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Mechanisms of large-scale low-frequency Dynamic Sea Level in Australia-Antarctica Basin: an adjoint sensitivity analysis

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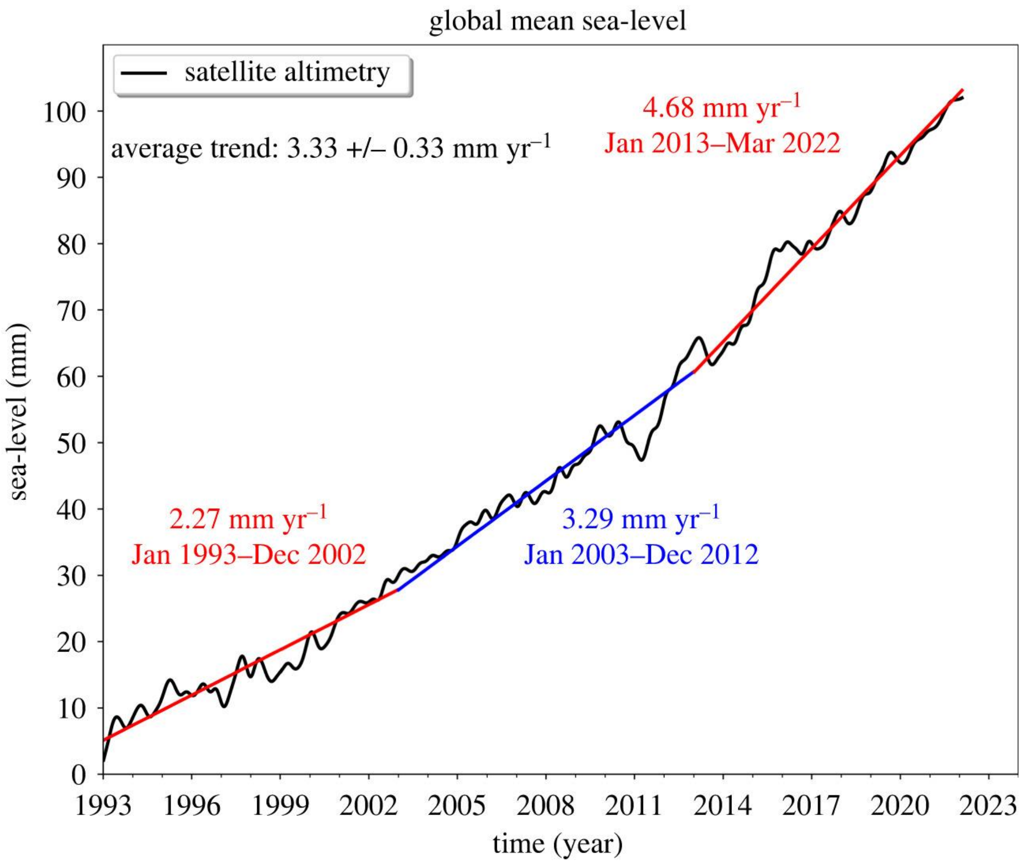
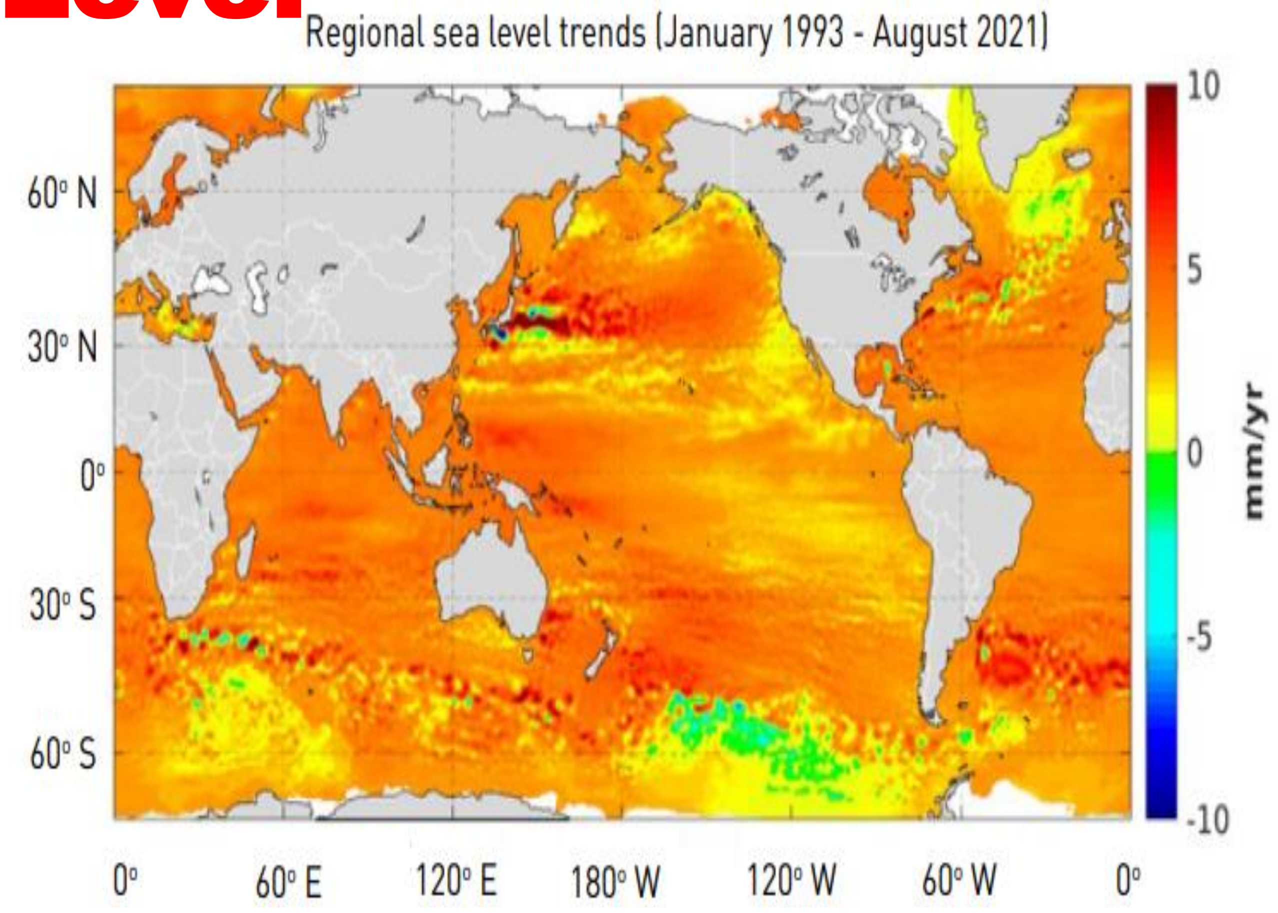
Institude of Oceanograhy, Universität Hamburg, January xx , 2022

1. Introduction: Sea Level

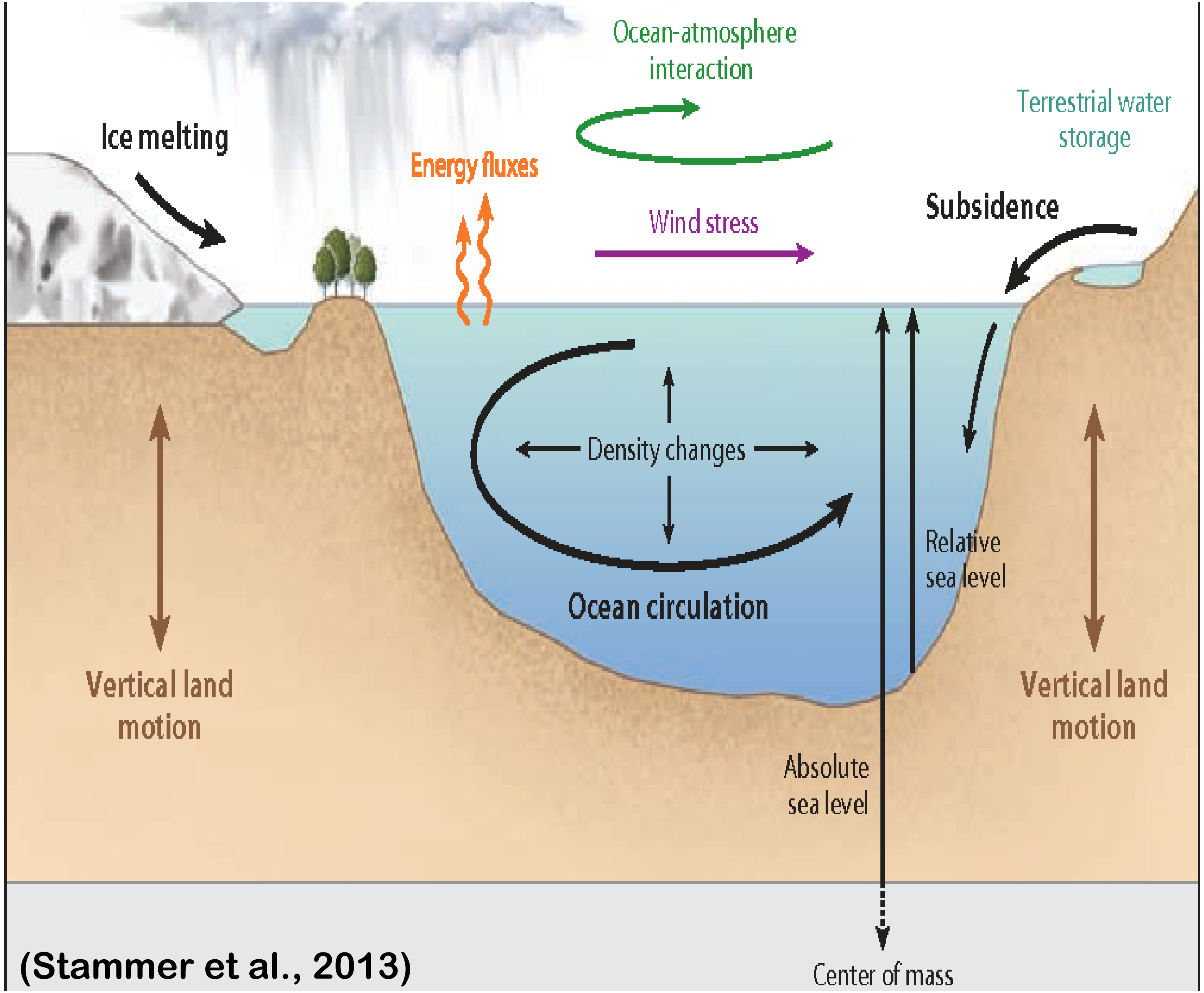




- GMSL rise 3.3 mm/yr
- Rate of rise has increased
- Thermal expansion (46%)
- Melting of grounded ice (44%)
- terestrial water change (10%)

- Not uniform spatially
- Southern Ocean
- Different regions have different dirvers/mechanisms

Processes that influence regional sea level



(Stammer et al., 2013)

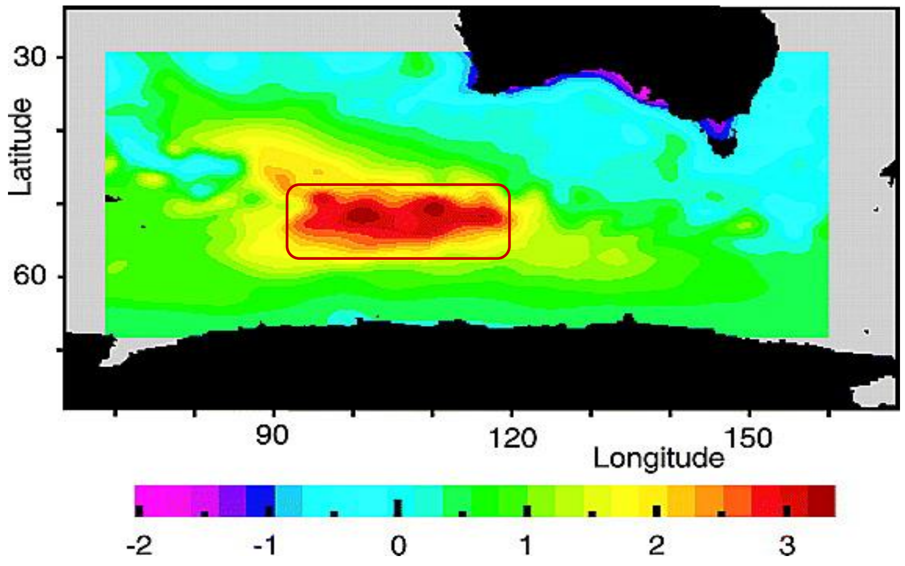
(1) Dynamical Sea Level

- **Ocean circulation:**
  - **Waves**
  - **Ekman processes**
- **Density changes:**
  - **Salinity**
  - **temperature**
- **Surface Wind Stress**
- **Surface Heat Flux:**
  - **Sensiable heat**
  - **latent heat**
  - **radiation**
- **Freshwater Flux:**
  - **Precipitation/Evaporation**
  - **Land water**

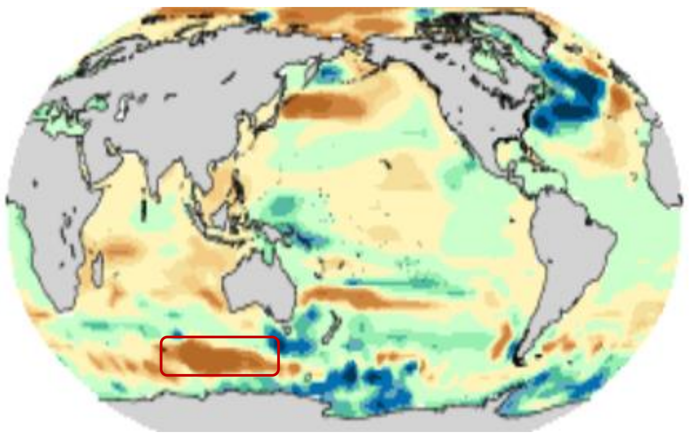
(2) Static Sea Level

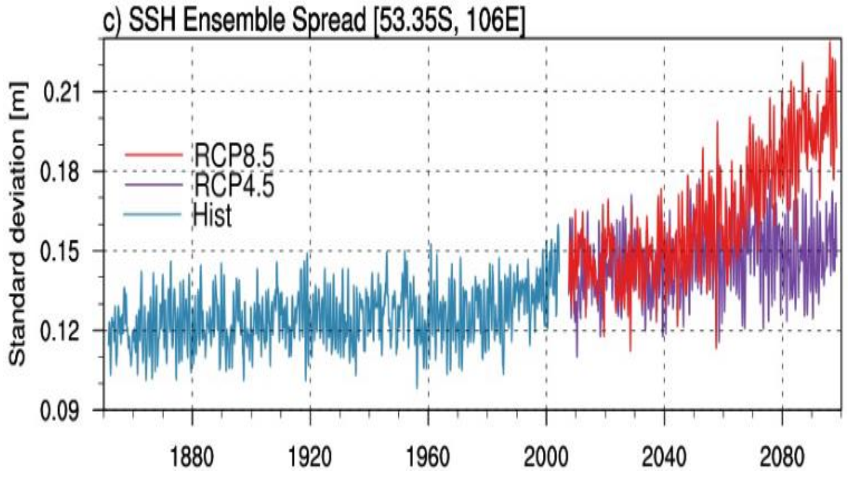
- **Ocean loadings:**
  - **Land motion**
  - **Gravity/rotation/solid earth**

Region:Australia-Antarctica Basin



SSH EOF1 (Webb and de Cuevas, 2002)





Chnages in interannual SSH variability under global warming (Nandini-Weiss, S.D., et,al, 2023)

- High-frequency barotropic variability
- Wind-driven Ekman pumping

- Increased interannual SSH variability under global warming
- regional wind stress

Relatively littile is known about low-frequency variability
What is mechanism of low-frequency (> 3 years) sea-level variability?

Research question:

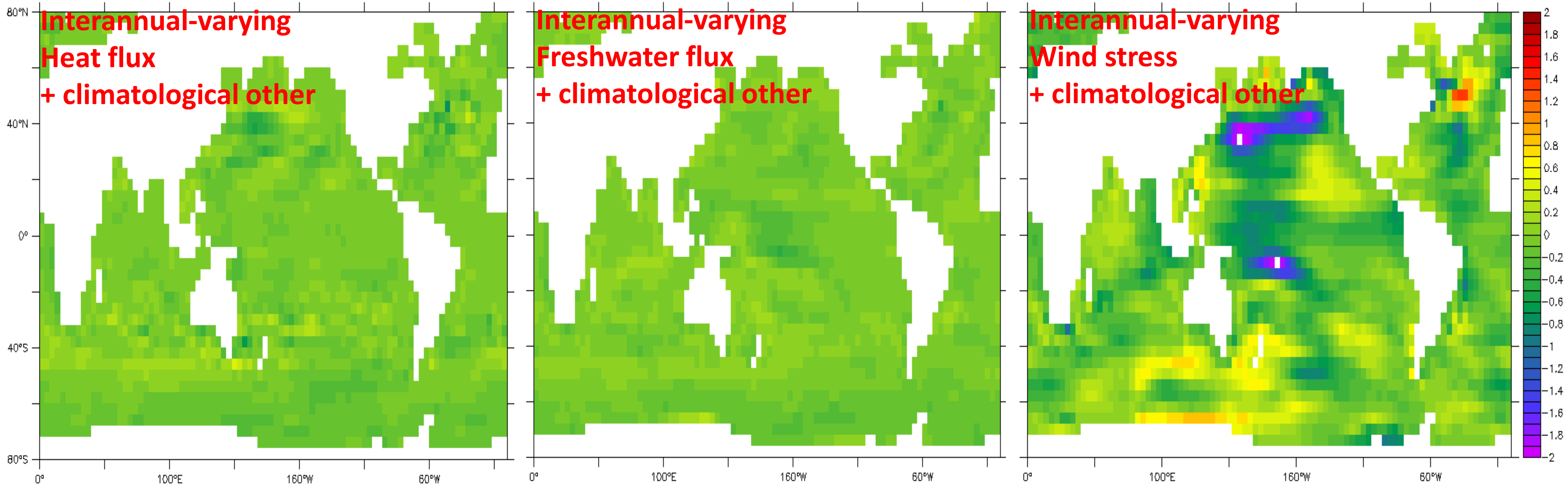
How sensitive of large–scale low-frequency dynamic sea level to surface forcing and whats its associated mechanism?

1. When/where/which forcing is able to generate SSH anomaly (a typical signal characterizing low-frequency variability) ?
2. Which forcing has the most contribution?
3. What ocean dynamics are involved to produce SSH anomaly?

An estimate (which forcing contributes more)

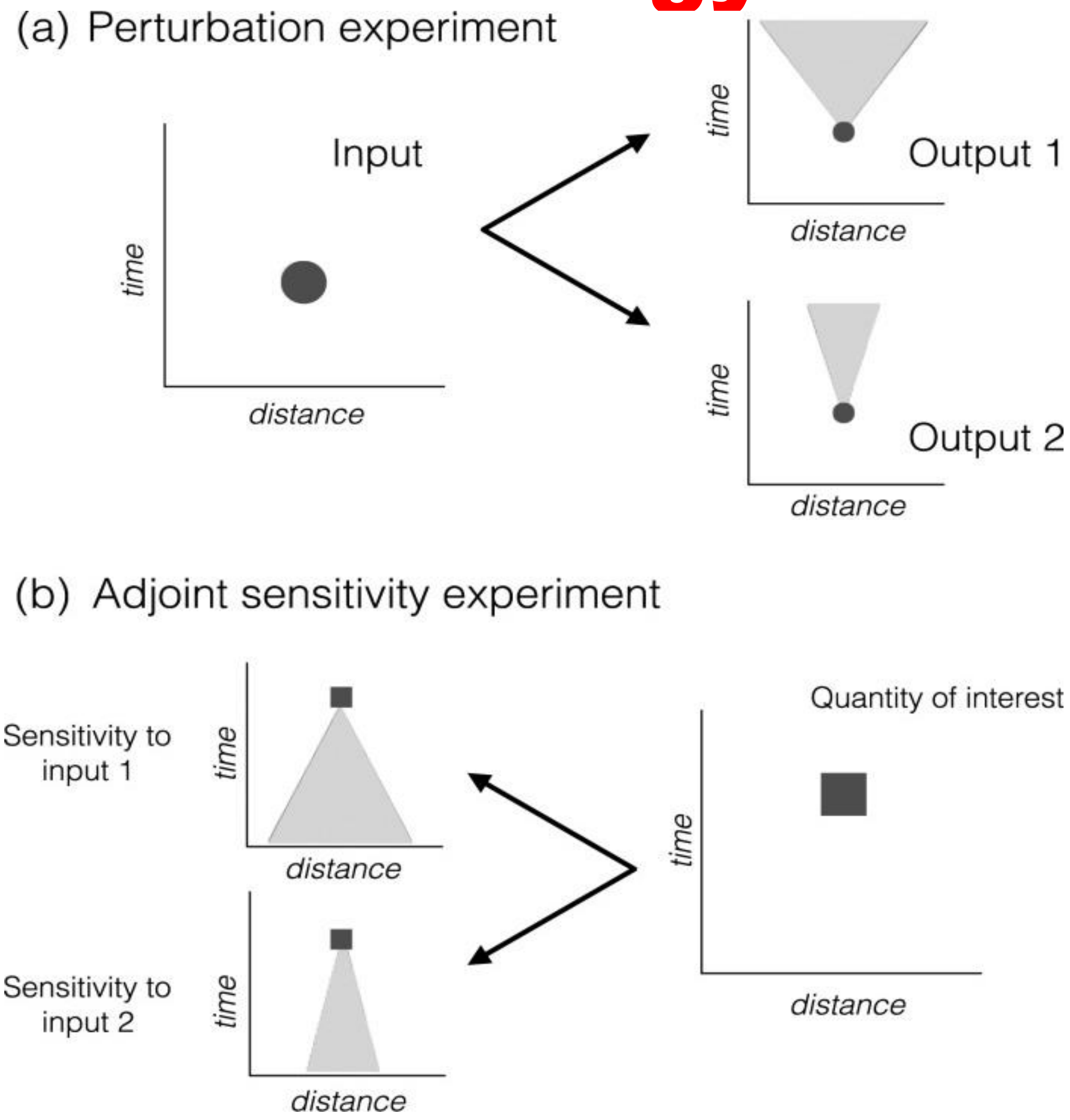
1. Monthly-varying input forcing: zonal wind, meridional wind, heat flux , freshwater flux
2. Specify only one interannually-varying forcing + other forcing as monthly climatologies
3. Compare changes in SSH variability (RCP 8.5 scenerio – historical scenario)

Differences in monthly sea level standard deviation



- Wind stress seems be to the most important to influence SSH variability
- Can we assess their contribution quantitatively?

2. Methodology: sensitivity analysis



$$S = \frac{\partial J}{\partial x}$$

S: Adjoint sensitivity

Reveal how the changes in x can affect J

J : Cost Function

A function of the mode state
Quantity of interest (e.g., mean sea level)

x : Controls

Vector in time and space of model inputs that can affect J
(e.g., surface wind stress)

How to derive the adjoint sensitivity?

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

Nonlinear Operator

Tangent Linear Operator

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

Perturbation

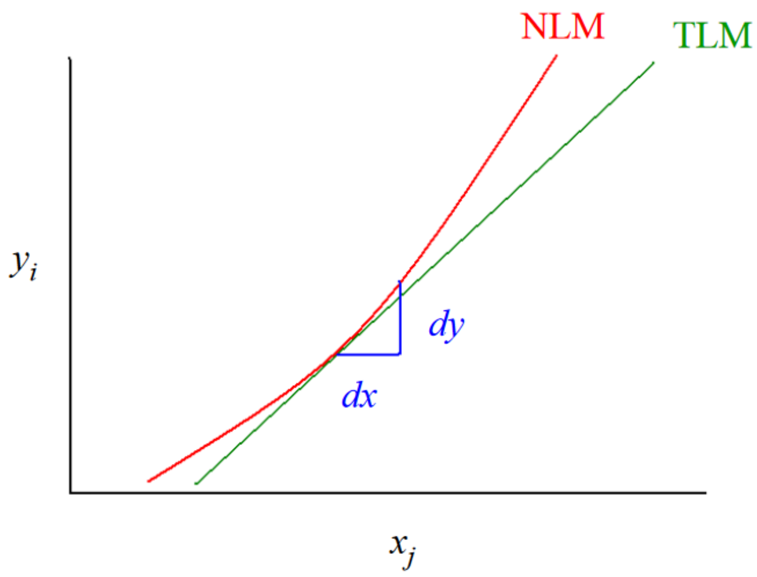
$$J = J(y) = J[M(x)]$$

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

Gradient

Adjoint Operator

A graphical TLM schematic



- Variables are different
- Reversed indices i & j
- Order of calculation differ
- Adjoint operator propagates gradients backward in time to the initial

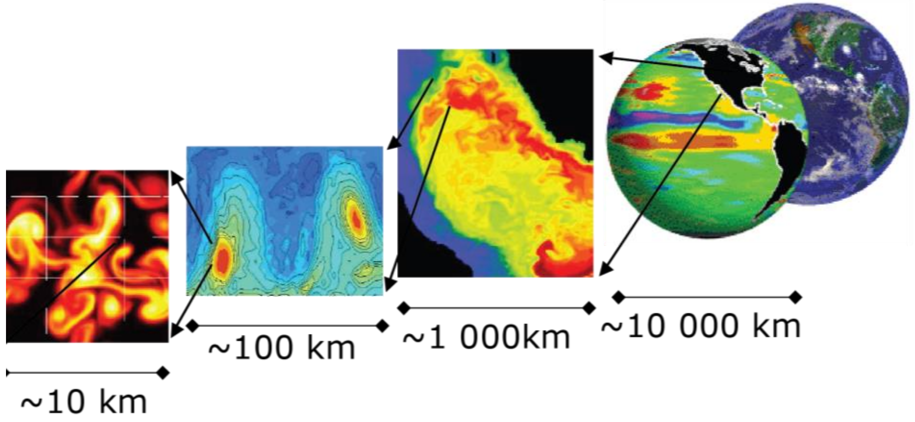
3. Model

MITgcm and its adjoint

- **Boussinesq Navier-Stokes equations**
- **Adjoint model via automatic differentiation**

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

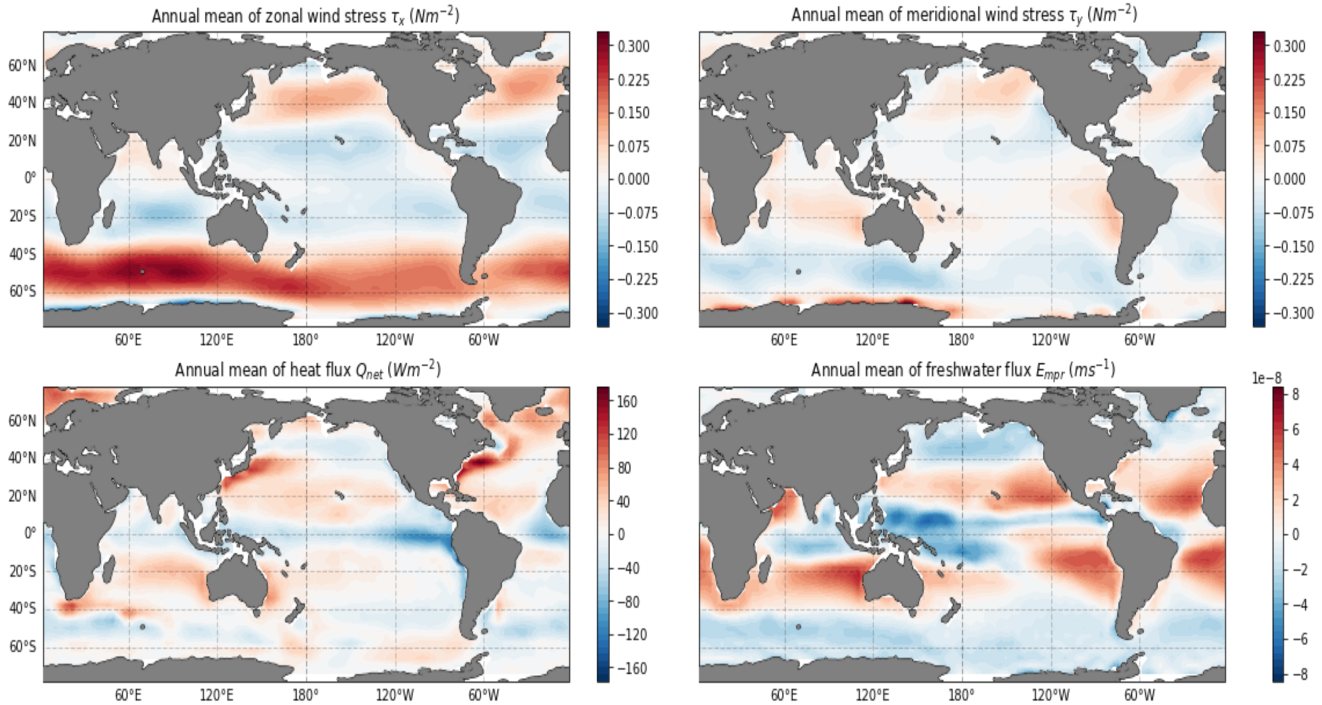
MIT general circulation model



configuration

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

- **Spin-up: 100 year**
- **Integrated forward 10 years**
- **SST/SSS relaxation**
- **Timestep:**
- **Monthly snapshot fields are saved**

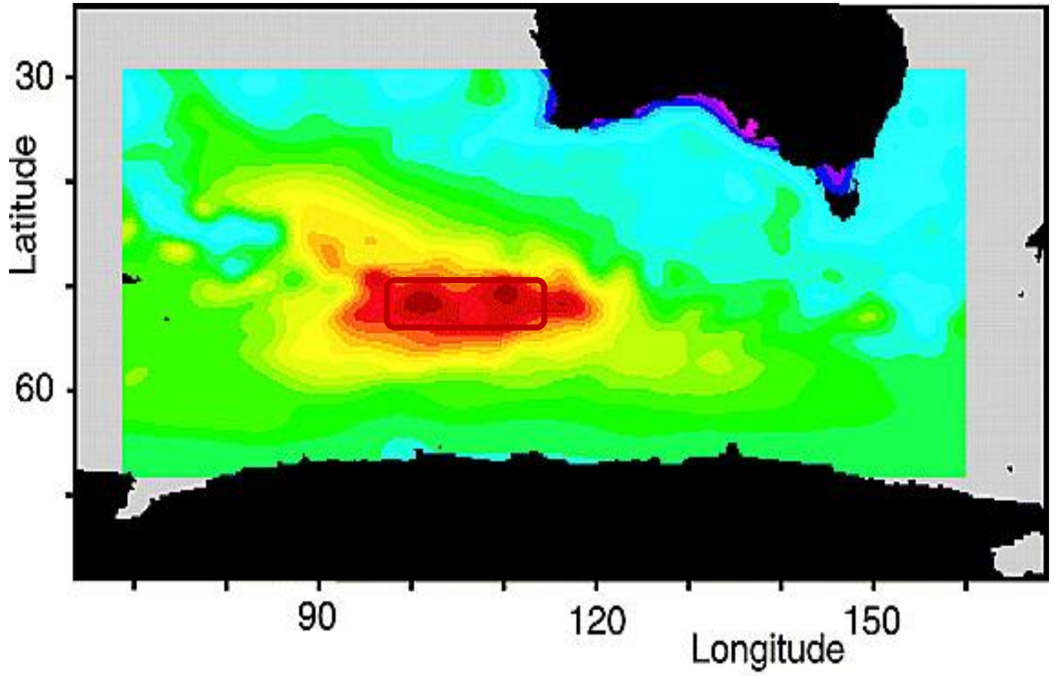


(NCEP/NCAR, Trenberth et al.)

https://github.com/MITgcm/MITgcm/tree/master/verification/global_ocean.90x40x15

Cost Function:
last 3 yr mean SLA averaged over target region

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



Quantity of interest *J* :
Characterizing large-scale (>300km), low-frequency (> 3yr) SL variability off southwest Australia

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

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

η : Dynamic Sea Level (sea level above geoid due to ocean dynamics)

Forward versus adjoint

Forward model $\xrightarrow{\text{Automatic differential}}$ **Adjoint model**

- **Surface wind and fluxes drive the forward model**
- **Output of forward model is ocean states**
- **Produce a background for adjoint model**

$$\boldsymbol{S} = \frac{\partial \boldsymbol{J}}{\partial \underline{\boldsymbol{x}}}$$

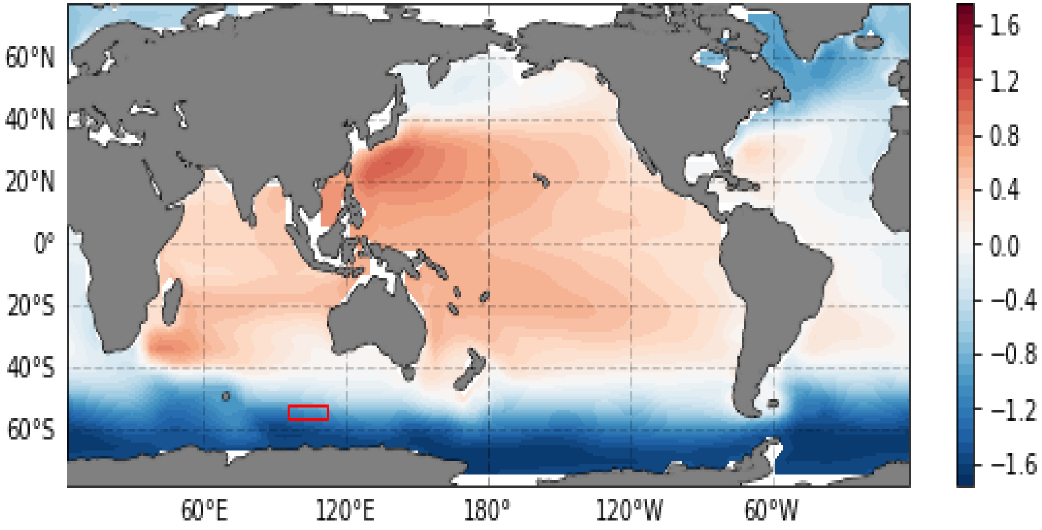
$\underline{\boldsymbol{x}}$:
- Zonal wind stress
- Meridional wind stress
- Net surface heat flux
- Net surface freshwater flux

- **Cost function (SL) as a forcing in the adjoint simulation**
- **Output is sensitivity/gradient of cost function to controls throughout the model domain and back in time**
- **Spatial and temporal details of adjoint fileds sugguest causality**

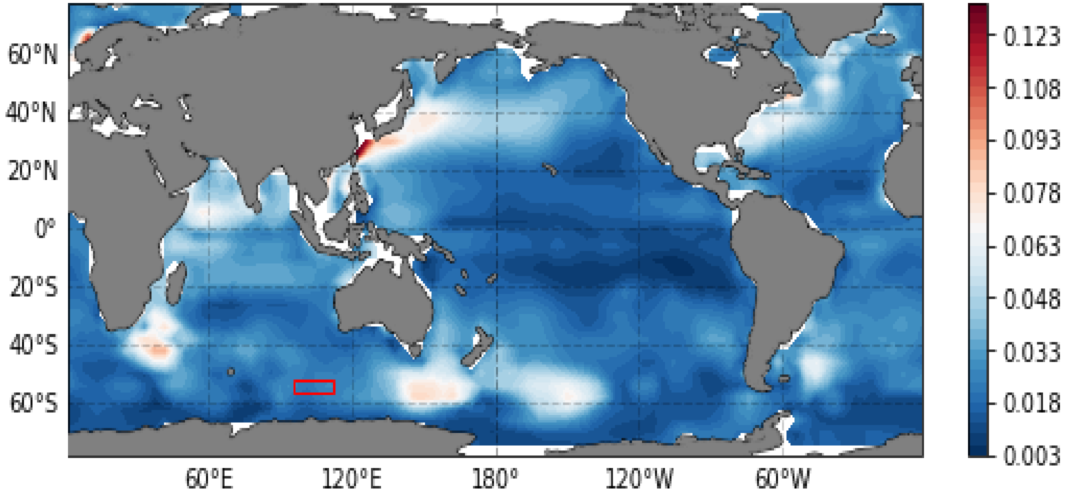
4. Results

Forward solution (MITgcm)

(a) Mean SSH anomaly (m)

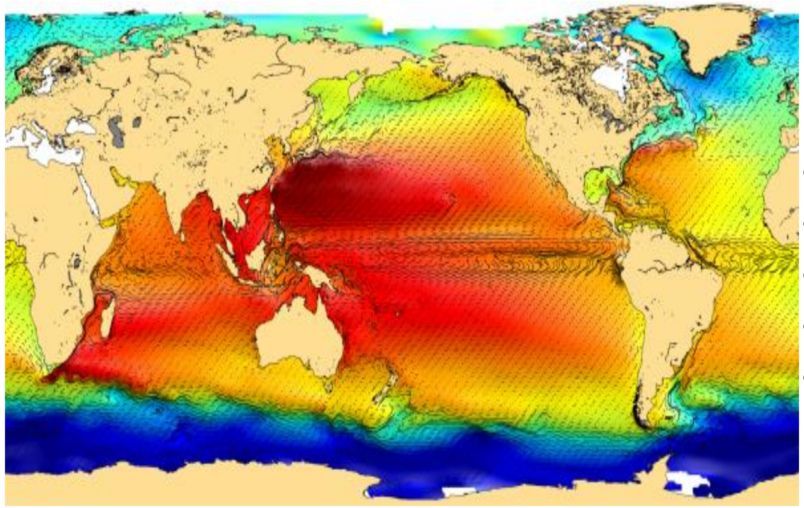


(b) Standard deviation of SSH anomaly (m)



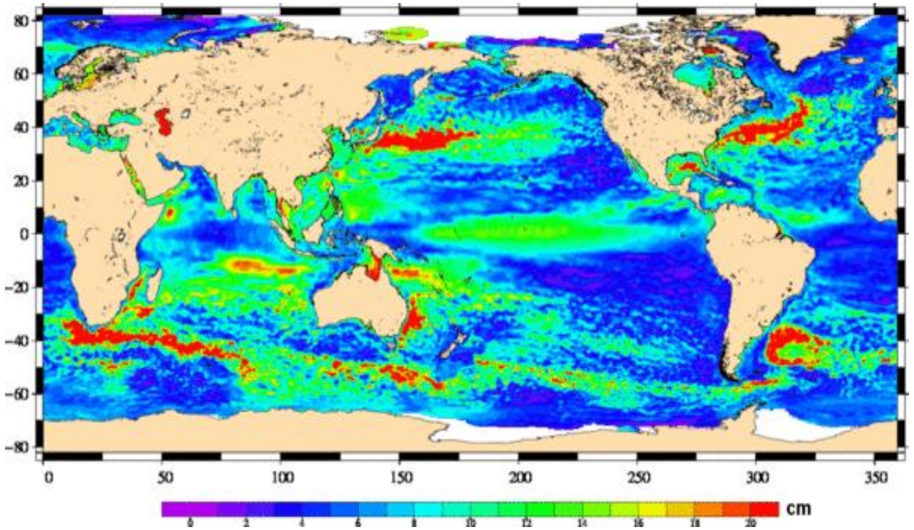
Observation (AVISO)

Mean dynamic topography (Credits CNES/CLS)



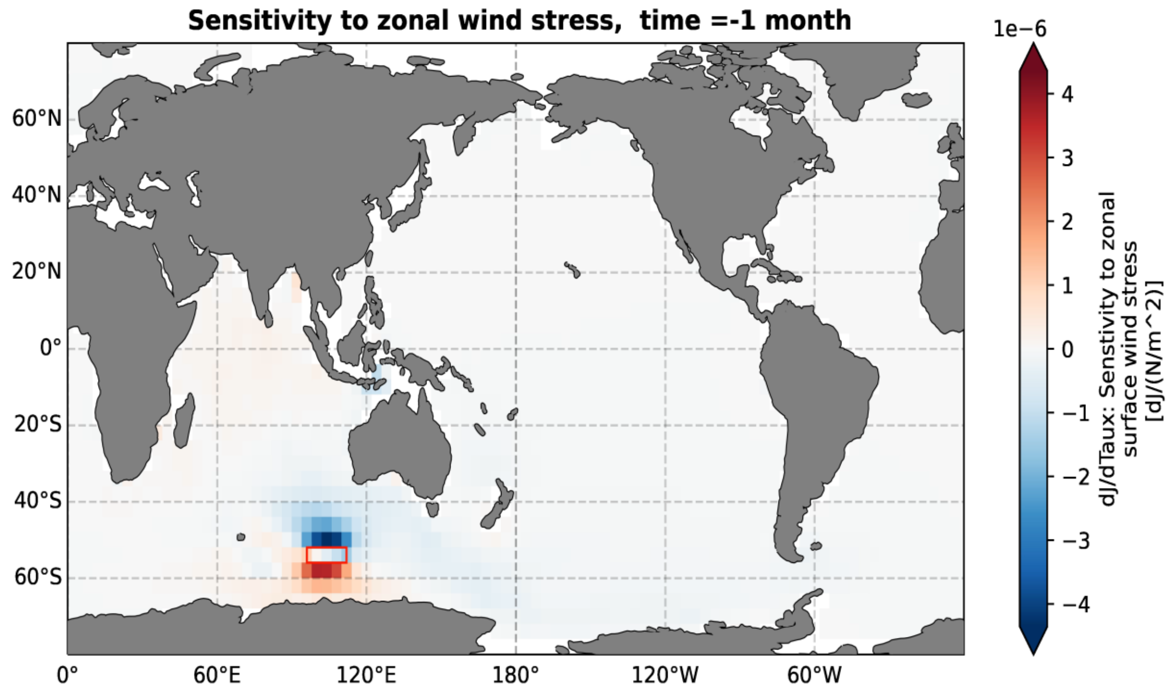
- High: West Pacific
- Low: Southern Ocean
- Positive: low-mid latitudes
- Ngative: high latitudes
- Pos-Neg gradient along 50S

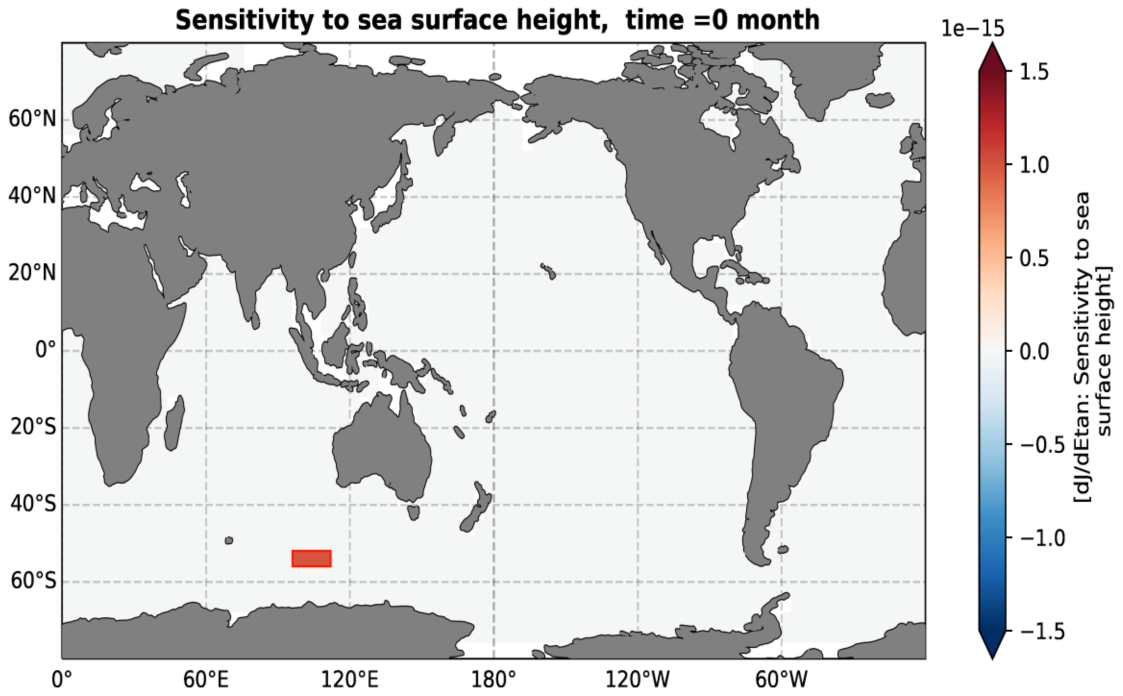
RMS of the SSHa (Credits Cnes/CLS)



- Kuroshio
- Gulf Stream
- Agulhas Current
- Falkland Current
- ACC

Adjoint Solution produces sensitivity backward in time





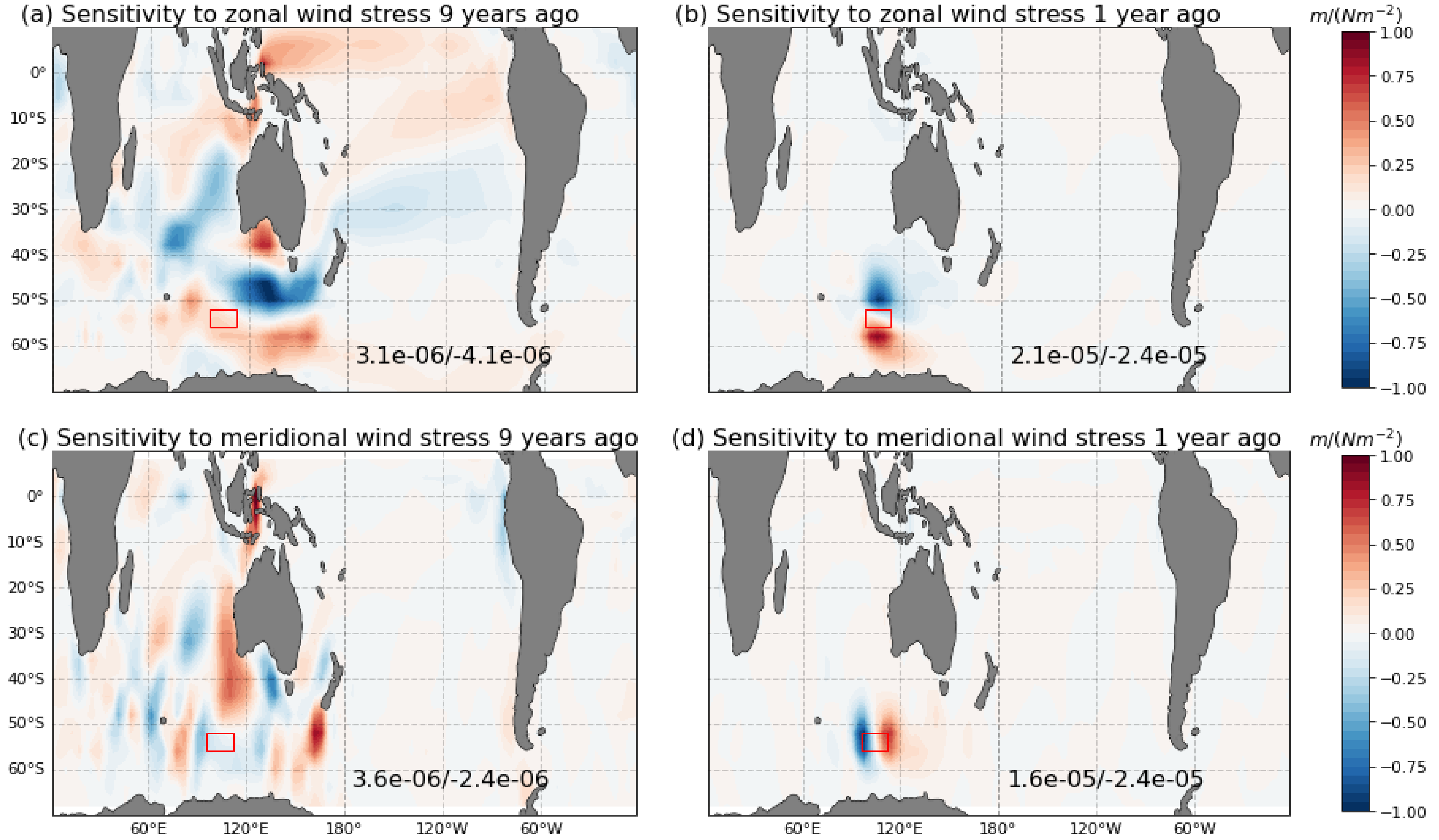
Sensitivity to Forcing(e.g. Zonal wind stress)

Sensitivity to model states (e.g. SSH…)

Positive Sensitivity: Cost function increases if given a standard perturbation at earlier time

Nagetive Sensitivity: Cost function decreases if given a standard perturbation at earlier time

sensitivity to wind stress



9 years go

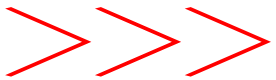
- **Strip structure → waves**
- **Northeast-southwest tilt→ Beta effect/Coriolis**
- **Coatsal trapped waves**
- **Indonisian throughflow connects Pacific and Indian Oceans**

1 year go

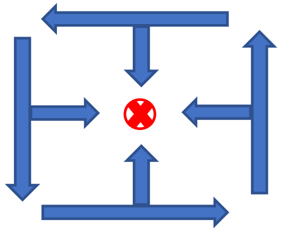
- **Dipole structure → Covergence/divergence Ekman pumping/suction**

From past to now

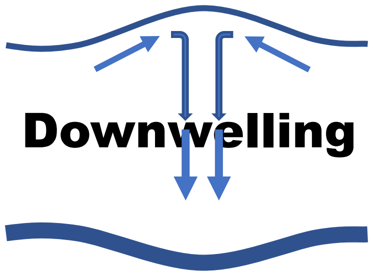
- **Primary sensitivities propagate westward against ACC**



Planetary Waves
Coastal waves

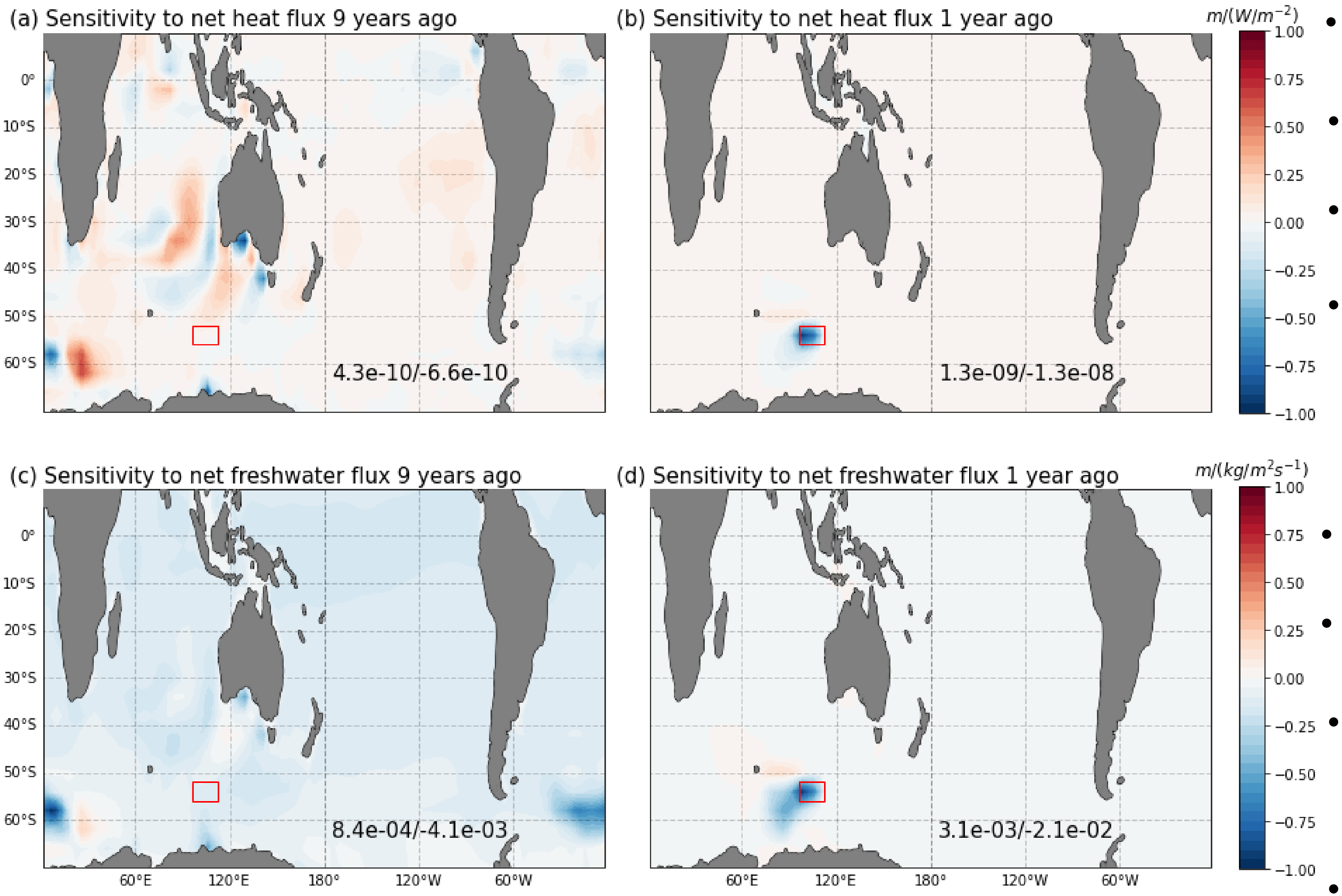


Anticyclolic wind



Ekman pumping

sensitivity to surface heat and freshwater flux



Eastward ACC mean flow (carrying T/S anomaly)

Heat flux

- **Net heat flux from ocean to atmosphere**
- **Negative sensitivity →Surface heating**
- **Positive sensitivity →Surface cooling**
- **Seasonal ocean wamring/cooling (not shown)**

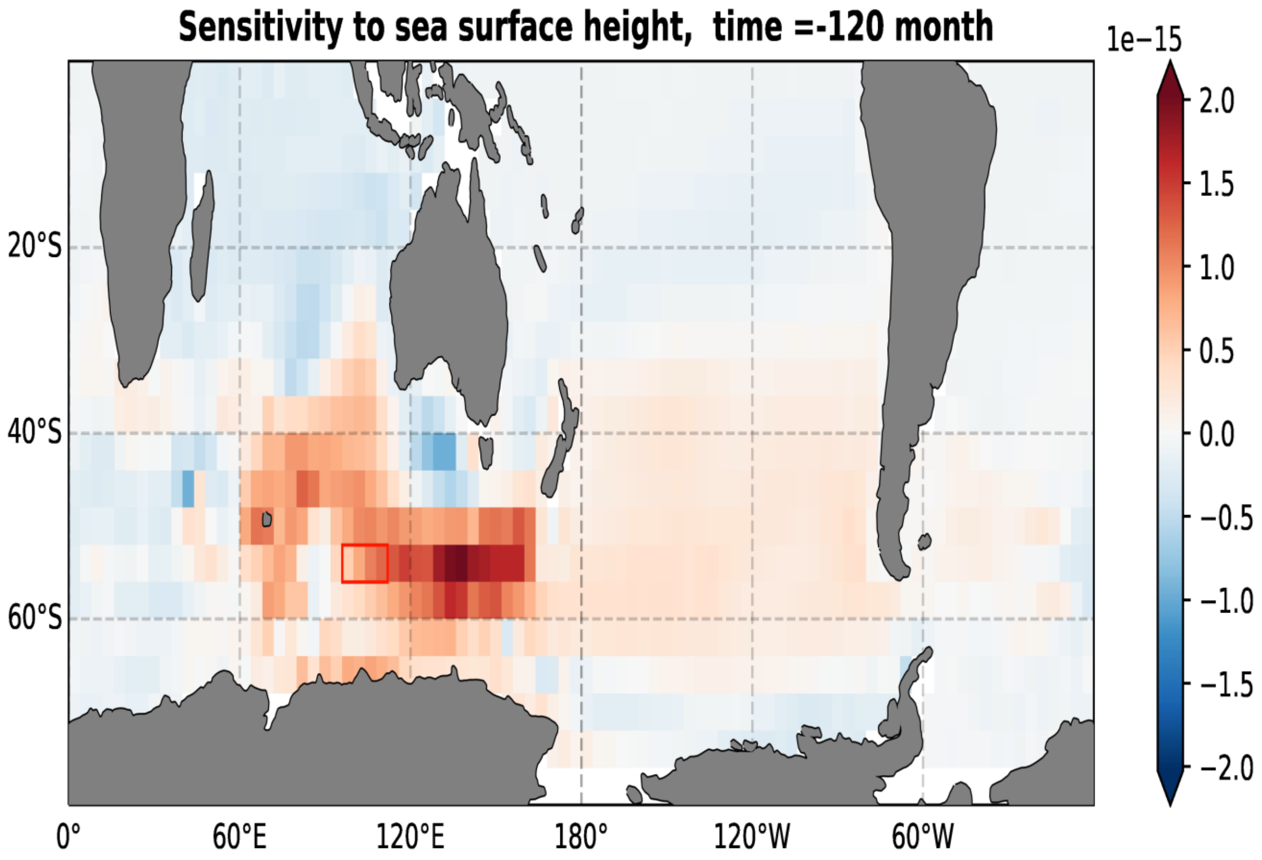
Freshwater flux

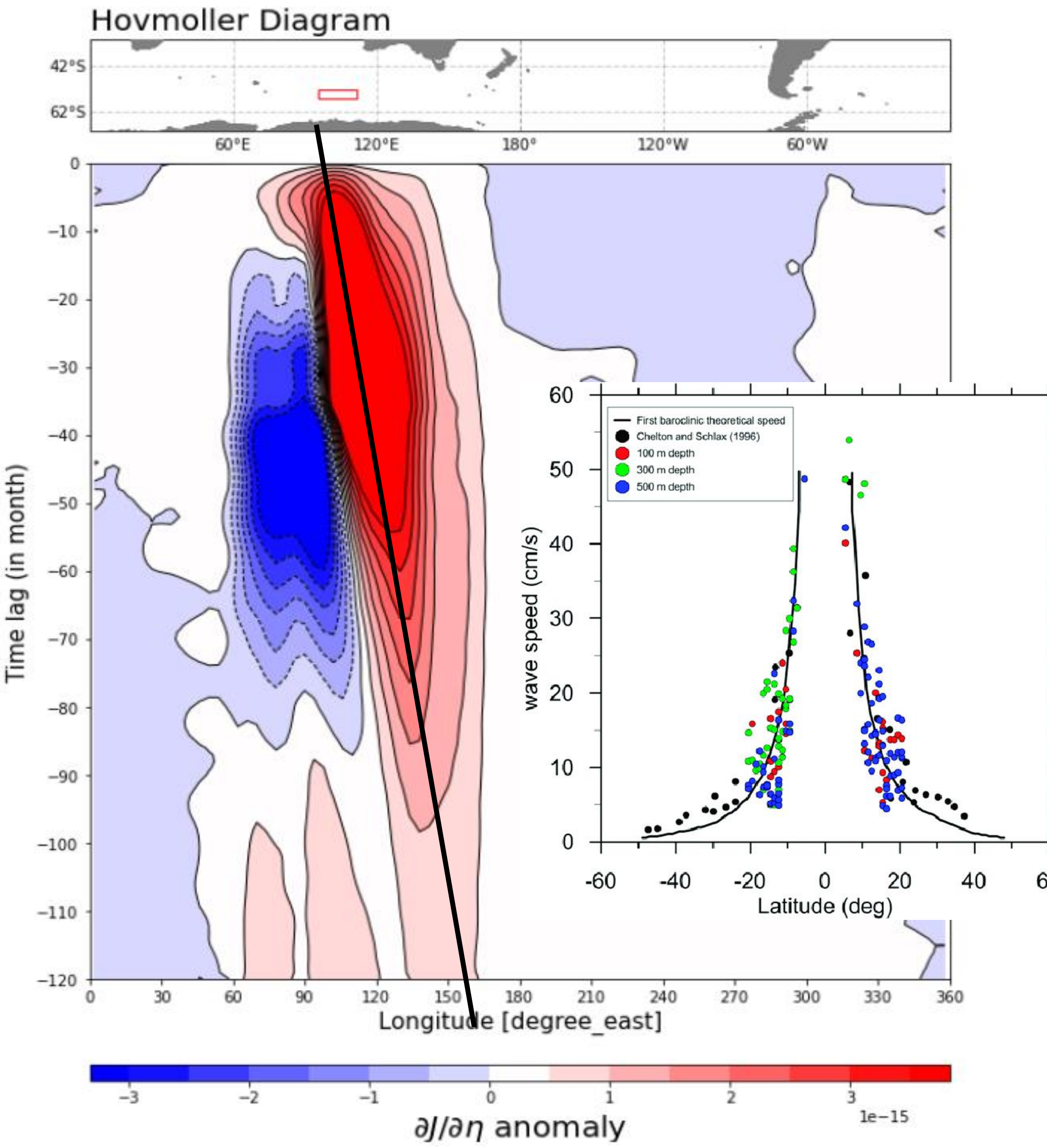
- **Negative sensitivity → Surface freshening**
- **Positive sensitivity → Surface salinification**
- **Negative sensitivity dominates**

From past to now

- **Primary sensitivities propagate westward against ACC**

Sensitivity to sea level anomaly

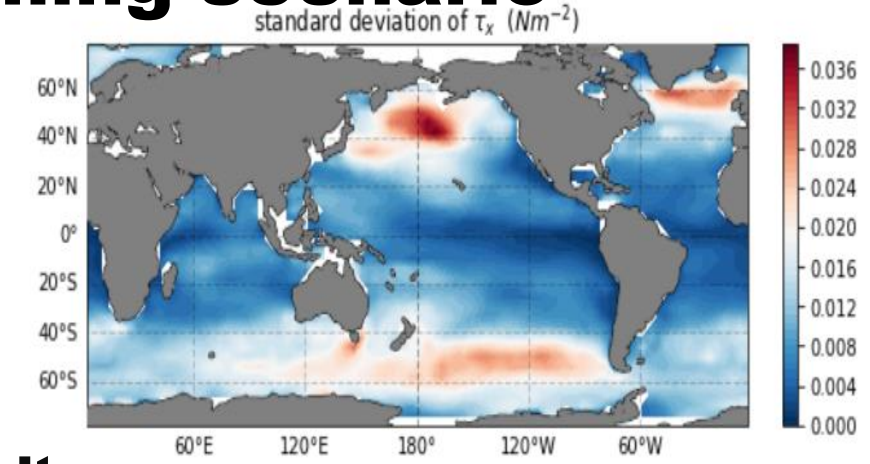




Phase speed estimated from the slope: 1.8 cm/s

Theoretical Rossby wave speed (Chelton and Schlax, 1996)

Relative contribution under global warming scenario

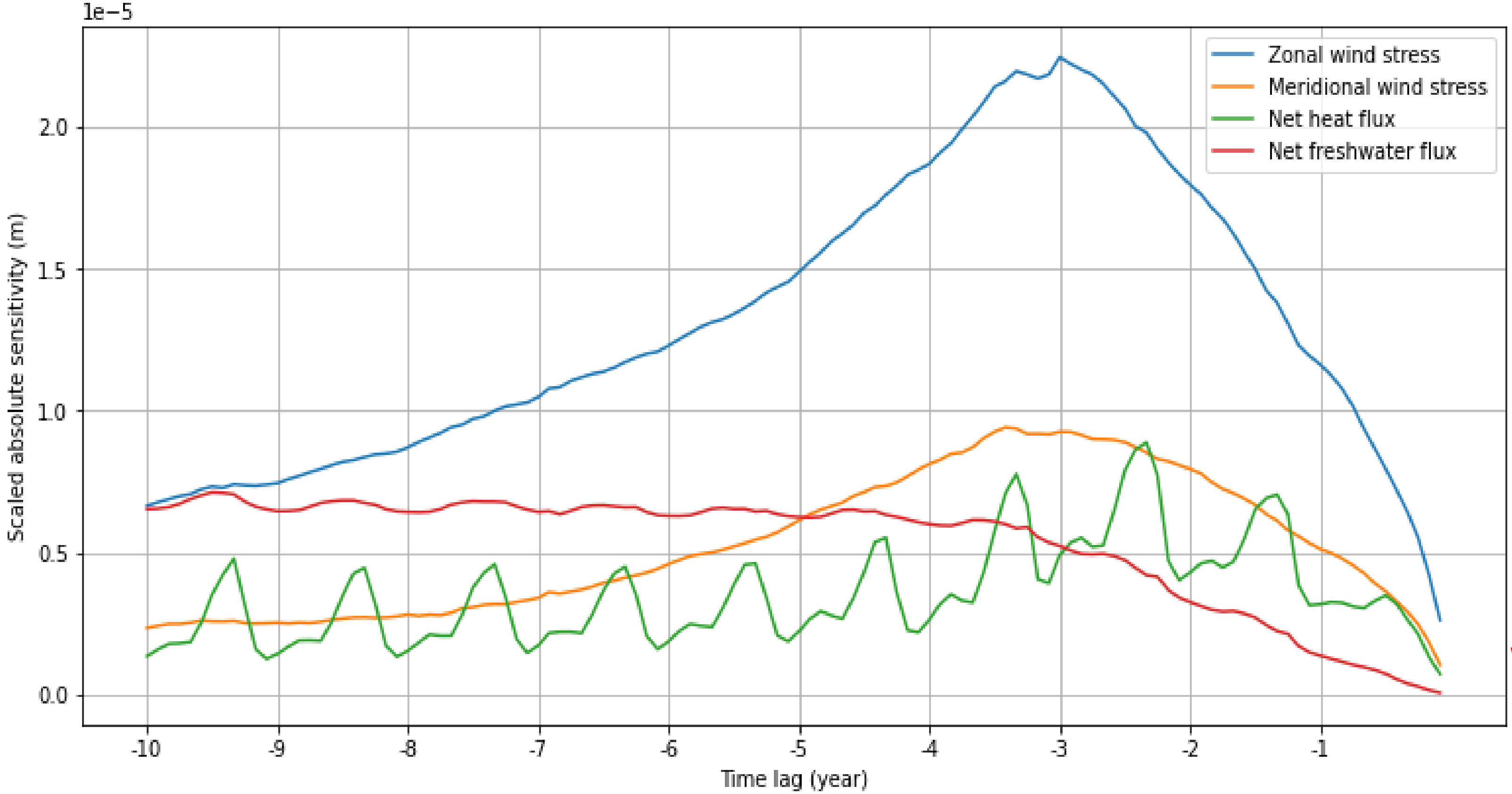


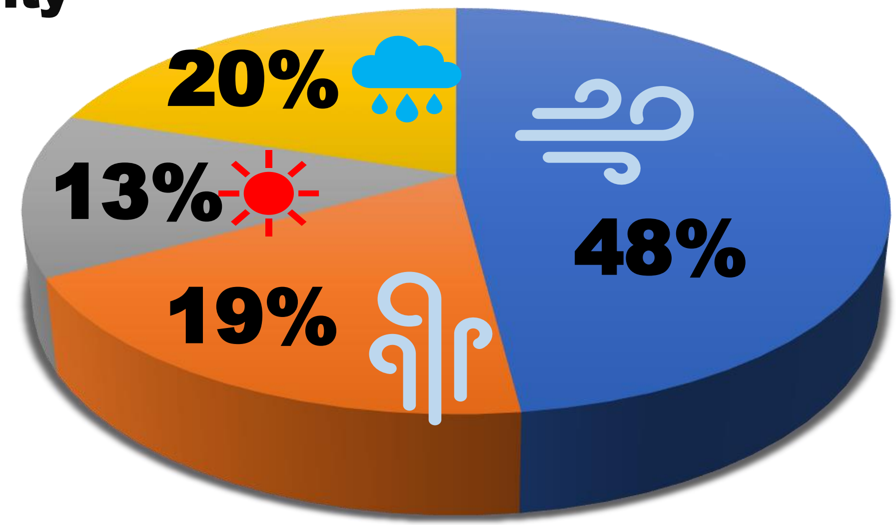
Scaled sensitivity=Sensitivity x Forcing Standard Deviation

$$\left|\frac{\partial J}{\partial x}\right| * \delta$$

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

Time evolution of domian-integrated absolute scaled sensitivity

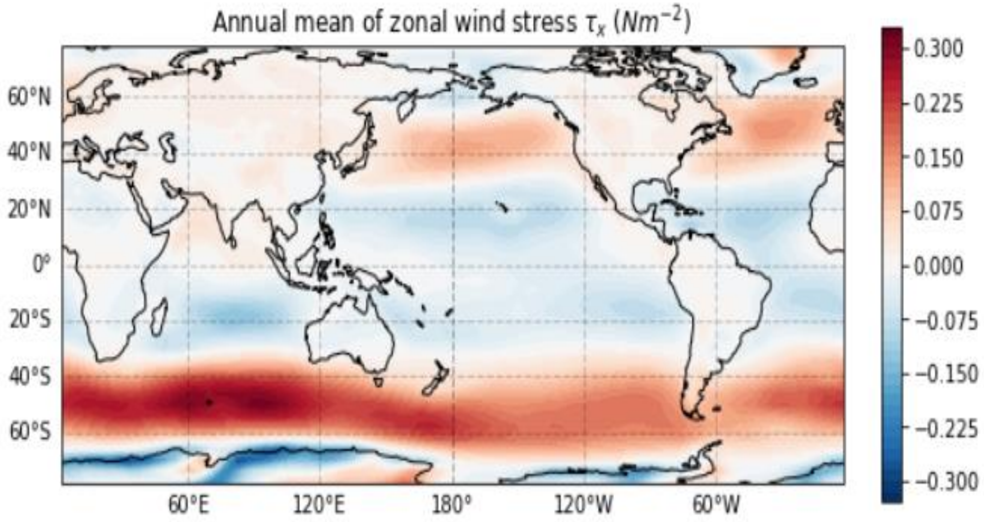




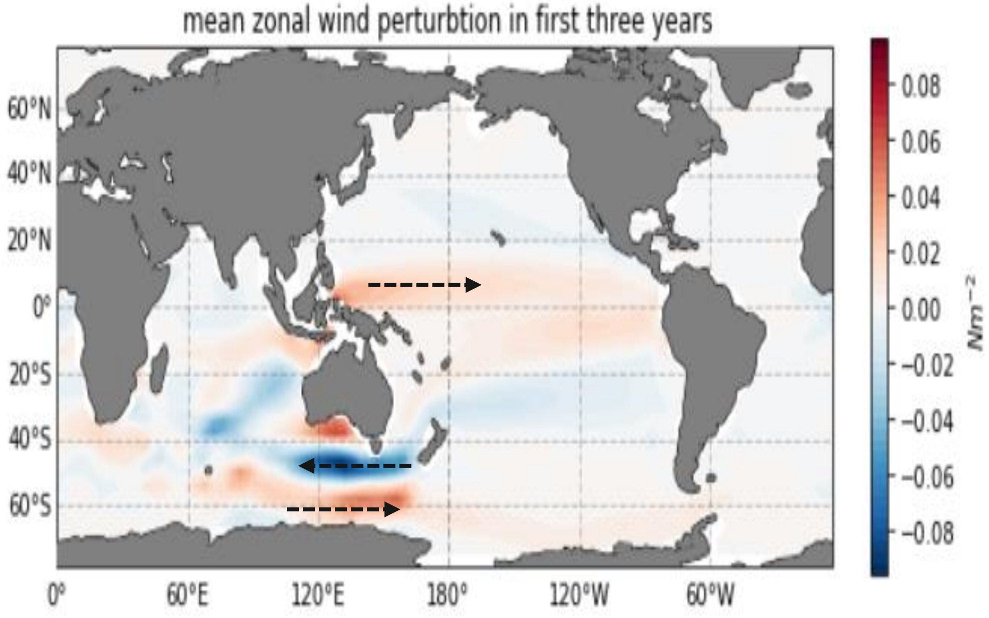
Relative contribution

Wind stress dominates

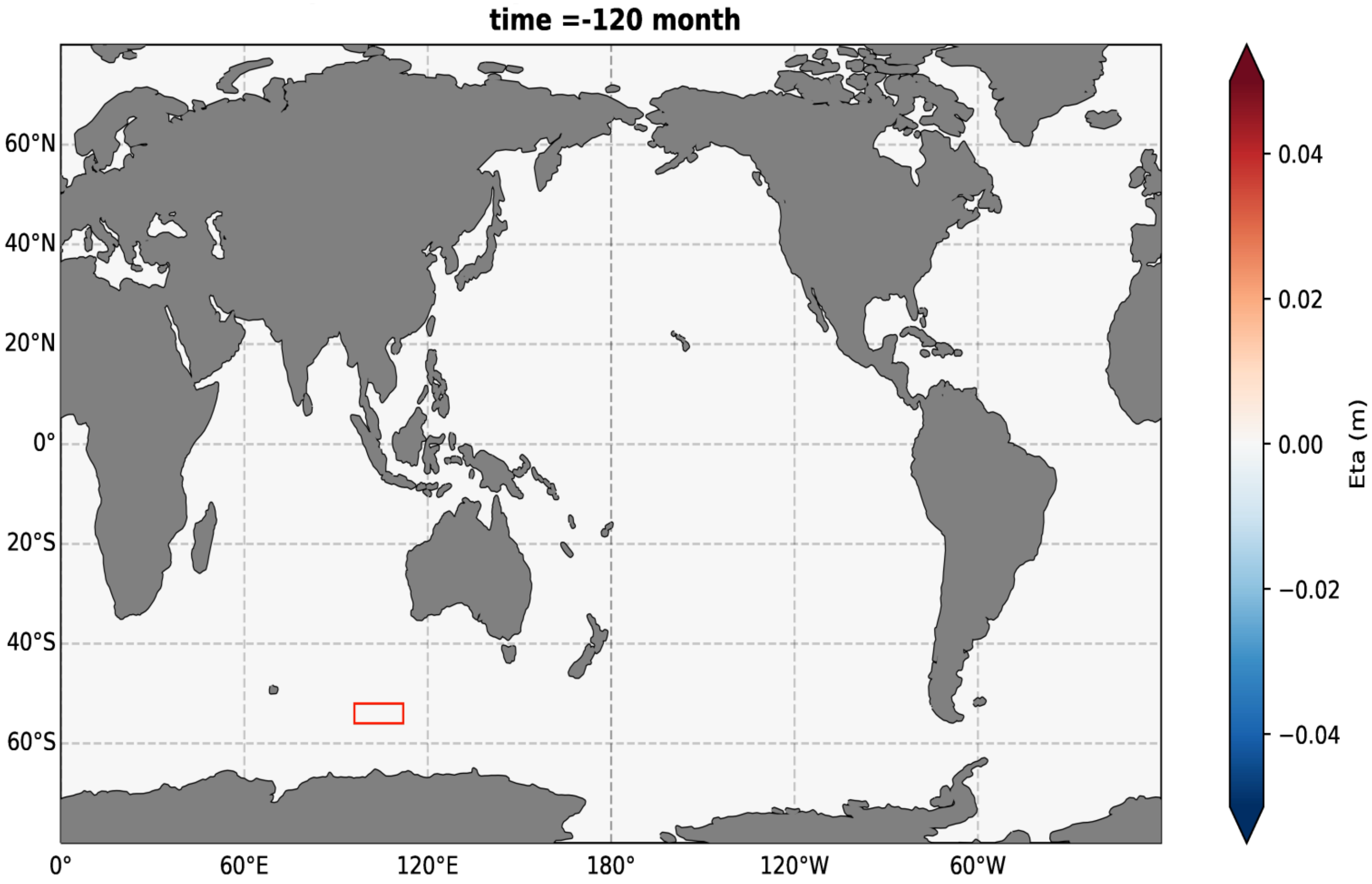
perturbation experiments



Background state of zonal wind stresss



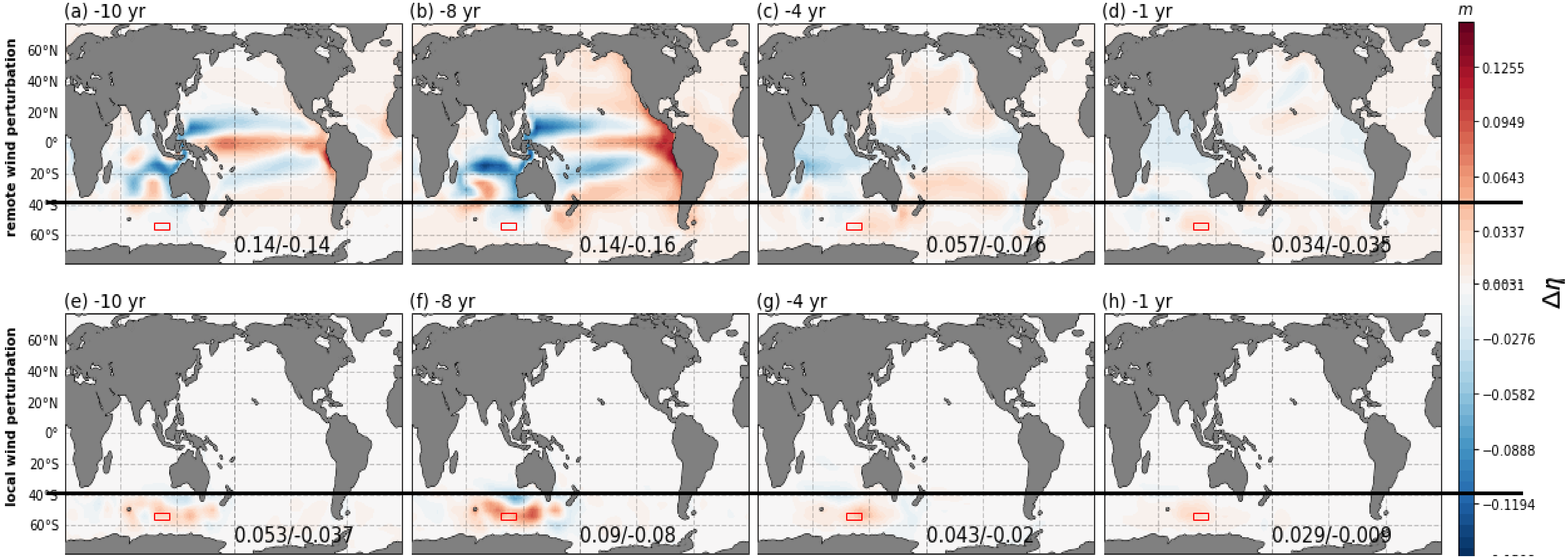
Sensitivity-like zonal wind stresss perturbation lasts 3 years

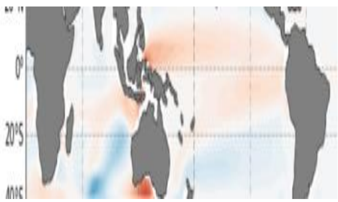


Response of SSH to perturbation

- **Equtorial Kelvin / Rossby waves**
- **Continental costal trapped waves**
- **Positive SSH anomaly in the target region in the end**

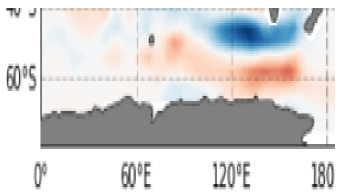
Local wind versus nonlocal wind





Strengthened Equtorial zonal wind ?

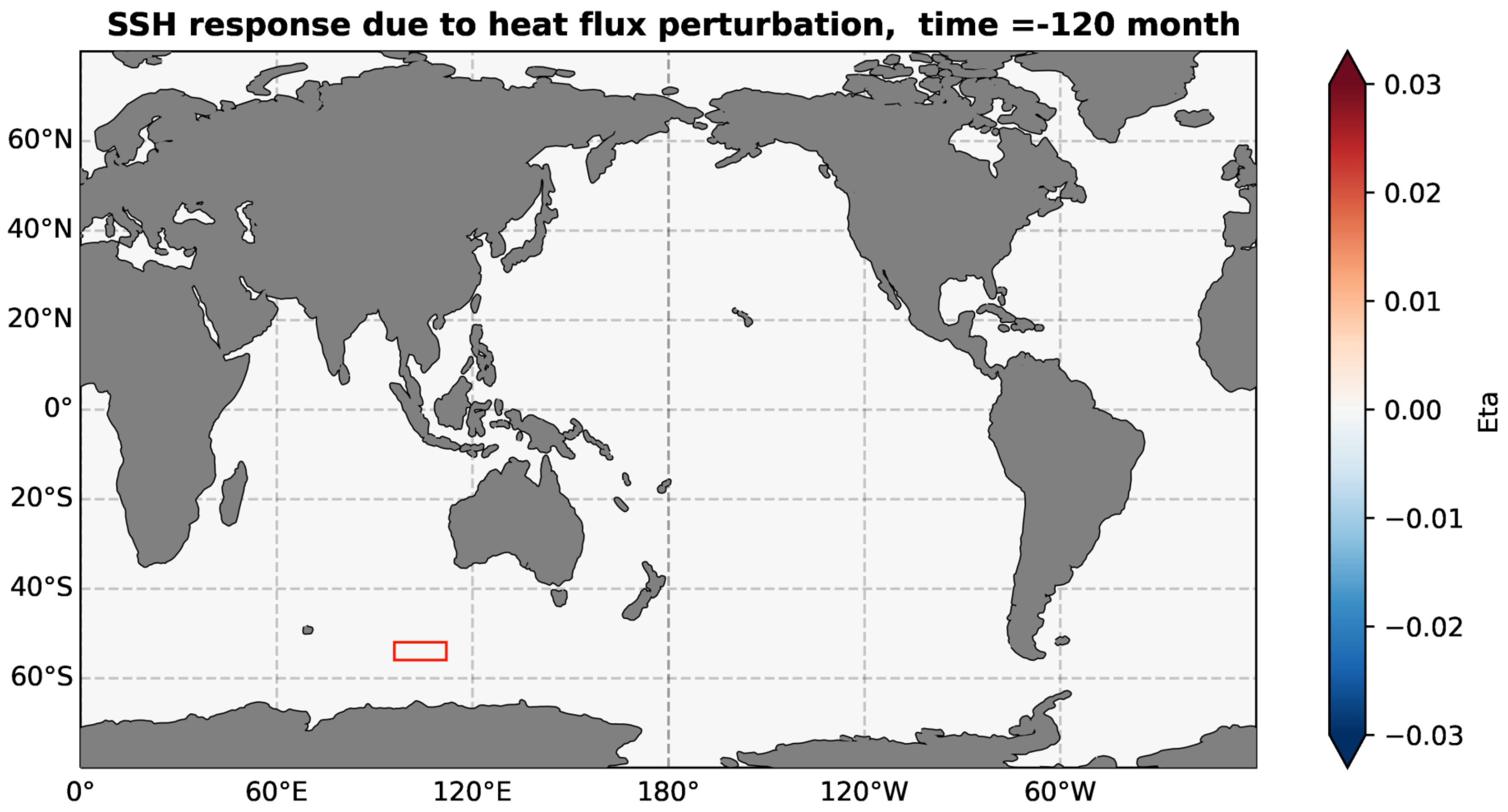
- **Kelvin wave → coastal waves → reflected Rossby wave → passing through Tasman Sea**
- **Takes several years to arrive**



Strengthened Southern Ocean wind stress curl ?

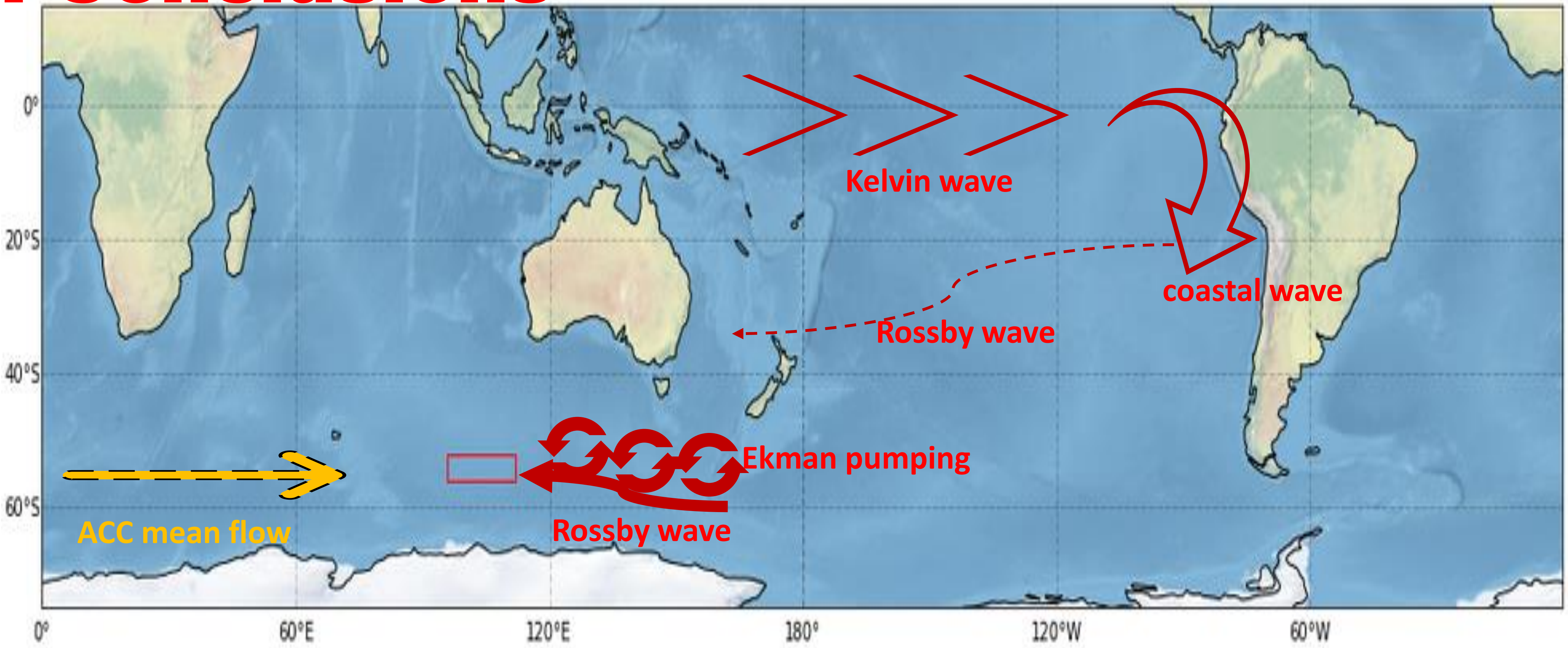
- **Westward Rossby wave (advected with ACC)**
- **Immediate response**

Heat flux-perturbation experiments



- **Sensitivity-like perturbation →generates signals chracterizing the cost function (positive SSH anomaly)**
- **Forcing, its location and timing, strength → influences the ocean response**

4. Conclusions



- **Large-scale circulation and SSH variability is essentially forced by surface wind stress**
- **SSH variability is mainly driven by wind-induced Ekman pumping and waves**
- **Local and regional winds is the leading factor, while remote winds take years**
- **Buoyancy fluxes modulate sea level variation via ACC mean flow**
- **Different mechanisms cause opposite pathways of sensitivities in the ACC section**

5. Outlook

1. Reconstruct sea level variability

$$f(t) = \sum_{i} \sum_{s} \sum_{\Delta t} \left(\frac{\partial J}{\partial F_i(s, \Delta t)} \delta F_i(S, t - \Delta t) \right)$$

2. Relation with ENSO, SAM?

3. Higher resolution configuration

- **Mesoscale processes?**
- **Small Currents?**