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Adjoint sensitivities: Mechanisms for sea level variability in the Southern Ocean Indian sector under strong warming scenario

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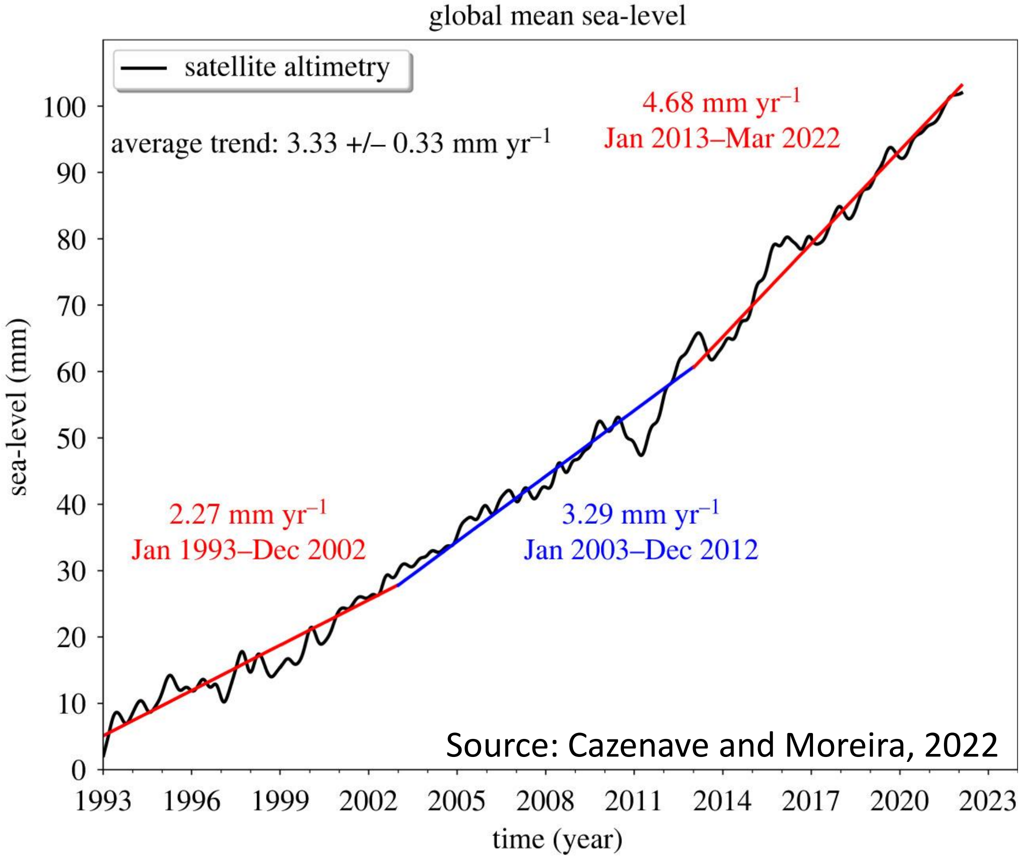
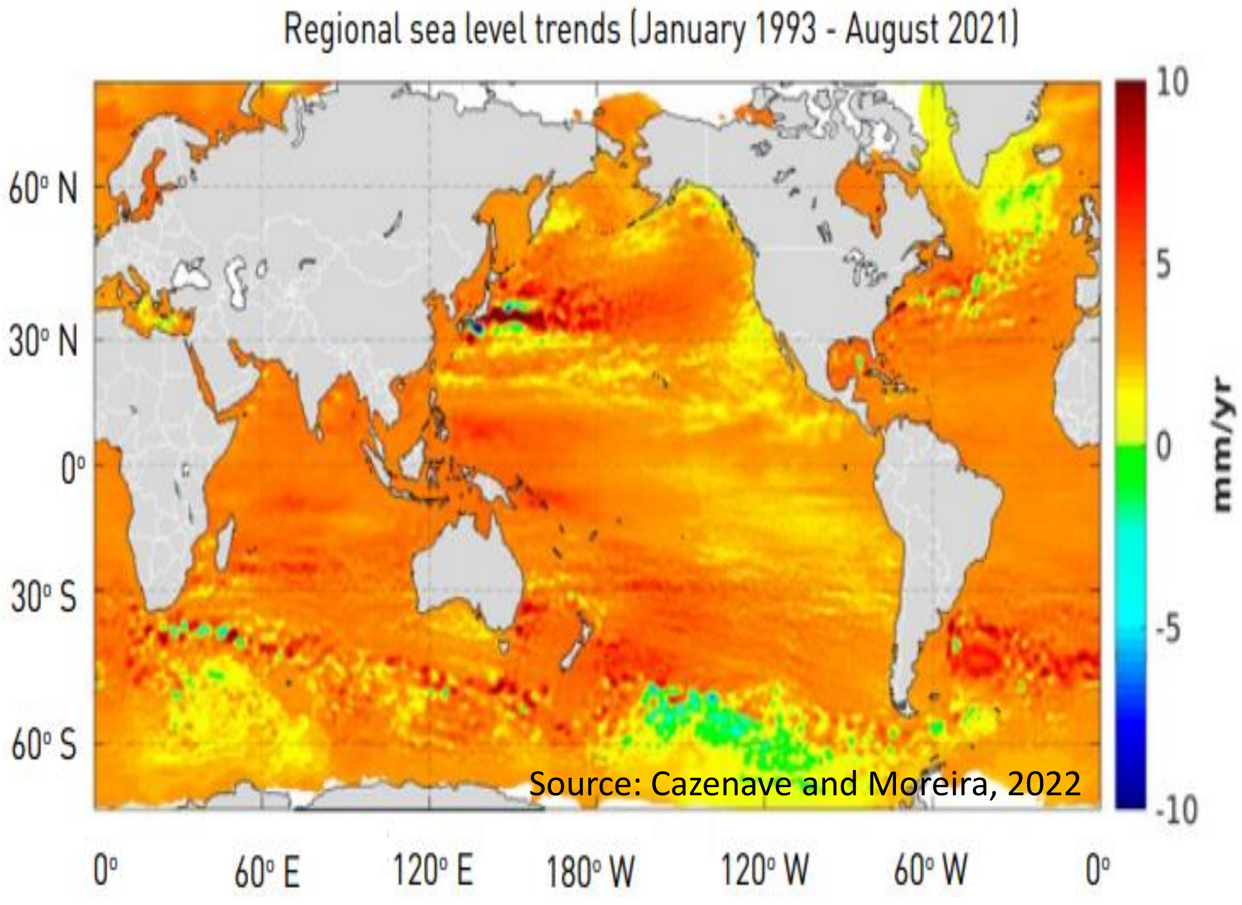
Southern Ocean, shot by Linsay Brown

Introduction

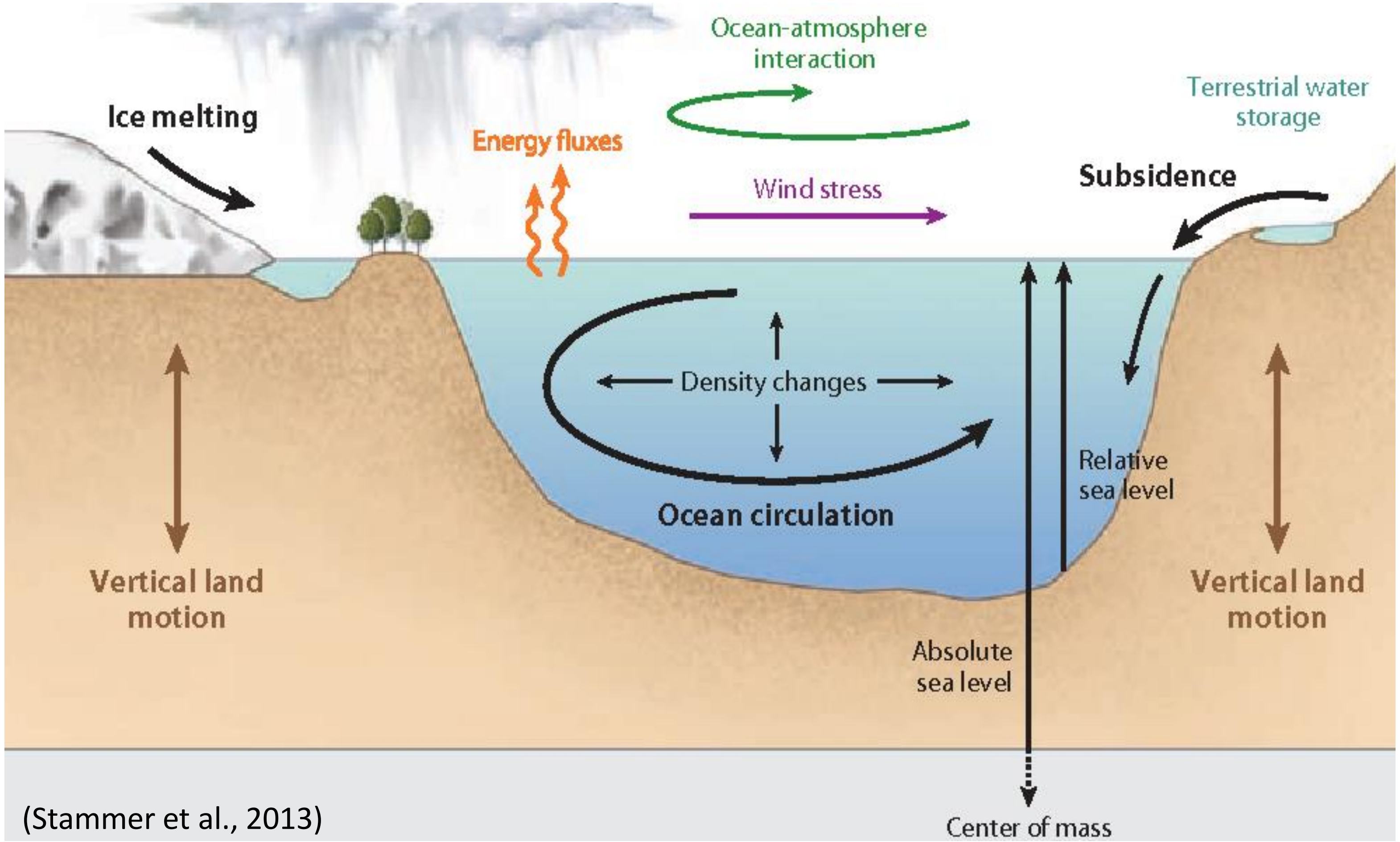




- Sea level is rising
- Global Mean Sea level is rising
- GMSL rise has accelerated due to global warming
- Imporant!

- Sea level trend is not uniform spatially
- Different regions different mechanisms

Processes that influence regional sea level



(Stammer et al., 2013)

(1) Dynamic Sea Level

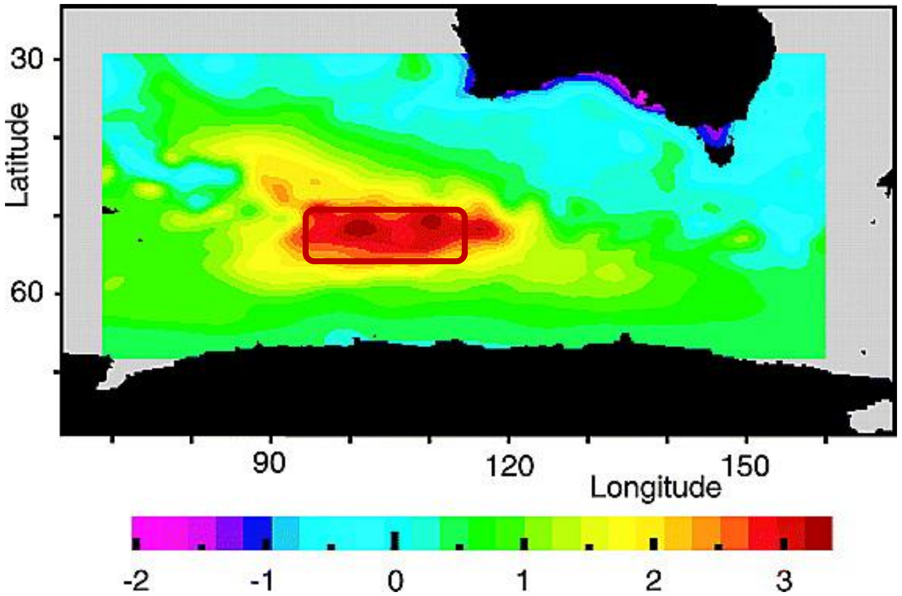
- **Ocean circulation**
- **Density changes**
- **Wind Stress**
- **Heat Flux**
- **Freshwater Flux**

(2) Other processes

- **Land motion**
- **Solid earth changes in the long term**

- **Need to consider the specific region and timescale**
- **In most places, dynamic sea level is dominant on interannual to decadal timescale!**

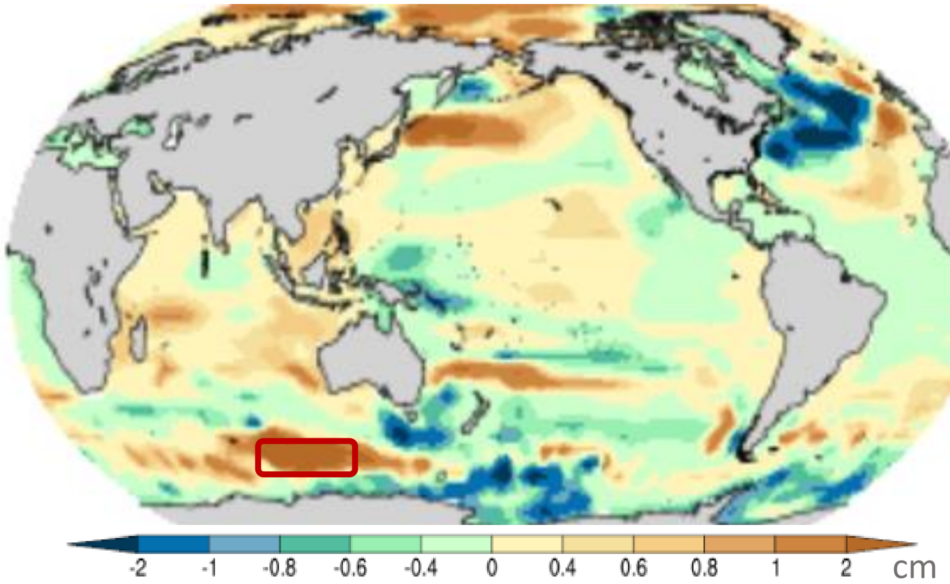
Motivation/Region/Previous studies



(Webb and de Cuevas, 2002)

Amplitude of 1st mode of SSH (normalized to have unit variance when averaged over the region)

- A region of high SSH variablity
- Wind-induced Ekman pumping



(Nandini-Weiss, S.D., et al., 2023)

Difference in standard deviation of monthly SSHa, RCP8.5(2081-2100)-Historical period (1986-2006)

- Increased SSH variability under global warming in Southern Ocean Indian sector, linked with wind stress

Knowledge gap:
Mechanisms of low-frequency SSH variability (>3yr) in this region is to be explored

Research question:

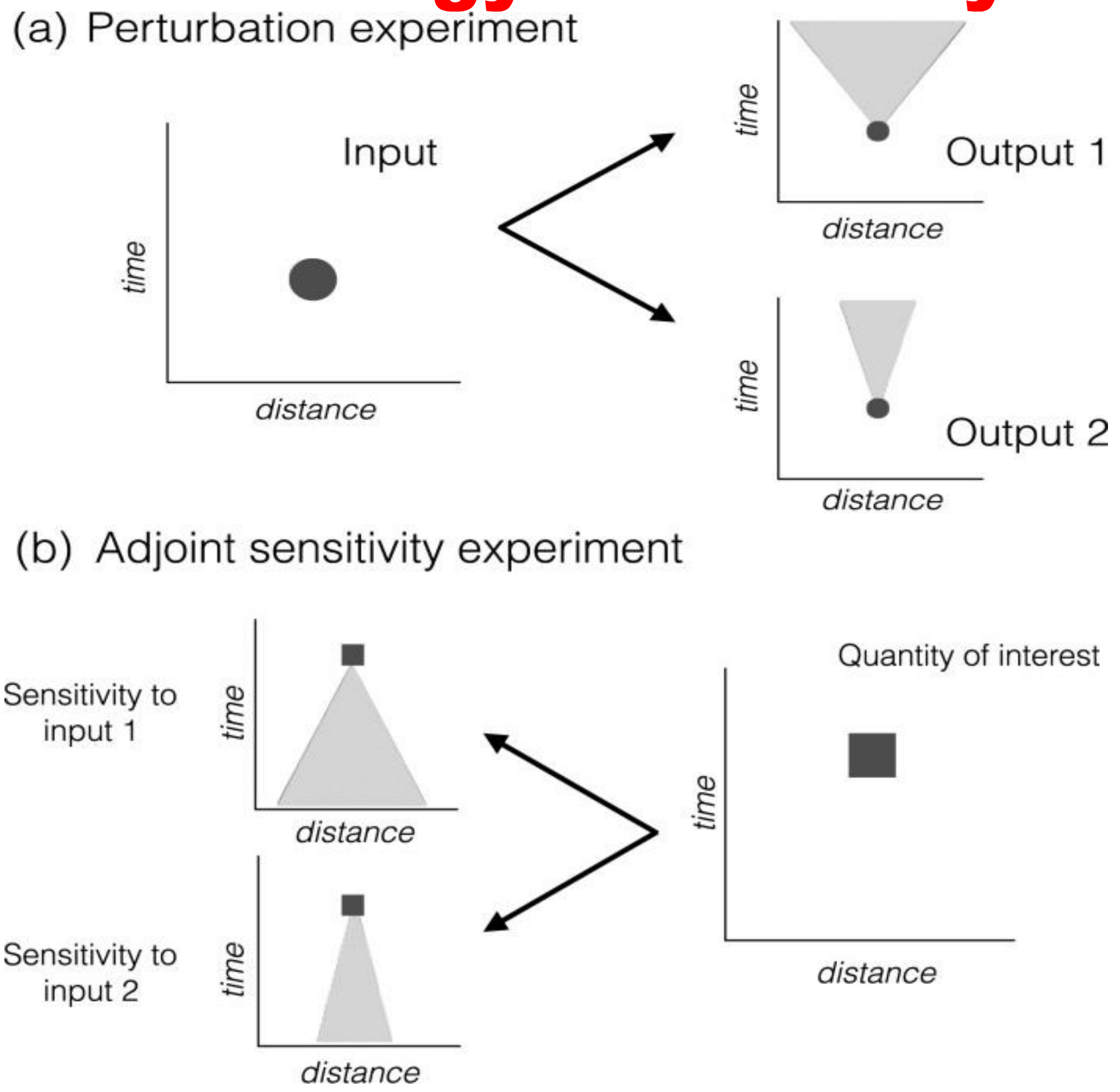
How sensitive of large–scale low-frequency dynamic sea level to surface forcing and whats are associated mechanisms?

1. When/where/which forcing is able to generate long term SSH anomaly (a typical signal of low-frequency variability) ?

2. Which forcing has the most contribution? Wind stress or Buoyancy fluxes?

3. What ocean dynamics are involved to produce SSH anomaly?

Methodology: sensitivity analysis



Schematic of (a) traditional forward perturbation experiment and (b) an adjoint sensitivity experiment. (Jones et al., 2018)

1. Perturbe one input
2. Run forward model
3. Obtain response in all outputs

- **Ensemble of perturbations**
- **Expensive, re-run for every change applied**

1. Perturb one output (e.g SSH)
2. Run **adjoint model** (“backward” model)
3. Obtain linearized sensitivity to all inputs

✓ **Efficient! One time simulation**

✓ **Identify physical processes and pathways via dynamic chain**

What is adjoint sensitivity? & how to derive it?

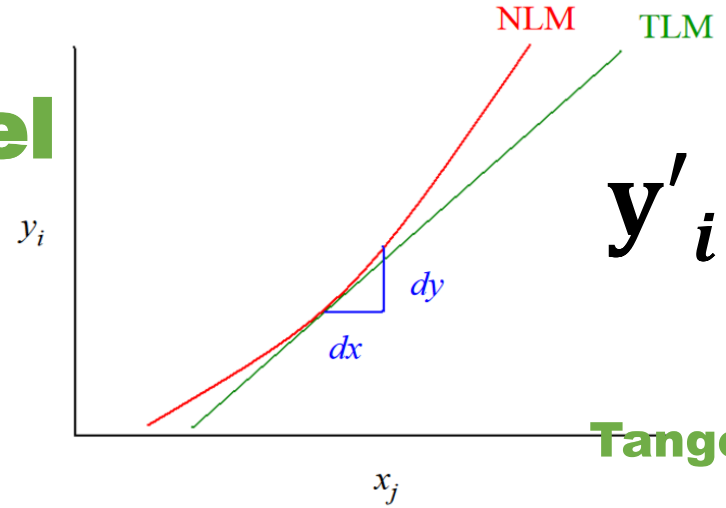
Nonlinear Forward Model

Maps inout x to output y

$$\mathrm{y} = \boxed{M}(x)$$

Nonlinear Operator

A graphical TLM schematic



Tangent Linear Model

First order approximation of nonlinear model

$$\mathrm{y}'_i = \boxed{\sum_j \frac{\partial y_i}{\partial x_j}} \boxed{x'_j}$$

Perturbation

Tangent Linear Operator

Adjoint Model

A transformation of tangent linear model

Cost Function J

A function of the mode state

$$J = J(y) = J[M(x)]$$

$$\frac{\partial J}{\partial x_j} = \boxed{\sum_i \frac{\partial y_i}{\partial x_j}} \boxed{\frac{\partial J}{\partial y_i}}$$

Gradient

Adjoint Operator

Adjoint sensitivity $\frac{\partial J}{\partial x}$

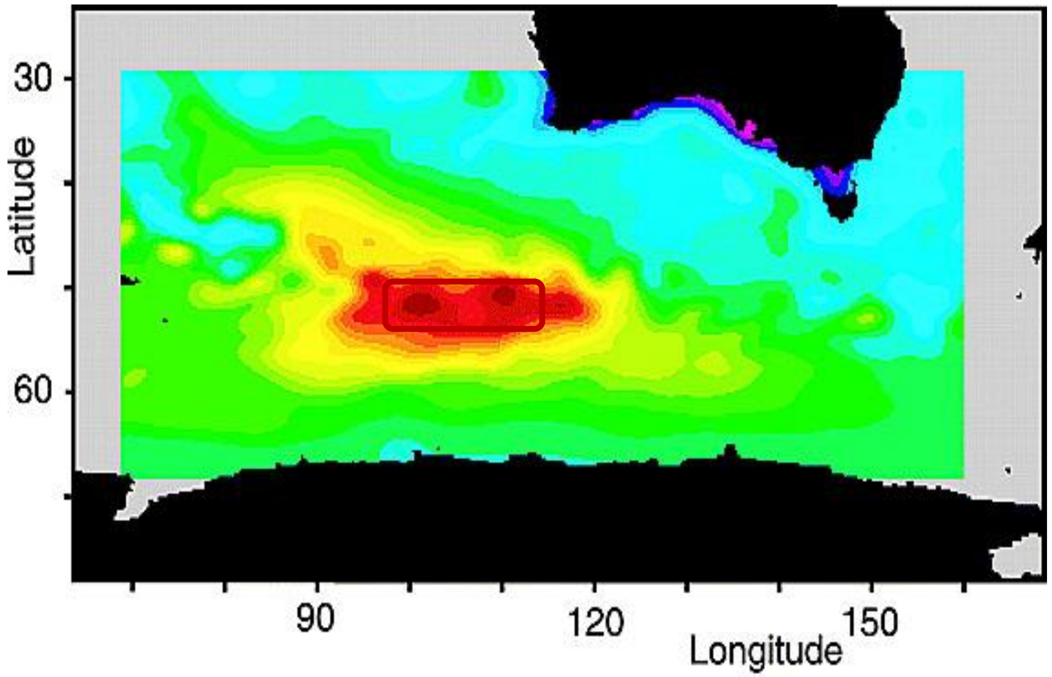
Reveal how the changes in x can affect J

Cost Function *J*

last 3 yr mean dynamic SL anomaly averaged over target region

$$J = \frac{1}{(t_2 - t_1)A} \int_{t_1}^{t_2} \int_A \eta \quad \mathrm{d}A\, \mathrm{d}t$$

- **A scaler value calculated from forward model**
- **A signal of large-scale sea level variability**
- **A forcing that drives adjoint model backward**



Timescale:
(t2 – t1) is the last 3 year over a 10-year simulation

***η* : Dynamic Sea Level (sea level anomaly above GMSL due to ocean dynamics)**

Region of interest A :
the box covering the first EOF mode
[52-56S, 96-112E] (1x4 grids box)

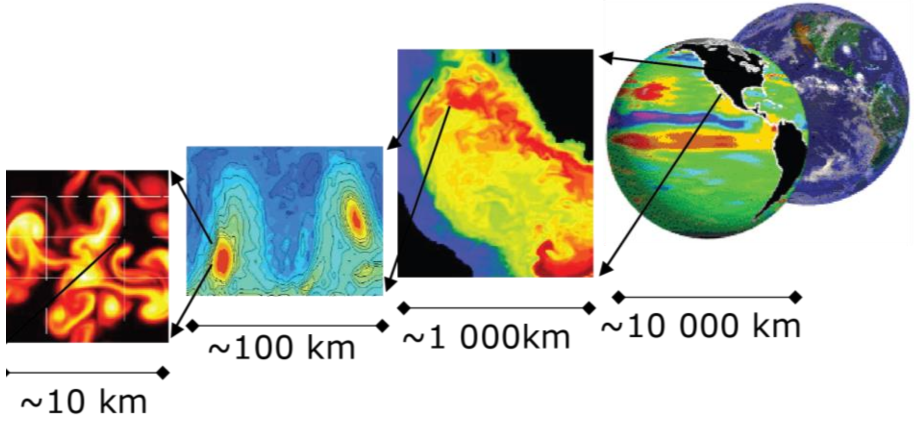
Model

MITgcm and its adjoint

- **Navier-Stokes equations**
- **Adjoint code via automatic differentiation**

$$\frac{\partial \boldsymbol{v}}{\partial t} + (f+\zeta)\hat{\boldsymbol{k}} \times \boldsymbol{v} + \nabla_{z^*}\mathrm{KE} + w\frac{\partial \boldsymbol{v}}{\partial z} + g\nabla_{z^*}\eta + \nabla_h \Phi'$$
$$= \boldsymbol{D}_{z^*,\boldsymbol{v}} + \boldsymbol{D}_{\perp,\boldsymbol{v}} + \mathcal{F}_{\boldsymbol{v}},$$
$$\frac{\partial \Phi'}{\partial z} = g\frac{\rho'}{\rho_c},$$
$$\frac{1}{H}\frac{\partial \eta}{\partial t} + \nabla_{z^*}(s^*\boldsymbol{v}) + \frac{\partial w}{\partial z^*} = s^*\mathcal{F},$$
$$\frac{\partial (s^*\theta)}{\partial t} + \nabla_{z^*}(s^*\theta\boldsymbol{v}_{\mathrm{res}}) + \frac{\partial (\theta w_{\mathrm{res}})}{\partial z^*}$$
$$= s^*(\mathcal{F}_\theta + D_{\sigma,\theta} + D_{\perp,\theta}),$$
$$\frac{\partial (s^*S)}{\partial t} + \nabla_{z^*}(s^*S\boldsymbol{v}_{\mathrm{res}}) + \frac{\partial (S w_{\mathrm{res}})}{\partial z^*}$$
$$= s^*(\mathcal{F}_S + D_{\sigma,S} + D_{\perp,S}),$$

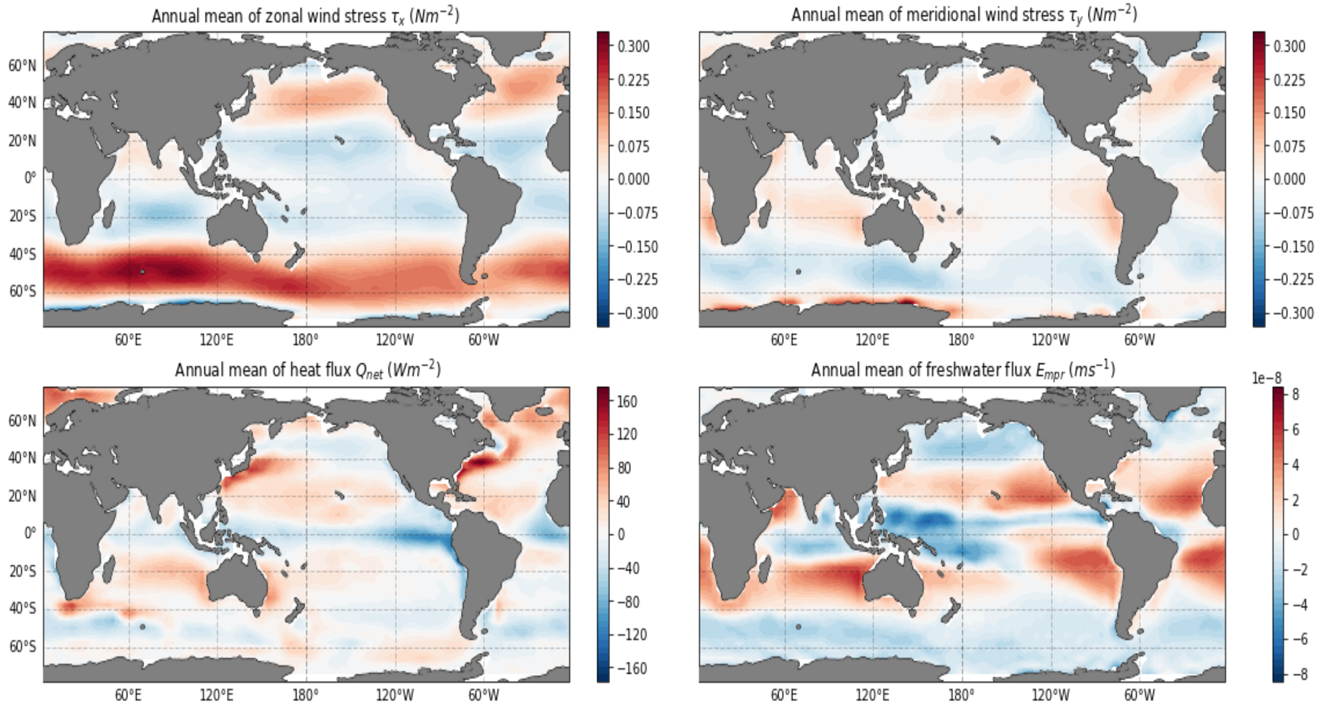
MIT general circulation model



configuration

- **4°x4° spherical polar grid**
- **Quasi-global (80N-80S)**
- **15 vertical layers (50m - 690m)**
- **Climatological monthly mean forcing**

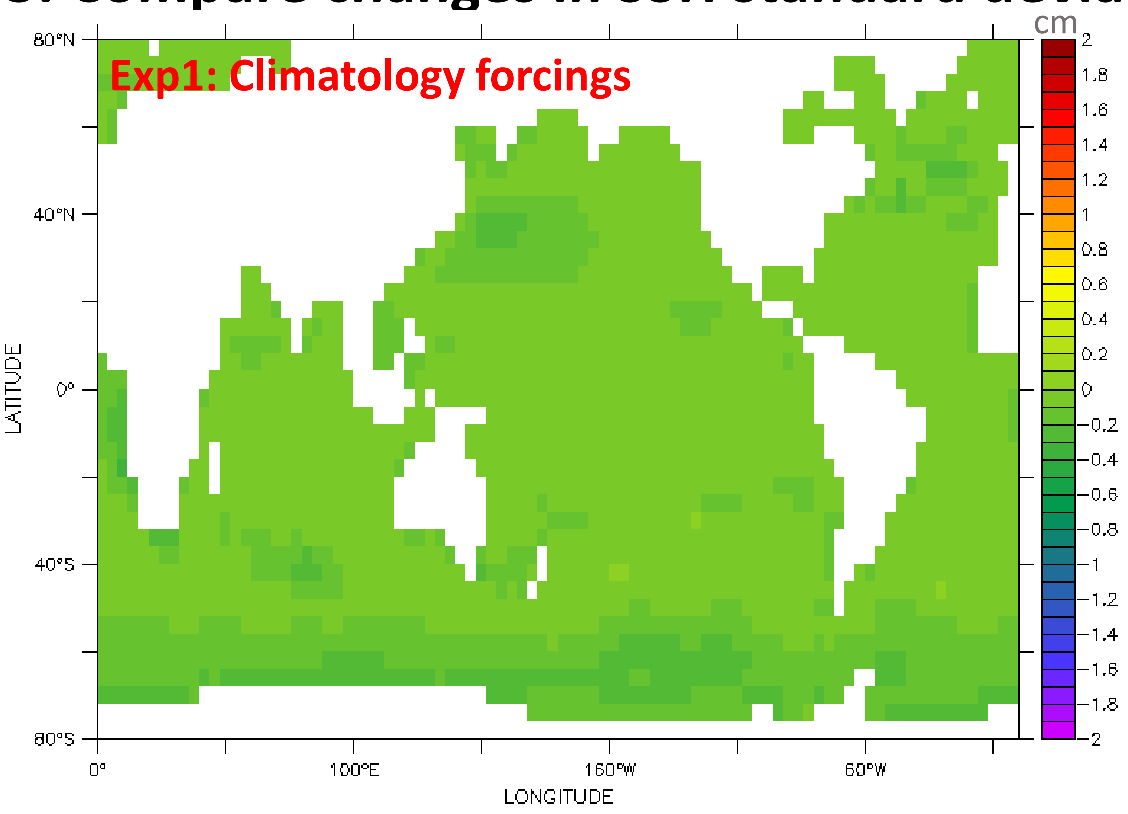
- **Initiated from climatology**
- **Spin-up: 100 year**
- **Run forward 10 years**
- **Timestep: 12 hours**
- **SST/SSS relaxation**
- **Monthly snapshot fields are saved**

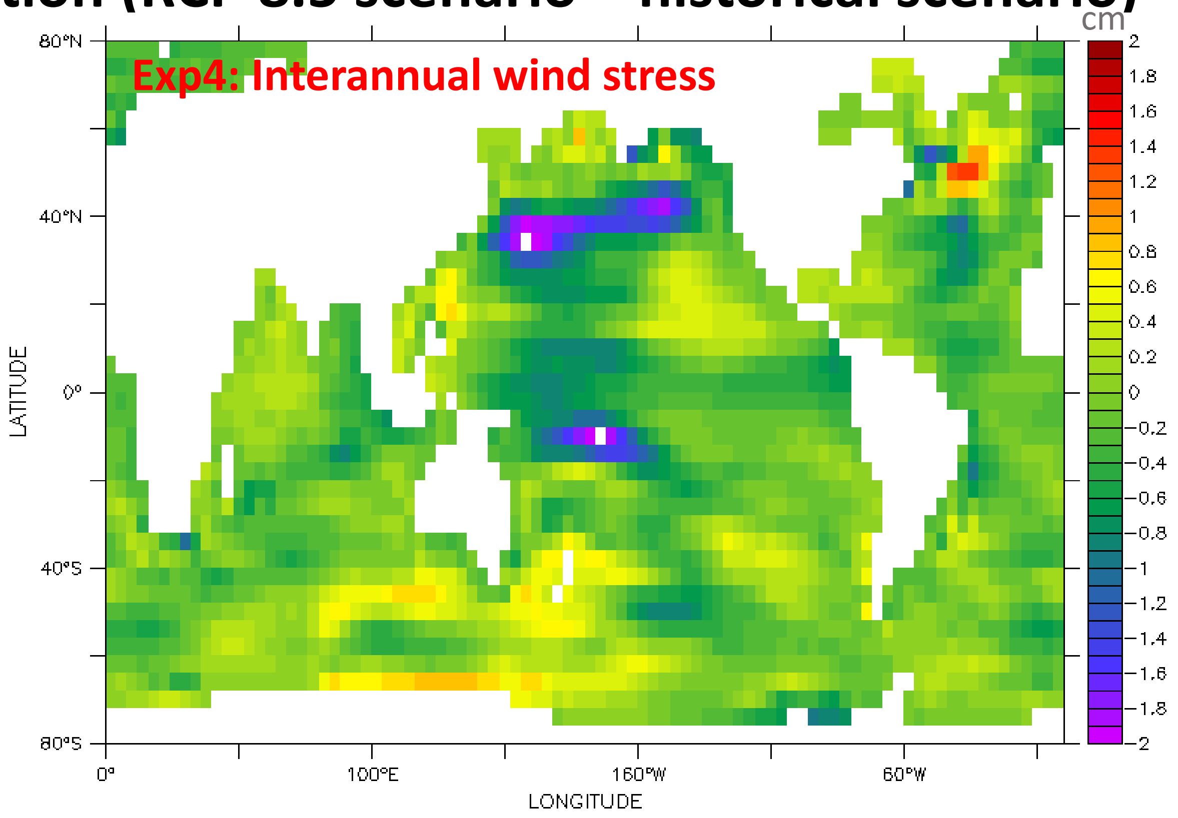


(NCEP/NCAR, Trenberth et al.)

The forward perturbation experiment

1. Driven by climatological zonal & meridional wind stress, heat & freshwater fluxes
2. Replace one forcing with interannual-varying forcing (with interannual variability)
3. Compare changes in SSH standard deviation (RCP 8.5 scenario – historical scenario)

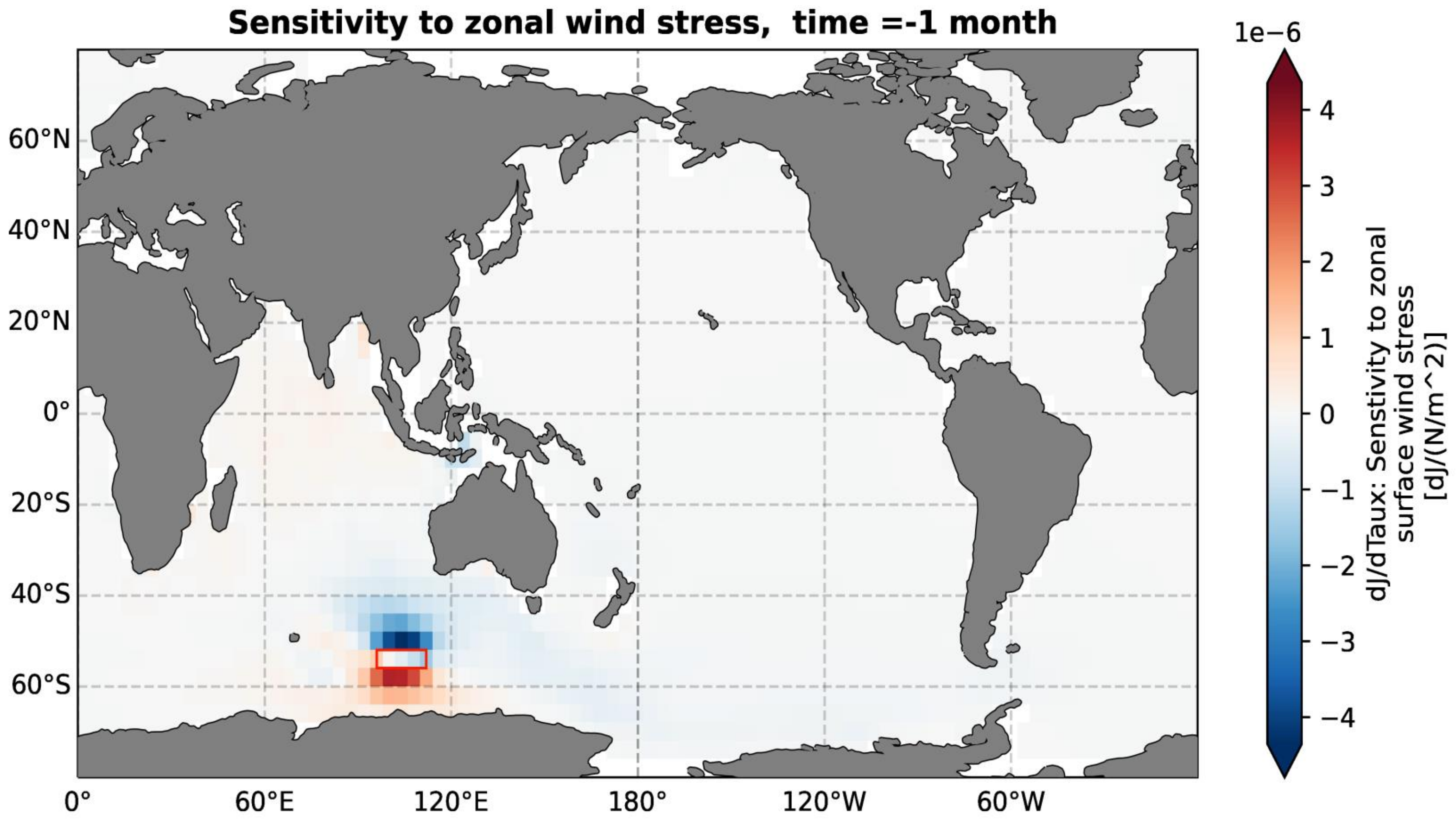




- Wind stress seems be to the most important to influence SSH variability
- But wehre and when wind stress is important?
- Can we assess of contribution of each forcing quantitatively?

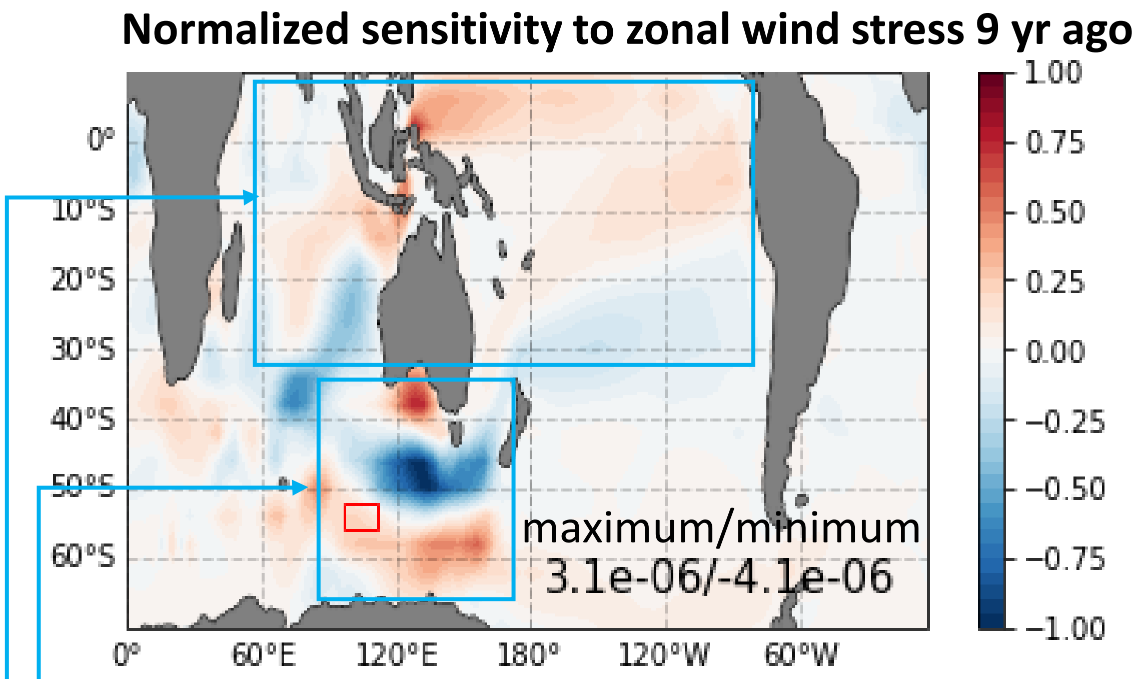
The Adjoint solutions

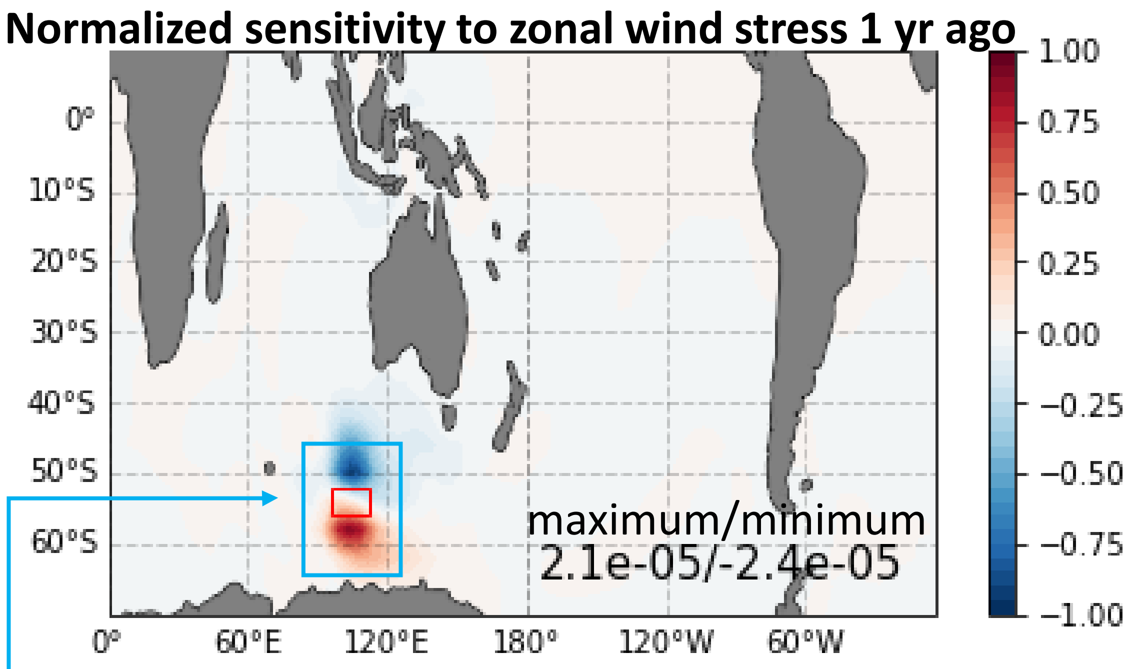
$\partial J/\partial \tau_x$



- **Pinpoint sensitive regions with time backwards**
- **Red colors show areas where positive zonal wind stress anomaly at that time lag increase SSHa in the target region over the last 3-year mean period**
- **Blue colors show areas where positive zonal wind stress anomaly at that time lag decrease SSHa in the target region over the last 3-year mean period**

sensitivity to zonal wind stress





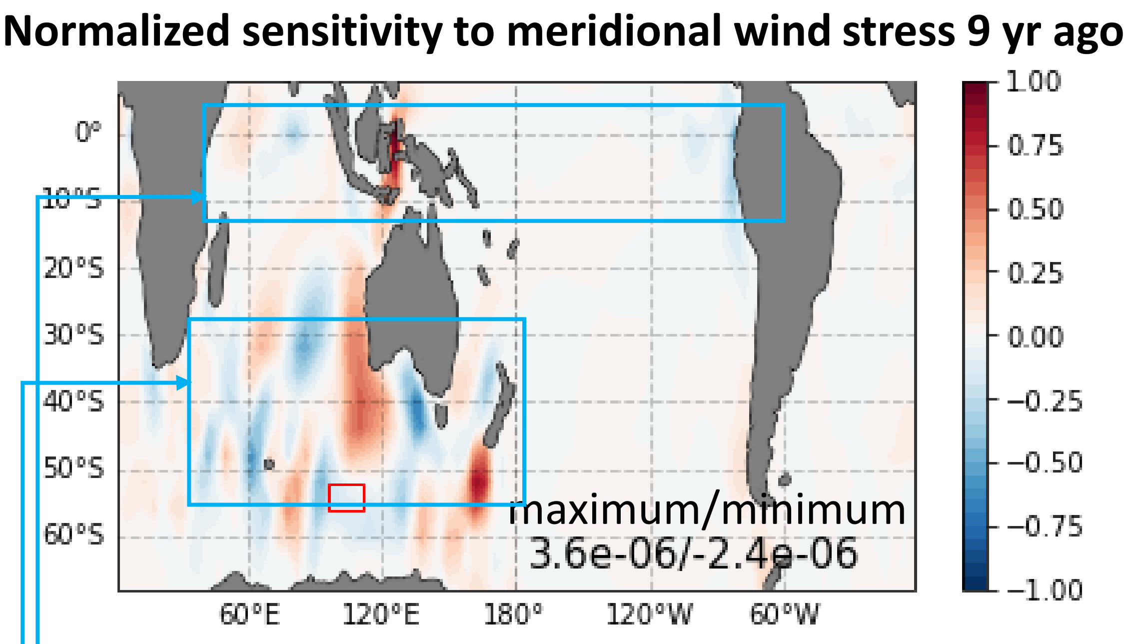
9 years ago

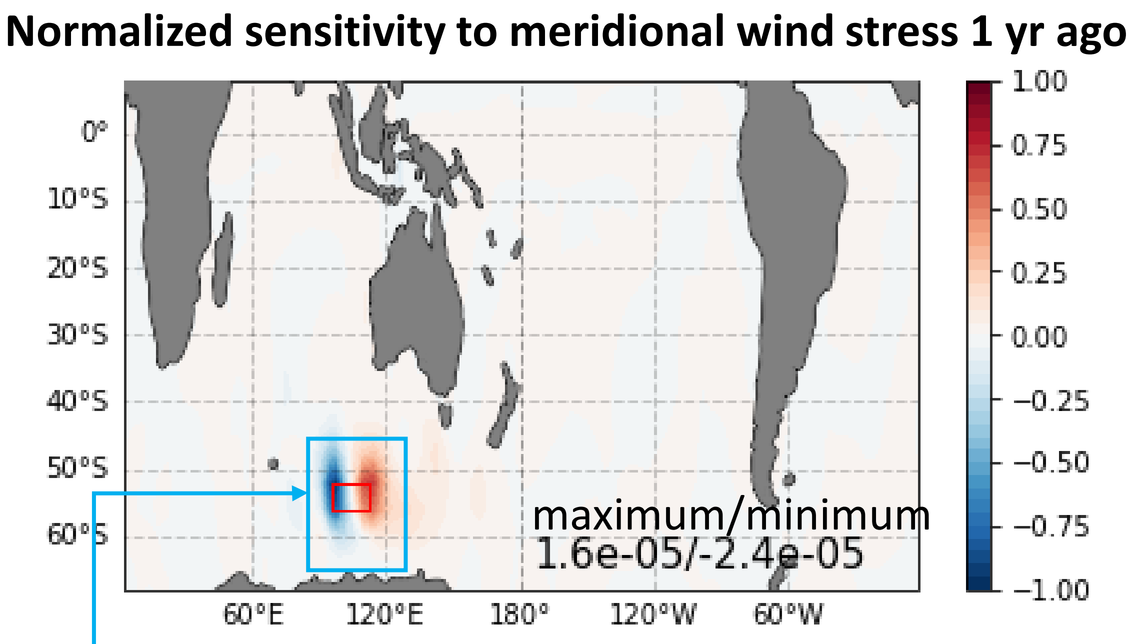
- **Most sensitive to local zonal wind stress between Australia & Antarctica**
- **Less sensitive to non-local wind stress over equator and subtropical**

1 year go

- **Sensitive to local zonal wind stress ONLY north & south of the target region**

sensitivity to meridional wind stress





9 years ago

- **Mostly sensitive to meridional wind stress over broad Southern Indian Ocean**
- **Also sensitive to far wind stress over indonesian passage and Peru coast**

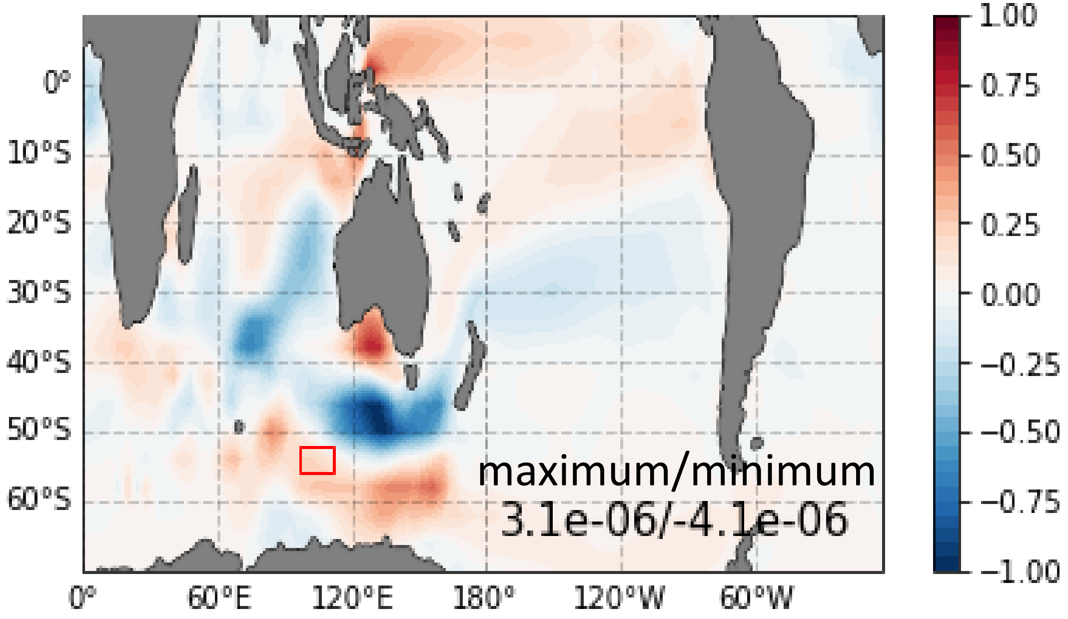
1 year go

- **Sensitive to meridional wind stress ONLY west & east of the target region**

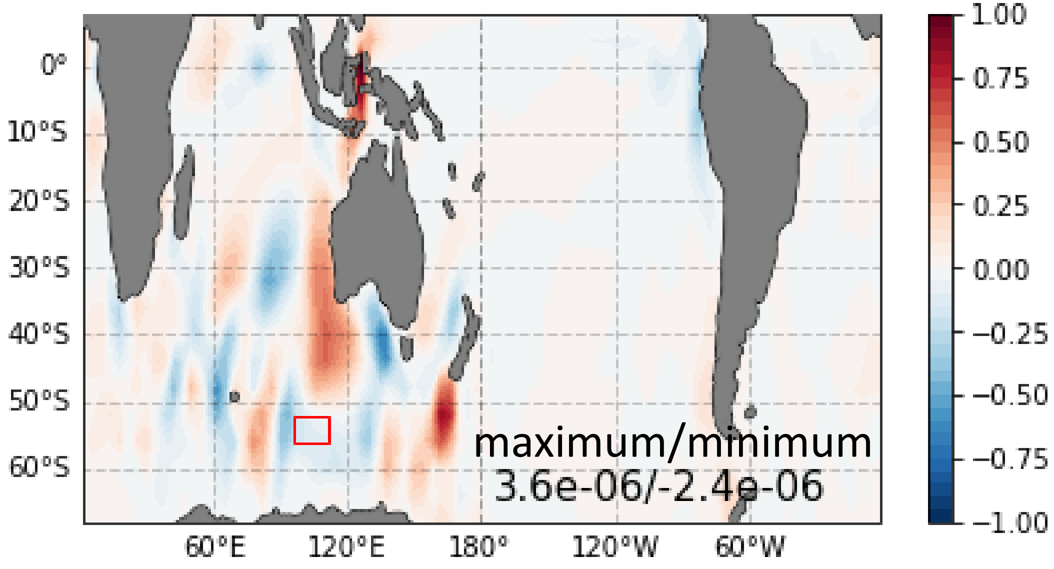
- **Why sensitive in these regions? What does the pattern mean?**

Mechanisms indicated by structure of sensitivity map

Normalized sensitivity to zonal wind stress 9 yr ago

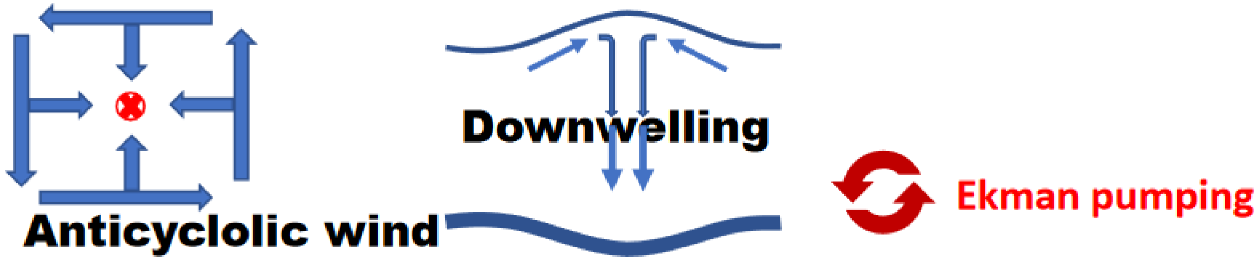


Normalized sensitivity to meridional wind stress 9 yr ago



Strip structure →
- **waves, gyres ?**
- **Northeast-southwest tilt→ Beta effect**

Dipole structure →
- **Convergence/divergence**
- **Ekman pumping/suction**

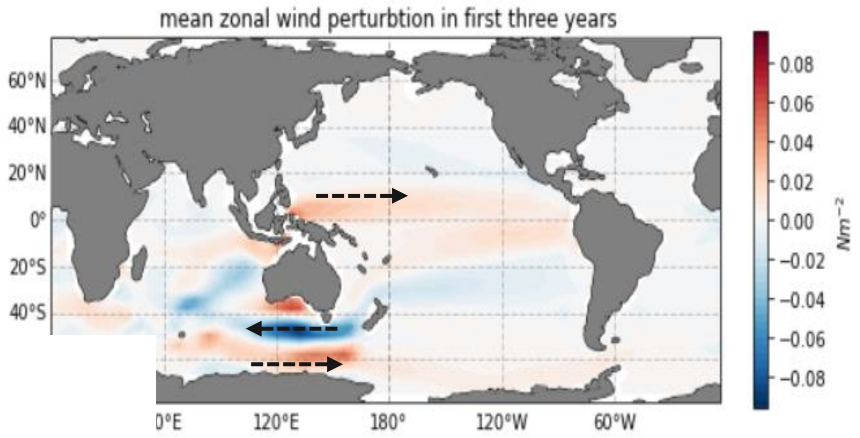


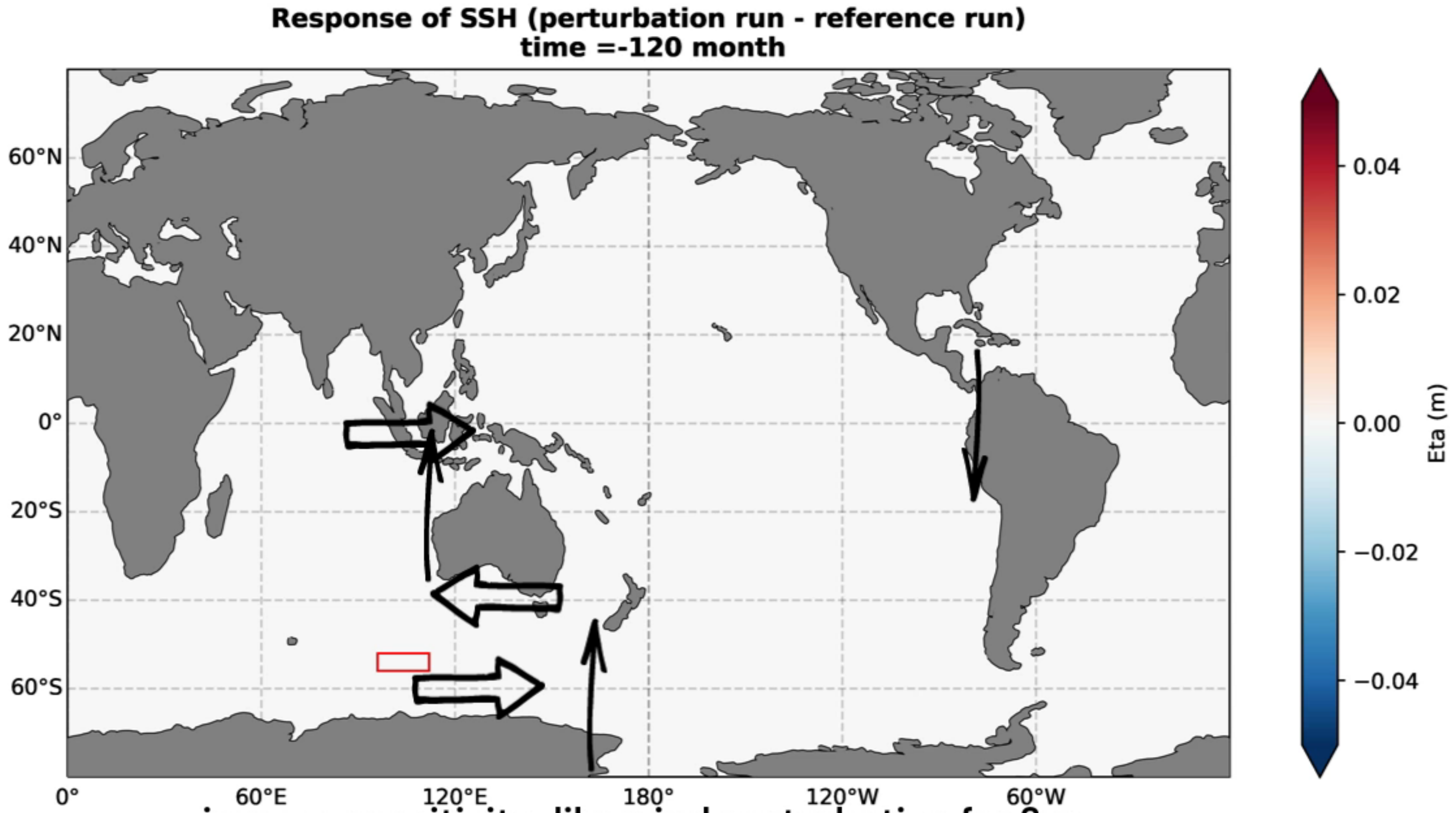
Mechanisms revealed by sensitivity-based perturbation experiments

1. Impose time-evolving wind stress perturbation for 3 years over the background wind field

2. Patterns resemble its sensitivity with a magnitude of 10% of background wind field

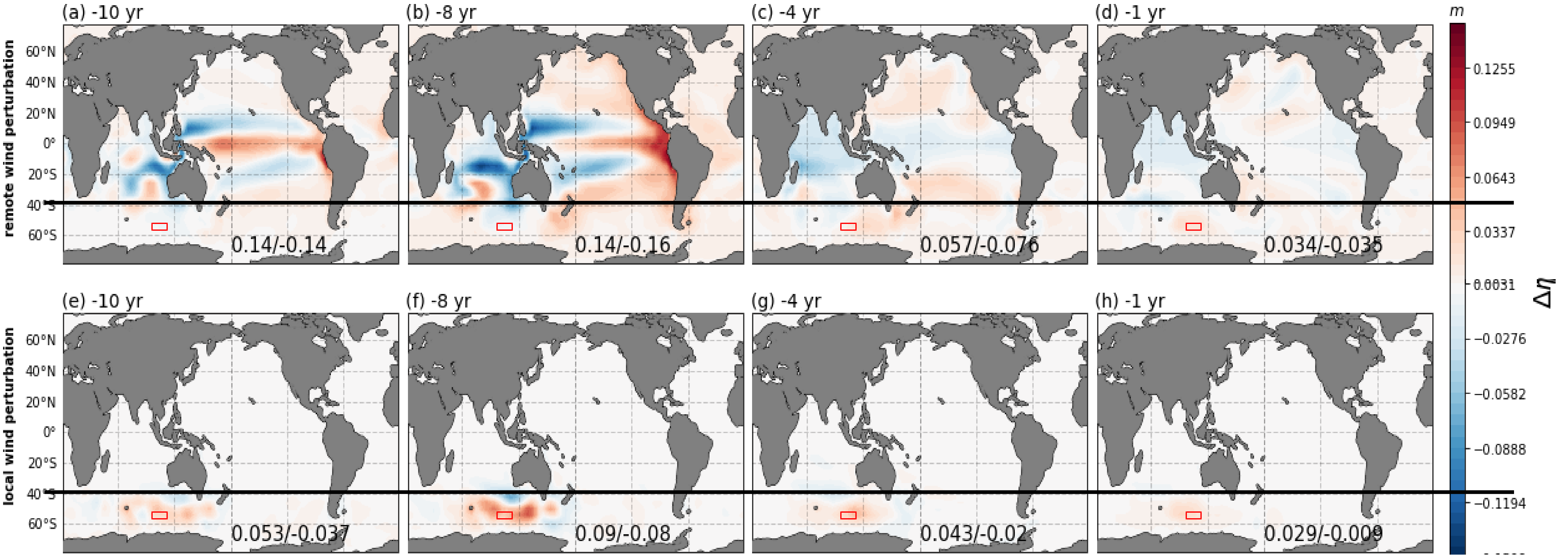
3. Compare the SSH with reference run

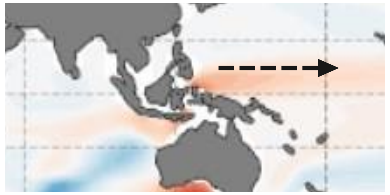




impose sensitivity-like wind perturbation for 3yr
with a magnitude of 10% of the background wind field

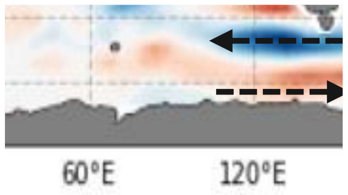
Split perturbation into local & nonlocal





Strengthened Equtorial zonal wind ?

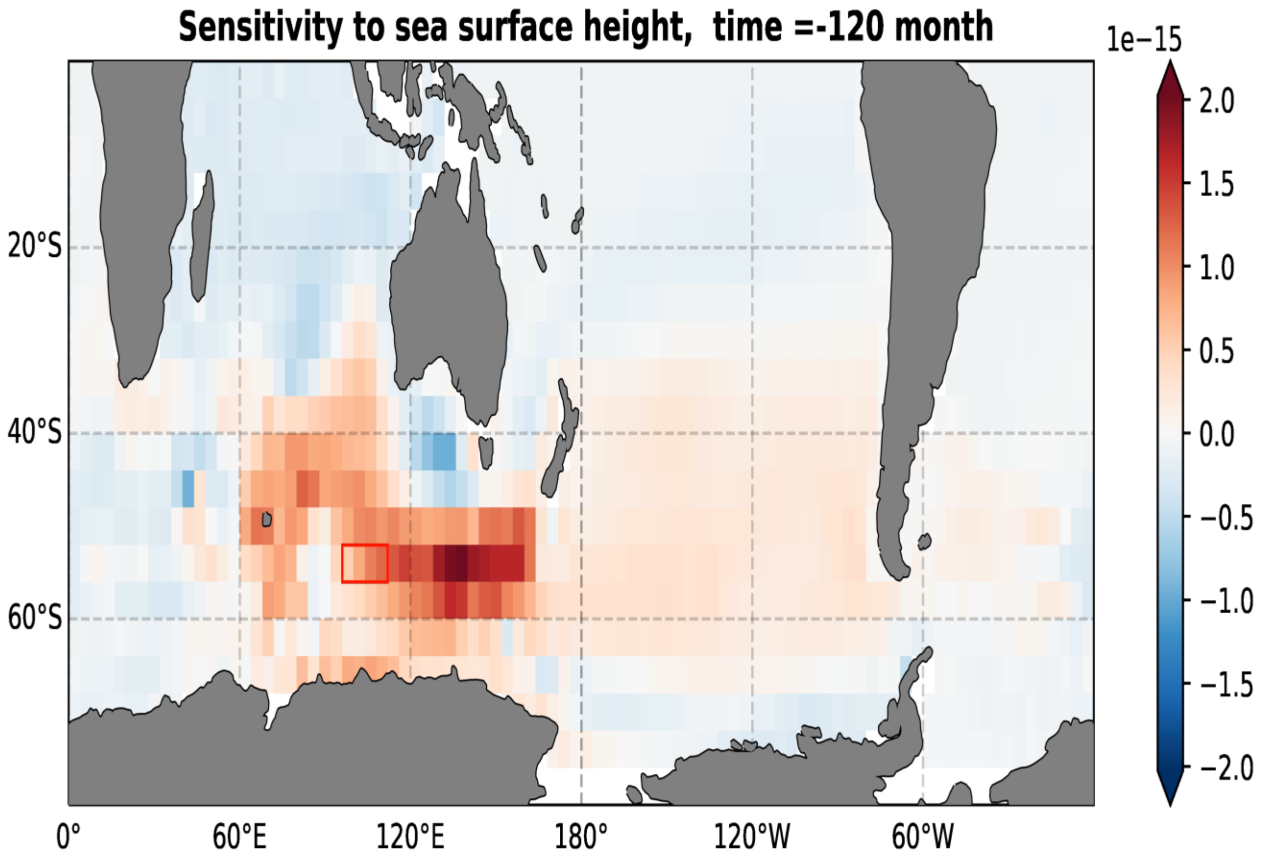
- **Kelvin wave → coastal waves → reflected Rossby wave → passing through Tasman Sea**
- **Takes several years to arrive**

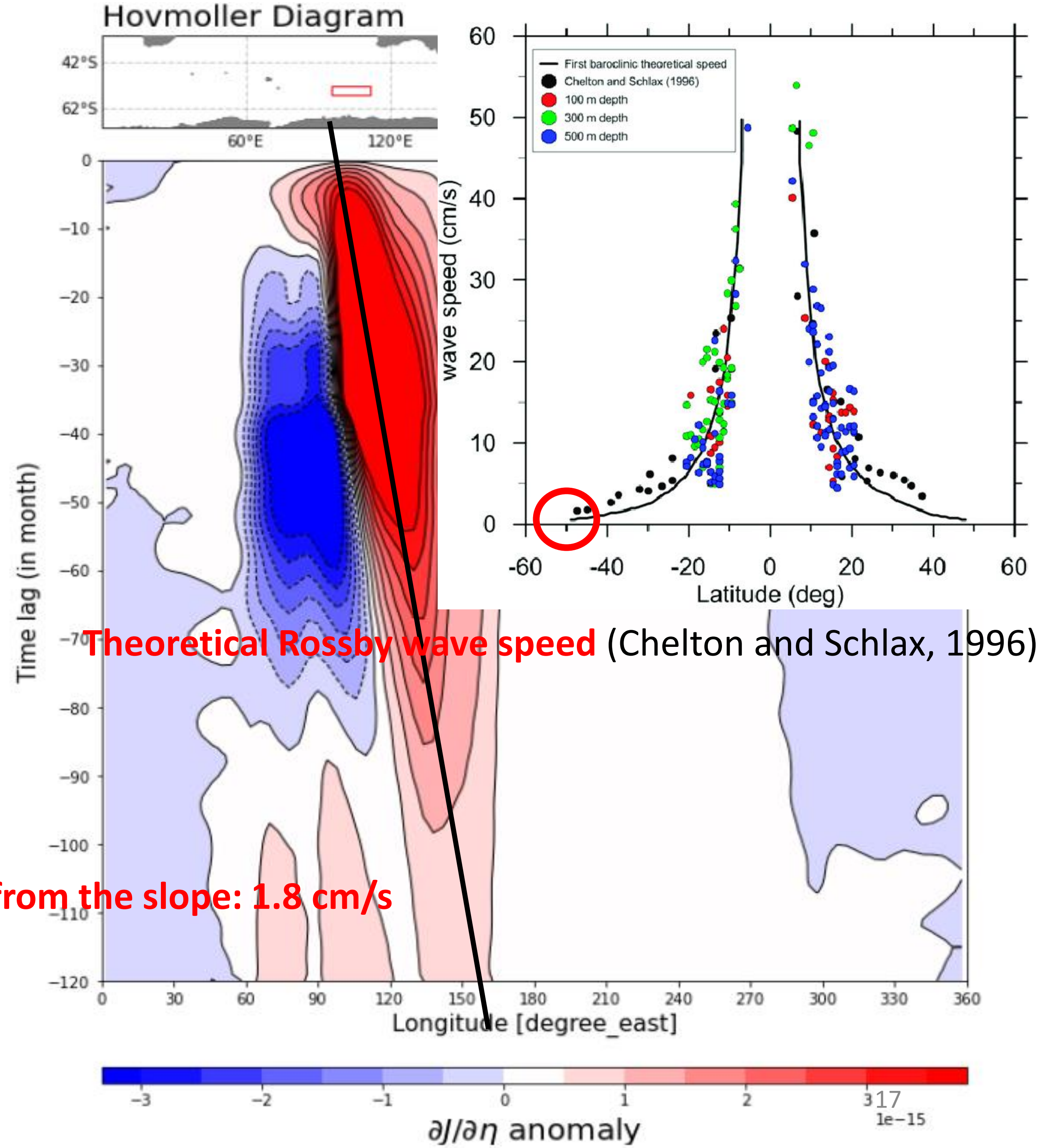


Strengthened Southern Ocean wind stress anomaly?

- **Westward Rossby wave (advected with ACC)**
- **Immediate response**

Sensitivity to sea level anomaly

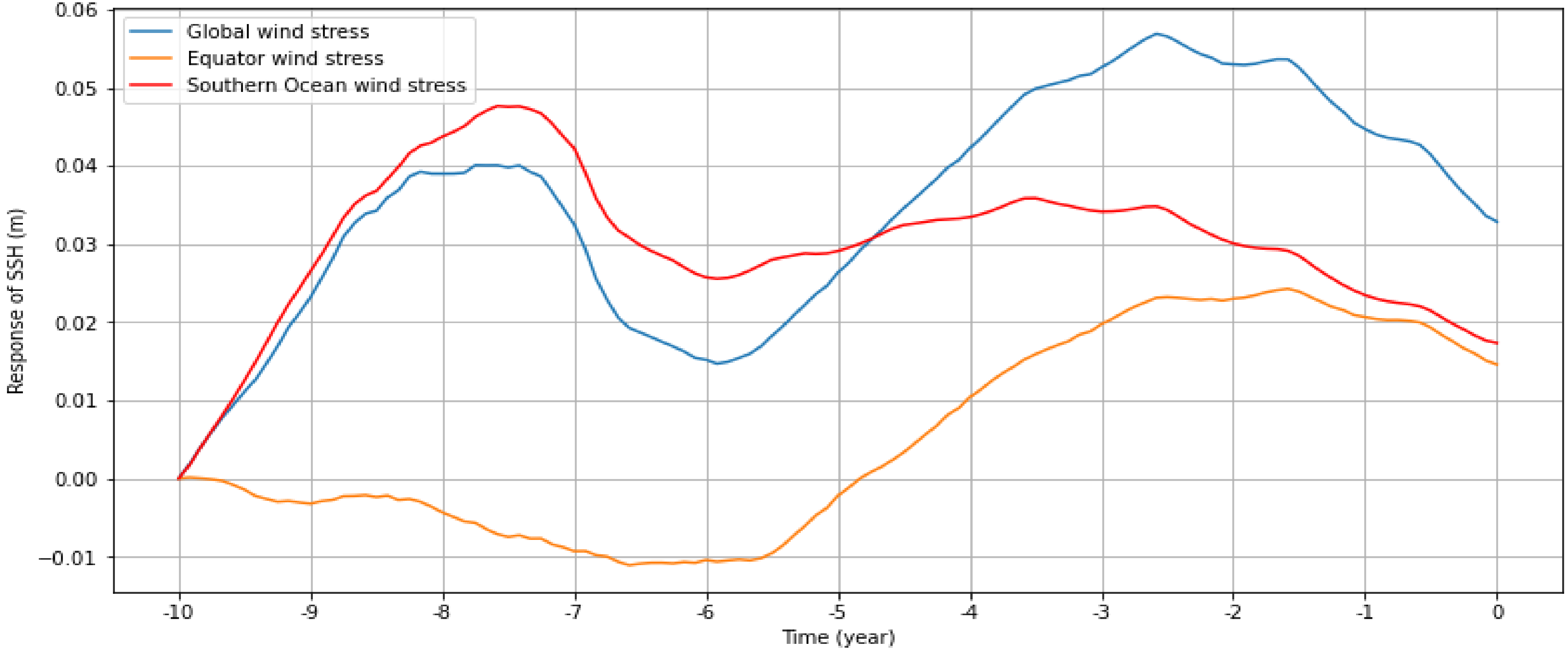




Theoretical Rossby wave speed (Chelton and Schlax, 1996)

Phase speed estimated from the slope: 1.8 cm/s

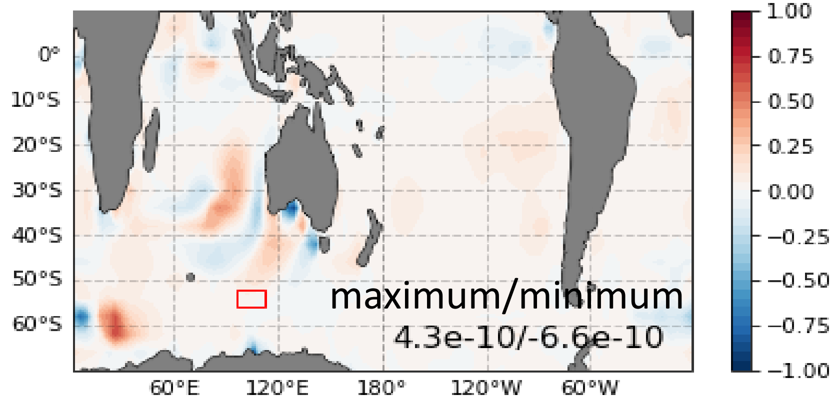
Time evolution of mean SL anomaly in the box region



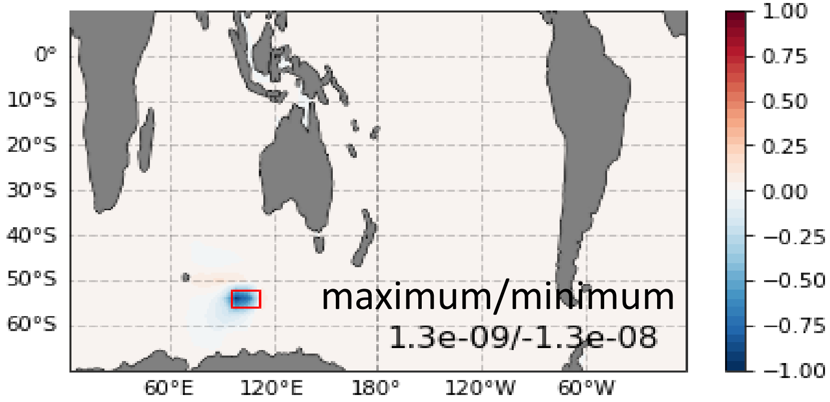
- **Red Curve: Southern Ocean wind stress perturbation has immediate effect on sea level in the target region**
- **Orange Curve: Equatorial wind stress perturbation causes negative SSHa at first and takes ~5 yr to produce positive SSHa in the target region**
- **Blue curve: the reponse of global wind perturbation is almost = the combined response of other two perturbation experiments**
- **Response is linear/ Large-scale surface circulation is linear**

sensitivity to surface heat and freshwater flux

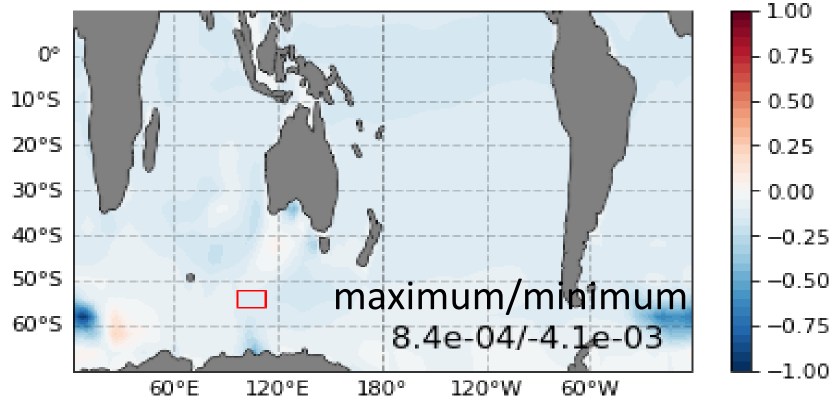
Nomalized sensitivity to heat flux 9 yr ago



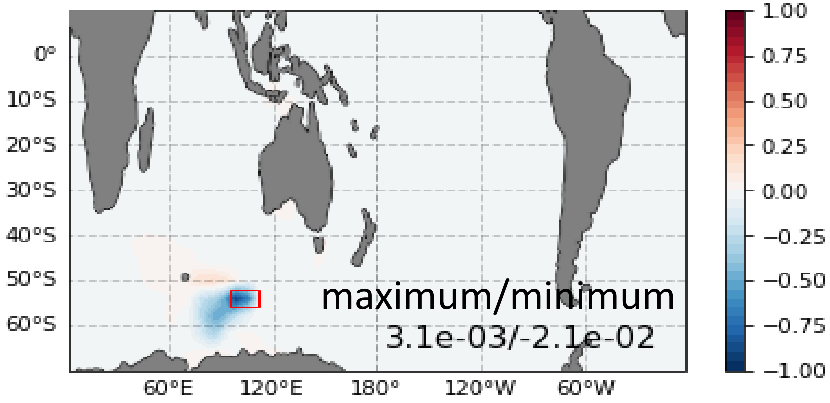
Nomalized sensitivity to heat flux 1 yr ago



Nomalized sensitivity to freshwater flux 9 yr ago



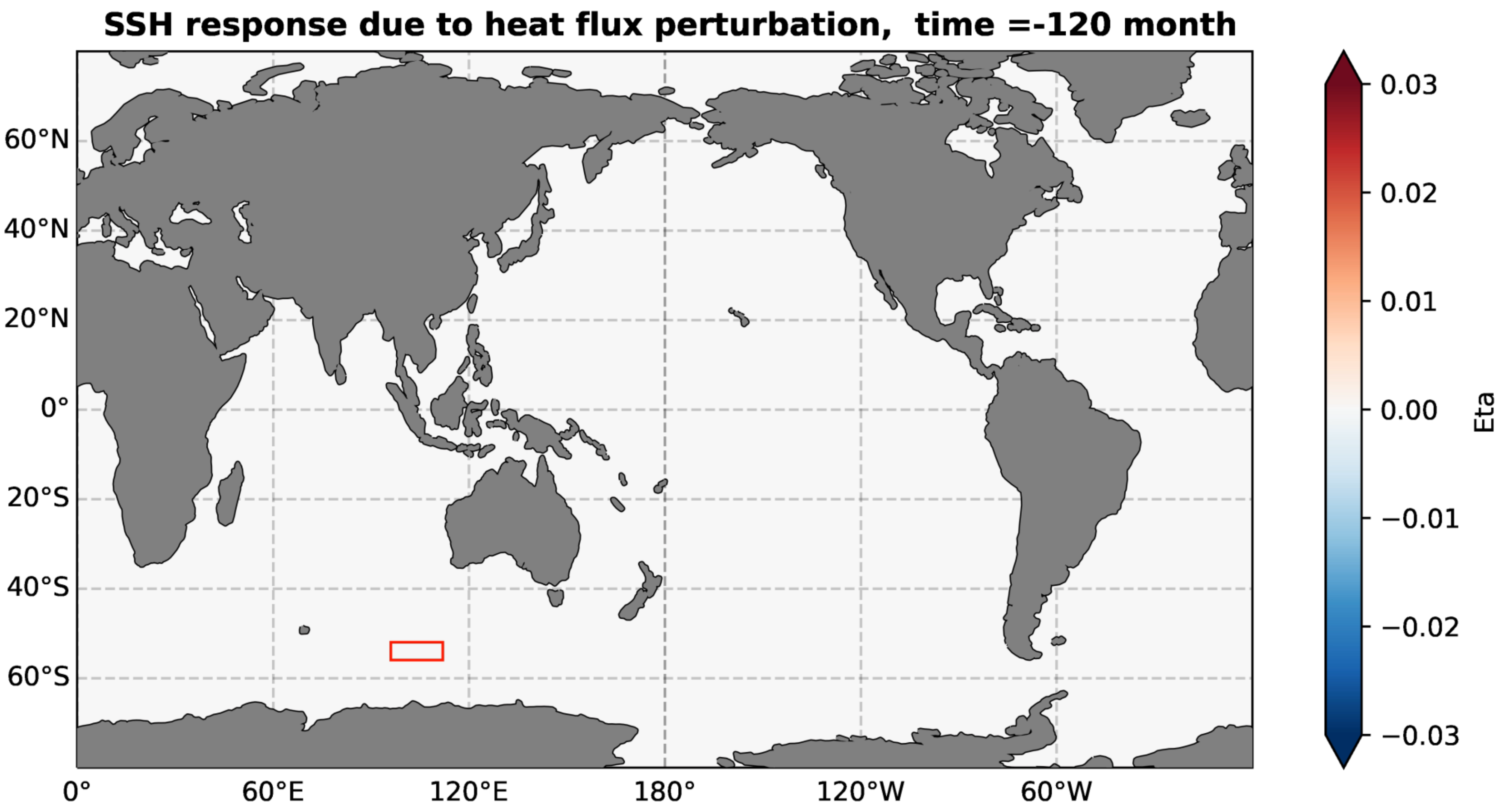
Nomalized sensitivity to freshwater flux 1 yr ago



- **Similar teamporal and spatial patterns**
- **Sensitivities moving along ACC indicates ACC propogates temperature&salinity anomaly**
- **Sensitivity to heat flux sugguests ocean surface heating/cooling**
- **Sensitivity to freshwater flux sugguests ocean freshening/salinification**

Heat flux-perturbation experiments

What if impose sensitivity-like heat flux perturbation for 3 yr ?



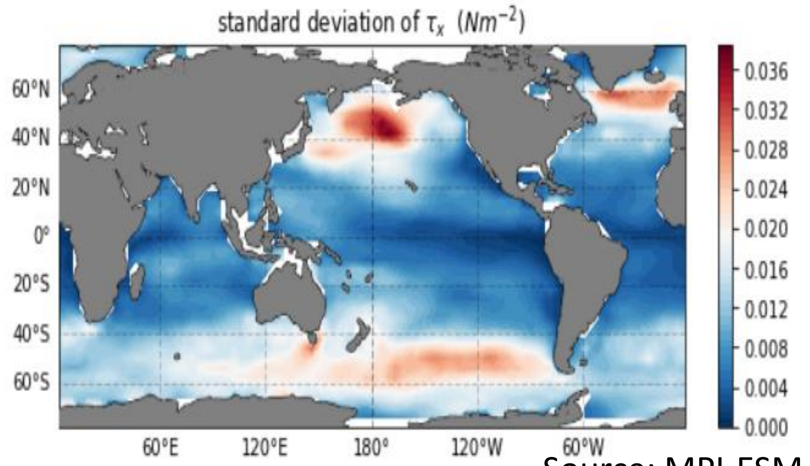
- **Generate positive SSH anomaly propogating along ACC mean flow**
- **Sea level response is less significant**

Relative contribution under a global warming scenario

$$J(x_i) = J(x_{i0}) + \left.\frac{\partial J}{\partial x_i}\right|_{x_0} \cdot (x_i - x_{i0}) + O\left(\|x_i - x_{i0}\|^2\right)$$

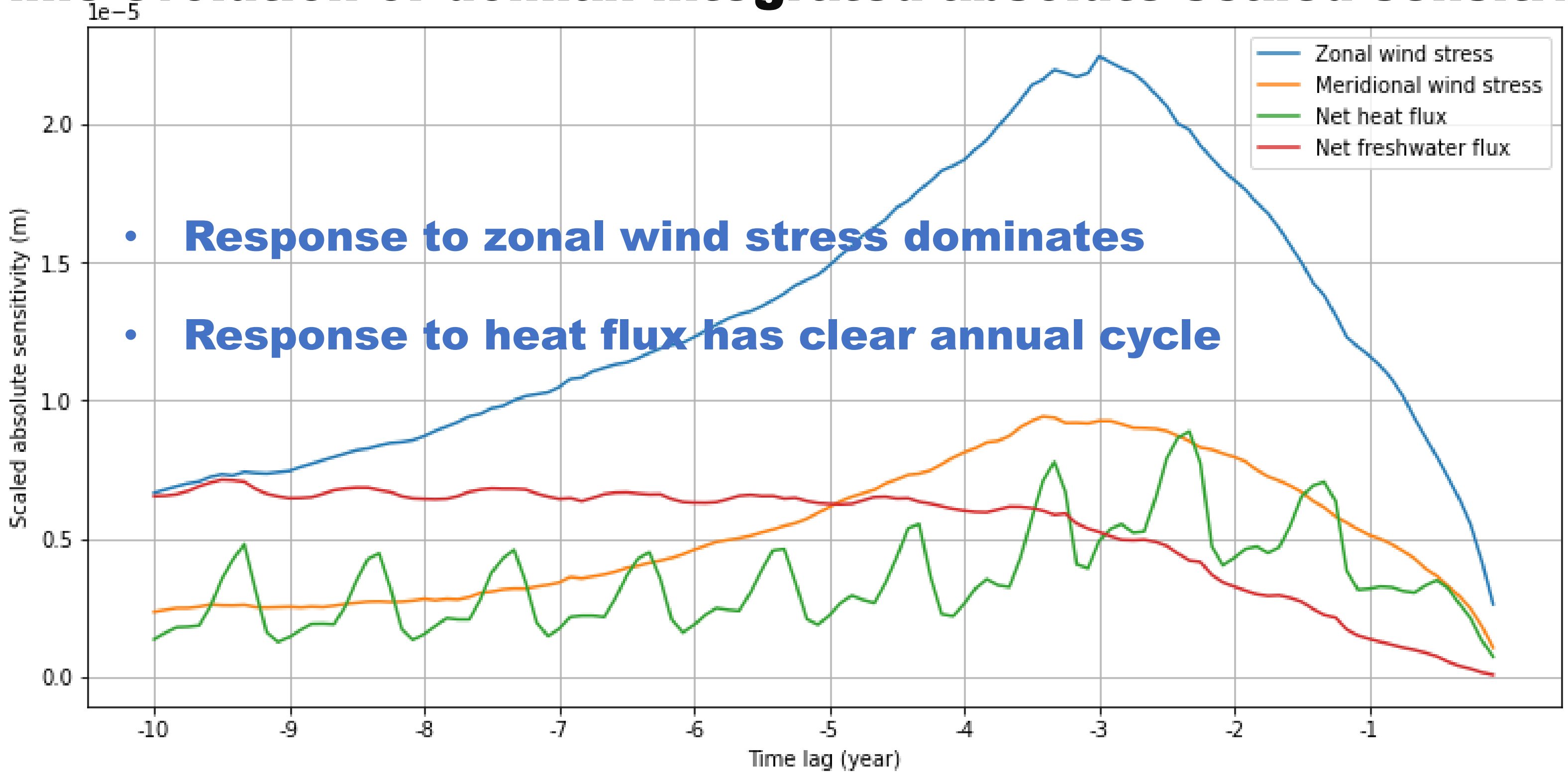
Cost Function Response ≈ Sensitivity x Forcing Perturbation

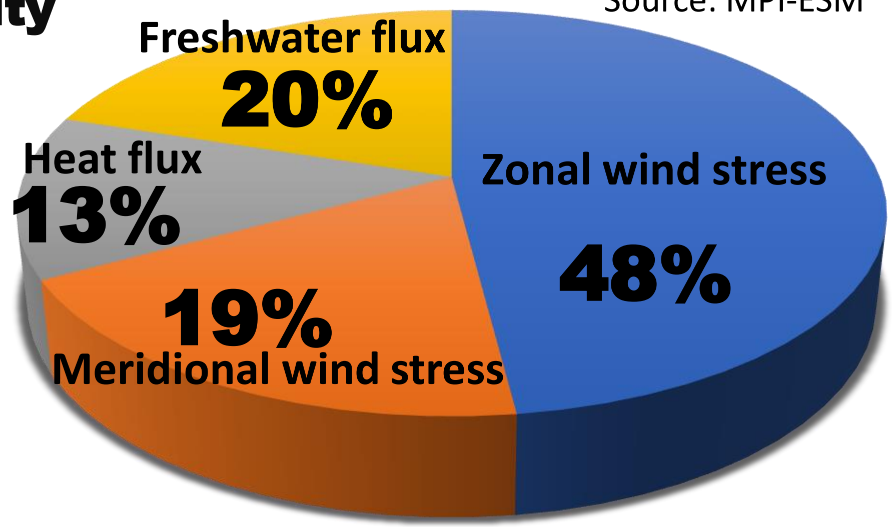
- **Strong sensitivity & high forcing variability →enhanced response**
- **Strong sensitivity & low forcing variability →diminished response**



Source: MPI-ESM

Time evolution of domian-integrated absolute scaled sensitivity

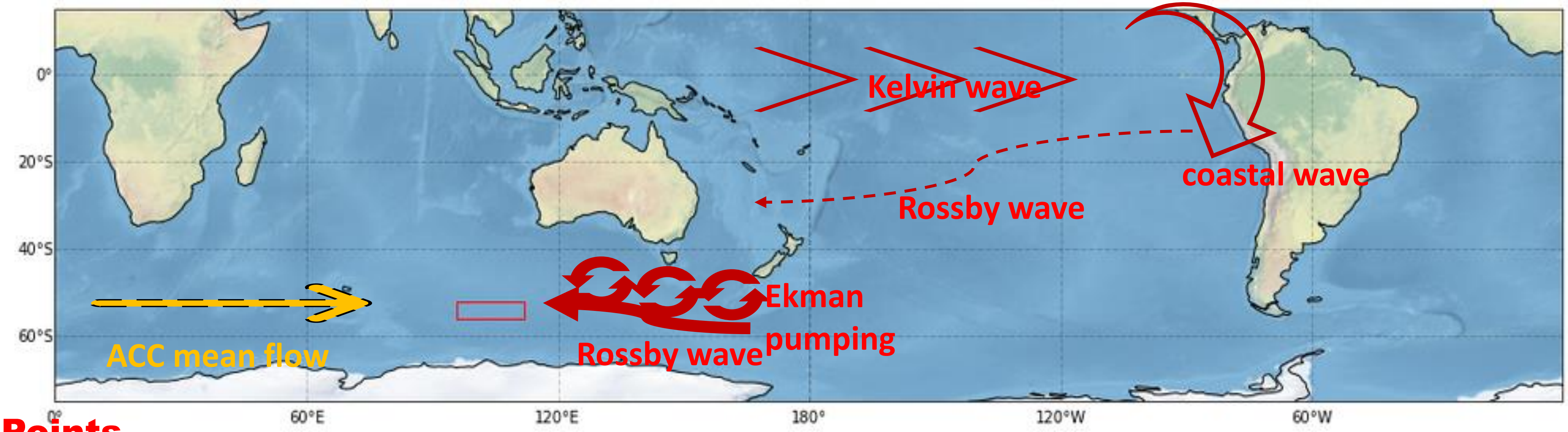




Relative contribution

Summary

- **I use the adjoint sensitivity analysis to reveal how local and remote atmospheric forcing anomalies contribute to low-frequency Sea-Level variability in the chosen region**



Key Points

1. Large-scale circulation and SSH variability is essentially forced by wind stress

2. Quantity of interest is mainly driven by wind-induced Ekman pumping and Rossby wave between Australia and Antarctica

3. Local and regional winds is the leading factor while remote winds take years

4. Buoyancy fluxes modulate sea level variation via ACC mean flow

5. Momentum and buoyancy-driven mechanisms have opposite pathways in Southern Ocean

Application

- **If forcing anomaly is observed, the associated mechanism is expected to be excited (sensitivity-based observation system design)**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Thank you all!
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