The impact of air-sea interaction on EPE generation in the Western Boundary Currents

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What are the physical controls on oceanic CO_2 uptake in WBCs?

1. **Sea-to-air CO_2 flux**
   a. pCO_2 solubility dependency on temperature
   b. k dependency on wind

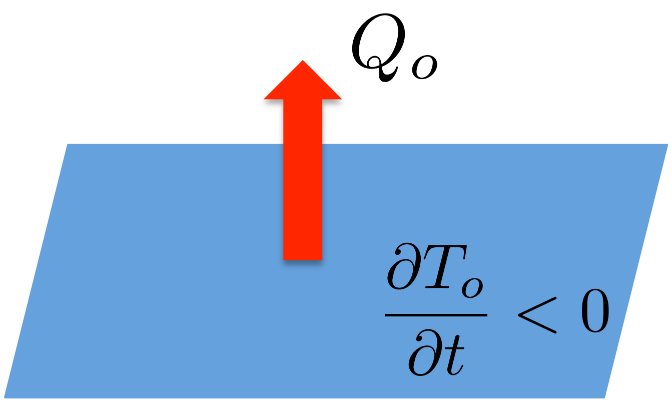
$$F_{CO_2} = \rho_a k \Delta pCO_2$$

2. **Phytoplankton blooms**
   a. Supply of nutrients to the euphotic zone
      i. Mesoscale vs submesoscale vertical velocities
      ii. Limiting nutrients
   b. Available sunlight (short wave radiation SWR)

3. **Sinking of particulate matter**

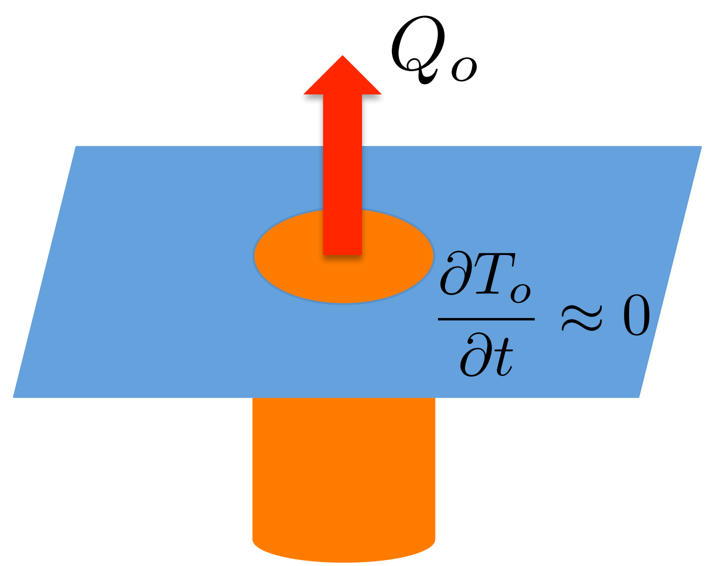
Atmosphere vs. internal processes driving SST variability

Passive Ocean



Disequilibrium between SST and near surface air temperature drives heat loss from the ocean and SST cooling.

Internal Processes



Propagation of an ocean eddy with a positive temperature anomaly drives heat loss with little change in SST in an Eulerian sense.

A simple stochastic Energy Balance model for midlatitude air-sea interaction

$$\frac{dT_a}{dt} = \alpha(T_o - T_a) - \gamma_a T_a + N_a$$

Atmospheric weather noise

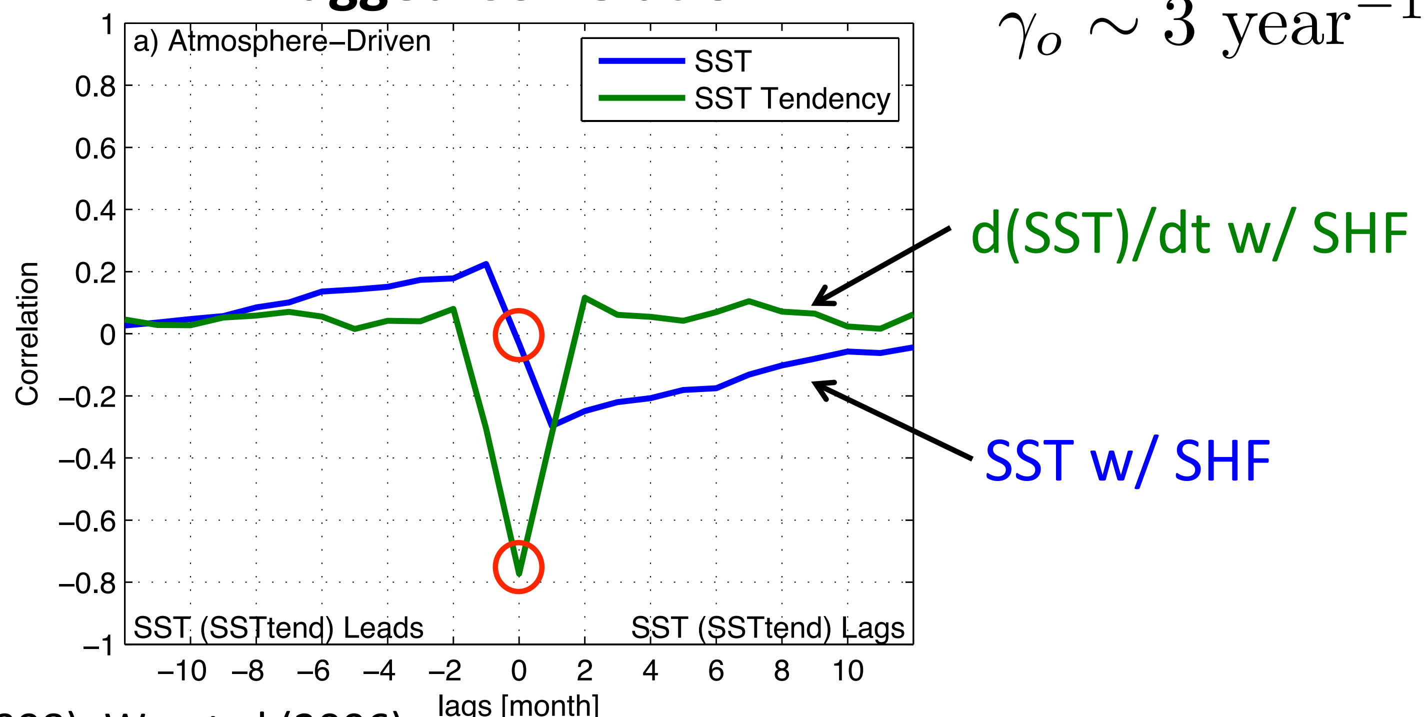
$$\frac{dT_o}{dt} = \beta(T_a - T_o) - \gamma_o T_o$$

$$\beta \sim \alpha/20$$

$$\gamma_a \sim 6 \text{ day}^{-1}$$

$$\gamma_o \sim 3 \text{ year}^{-1}$$

Lagged Correlation



Barsugli and Battisti (1998); Wu et al (2006)

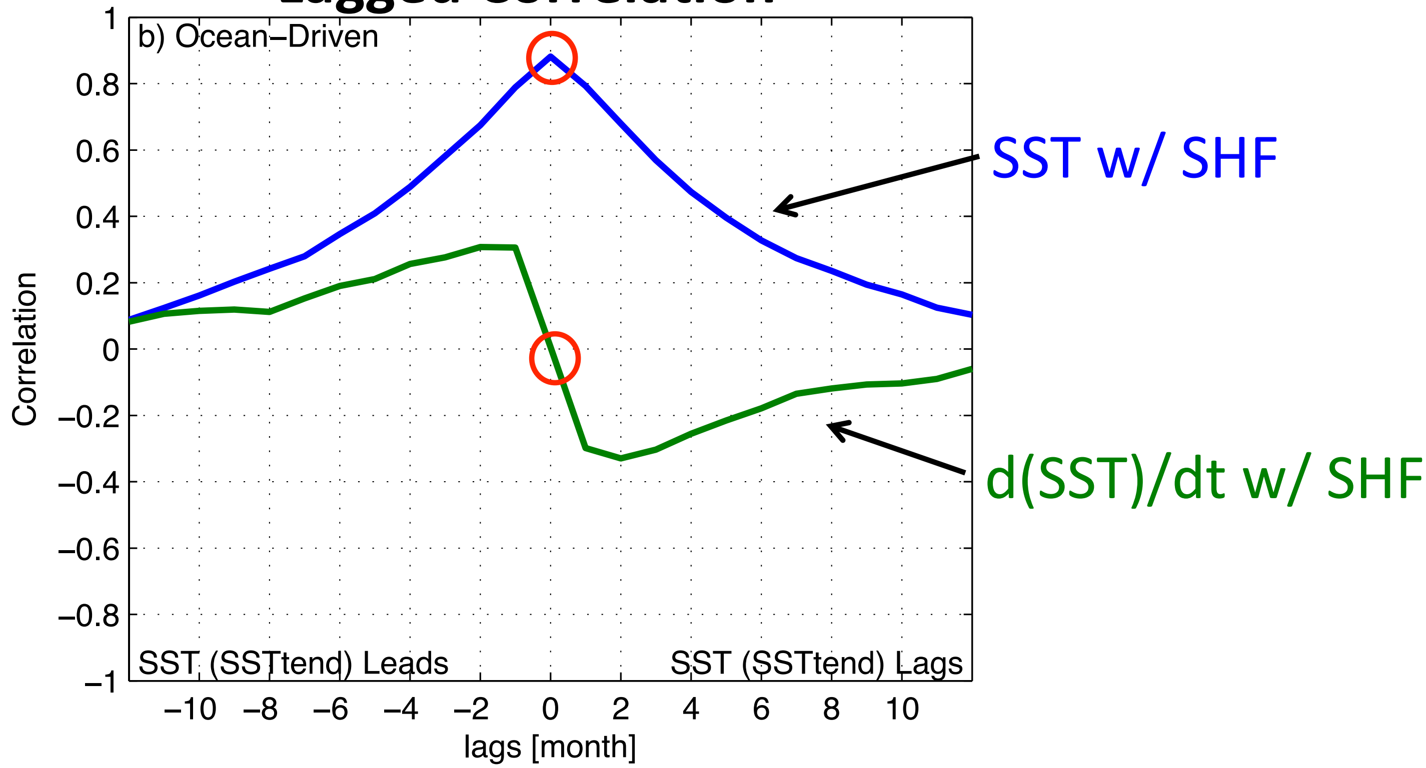
An alternative model: Oceanic-driven variability

$$\frac{dT_a}{dt} = \alpha(T_o - T_a) - \gamma_a T_a$$

$$\frac{dT_o}{dt} = \beta(T_a - T_o) - \gamma_o T_o + N_o$$

Oceanic weather noise

Lagged Correlation



Wu et al. (2006)

An alternative model: Atmospheric & oceanic weather noise

$$\frac{dT_a}{dt} = \alpha(T_o - T_a) - \gamma_a T_a + N_a$$

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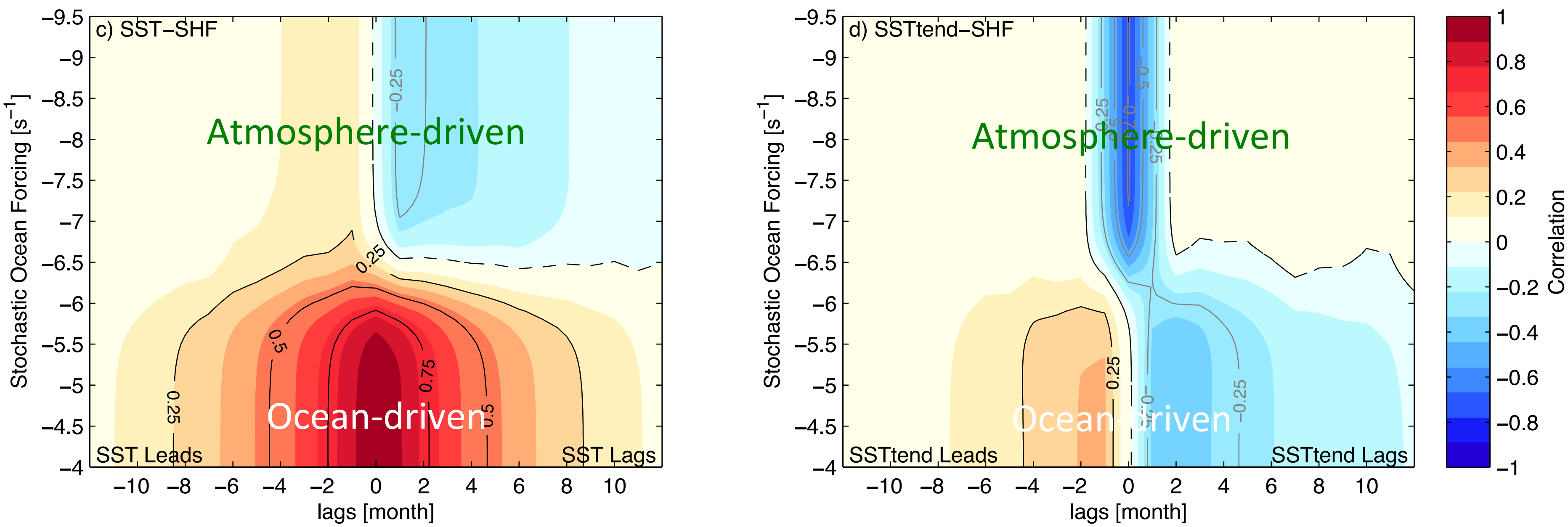
SST-SHF Lagged Correlation **d(SST)/dt-SHF Lagged Correlation**



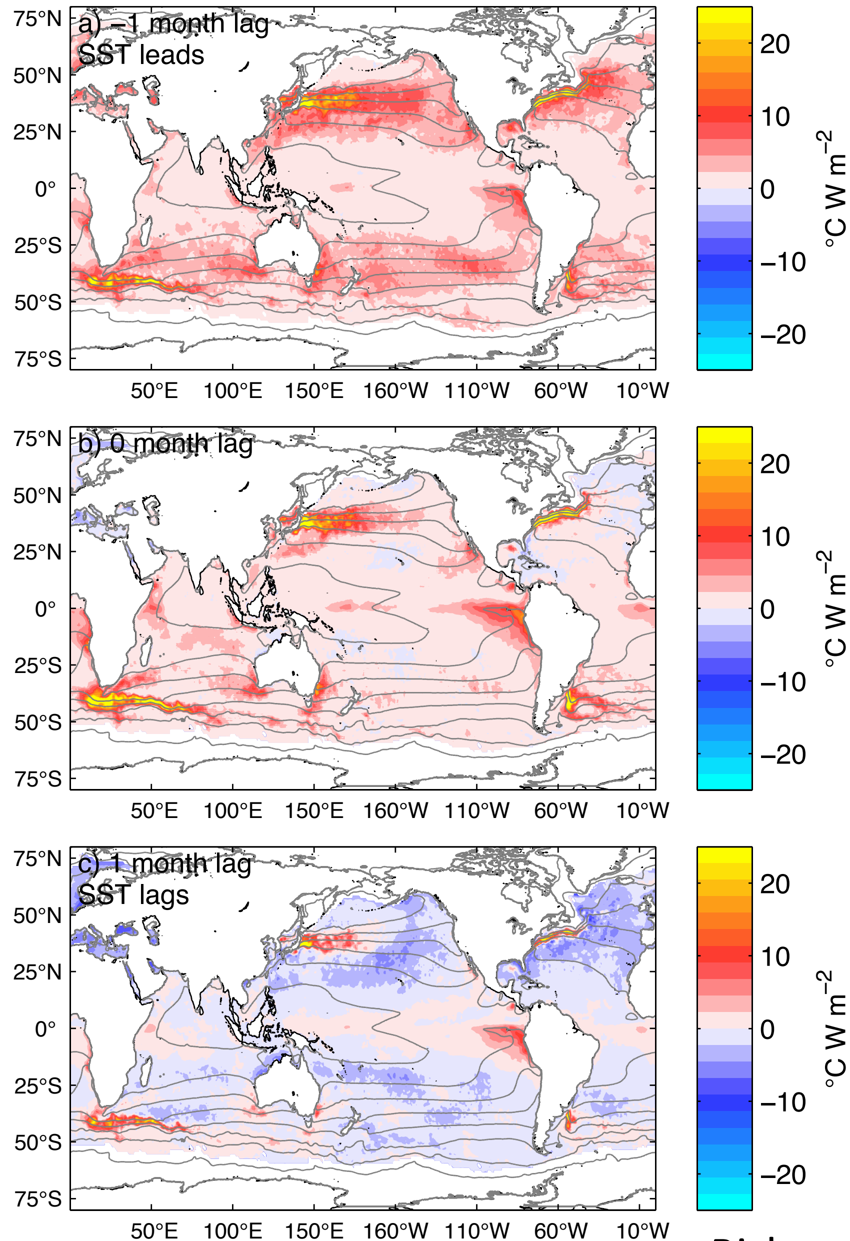
Bishop et al. (2017)

SST-SHF Lagged Covariance

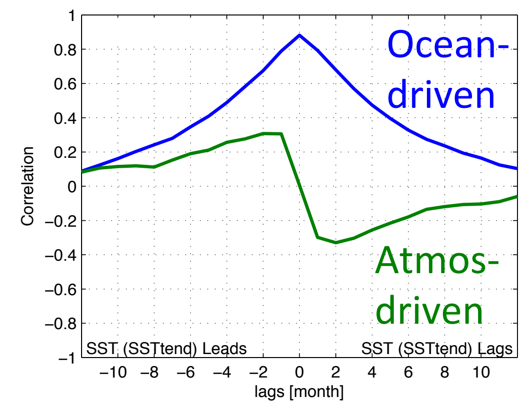
SST Leads by 1 month

Simultaneous

SST Lags by 1 month



SST-SHF Correlation



Symmetric

Bishop et al. (2017)

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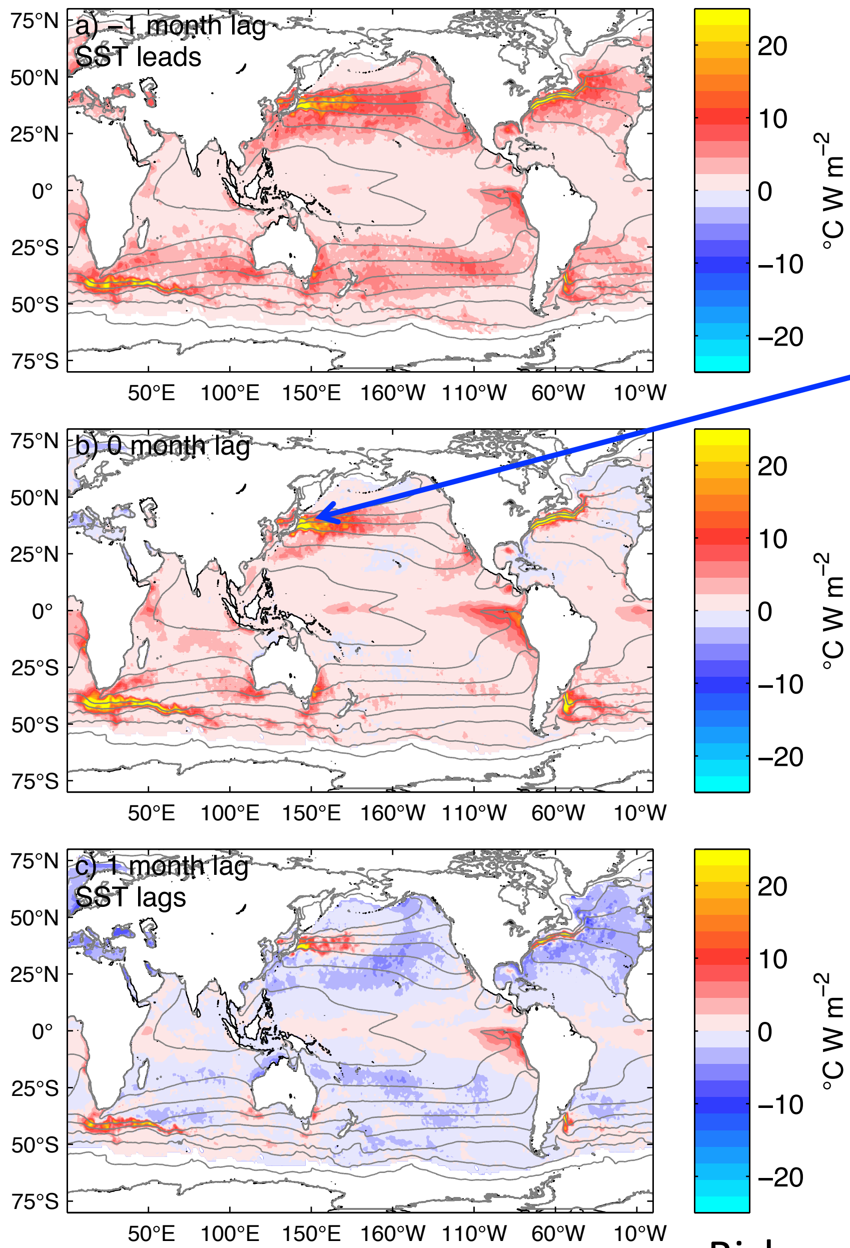

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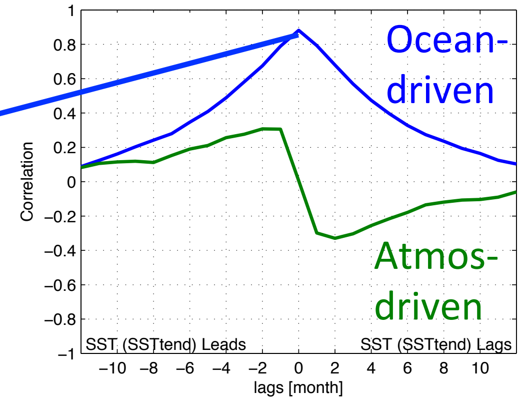

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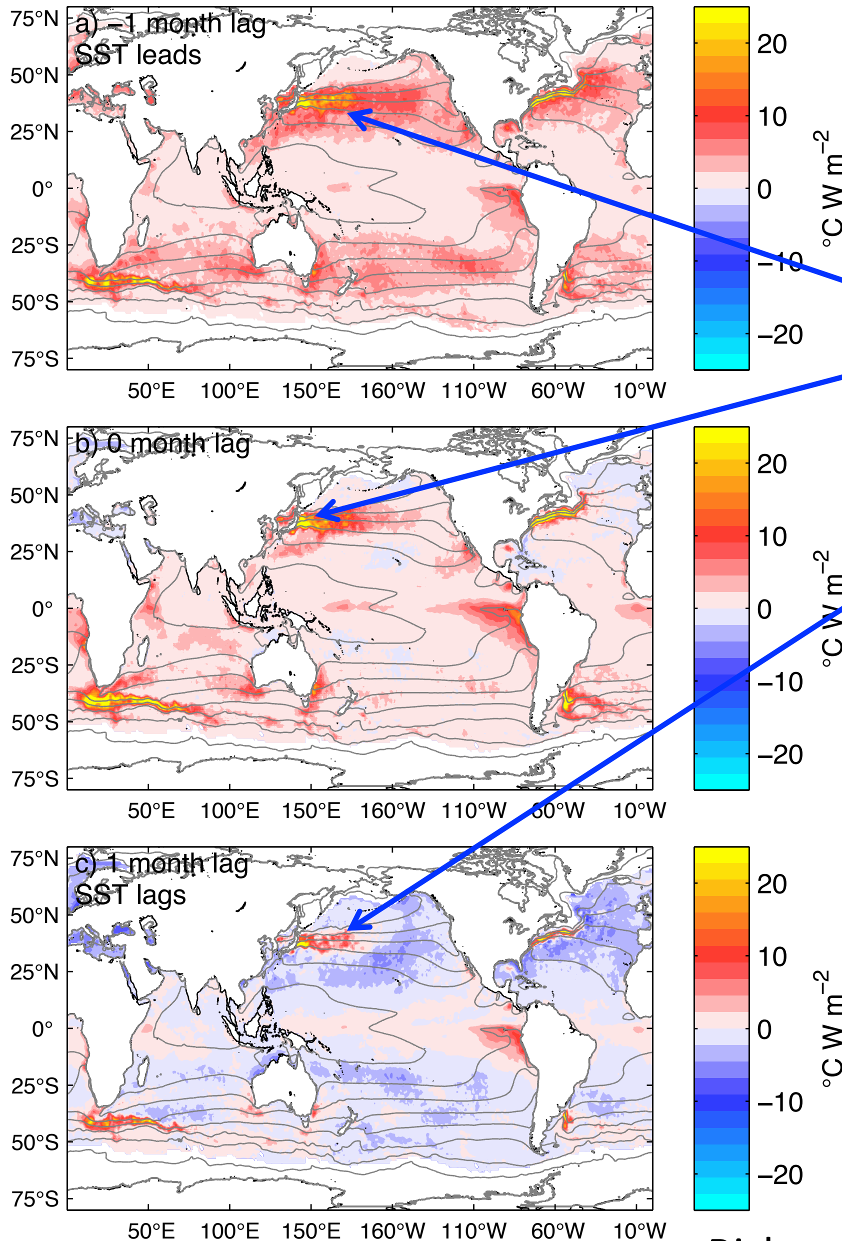
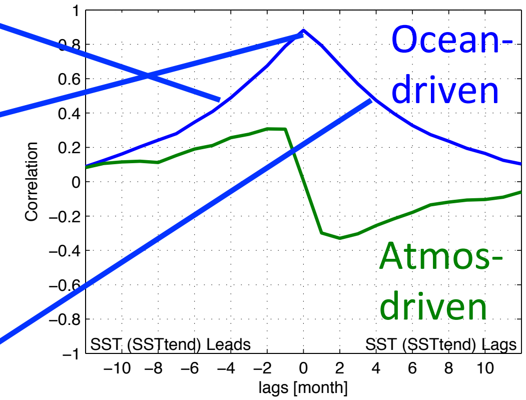


SST-SHF Correlation



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Bishop et al. (2017)

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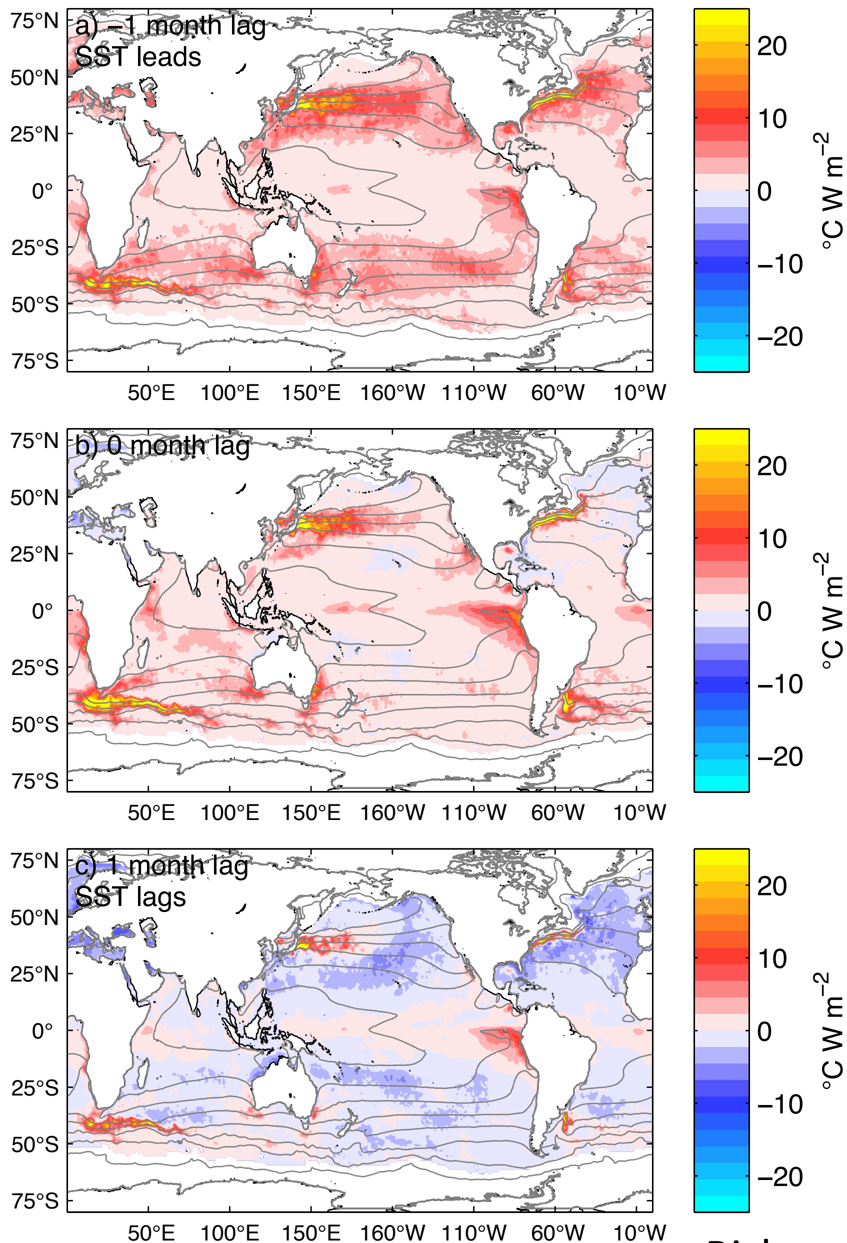
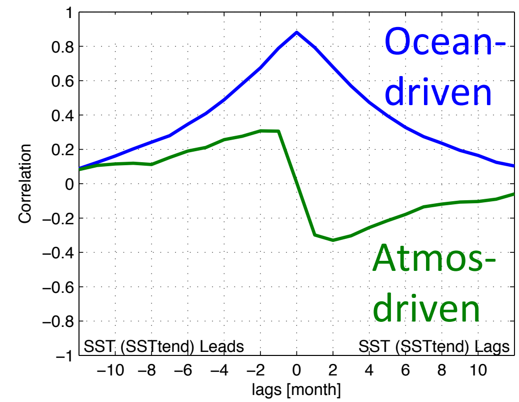


SST-SHF Correlation



Asymmetric

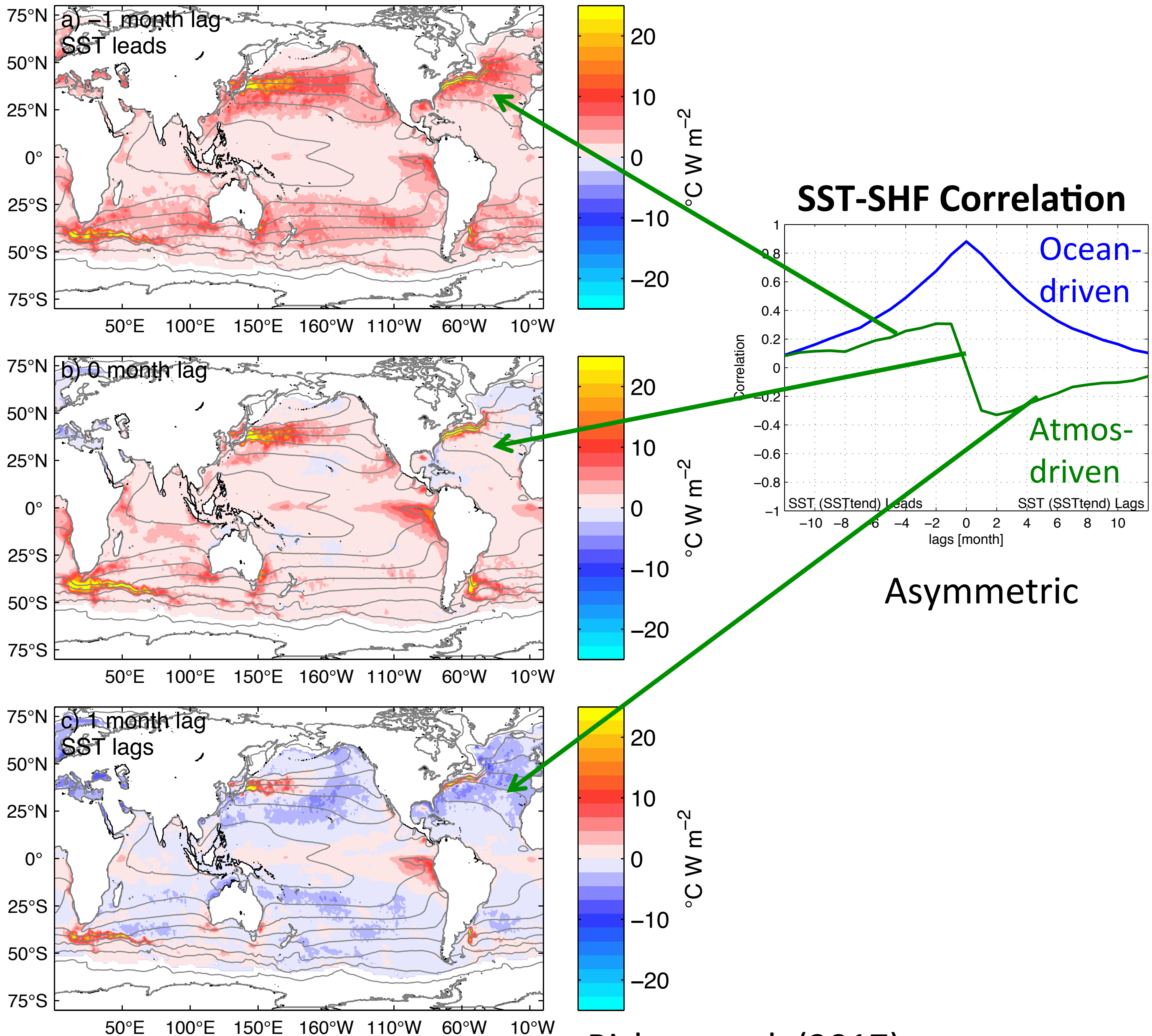
Bishop et al. (2017)

SST-SHF Lagged Covariance

SST Leads by 1 month

Simultaneous

SST Lags by 1 month

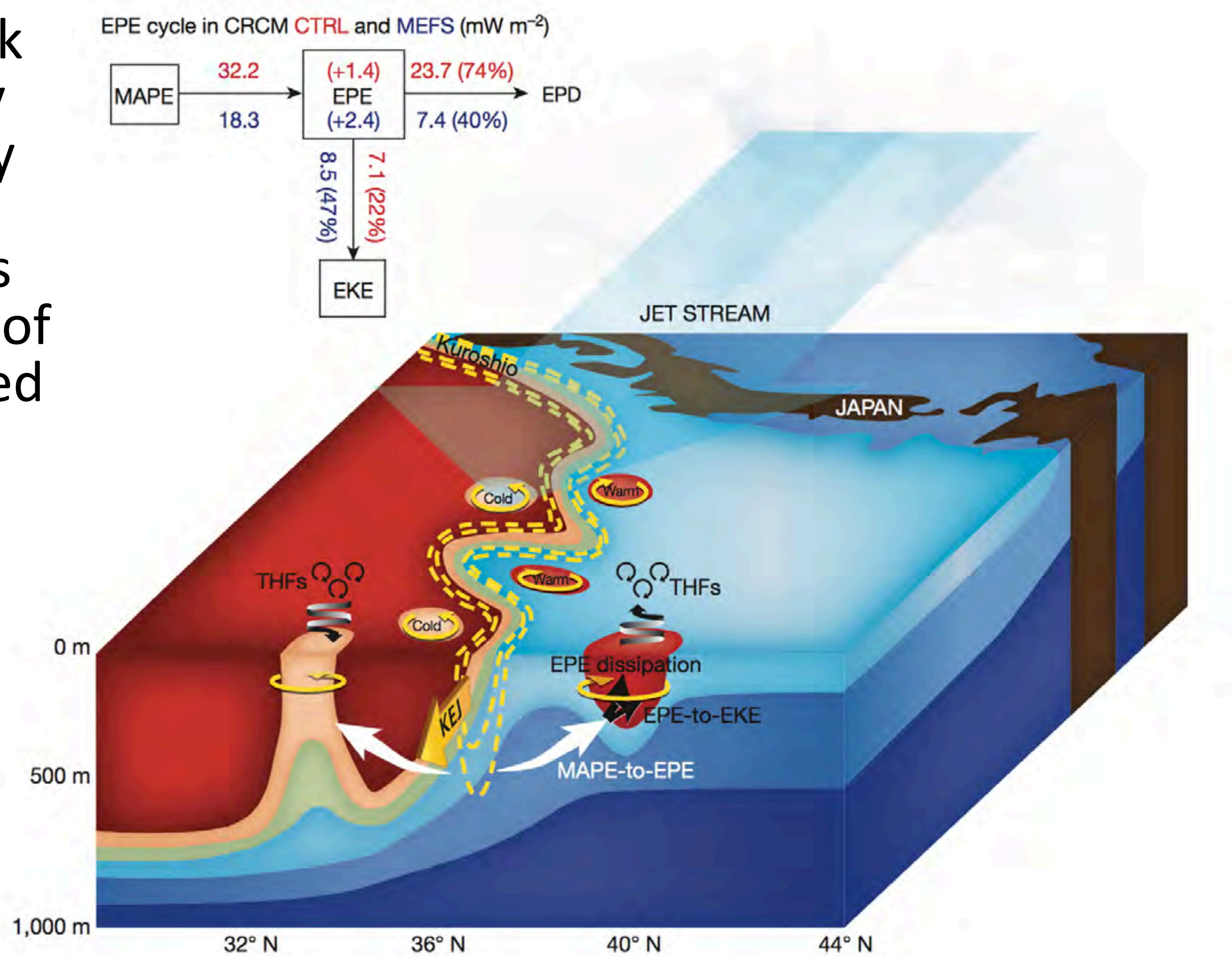


Asymmetric

Bishop et al. (2017)

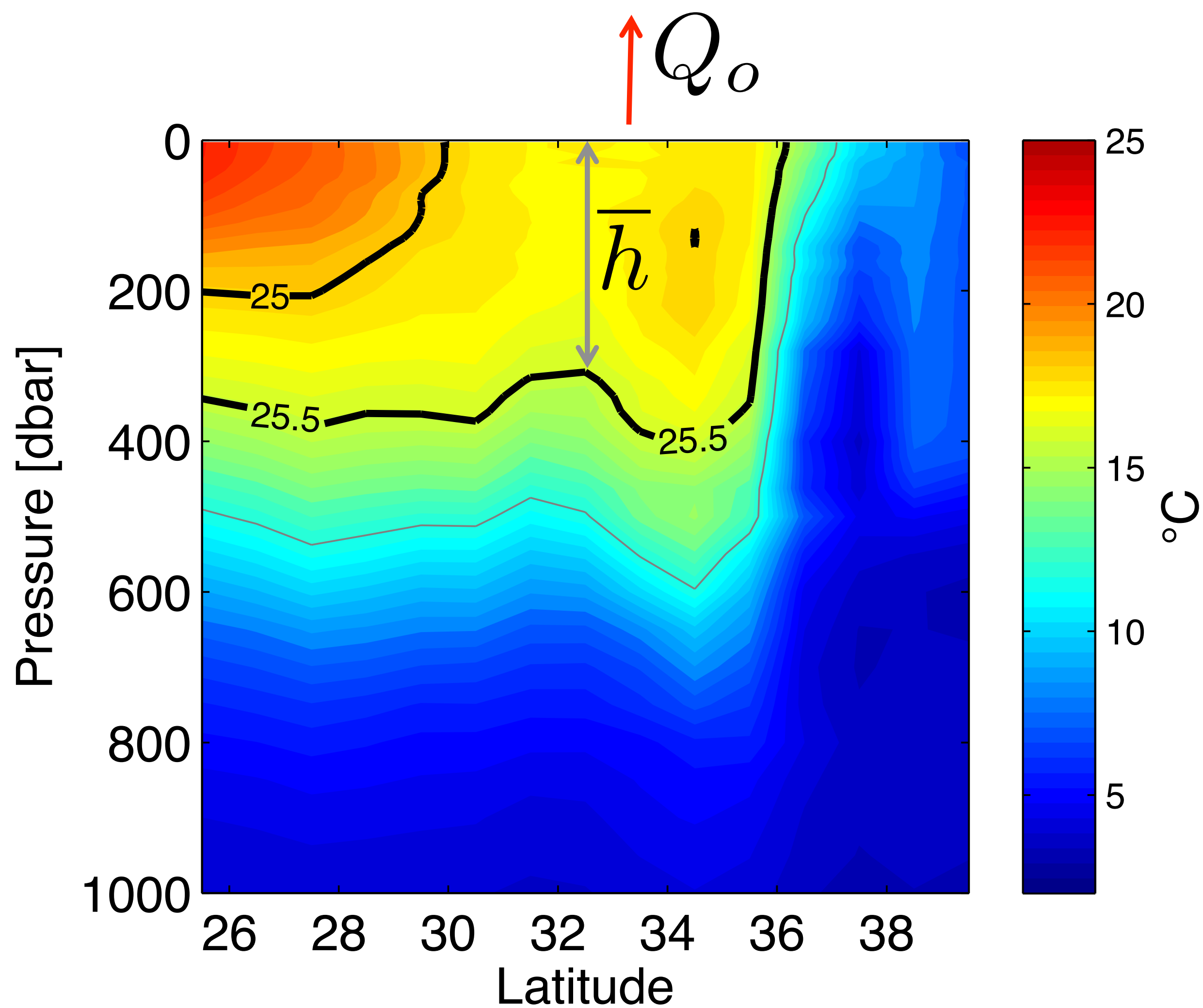
Mixed Layer Dissipation of EPE

- OME-A feedback dominates eddy potential energy destruction, which dissipates more than **70%** of the EPE extracted from the Kuroshio Extension Jet.



Ma et al. 2016 Nature

Baroclinic Conversion Balances EPE Dissipation



Kuroshio Extension meridional cross-section of potential temperature from Scripps Argo product in March 2011 at 145°E.

$$K_e |\nabla \overline{T}|^2 \approx \frac{\overline{T' Q_o'}}{\rho_o c_p \overline{h}}$$

Greatbatch et al. 2006 GRL

- Vertically integrated temperature variance equation to a constant temperature (T_o) representative of the base of the mixed layer.

- Parameterize BC

$$-\overline{\mathbf{u}' T'}^{div} \cdot \nabla \overline{T} = -K_e \nabla \overline{T}$$

Gent and McWilliams 1990 JPO

Data Sets

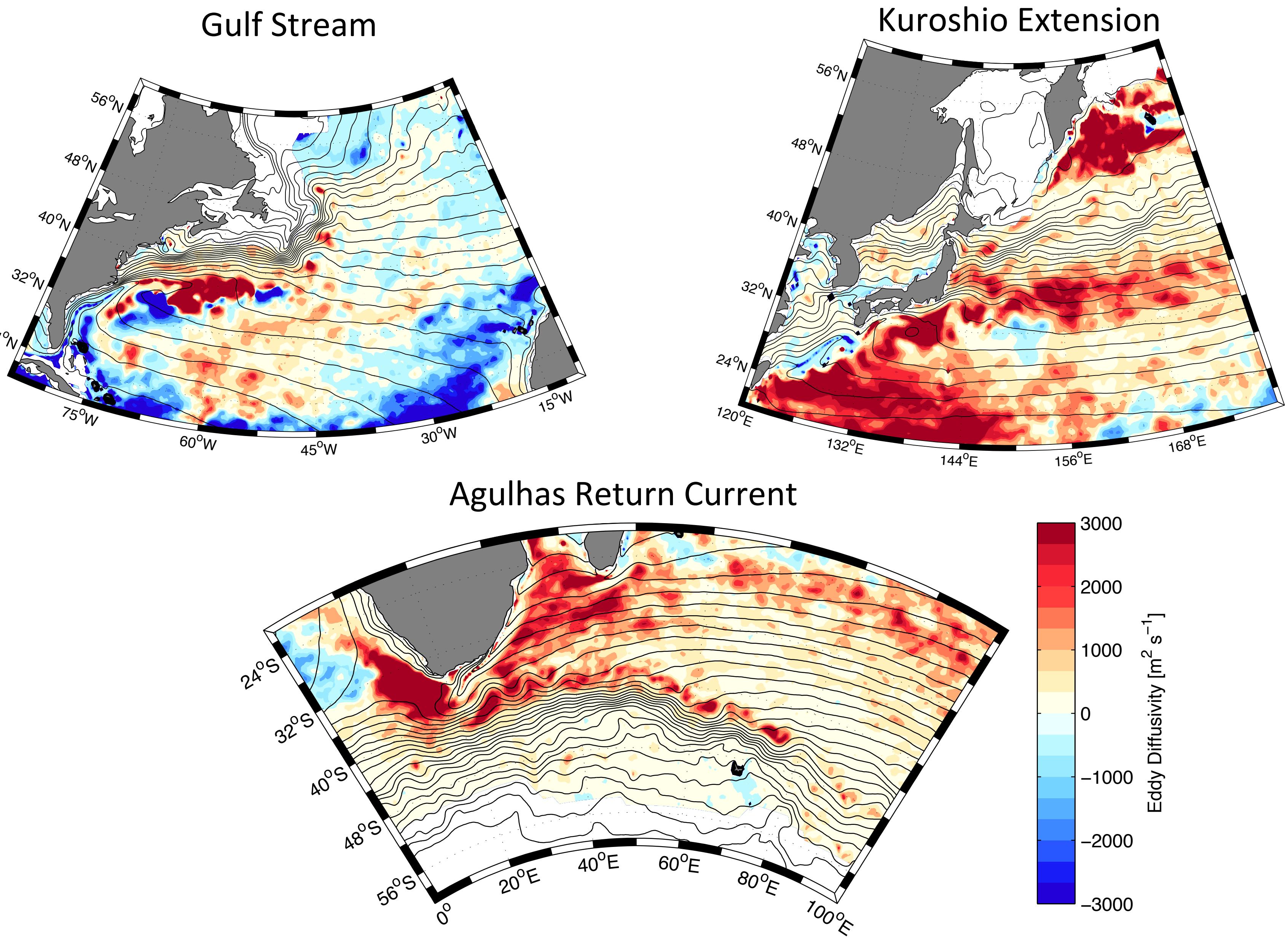
- **J-OFURO3 (Japanese Ocean Flux Data sets with Use of Remote Sensing Observations version 3)**
  - Monthly from 2002-2013
  - 0.25 Degree
  - SST, NHF, SWR, LWR, SHF, LHF
  - Sign convention positive heat flux is out of the ocean

$$\underbrace{Q_o}_{\text{NHF}} = \underbrace{Q_{sw}}_{\text{SWR}} + \underbrace{Q_{lw}}_{\text{LWR}} + \underbrace{Q_s}_{\text{SHF}} + \underbrace{Q_l}_{\text{LHF}}$$

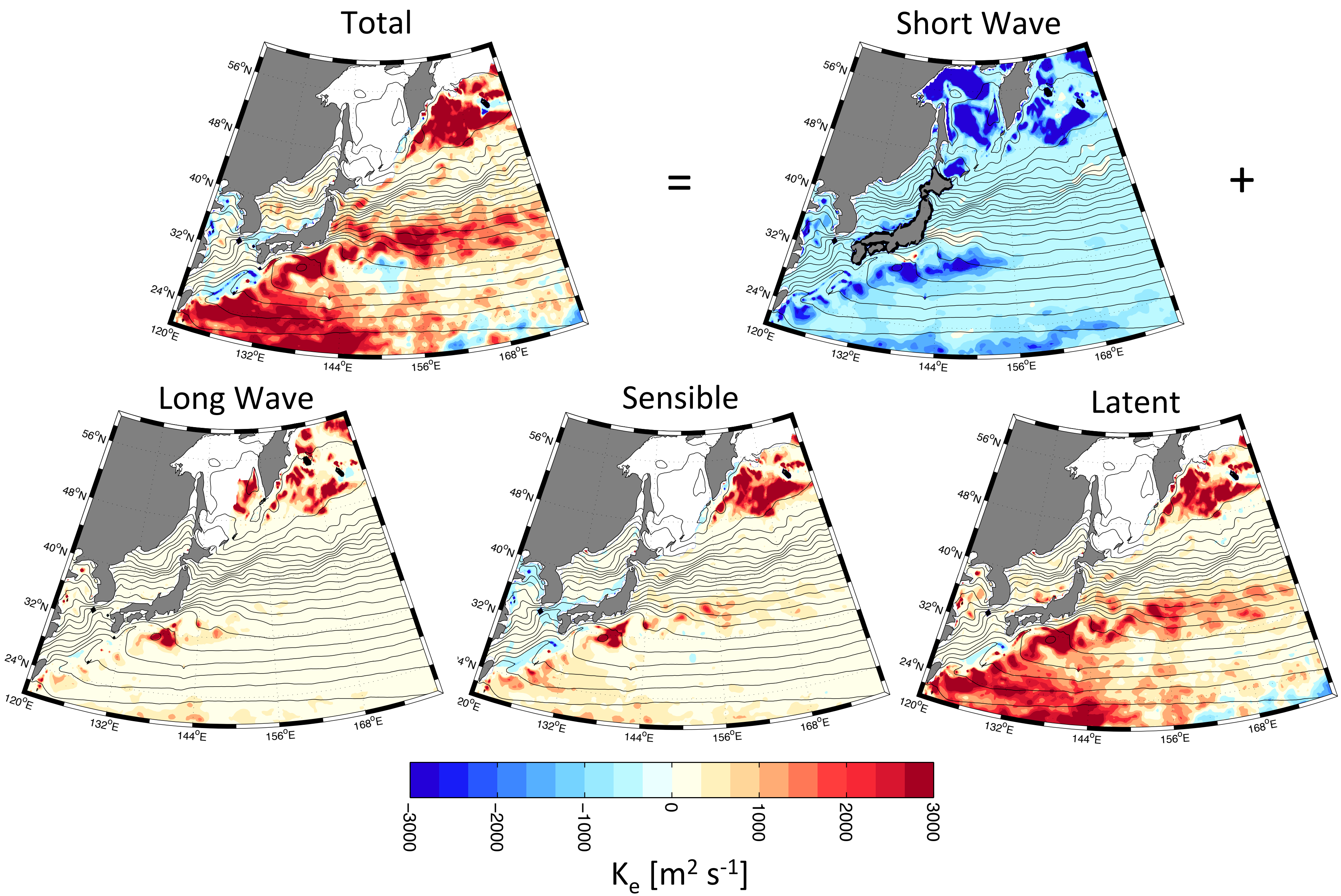
  - "Eddy" terms are deviations from the 2002-2013 climatological mean

- **MIMOC (Monthly Isopycnal / Mixed-layer Ocean Climatology)**
  - Climatology of mixed layer depths from Argo floats
  - 0.5 degree, remapped to 0.25 J-OFURO3 grid

WBC Eddy Diffusivity

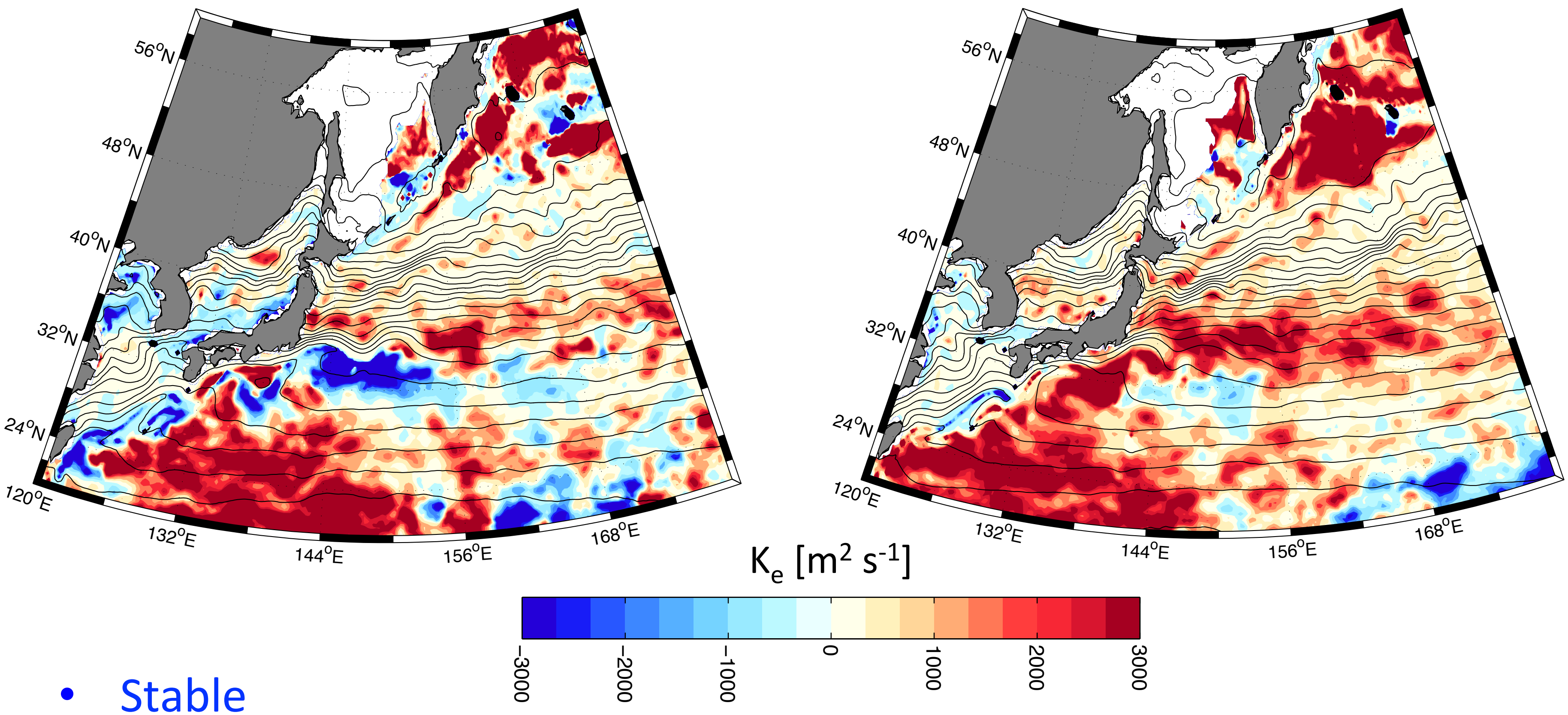


Kuroshio Extension Eddy Diffusivity (K_e)



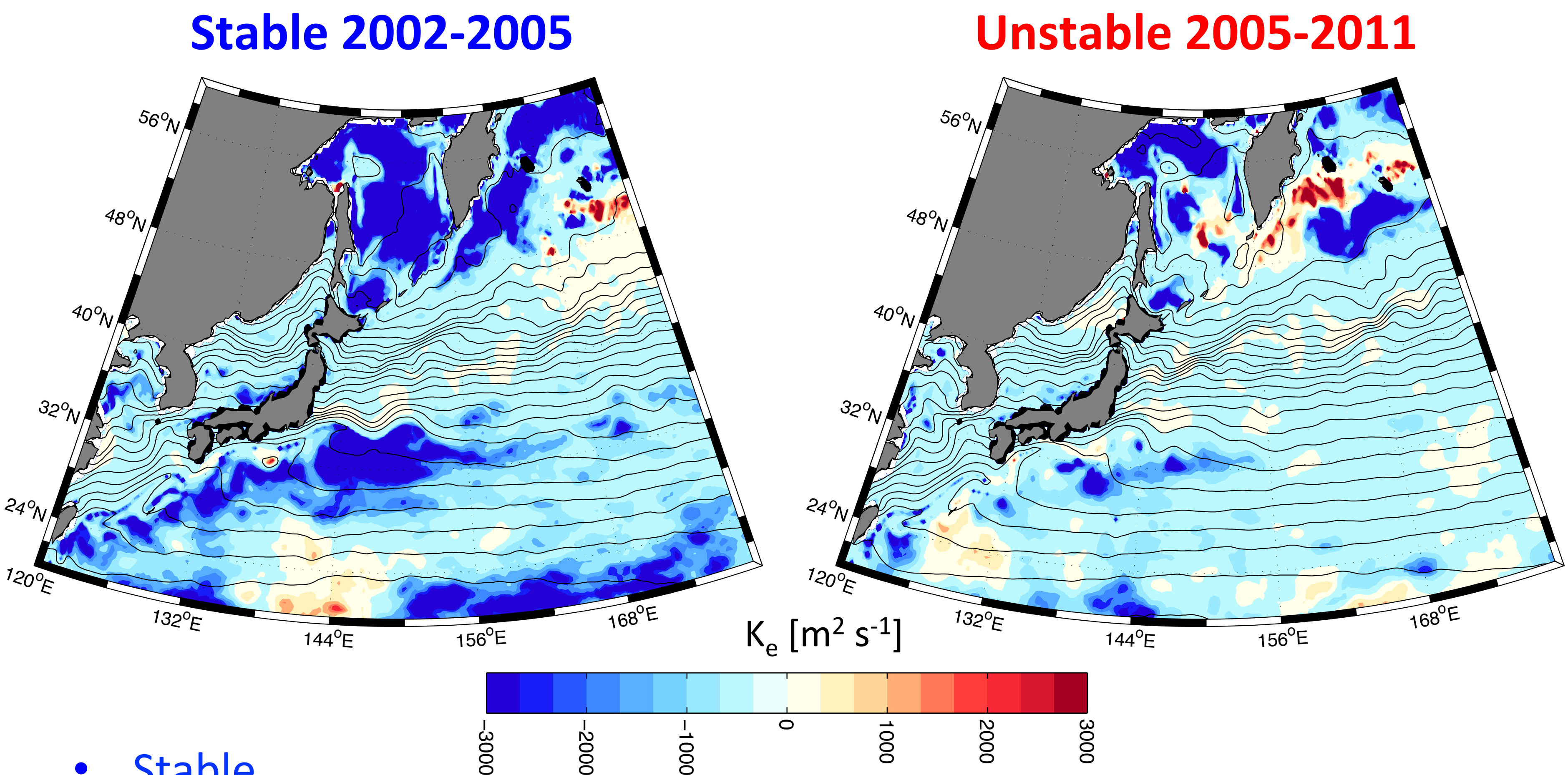
K_e stable vs. unstable states

Stable 2002-2005 **Unstable 2005-2011**



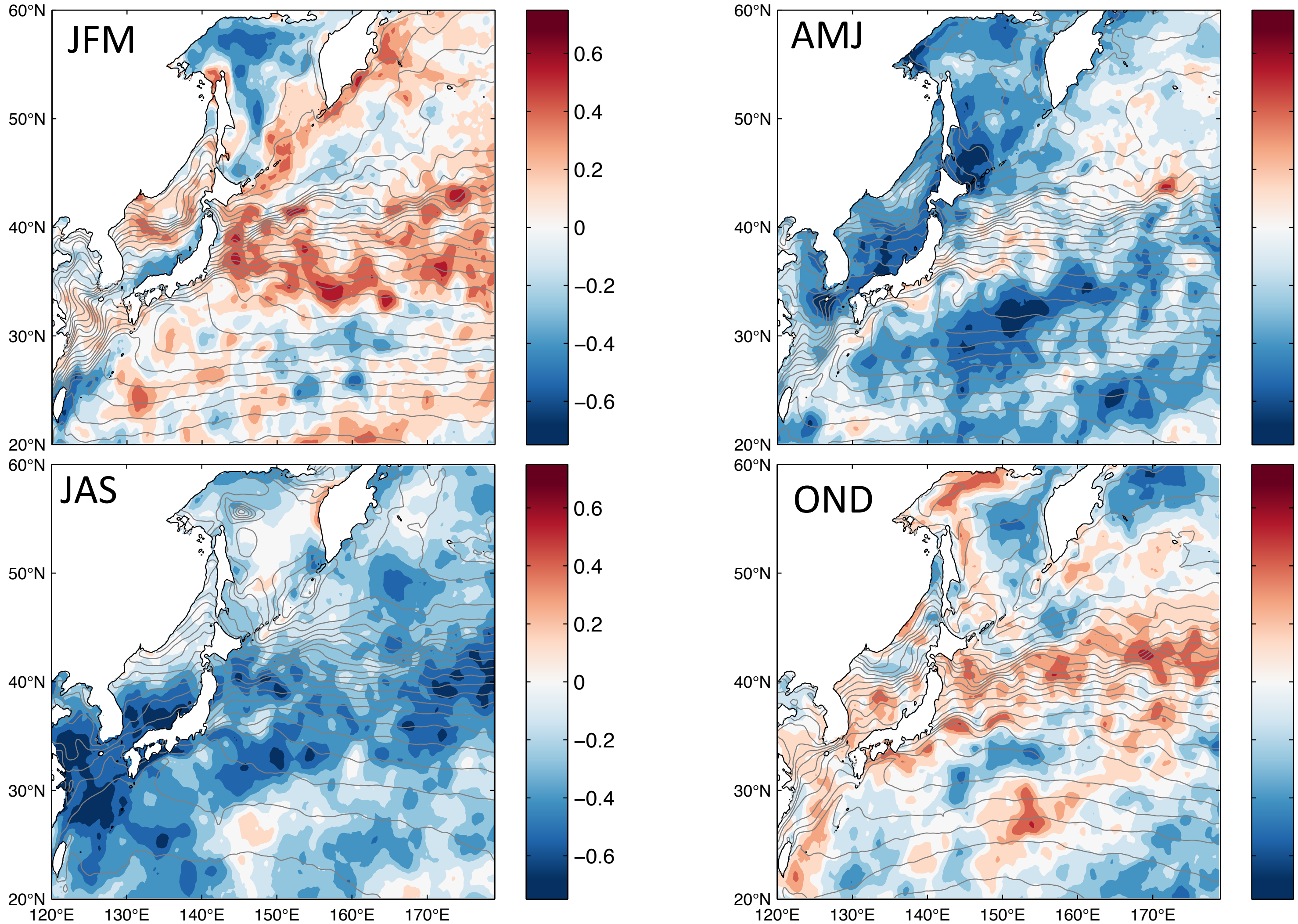
- Stable
  - K_e near the Kuroshio Extension is near zero or largely negative
  - EPE generation in the absence of eddies
- Unstable
  - K_e is mostly positive
  - EPE dissipation in the presence of eddies (e.g. cold-core rings)

K_e Short Wave Radiation Contribution



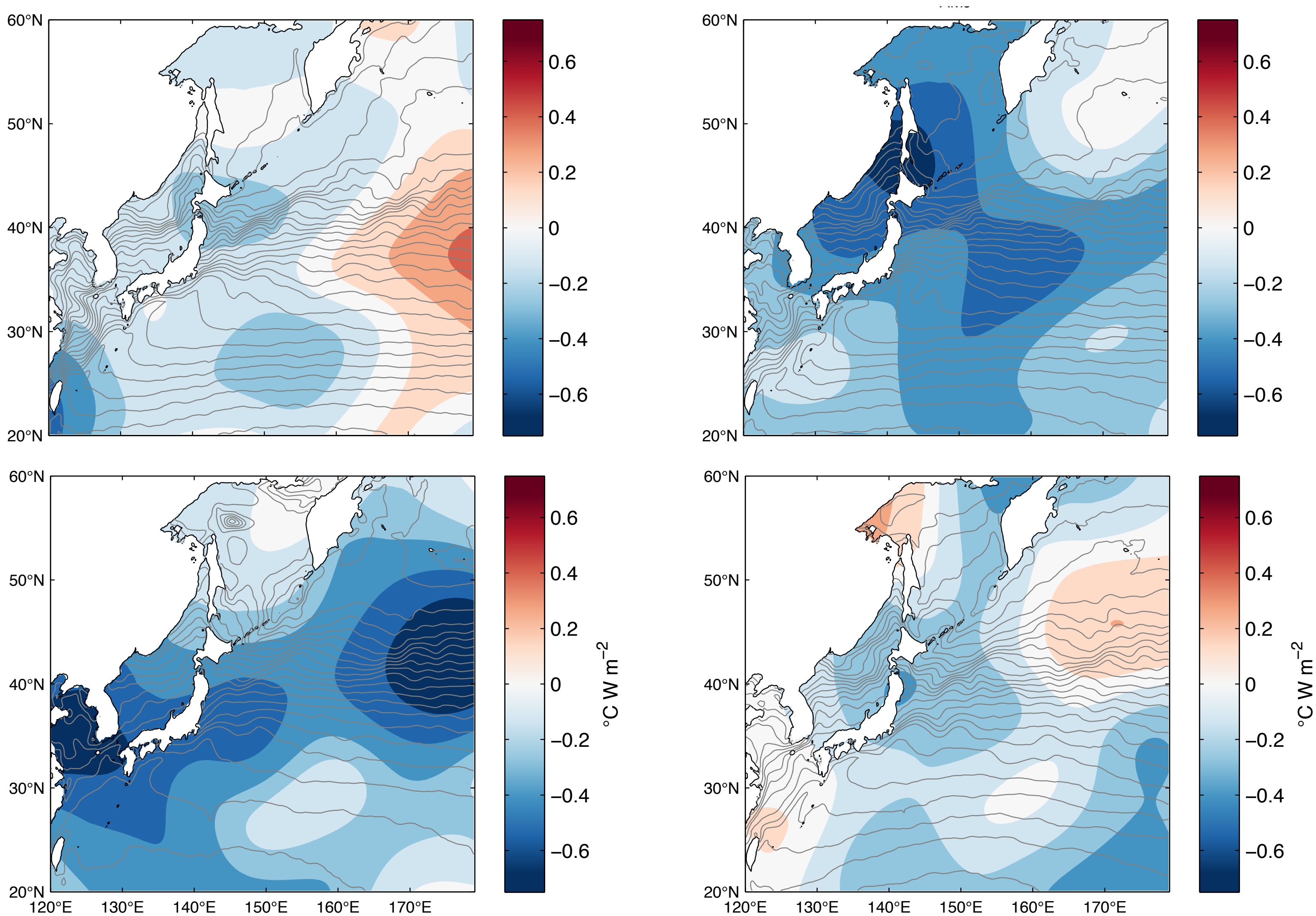
- Stable
  - K_e SWR contributions large and negative (EPE generation) within STMW formation region.
- Unstable
  - K_e SWR contributions are close to negligible due to possible mesoscale eddy-cloud feedbacks.

SST-SWR Correlation Seasonality



- Wintertime positive correlations indicate possible mesoscale eddy-cloud feedbacks
- Over the course of a year seasonal positive and negative correlations cancel each other

SST-SWR Correlation: Smoothed



- Smoothed anomaly field SST-SWR correlations remove mesoscale eddies and dampens positive correlations.

Conclusions

1. Western Boundary Current (WBC) regions exhibit internal (mesoscale) ocean-driven SST variability, which may impact CO_2 fluxes.

2. Outside of WBCs ocean is passive with the atmosphere driving SST variability.

3. Mesoscale eddies impact air-sea interaction in the WBCs and act to dissipate EPE, which is not represented in low-resolution coupled climate models.

4. The Kuroshio Extension stable vs. unstable states:
   - Stable states with no mesoscale rings enhances anomalous negative SST-SWR correlations and EPE generation.
   - Unstables states rich in mesoscale eddies have possible wintertime mesoscale eddy-cloud feedbacks that cancel seasonally with summertime EPE generation.

Mixed Layer Eddy Potential Energy Equation

$$\left(\frac{\partial}{\partial t} + \mathbf{u}_a \cdot \nabla\right) T_a = \frac{Q_o}{\rho_o c_p h} + \frac{\kappa_T}{h}\frac{\partial T}{\partial z}\Big|_{-h} + V_{ent}$$

$$\left(\frac{\partial}{\partial t} + \overline{\mathbf{u}}_a \cdot \nabla\right) \frac{1}{2}\overline{T_a'^2} = \frac{-\overline{T_a' Q_o'}}{\rho_o c_p \overline{h}} - \overline{\mathbf{u}_a' T_a'} \cdot \nabla \overline{T}_a + \overline{T_a' V_{ent}'}$$

Buoyancy Generation/ Dissipation of ML-EPE

Baroclinic Conversion ML-MPE -> ML-EPE

ML-EPE -> ML-EKE

- Correlation between SST-NHF generates or dissipates SST variance (e.g. EPE).
- Positive (negative) correlation (+ve heat flux out of the ocean) dissipates (generates) EPE.