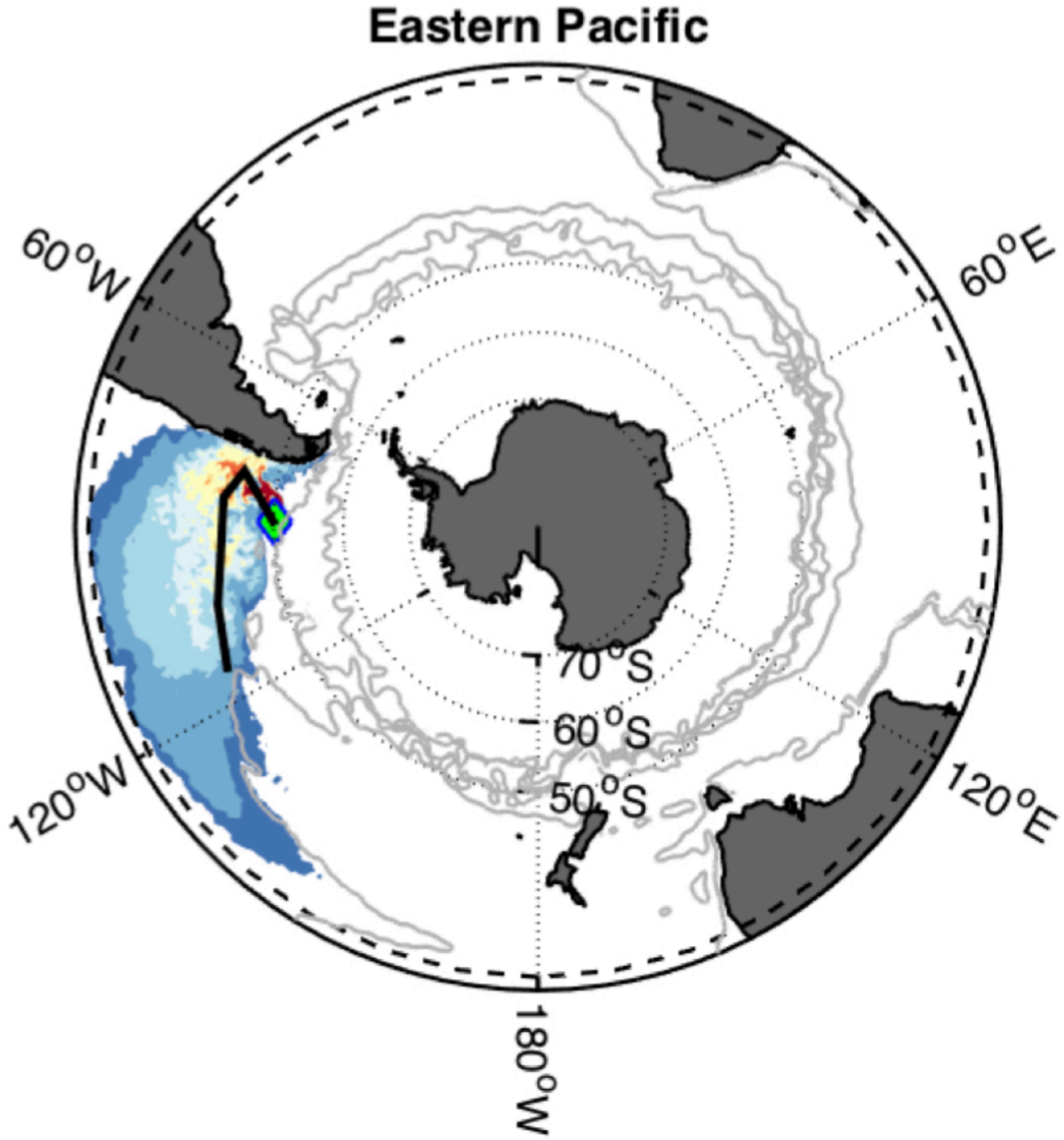
Ventilation is about more than just the overturning circulation

More generally, all of these processes are important:

1. Overturning
2. Isopycnal mixing
3. Subduction
4. Gyre circulation



Morrison et al. (submitted)



Jones et al. (JGR-Oceans, 2016)

Numerical tracer experiments reveal the patterns and timescales of ventilation

But how sensitive is the recently ventilated interior to changes in ocean properties or surface forcing?

To address this question, we will use *adjoint modelling*



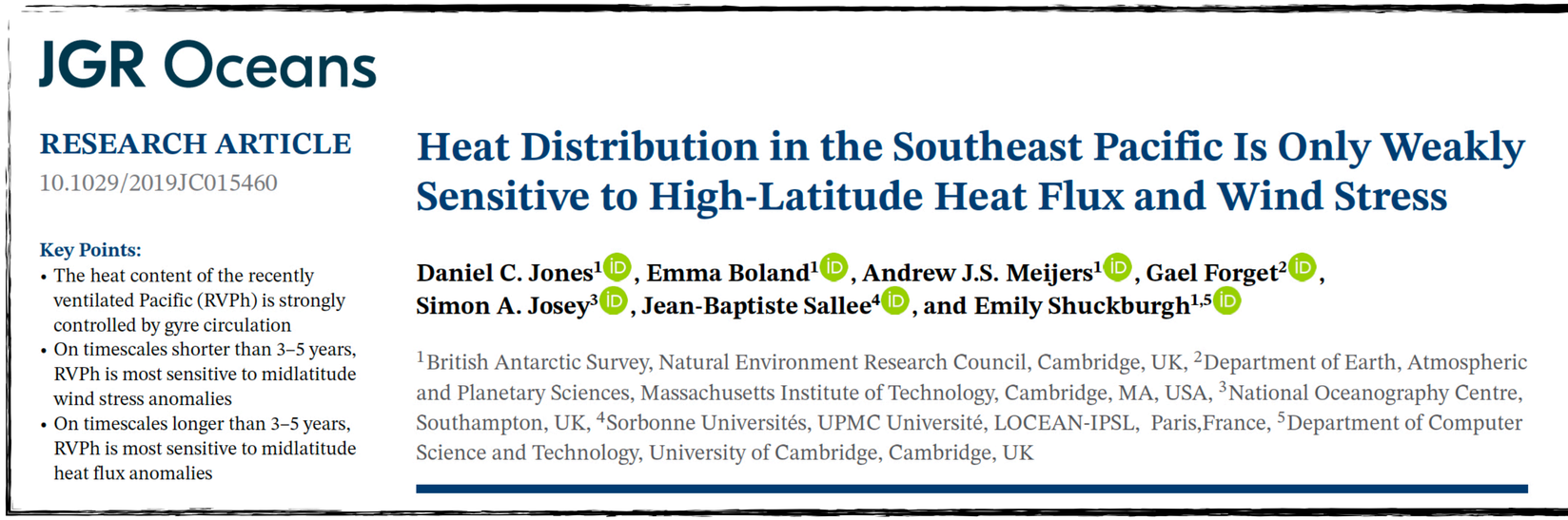
An adjoint model is a tool for
sensitivity analysis.

All other applications derive from
sensitivity analysis.

Errico (BAMS, 1997)

For more info:
a trio of Southern Ocean adjoint sensitivity papers in ECCOv4

(Images are clickable links)



JGR Oceans

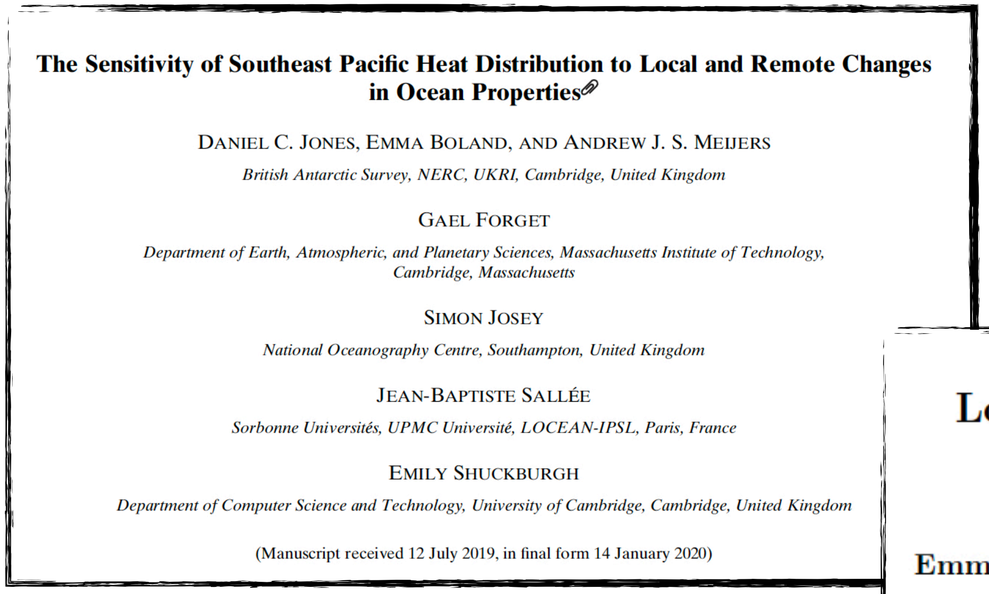
RESEARCH ARTICLE
10.1029/2019JC015460

Key Points:
- The heat content of the recently ventilated Pacific (RVPh) is strongly controlled by gyre circulation
- On timescales shorter than 3–5 years, RVPh is most sensitive to midlatitude wind stress anomalies
- On timescales longer than 3–5 years, RVPh is most sensitive to midlatitude heat flux anomalies

Heat Distribution in the Southeast Pacific Is Only Weakly Sensitive to High-Latitude Heat Flux and Wind Stress

Daniel C. Jones[1], Emma Boland[1], Andrew J.S. Meijers[1], Gael Forget[2], Simon A. Josey[3], Jean-Baptiste Sallee[4], and Emily Shuckburgh[1,5]

[1]British Antarctic Survey, Natural Environment Research Council, Cambridge, UK, [2]Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA, USA, [3]National Oceanography Centre, Southampton, UK, [4]Sorbonne Universités, UPMC Université, LOCEAN-IPSL, Paris,France, [5]Department of Computer Science and Technology, University of Cambridge, Cambridge, UK



The Sensitivity of Southeast Pacific Heat Distribution to Local and Remote Changes in Ocean Properties

DANIEL C. JONES, EMMA BOLAND, AND ANDREW J. S. MEIJERS
British Antarctic Survey, NERC, UKRI, Cambridge, United Kingdom

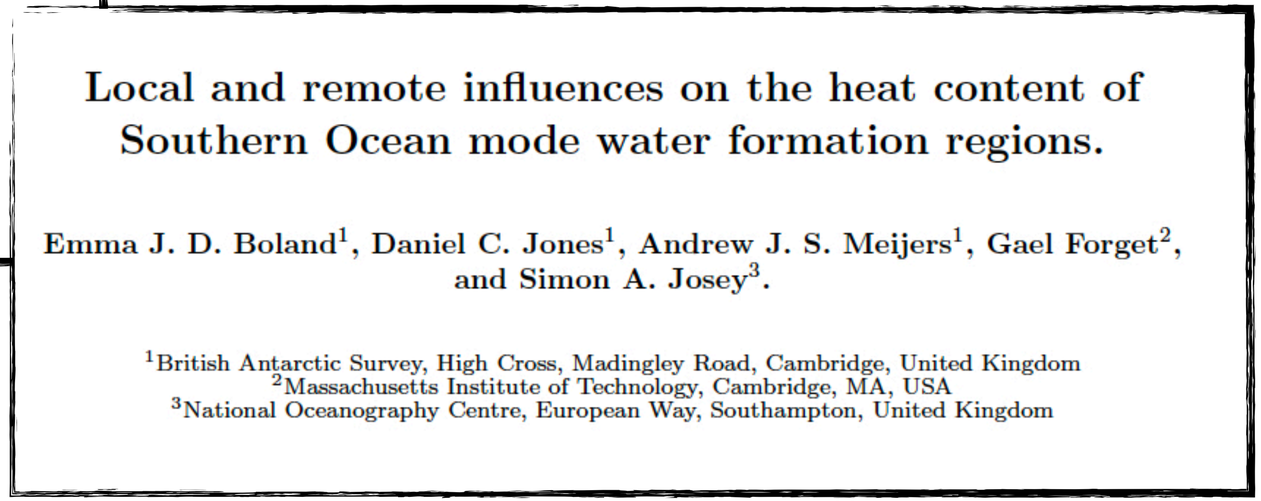
GAEL FORGET
Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, Massachusetts

SIMON JOSEY
National Oceanography Centre, Southampton, United Kingdom

JEAN-BAPTISTE SALLÉE
Sorbonne Universités, UPMC Université, LOCEAN-IPSL, Paris, France

EMILY SHUCKBURGH
Department of Computer Science and Technology, University of Cambridge, Cambridge, United Kingdom

(Manuscript received 12 July 2019, in final form 14 January 2020)



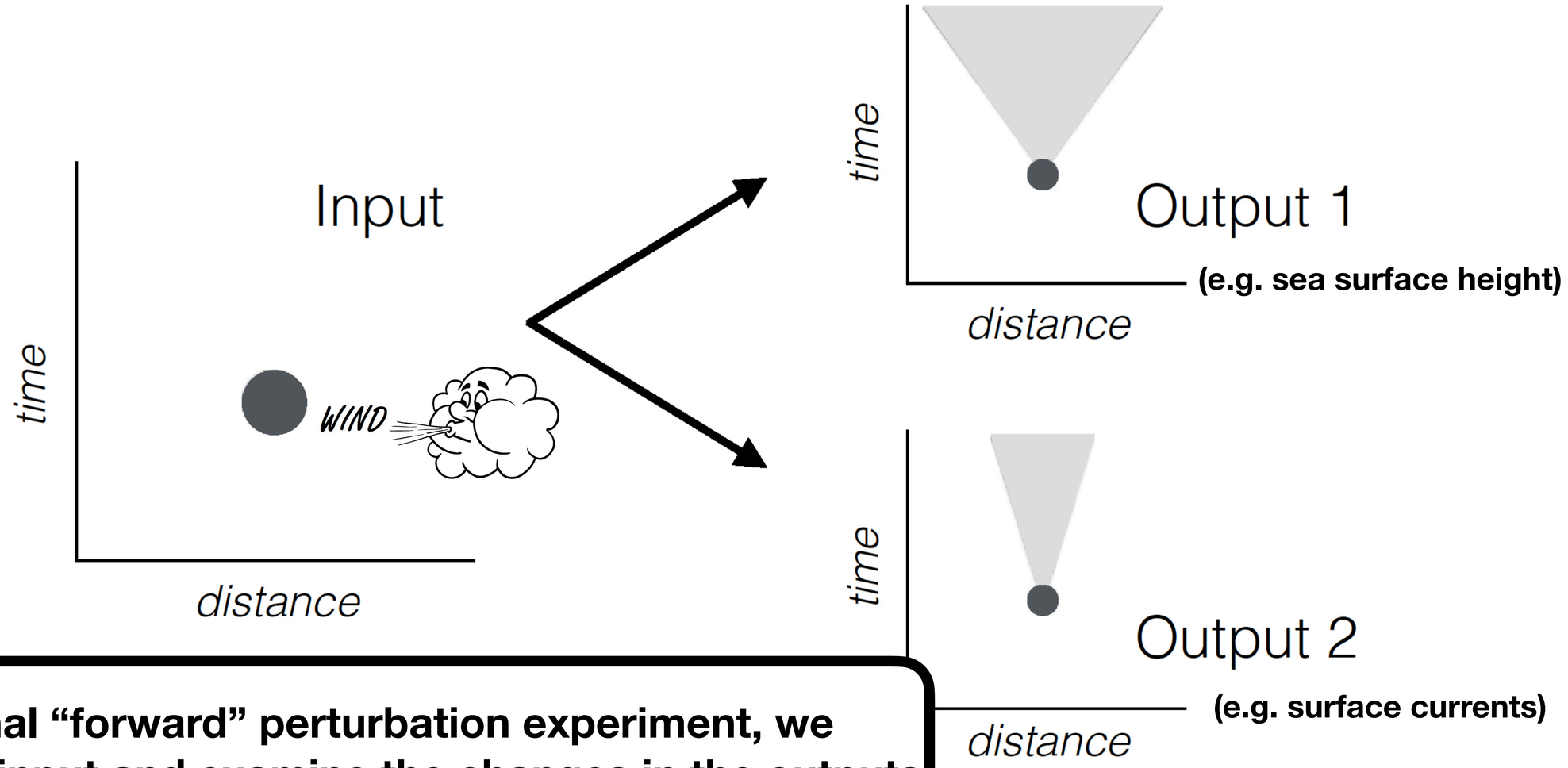
Local and remote influences on the heat content of Southern Ocean mode water formation regions.

Emma J. D. Boland[1], Daniel C. Jones[1], Andrew J. S. Meijers[1], Gael Forget[2], and Simon A. Josey[3].

[1]British Antarctic Survey, High Cross, Madingley Road, Cambridge, United Kingdom
[2]Massachusetts Institute of Technology, Cambridge, MA, USA
[3]National Oceanography Centre, European Way, Southampton, United Kingdom

Jones et al. (JGR-Oceans, 2019)
Jones et al. (JPO, 2020)
Boland et al. (JGR-Oceans, 2021)

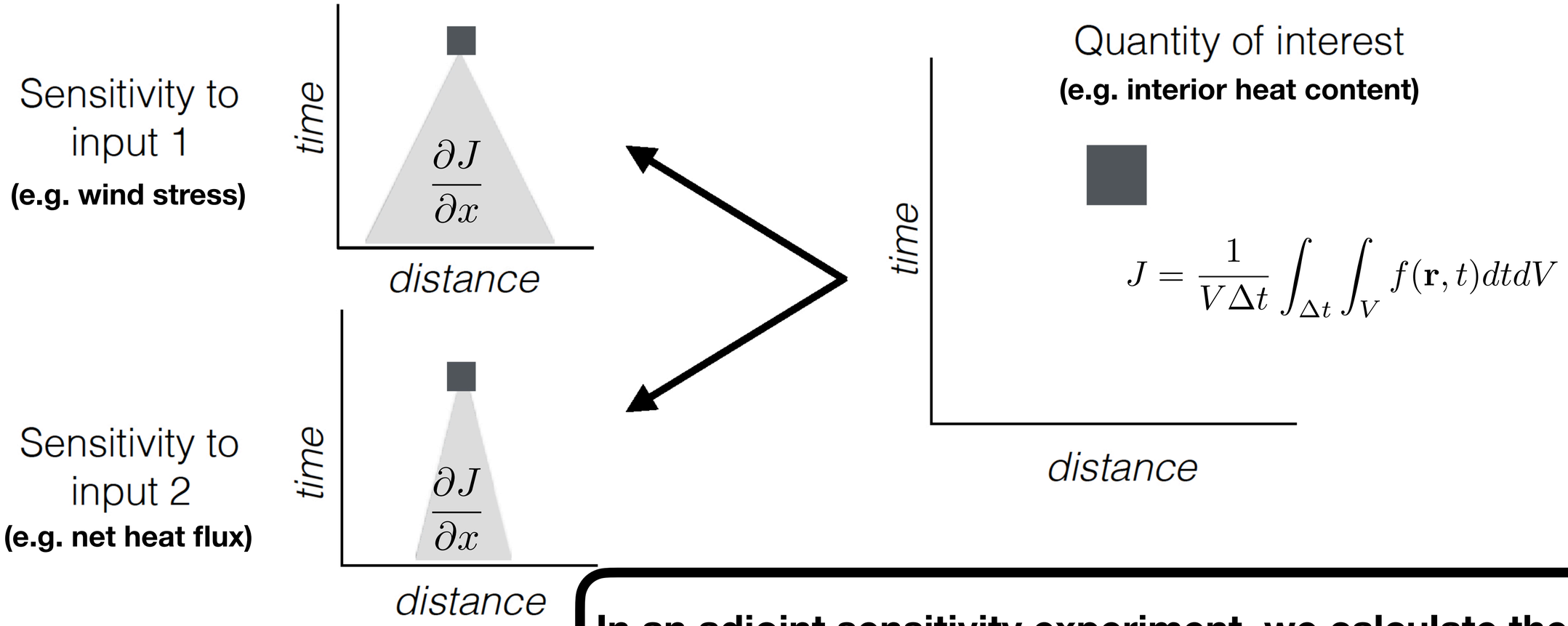
A traditional perturbation experiment



In a traditional "forward" perturbation experiment, we perturb one input and examine the changes in the outputs

Jones et al. (JGR-Oceans, 2018)

An adjoint sensitivity experiment: how does the “output” depend on all the “inputs”?

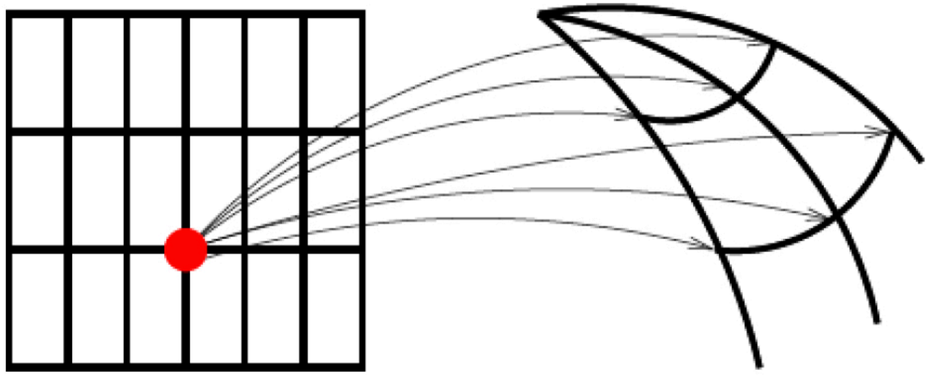


In an adjoint sensitivity experiment, we calculate the sensitivities of a quantity of interest to a large set of inputs

Jones et al. (JGR-Oceans, 2018)

An alternative way to visualise an adjoint sensitivity experiment

Traditional “forward" experiment



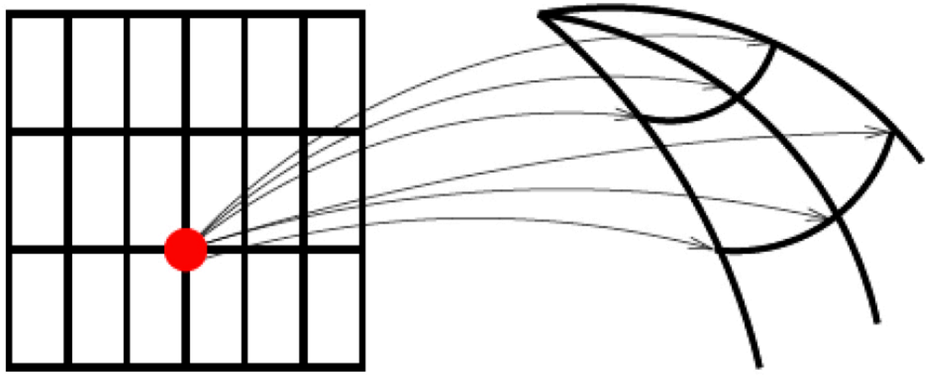
Perturb *one* input, examine all outputs

EXPENSIVE!

P. Heimbach, *from presentation*

An alternative way to visualise an adjoint sensitivity experiment

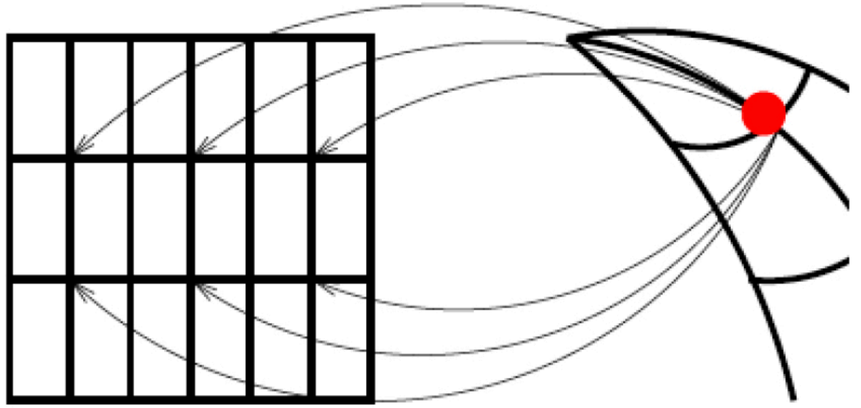
Traditional “forward" experiment



Perturb *one* input, examine all outputs

EXPENSIVE!

Adjoint sensitivity experiment



Sensitivity of one output to *all* inputs

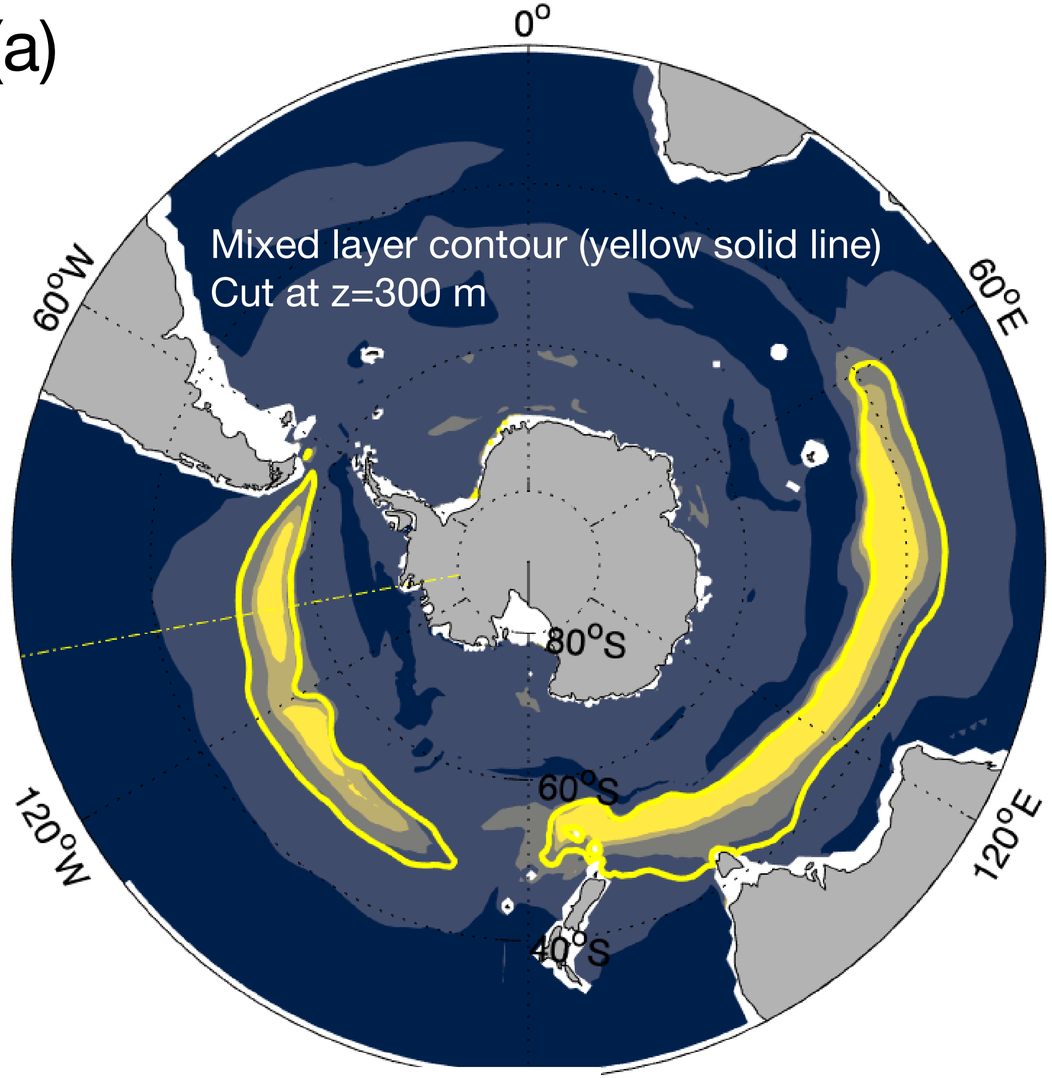
EFFICIENT!

(Albeit linearlized)

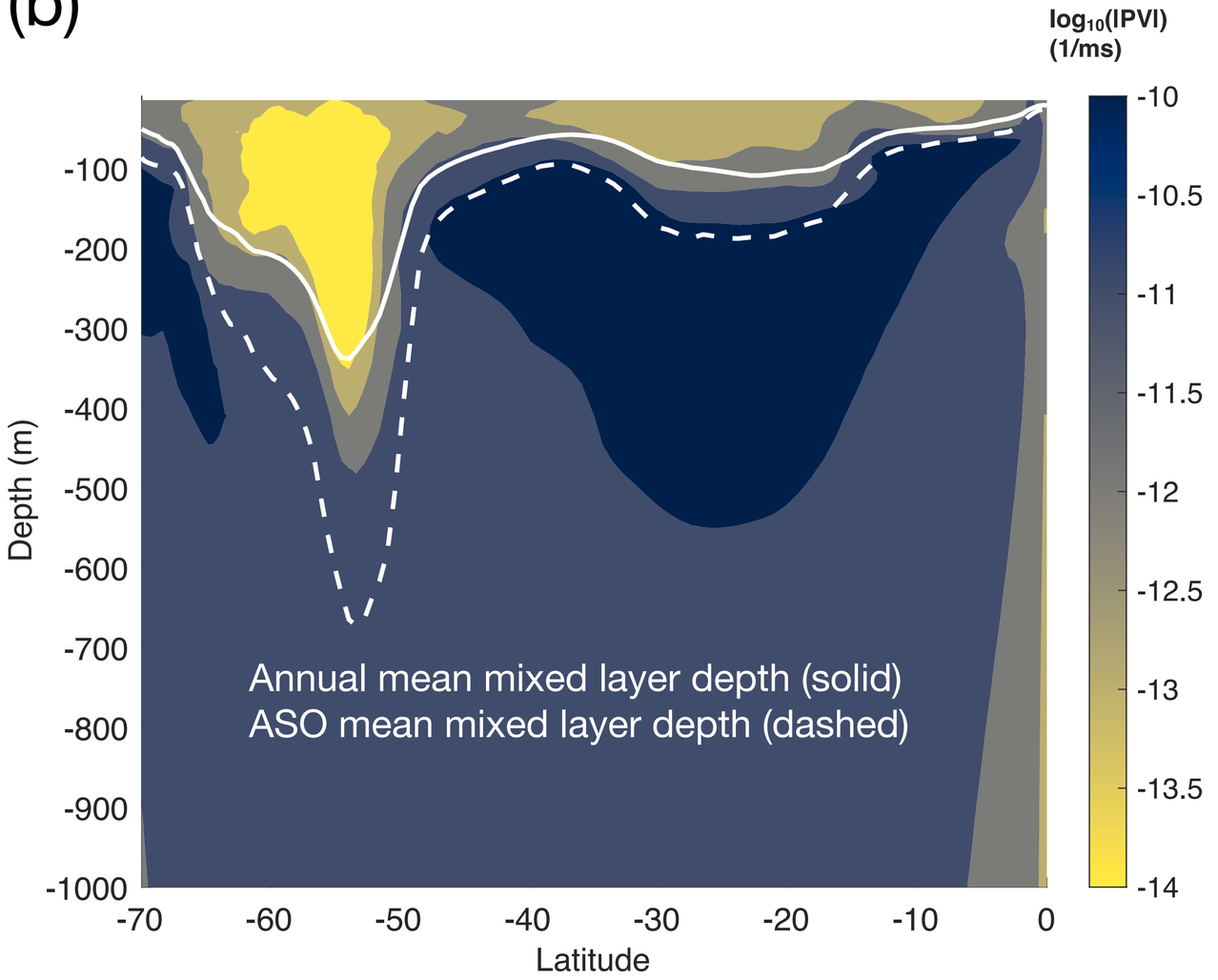
P. Heimbach, *from presentation*

We use potential vorticity and mixed layer depth to identify potential subduction hotspots

(a)

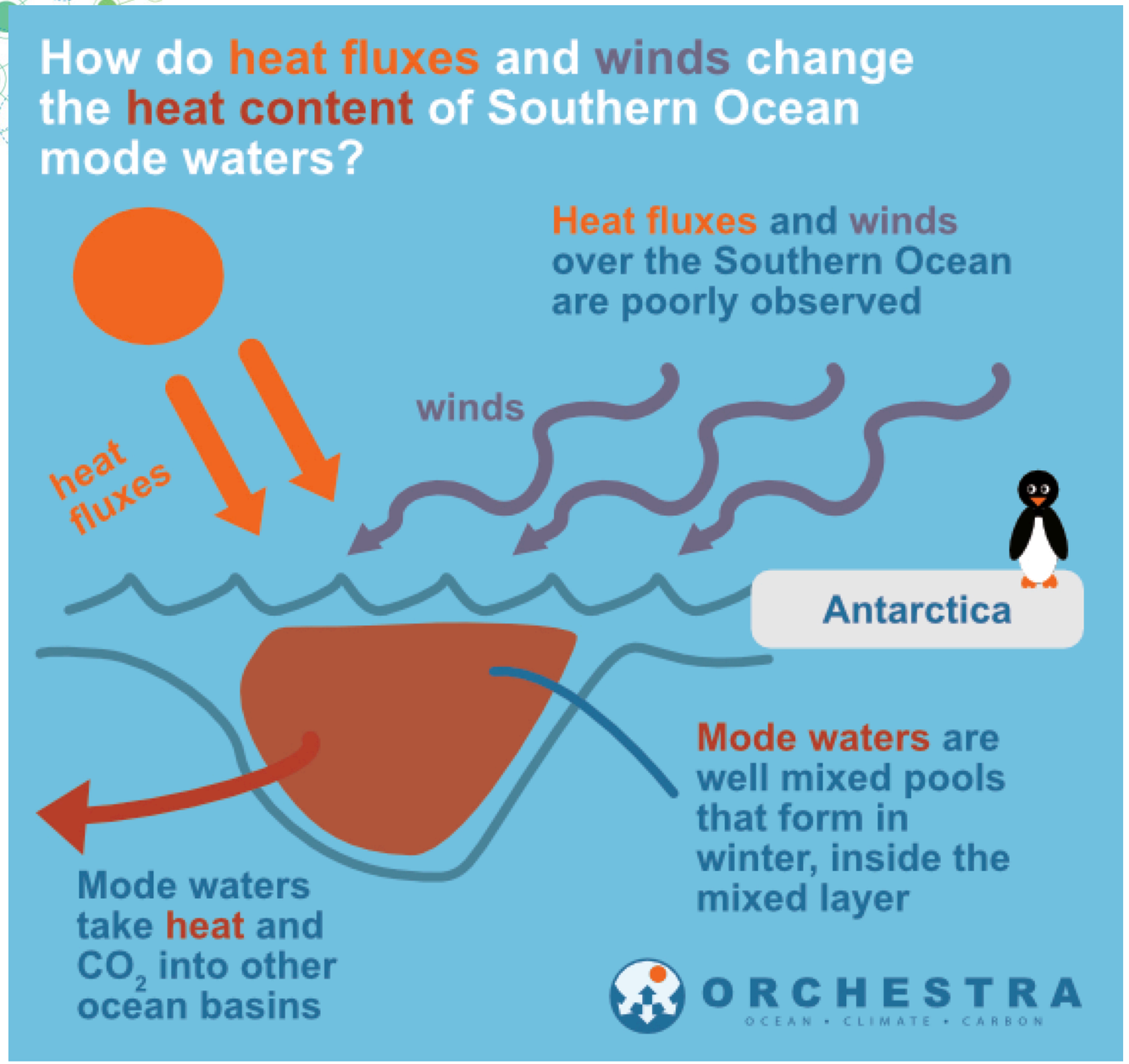


(b)



Median values of annual minimum PV across 1992-2011
Data from ECCOv4-r2

Jones et al. (JGR-Oceans, 2019)
Jones et al. (JPO, 2020)
Boland et al. (JGR-Oceans, 2021)



Boland et al. (JGR-Oceans, 2021)

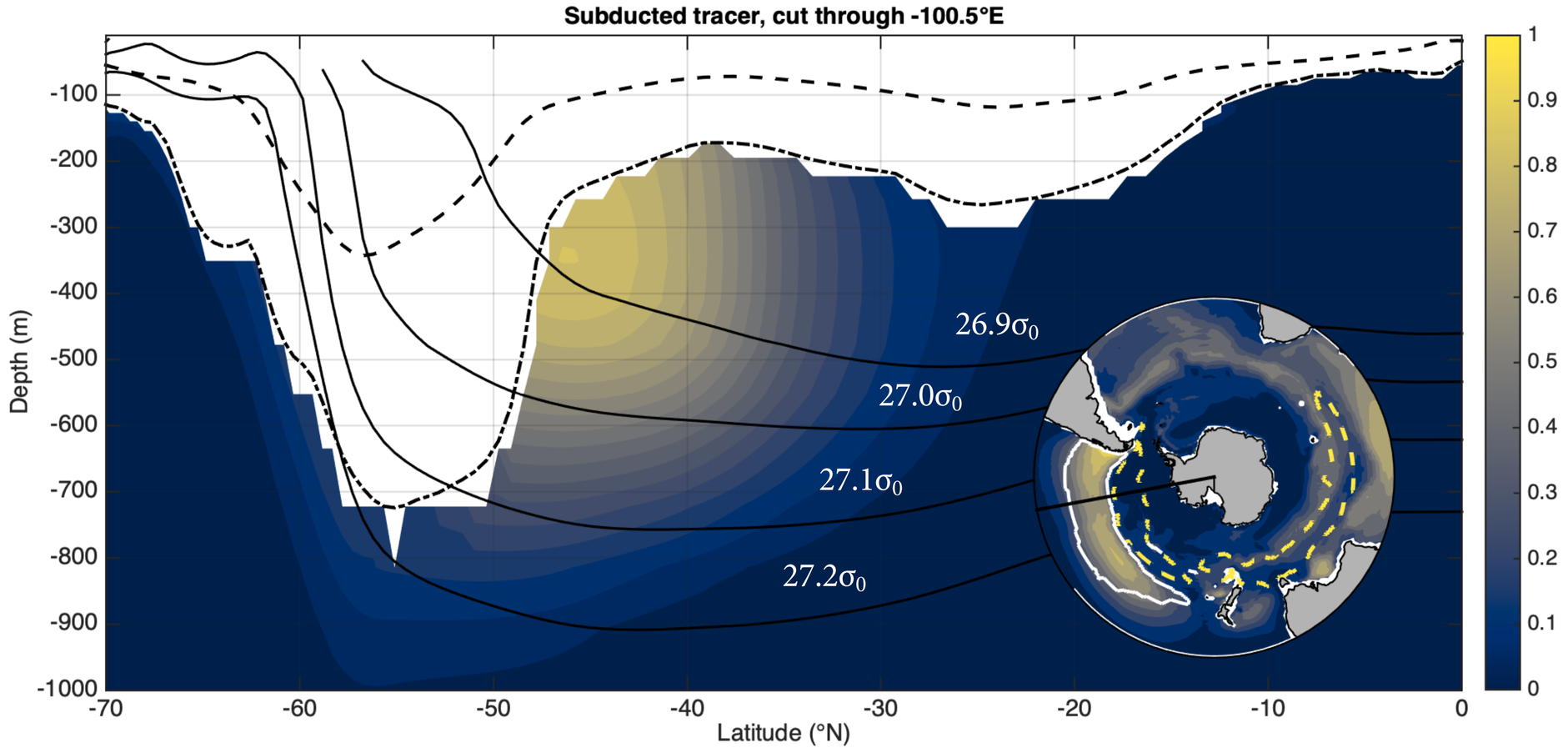
What did we find?

The heat content of Southern Ocean mode water is most sensitive to...

	heat fluxes	winds
What?		
Where?	Local	Local and remote
When?	The same winter	For at least 8 years

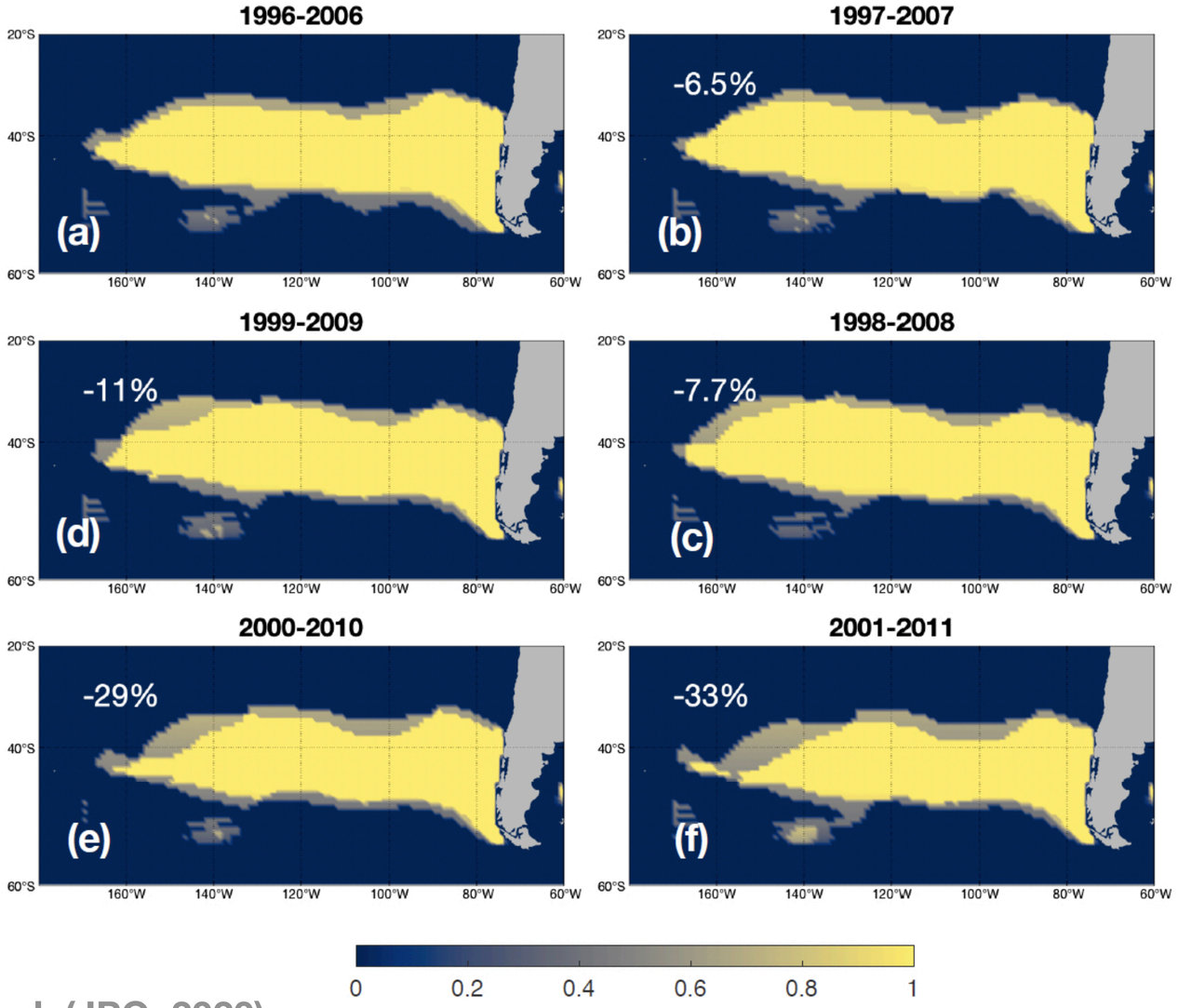
Boland et al. (JGR-Oceans, 2021)

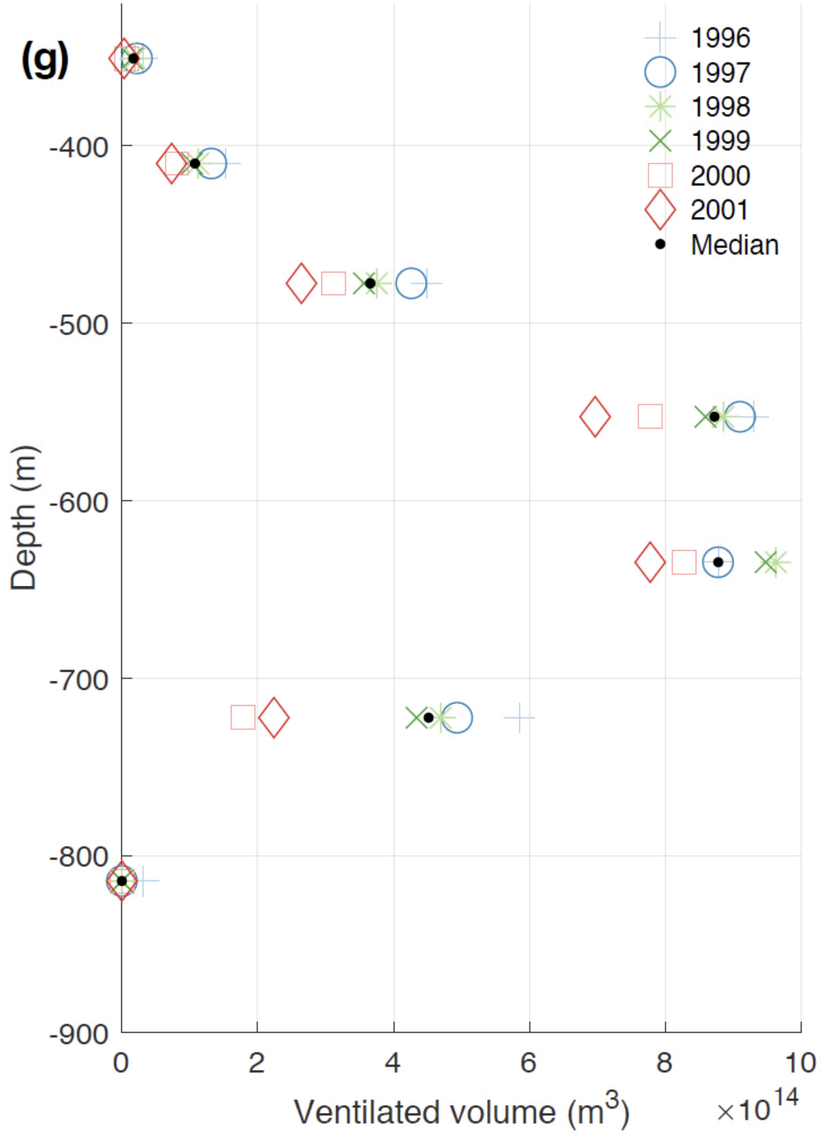
We release passive tracers in the mode water pools; the tracer distribution highlights surface-to-interior ventilation pathways



Jones et al. (JGR-Oceans, 2019)
Jones et al. (JPO, 2020)
Boland et al. (JGR-Oceans, 2021)

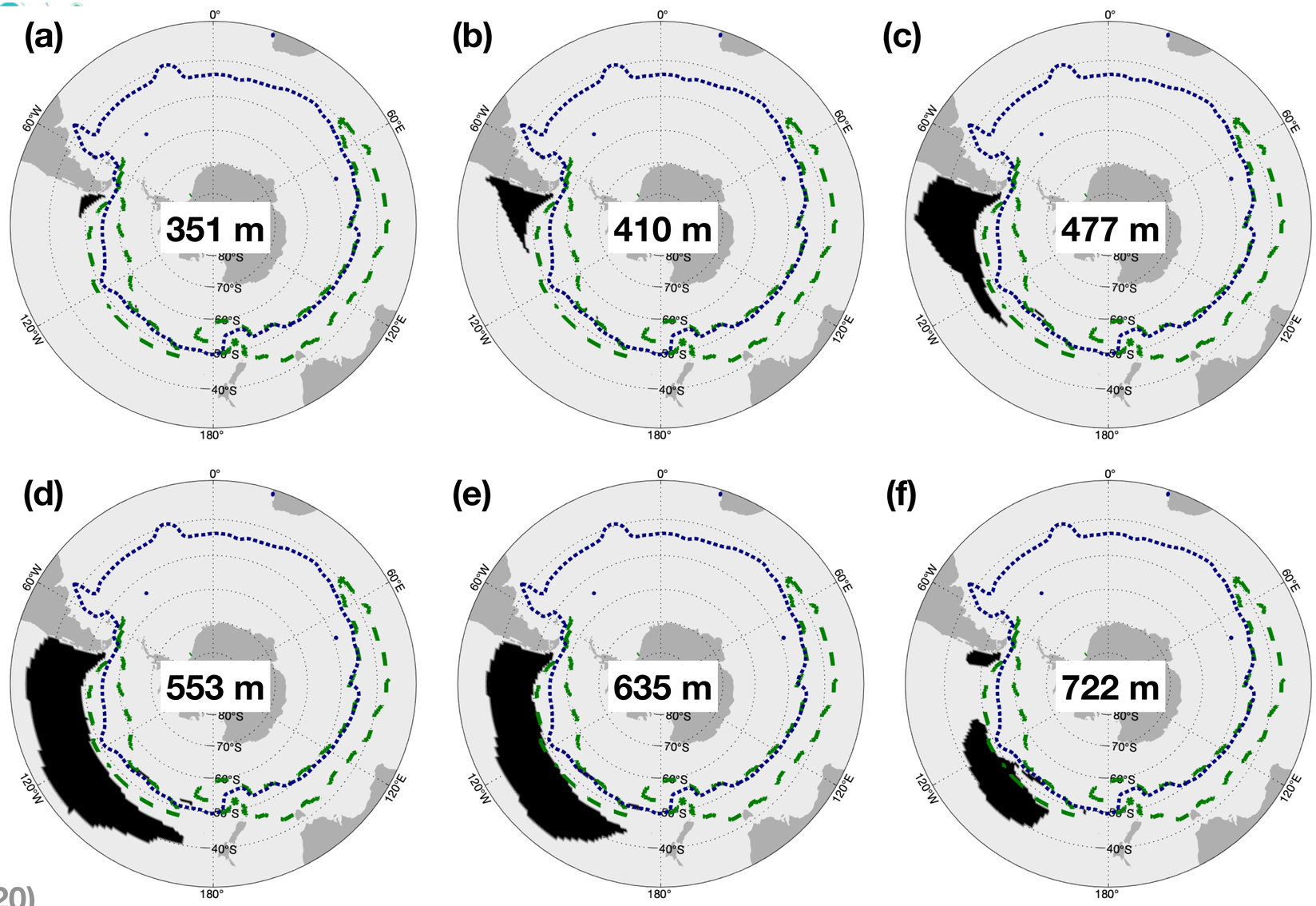
A quick aside: the volume of the RVP varies inter-annually (and has a multi-year trend)





Jones et al. (JPO, 2020)

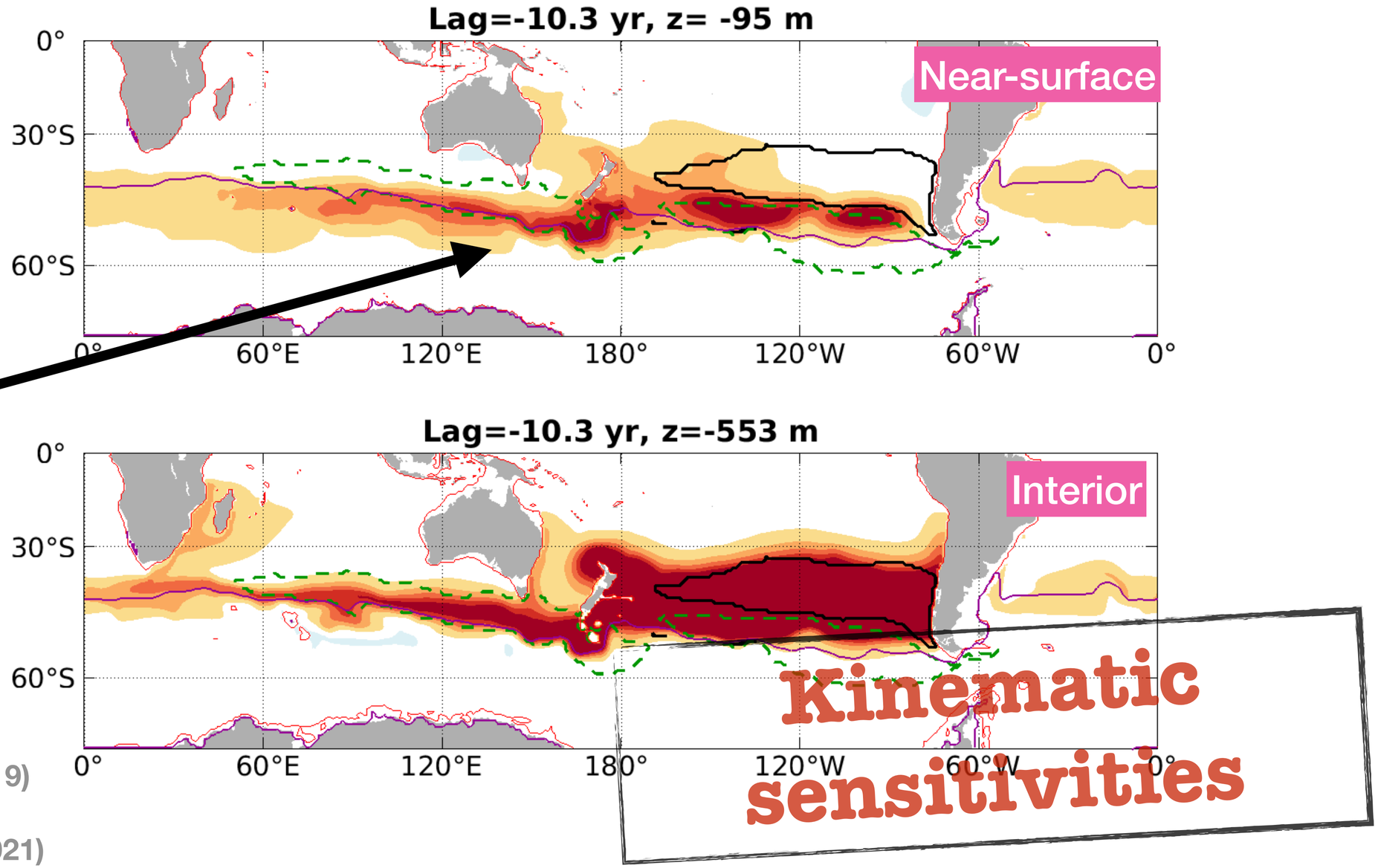
We use the tracer distribution and mixed layer depth to define the “recently ventilated Pacific”



Jones et al. (JPO, 2020)

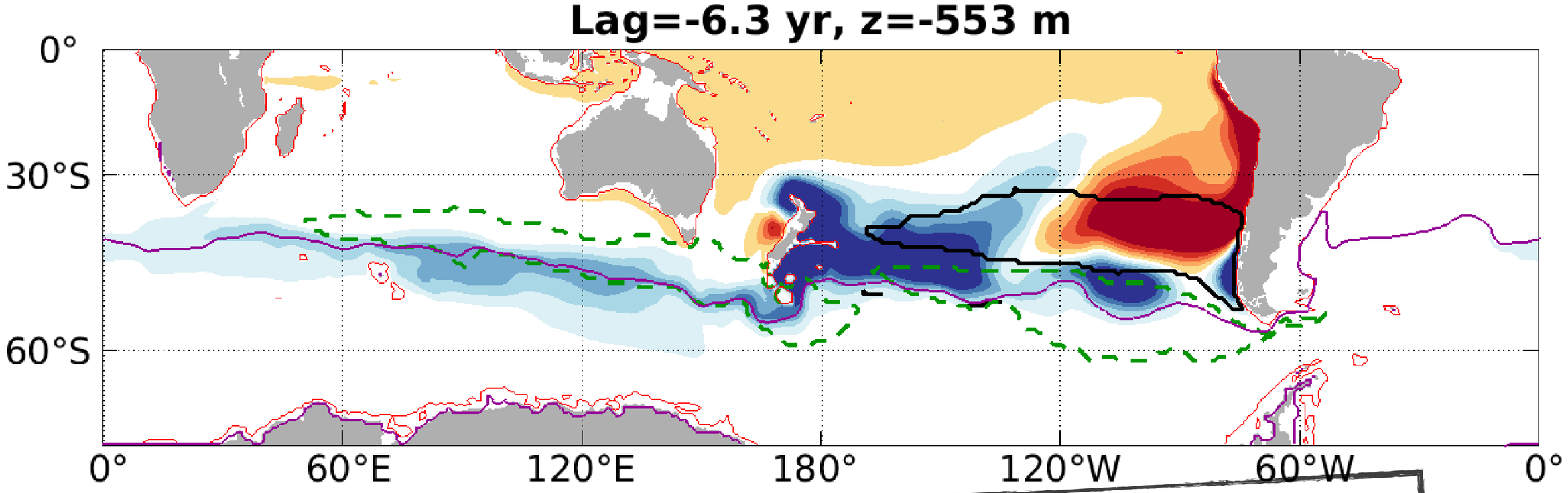
Kinematic sensitivities reveal source water pathways

Sensitivities to near-surface processes cross the SAF (solid line) around AUS-NZ



Jones et al. (JGR-Oceans, 2019)
Jones et al. (JPO, 2020)
Boland et al. (JGR-Oceans, 2021)

East Pacific heat content is sensitive to basin-scale density changes



Dynamic sensitivities

approx. sensitivity to changes in density

Jones et al. (JGR-Oceans, 2019)
Jones et al. (JPO, 2020)
Boland et al. (JGR-Oceans, 2021)

Kinematic

Dynamic

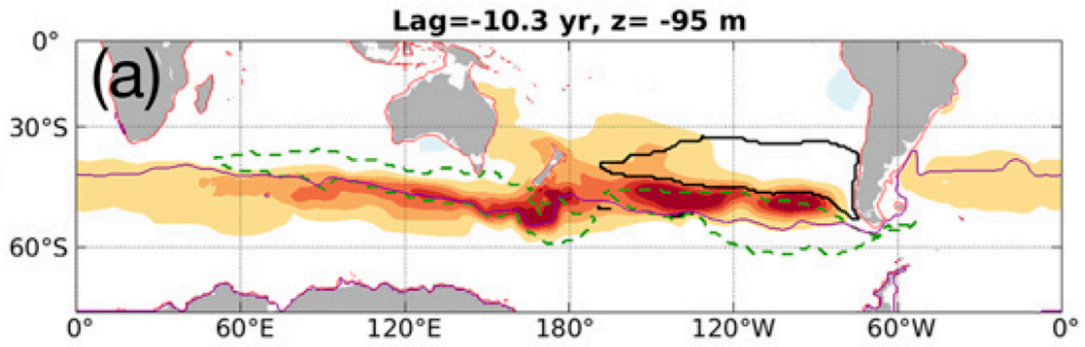
95 m

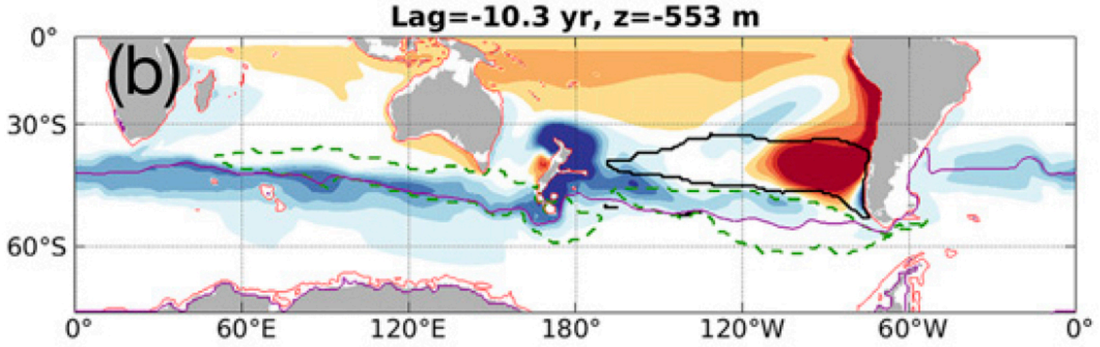
553 m

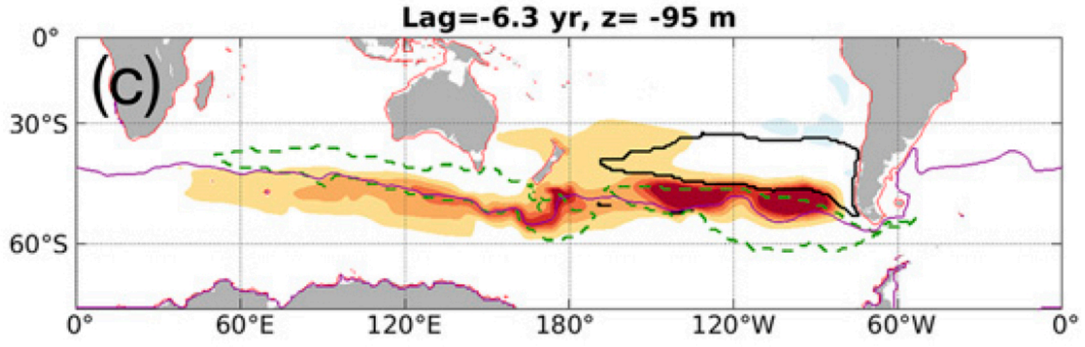
10 yr

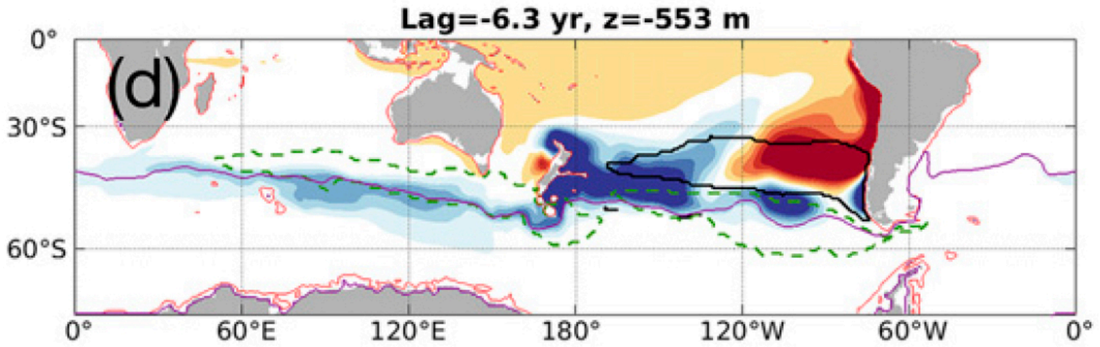
6 yr

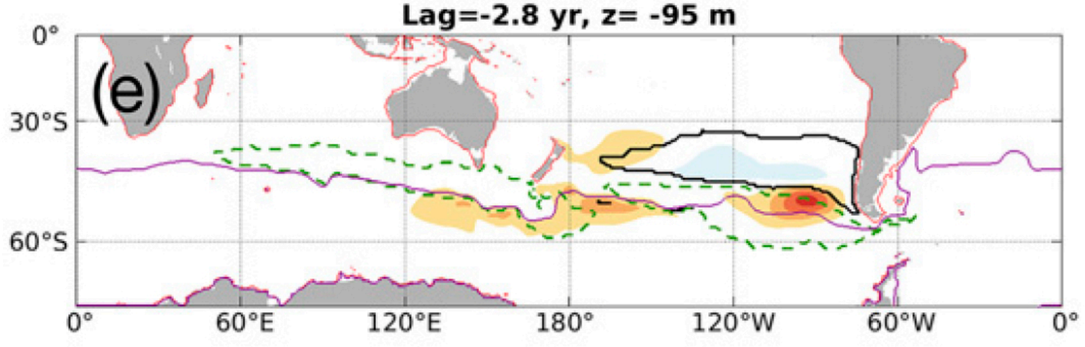
3 yr

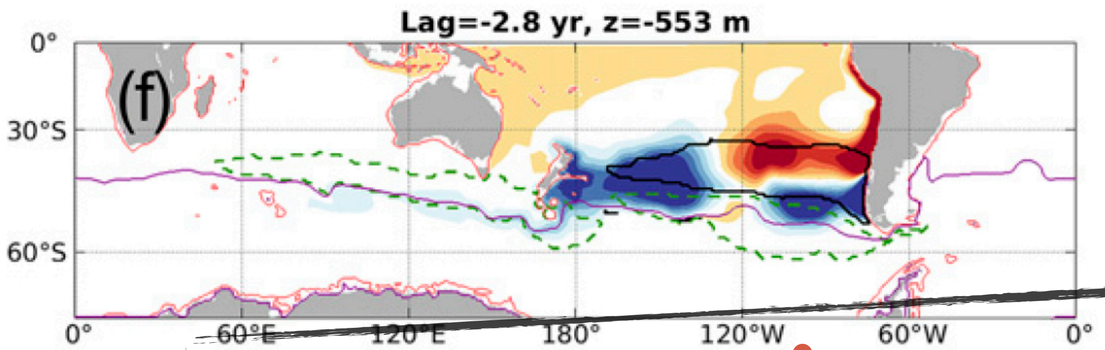








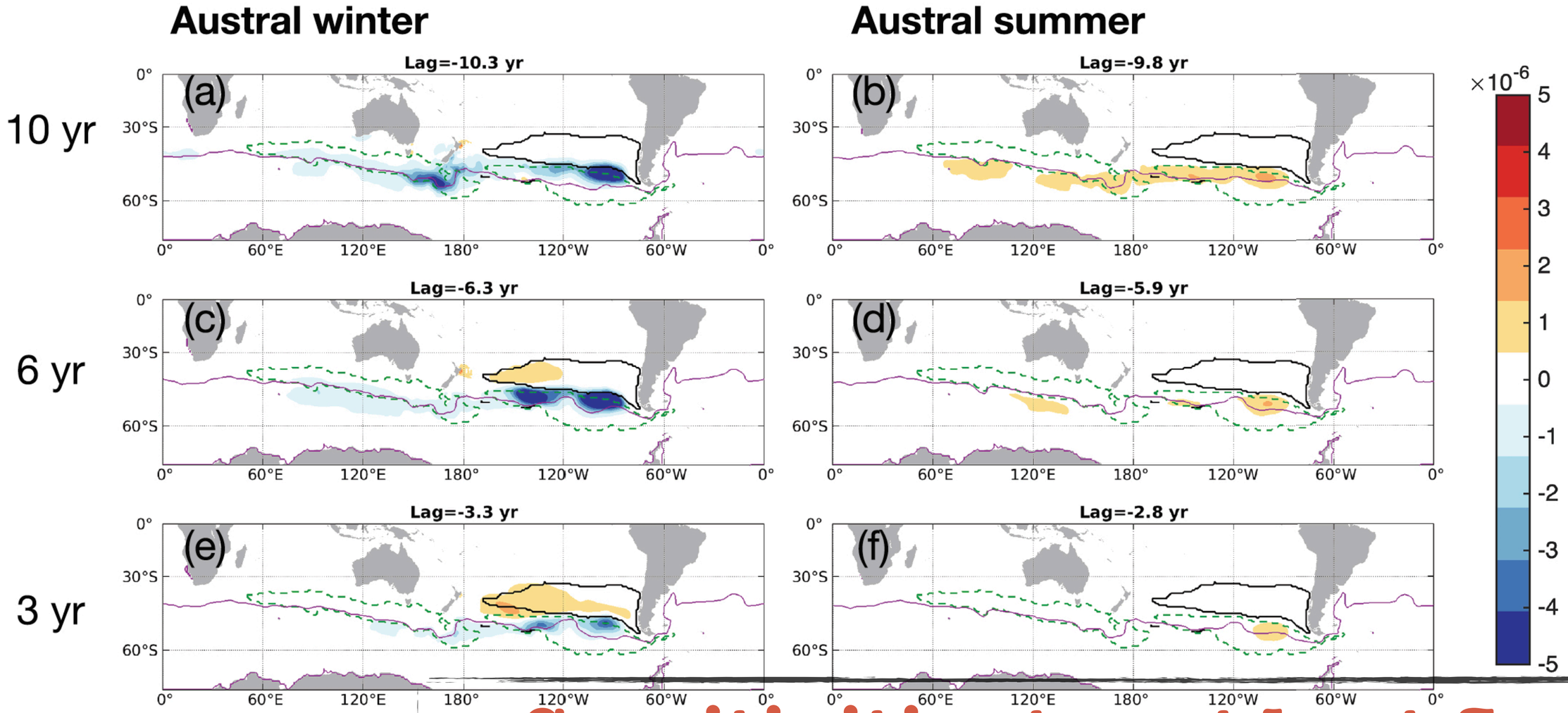




Comparison

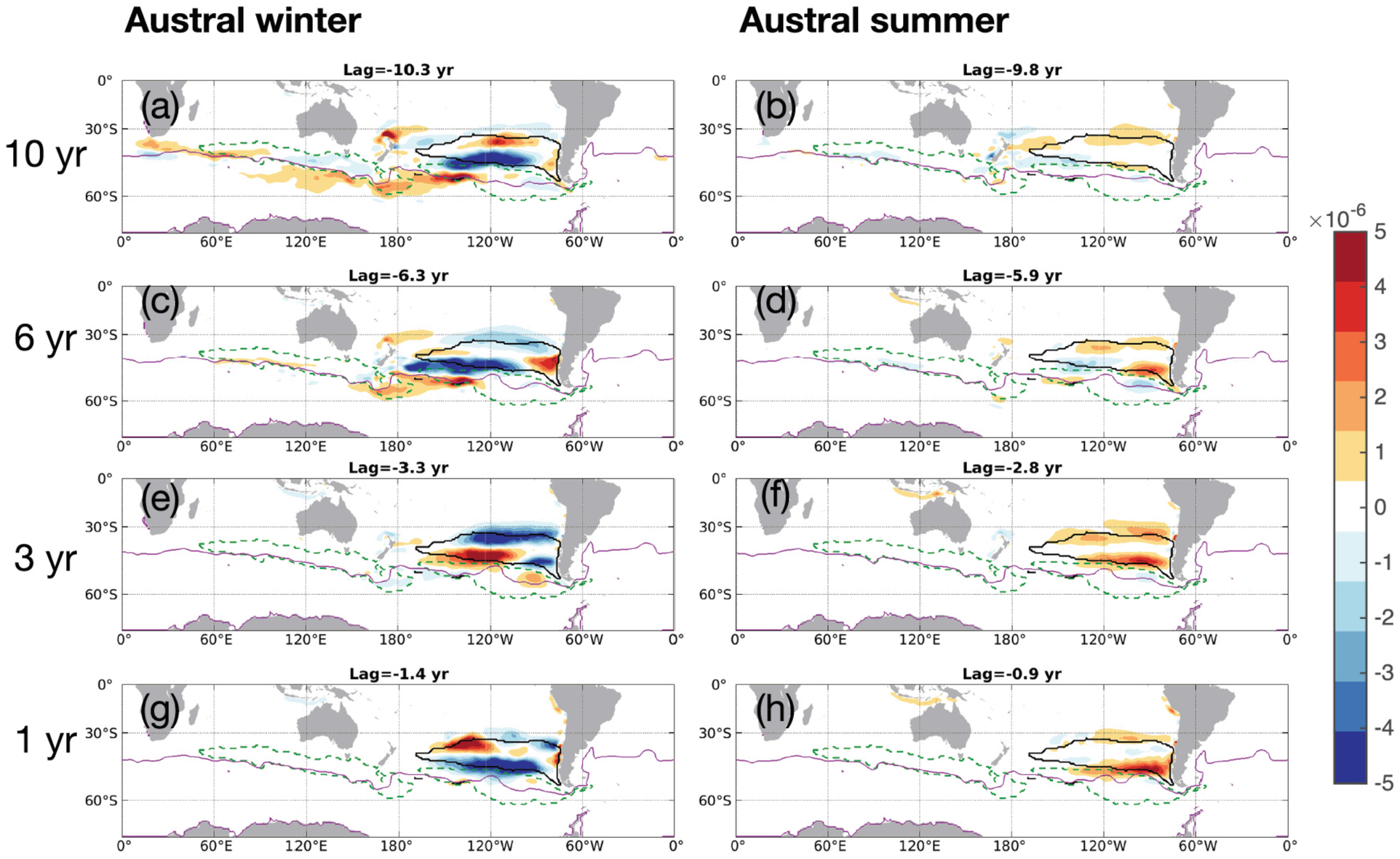
Jones et al. (JGR-Oceans, 2020)

East Pacific heat content is sensitive to net heat flux anomalies along the SAF



Sensitivities to net heat flux

Jones et al. (JGR-Oceans, 2019)

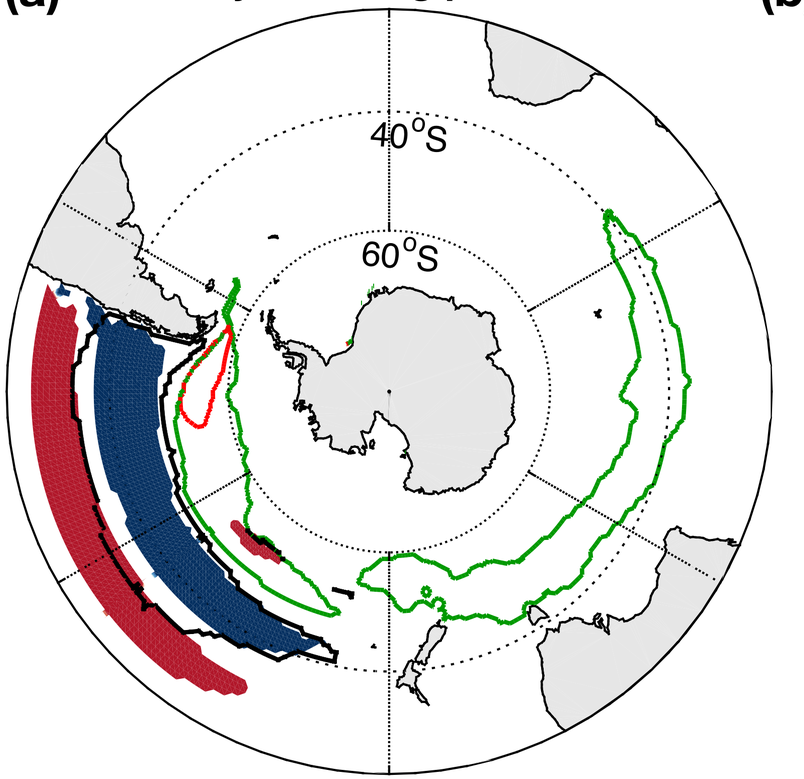


Sensitivities to zonal wind stress

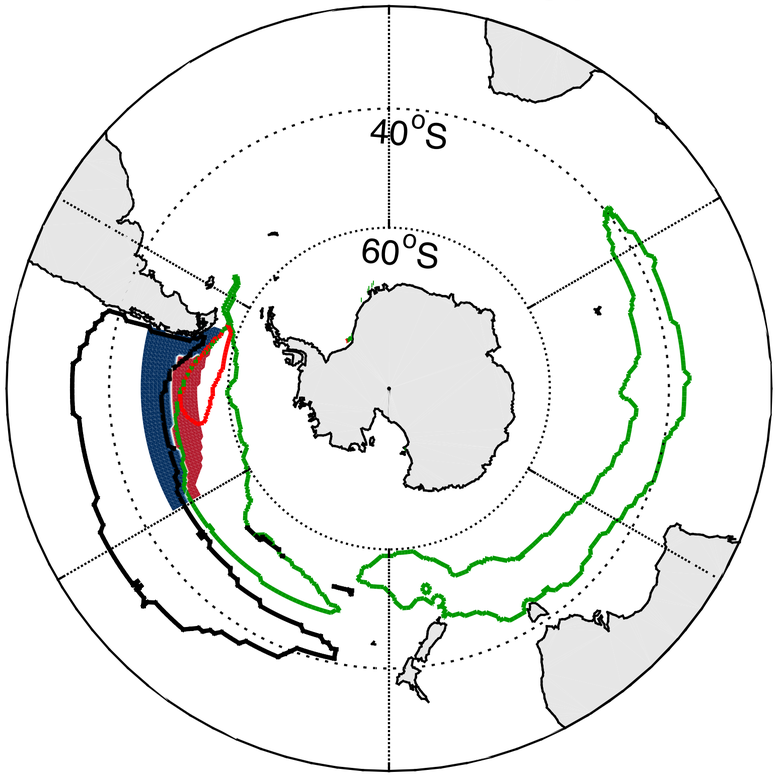
Jones et al. (JGR-Oceans, 2019)

Examining the response mechanisms: three step response experiments

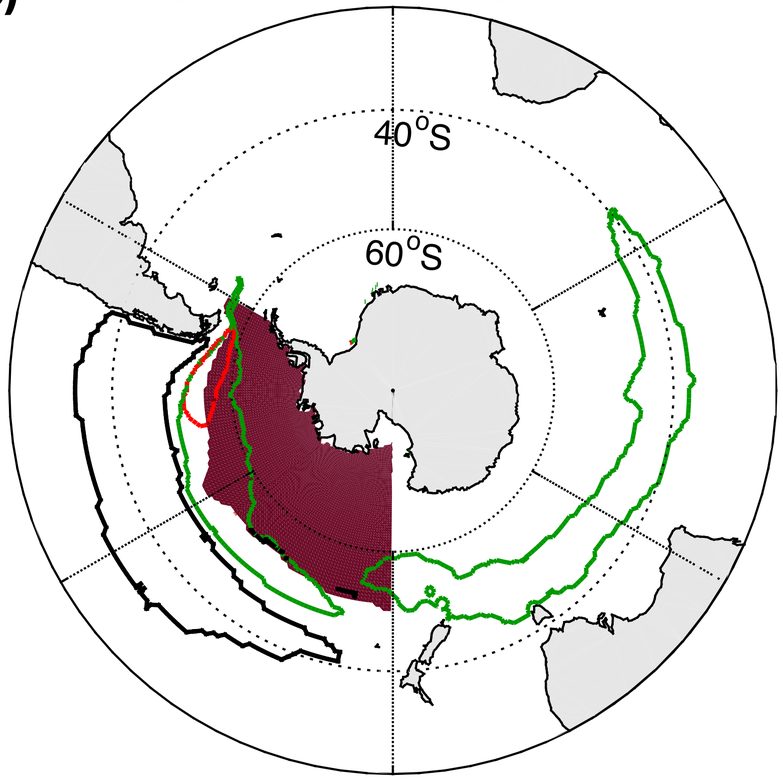
(a) Gyre forcing pattern



(b) Subduction region forcing pattern



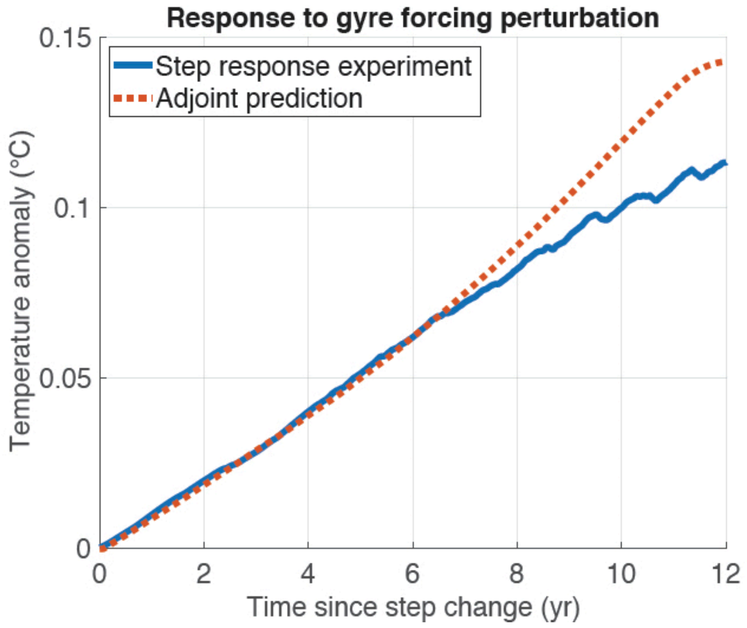
(c) High latitude forcing pattern

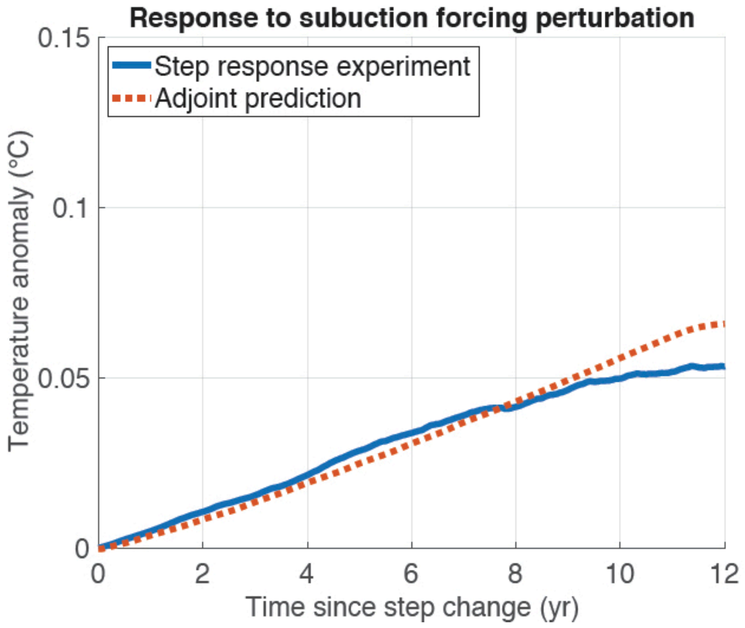


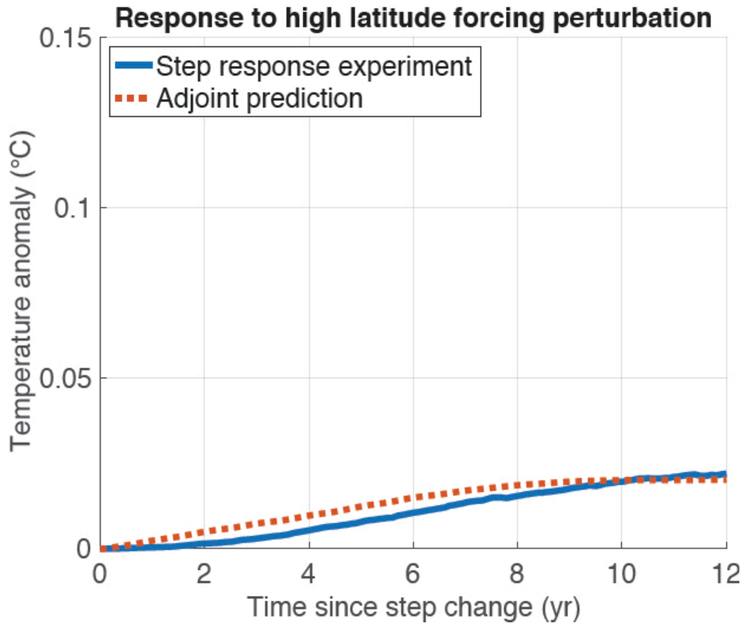
Jones et al. (JGR-Oceans, 2019)
Jones et al. (JPO, 2020)
Boland et al. (JGR-Oceans, 2021)

Inspired by the sensitivity fields

East Pacific heat content is only weakly sensitive to high-latitude wind stress on 10-year timescales







Jones et al. (JGR-Oceans, 2019)
Jones et al. (JPO, 2020)
Boland et al. (JGR-Oceans, 2021)

The linear approximation works well here

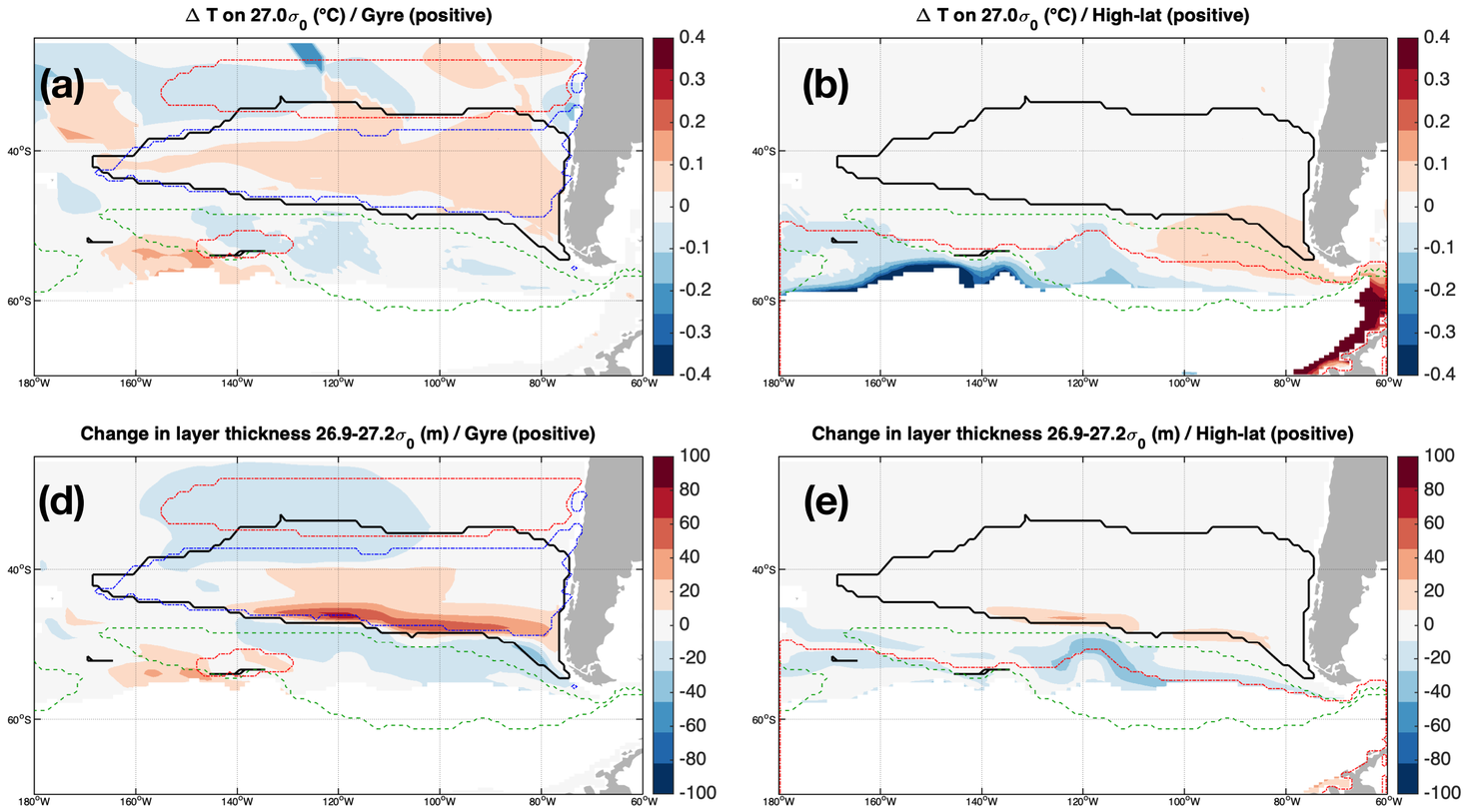
Temperature on isopycnals and layer thickness is only weakly sensitive to high-latitude wind stress on 10-year timescales

Gyre forcing

High-latitude forcing

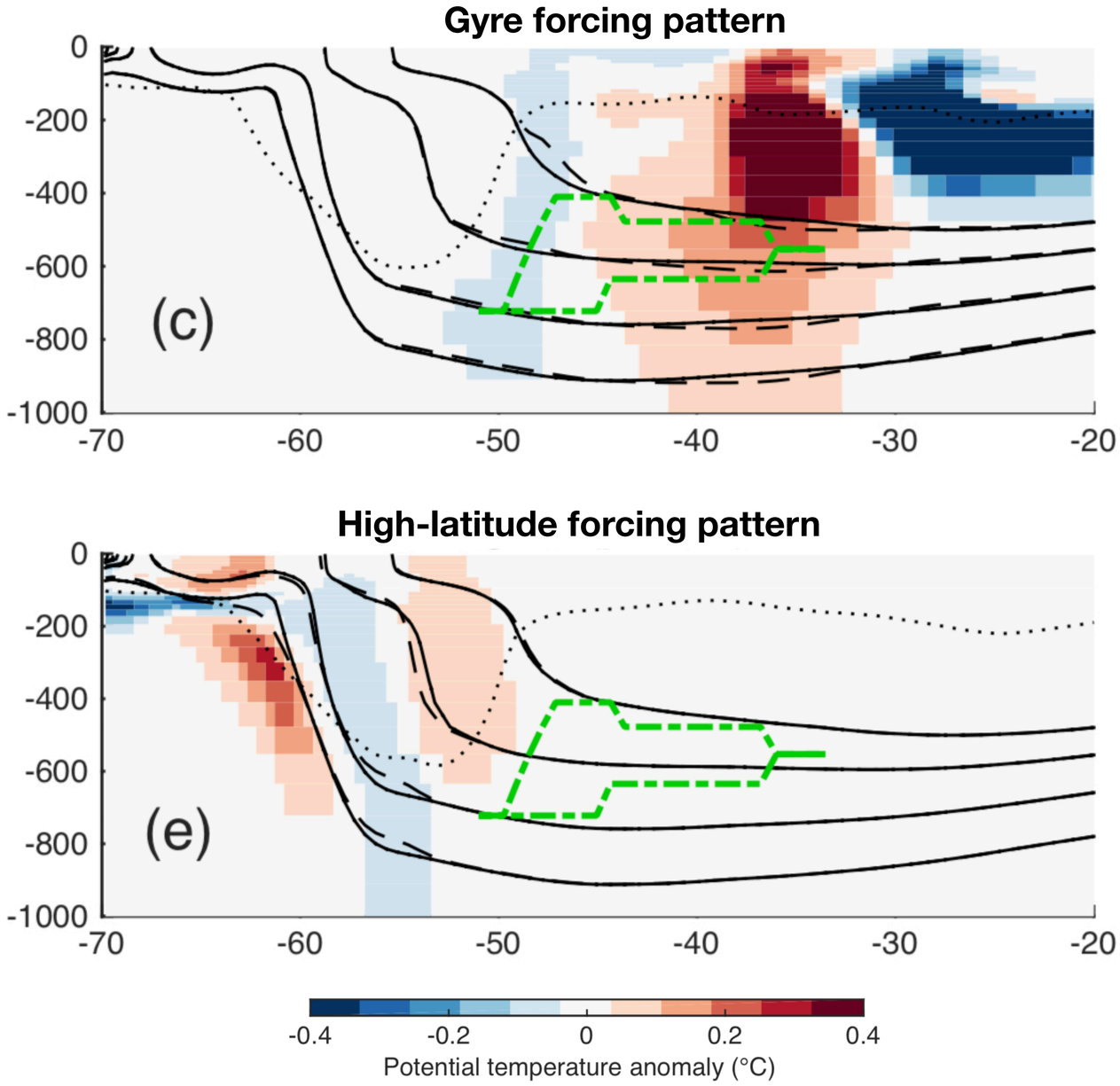
ΔT on 27.0σ0

Change in layer thickness



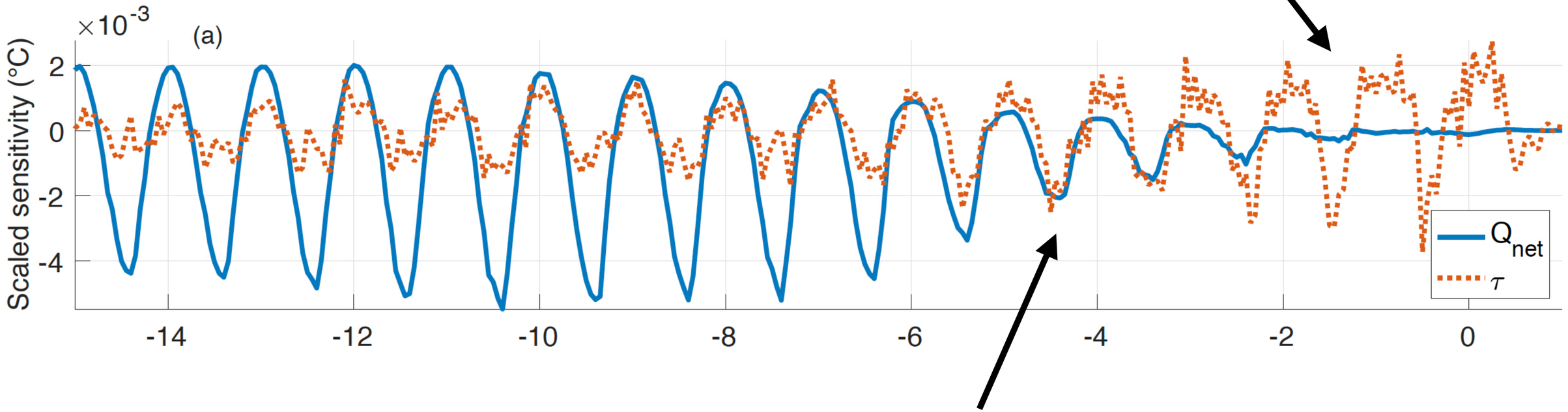
Jones et al. (JGR-Oceans, 2019)
Jones et al. (JPO, 2020)
Boland et al. (JGR-Oceans, 2021)

Sustained changes in **gyre circulation** have a larger impact on RVP heat content compared with high-latitude changes



Jones et al. (JGR-Oceans, 2019)
Jones et al. (JPO, 2020)
Boland et al. (JGR-Oceans, 2021)

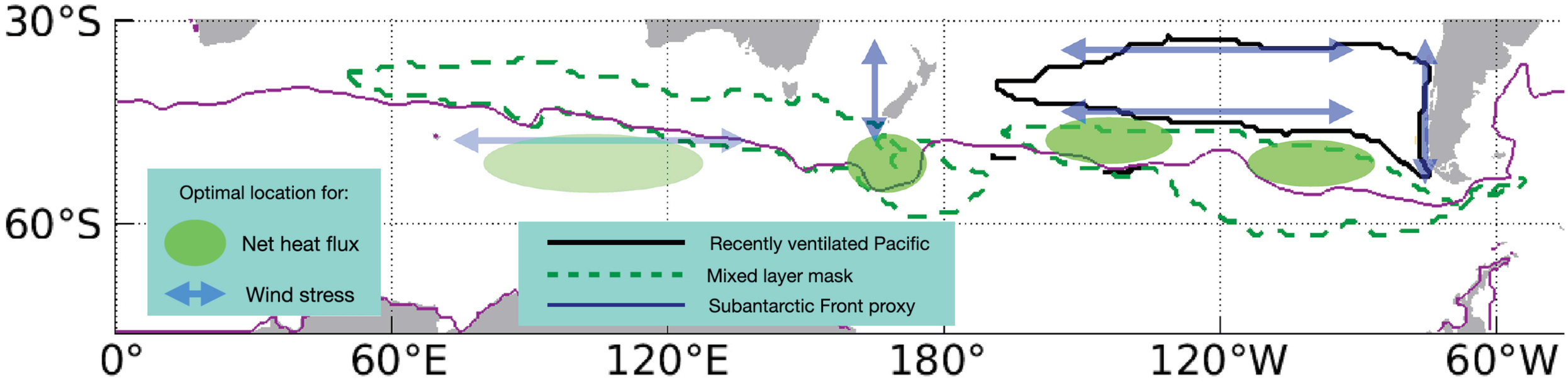
Recently ventilated Pacific sector heat content is most sensitive to mid-latitude wind-stress anomalies (timescales less than 3-5 years)…



…and mid-latitude heat flux anomalies (timescales longer than 3-5 years)

Jones et al. (JGR-Oceans, 2019)
Jones et al. (JPO, 2020)
Boland et al. (JGR-Oceans, 2021)

Optimal perturbation recipes: how to change the annual mean heat content of the recently ventilated interior Pacific Ocean



Jones et al. (JGR-Oceans, 2019)
Jones et al. (JPO, 2020)
Boland et al. (JGR-Oceans, 2021)

Conclusions

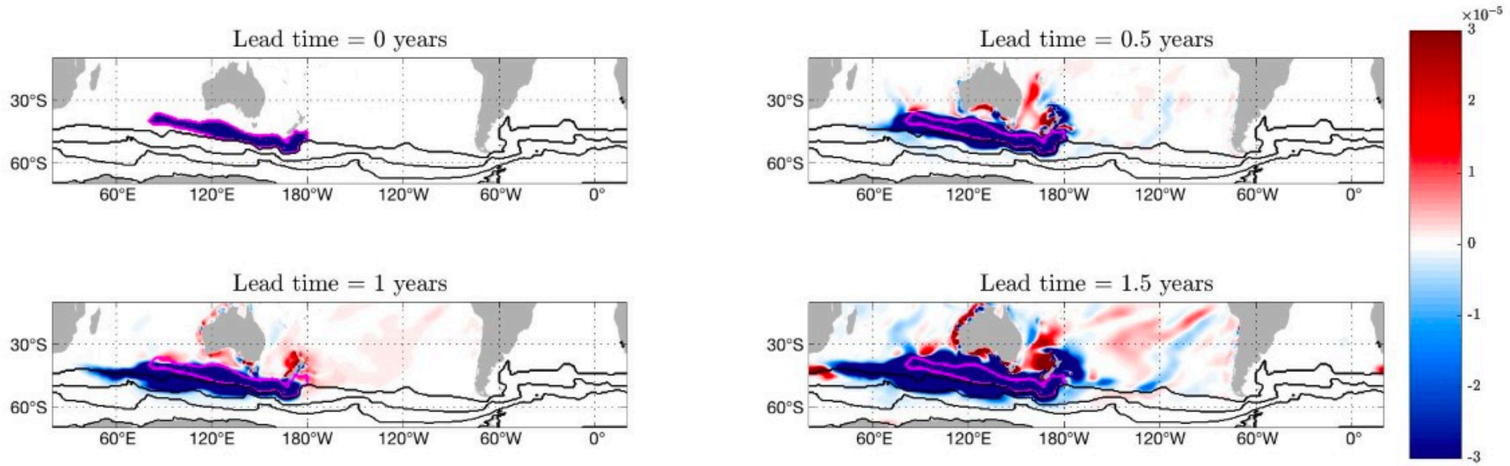
We defined the recently ventilated Pacific (RVP) using passive tracers in an observationally-constrained state estimate (i.e. ECCOv4-r2)

We used an adjoint approach to produce a **comprehensive sensitivity analysis** and recommendations for optimal perturbations

RVP heat content is most sensitive to basin-scale changes, South Pacific gyre circulation, mid-latitude wind-stress anomalies (timescales less than 3-5 years), and mid-latitude heat flux anomalies (timescales longer than 3-5 years)

Jones et al. (JGR-Oceans, 2019)
Jones et al. (JPO, 2020)
Boland et al. (JGR-Oceans, 2021)

Next steps



Objective functions defined by a range in density (Ciara Pimm, PhD student, U. Liverpool)

Perturbation experiments in high-resolution Southern Ocean models (Dave Munday, BAS)

For more info:
a trio of Southern Ocean adjoint sensitivity papers in ECCOv4

JGR Oceans

RESEARCH ARTICLE
10.1029/2019JC015460

Key Points:
- The heat content of the recently ventilated Pacific (RVPh) is strongly controlled by gyre circulation
- On timescales shorter than 3–5 years, RVPh is most sensitive to midlatitude wind stress anomalies
- On timescales longer than 3–5 years, RVPh is most sensitive to midlatitude heat flux anomalies

Heat Distribution in the Southeast Pacific Is Only Weakly Sensitive to High-Latitude Heat Flux and Wind Stress

Daniel C. Jones[1], Emma Boland[1], Andrew J.S. Meijers[1], Gael Forget[2], Simon A. Josey[3], Jean-Baptiste Sallee[4], and Emily Shuckburgh[1,5]

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The Sensitivity of Southeast Pacific Heat Distribution to Local and Remote Changes in Ocean Properties

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Local and remote influences on the heat content of Southern Ocean mode water formation regions.

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Jones et al. (JGR-Oceans, 2019)
Jones et al. (JPO, 2020)
Boland et al. (JGR-Oceans, 2021)



Supplemental slides: More on adjoint modelling and state estimation

Computer programs as functions (1 of 3)

A vector that describes the model state (every variable, every grid cell) at time *t*:

$$\mathbf{x}(t) = [x_1(t), x_2(t), \ldots, x_n(t)]$$

The full nonlinear model advances the model state by one timestep:

$$\mathbf{x}(t) = \mathcal{M}[\mathbf{x}(t-1)]$$

A simple objective function (e.g. mean potential temperature at the end of the model run):

$$J = J[\mathbf{x}(t_f)]$$

COMPOSITION!

$$J = J[\mathbf{x}(t_f)] = J[\mathcal{M}[\mathcal{M}[\mathcal{M}[\cdots\mathcal{M}[\mathbf{x}(t=0)]\cdots]]]]$$

Computer programs as functions (2 of 3)

If we think of the full nonlinear model as an operator that we apply over and over again:

$$J = J[\mathbf{x}(t_f)] = J[\mathcal{M}[\mathcal{M}[\mathcal{M}[\cdots \mathcal{M}[\mathbf{x}(t=0)]\cdots]]]]$$

Then a perturbation in the initial conditions ultimately changes the objective function as follows:

$$\delta J = \frac{\partial J}{\partial \mathbf{x}(t_f)} \delta \mathbf{x}(t_f)$$

CHAIN RULE!

Evaluate from right to left (always a matrix times a vector)

$$= \frac{\partial J}{\partial \mathbf{x}(t_f)} \cdot \frac{\partial \mathbf{x}(t_f)}{\partial \mathbf{x}(t_f - 1)} \cdot \ldots \cdot \frac{\partial \mathbf{x}(t=1)}{\partial \mathbf{x}(t=0)} \cdot \delta \mathbf{x}(t=0)$$

Computer programs as functions (3 of 3)

$$\delta J = \left\langle \frac{\partial J}{\partial \mathbf{x}(t_f)} \middle| \underbrace{\frac{\partial \mathbf{x}(t_f)}{\partial \mathbf{x}(t_f - 1)} \cdot \ldots \cdot \frac{\partial \mathbf{x}(t=1)}{\partial \mathbf{x}(t=0)}} \cdot \delta \mathbf{x}(t=0) \right\rangle$$

This is the "tangent linear model"

$$= \left\langle \underbrace{\left[\frac{\partial \mathbf{x}(t=1)}{\partial \mathbf{x}(t=0)}\right]^T \cdot \ldots \cdot \left[\frac{\partial \mathbf{x}(t_f)}{\partial \mathbf{x}(t_f - 1)}\right]^T} \cdot \frac{\partial J}{\partial \mathbf{x}(t_f)} \middle| \delta \mathbf{x}(t=0) \right\rangle$$

ADJOINT!

You can think of this as the adjoint model - a bunch of partial derivatives!

$$= \left\langle \frac{\partial J}{\partial \mathbf{x}(t=0)} \middle| \delta \mathbf{x}(t=0) \right\rangle$$

In general, *M* and its adjoint *M:**

$$\langle Ma | b \rangle = \langle a | M^* b \rangle$$

So how do we get all those partial derivatives?

ALGORITHMIC DIFFERENTIATION!

22nd European Workshop on Automatic Differentiation
1.-2. July 2019, Imperial College London, UK



http://www.AutoDiff.org



Algorithmic differentiation is amazing

```
SUBROUTINE FOO(x,    y,    z,    p)

 REAL x,y,t,z,p


 t = 2.0*x + 5.0


 z = t + p*y/t
END
```

```
SUBROUTINE FOO(x, xd, y, yd, z, zd, p)
 REAL xd,yd,td,zd
 REAL x,y,t,z,p

 td = 2.0*xd
 t = 2.0*x + 5.0
 zd = td + p*(yd*t-y*td)/(t*t)
 z = t + p*y/t
END
```

Inserts Differentiated instructions into FOO, Automatically.

Ideal for complex, long, constantly evolving source code

L. Hascoet, *from presentation*

“source to source transformation”

FastOpt
Fast Optimisation and Sensitivities

OpenAD



Problem (minor): how do you go backwards through “if” statements?

Solution: the forward sweep must store all of its control flow choices. The reverse sweep reads them in.




```
if (T(i).lt.0.0) then
  T(i) = S(i)*T(i)
  push(true)
else
  push(false)
endif

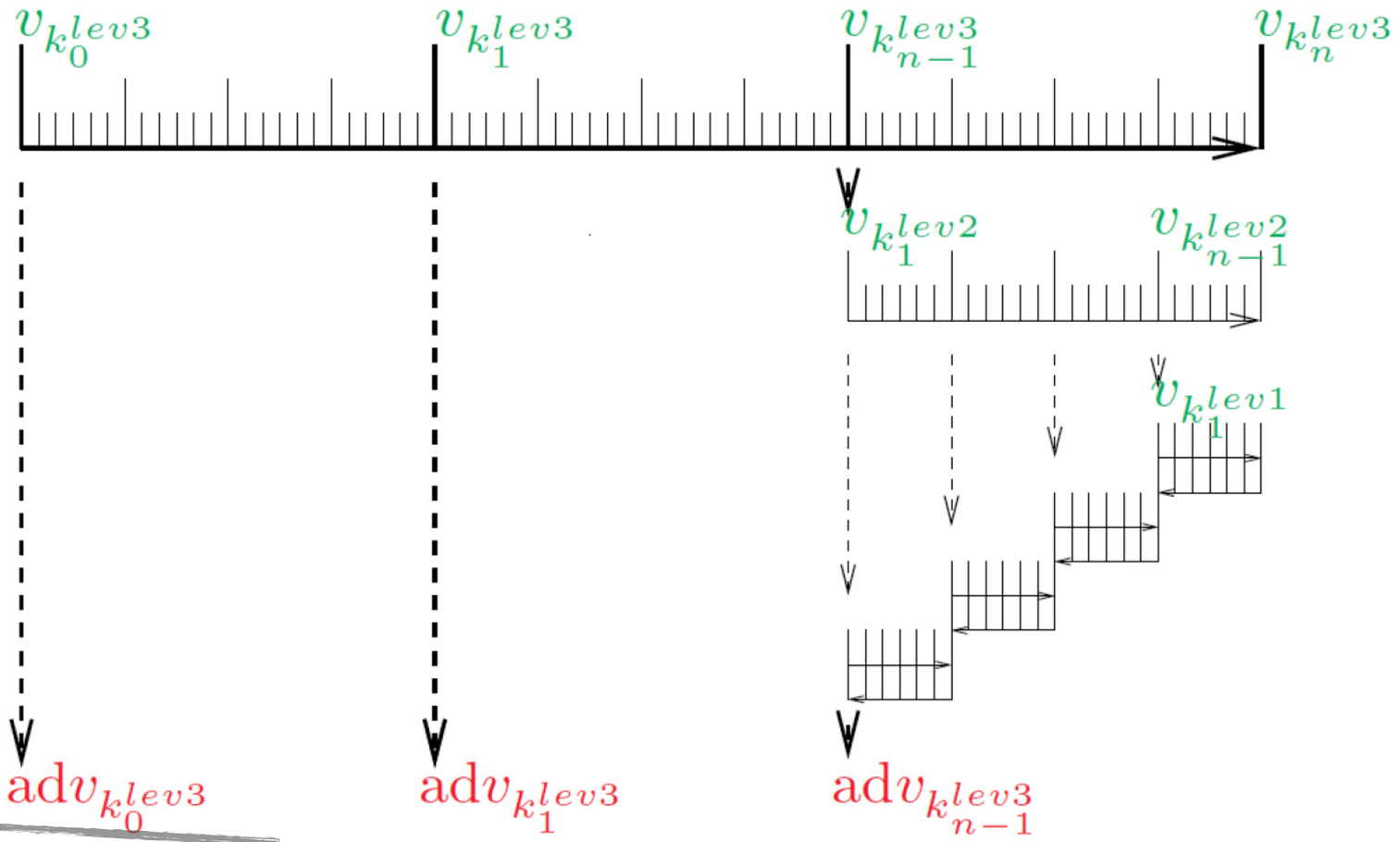
...
pop(test)
if (test) then
  Sb(i) = Sb(i) + T(i)*Tb(i)
  Tb(i) = S(i)*Tb(i)
endif
```

L. Hascoet, *from presentation*



Problem (major): adjoint runs require the entire model state *at every timestep, in reverse*

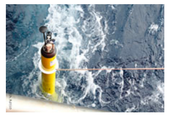
Solution: a mixture of temporarily storing "checkpoints" of the model state on disk and recomputing the model state from those checkpoints



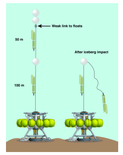
CHECKPOINTING!

Adjoint application: state estimation

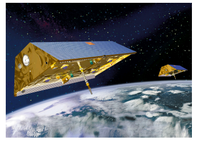
1. Datasets



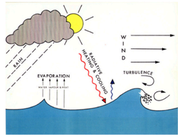
Argo profiles



Mooring data (OSNAP, RAPID)



Sea surface height



Surface fluxes

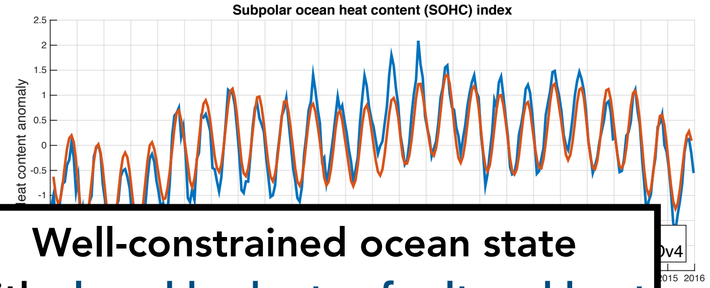
2. State estimation framework (e.g. MITgcm, NEMO+NEMOTAM)

Forward model. Calculates time-evolving ocean state based on initial conditions and surface forcing

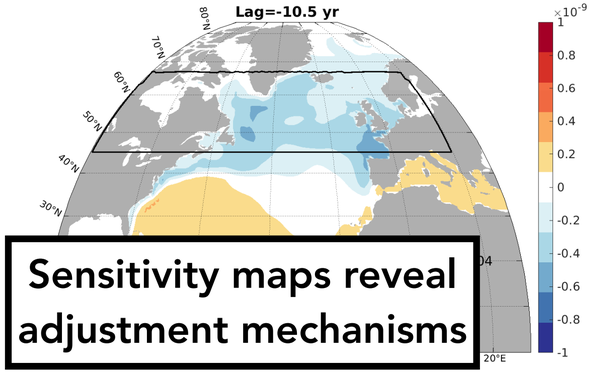
Iterative improvements

Adjoint model. Modifies initial conditions and surface forcing to improve model-data agreement

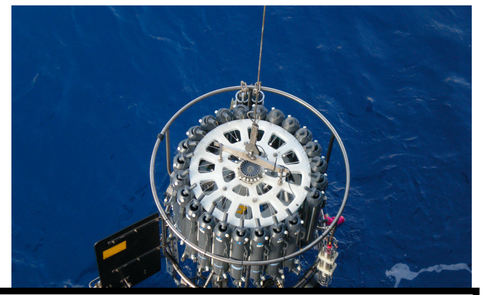
3. Parameter estimates and sensitivities



Well-constrained ocean state with closed budgets of salt and heat



Sensitivity maps reveal adjustment mechanisms



Targets for new observations

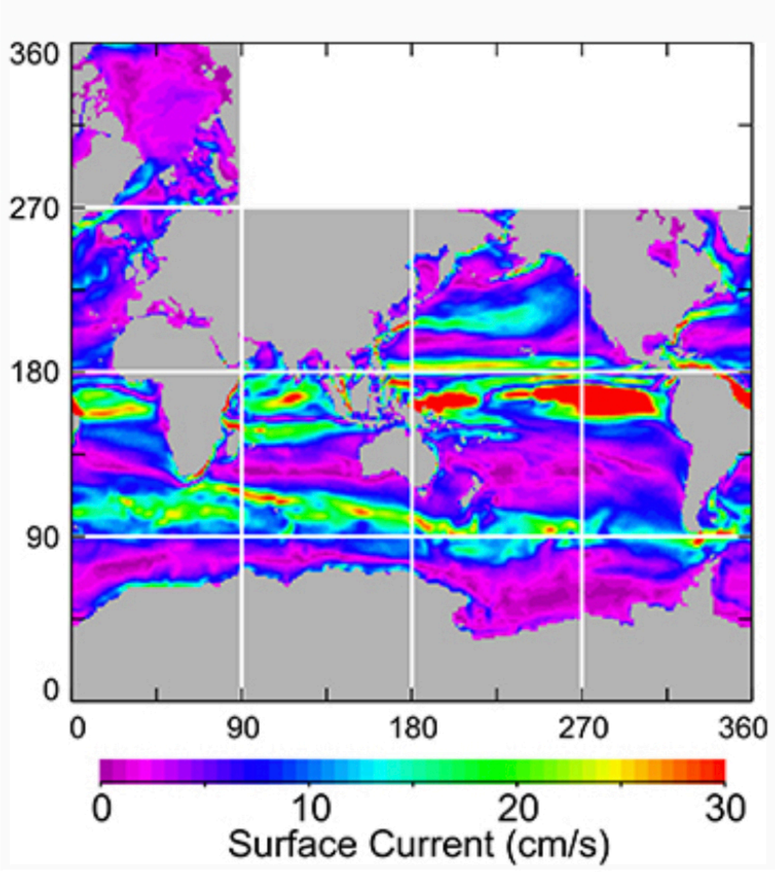
ECCO-V4r3

Authors: Fukumori, Ichiro; Wang, Ou; Fenty, Ian; Forget, Gael; Heimbach, Patrick; Ponte, Rui M.

Description:

Version 4 Release 3 (V4r3), covering the period 1992-2015, represents ECCO's latest ocean state estimate. This product is an updated edition to that described by Forget et al. (2015, Geosci. Model Dev.). Version 4 is the first multi-decadal ECCO estimate that is truly global, including the Arctic Ocean. The Release 3 edition includes improvements in time-period (1992-2015), model (e.g., sea-ice), observations (e.g., GRACE, Aquarius), and constraints (e.g., correlated errors).

[*Image at right*] Speed (cm/s) of 1992-2015 time-mean current at 5m depth. The figure combines into a global image, V4r3's thirteen tiles, each a 90-by-90 grid delineated by white lines.



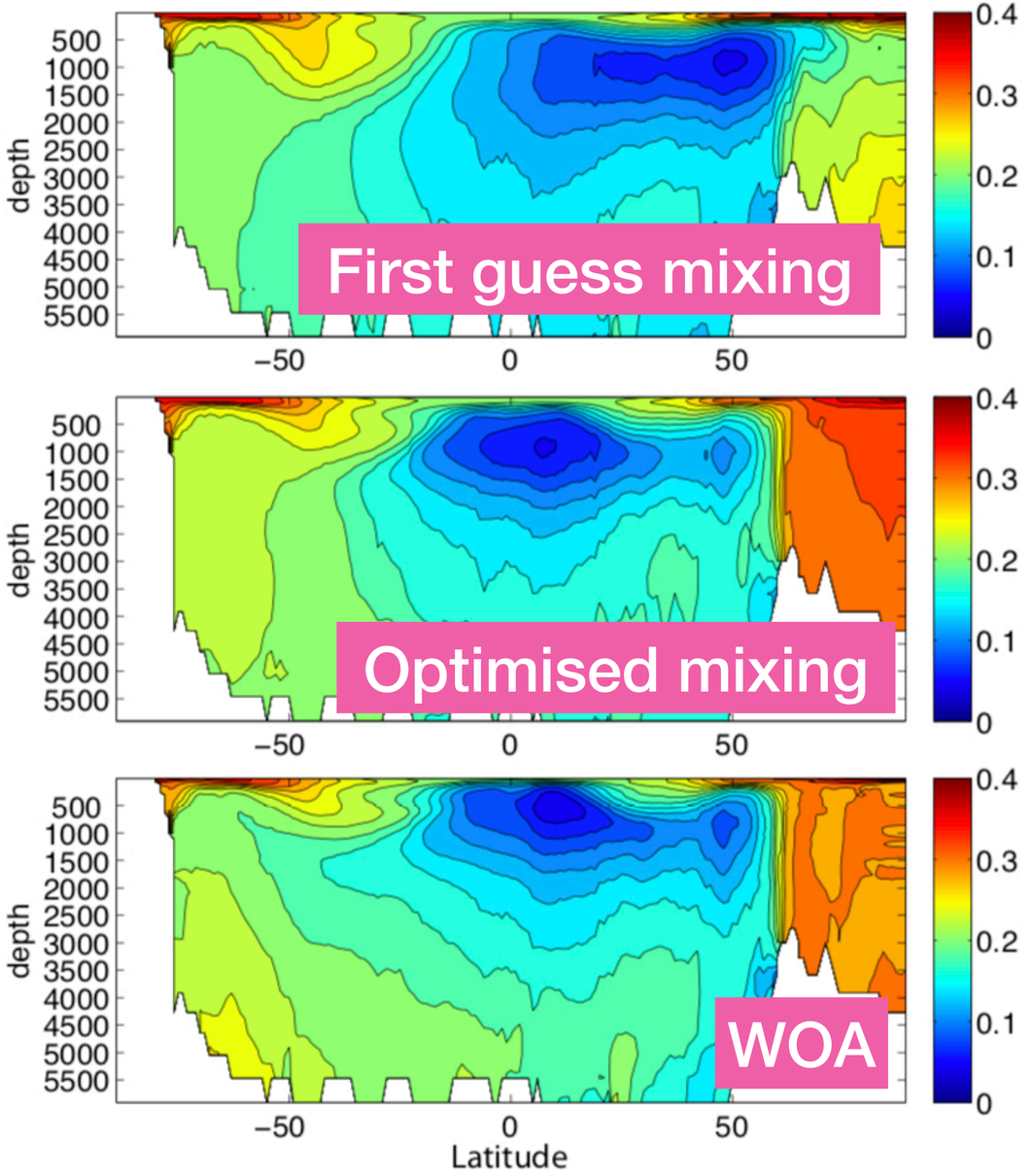
Download Product

Download Product (mirror)

https://ecco.jpl.nasa.gov

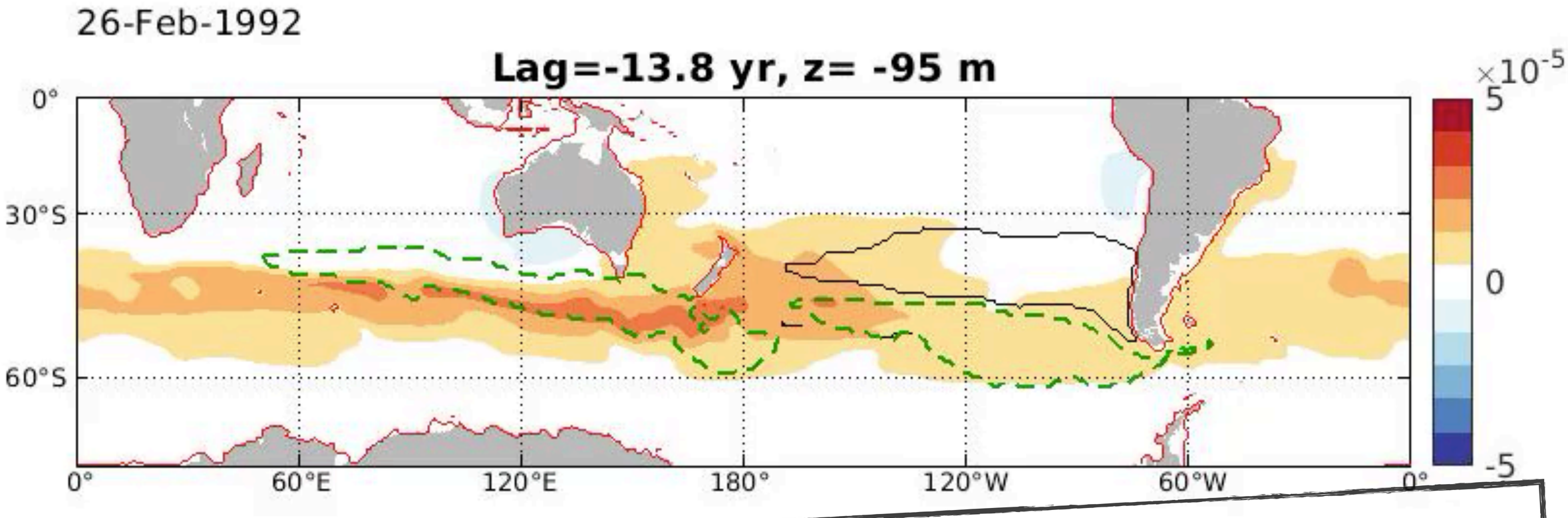
ECCOv4 is constrained by observations

Simulated oxygen concentration, derived using optimised mixing rates, shows that the **ventilation process compares well with observations** (e.g. World Ocean Atlas)



Forget, Ferreira, and Liang (2015)

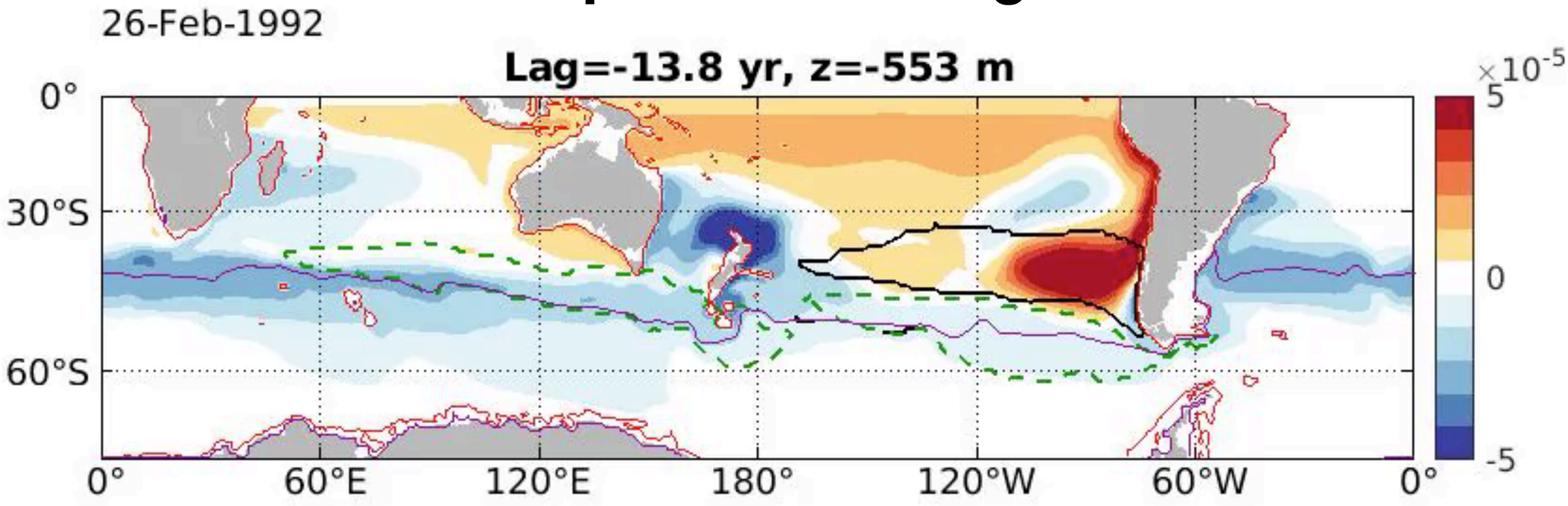
Kinematic sensitivities reveal source water pathways



(Animation, supplemental info)

Jones et al. (JGR-Oceans, 2019)
Jones et al. (JPO, 2020)
Boland et al. (JGR-Oceans, 2021)

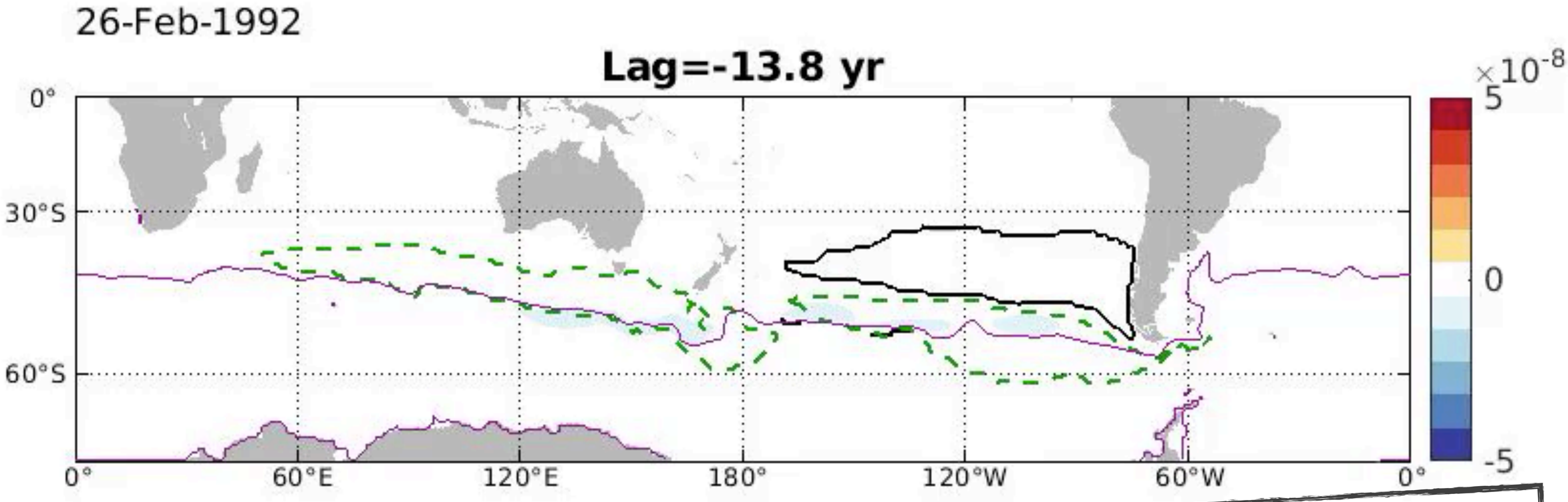
East Pacific heat content is sensitive to basin-scale temperature changes



(Animation, supplemental info)

Jones et al. (JGR-Oceans, 2019)
Jones et al. (JPO, 2020)
Boland et al. (JGR-Oceans, 2021)

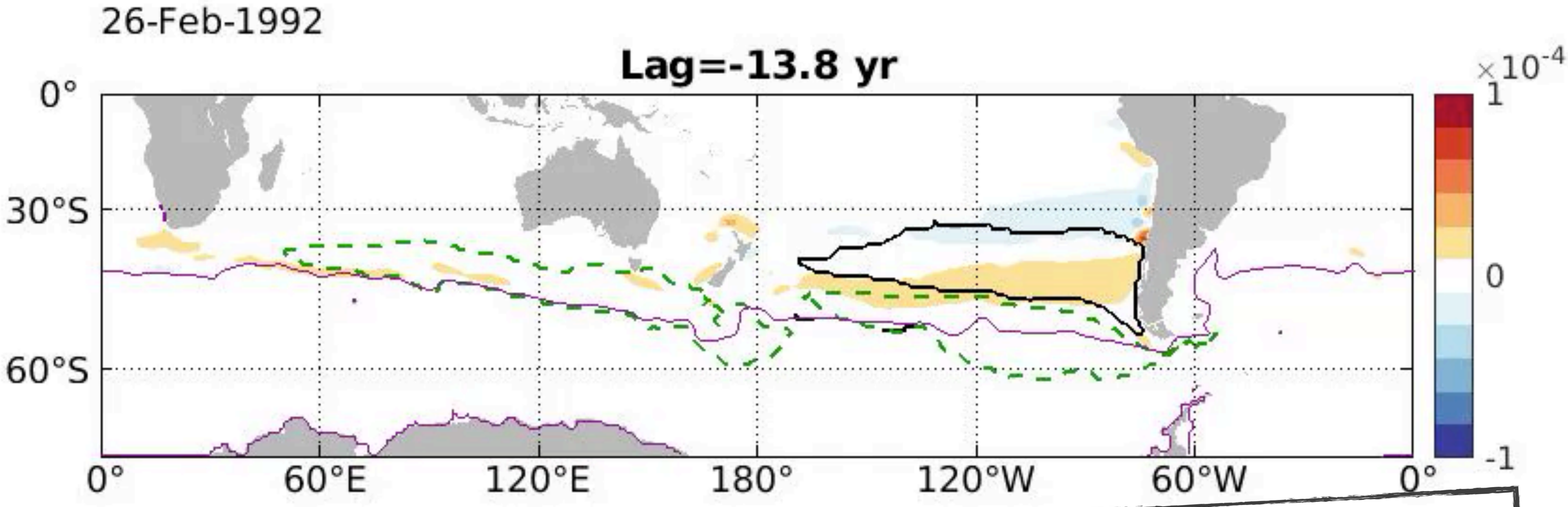
East Pacific heat content is sensitive to net heat flux anomalies along the SAF



(Animation, supplemental info)

Jones et al. (JGR-Oceans, 2019)
Jones et al. (JPO, 2020)
Boland et al. (JGR-Oceans, 2021)

East Pacific heat content is sensitive to wind stress as the RVP boundaries



Jones et al. (JGR-Oceans, 2019)
Jones et al. (JPO, 2020)
Boland et al. (JGR-Oceans, 2021)

Animation, supplemental info