Eddy-induced air-sea coupling in momentum and heat budgets

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WHOI seminar May 21, 2024

Outline

01 - Introduction and motivations

Air-sea coupling in theories.

02 - Nonlinear Ekman theory

Slab Ekman layer; Response to balanced eddies; Coupled with 2-layer shallow water model.

03 - SSH-SST inconsistency in mesoscale eddies

SST signatures within SSH-detected eddies; Influences on meridional heat transport.

04 - Isopycnic water mass subduction

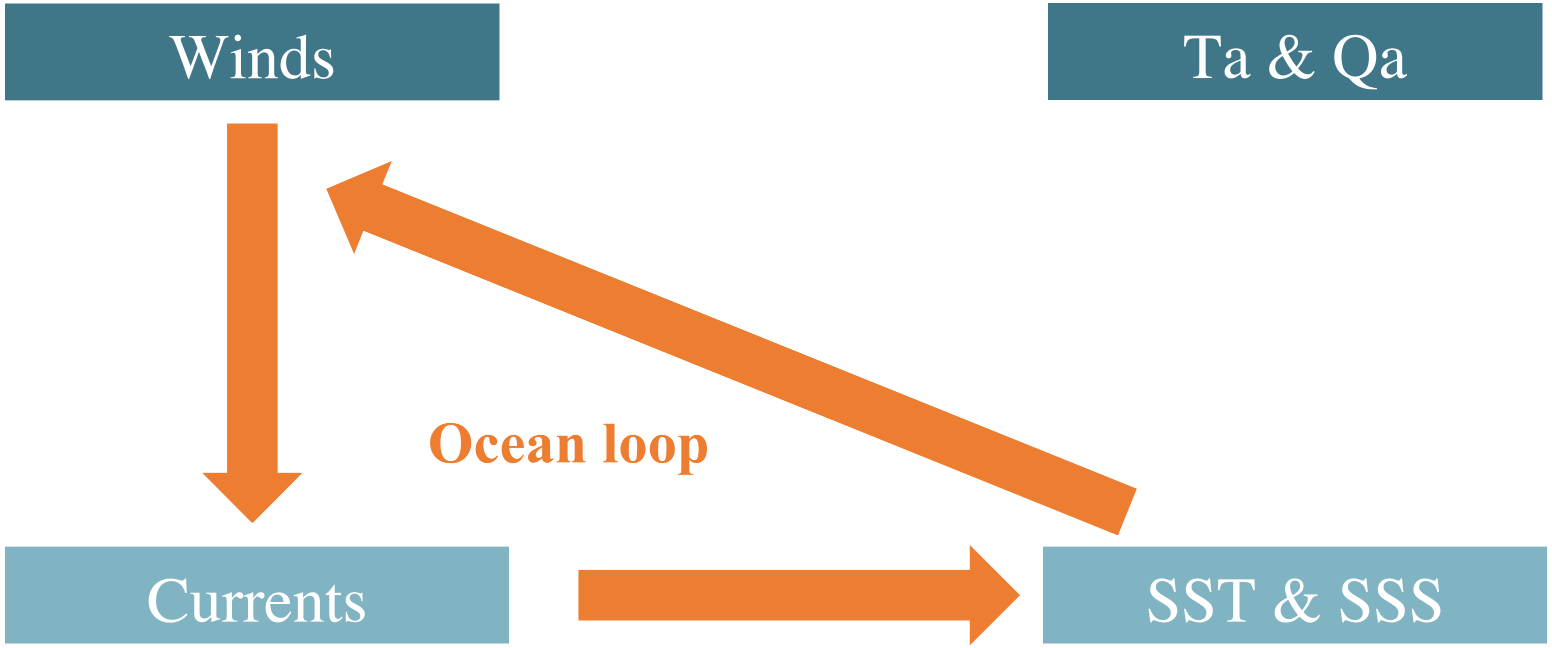
Stommel's demon? Meridional movement of isopycnals.

05 - Discussions

Prospectives for future studies.

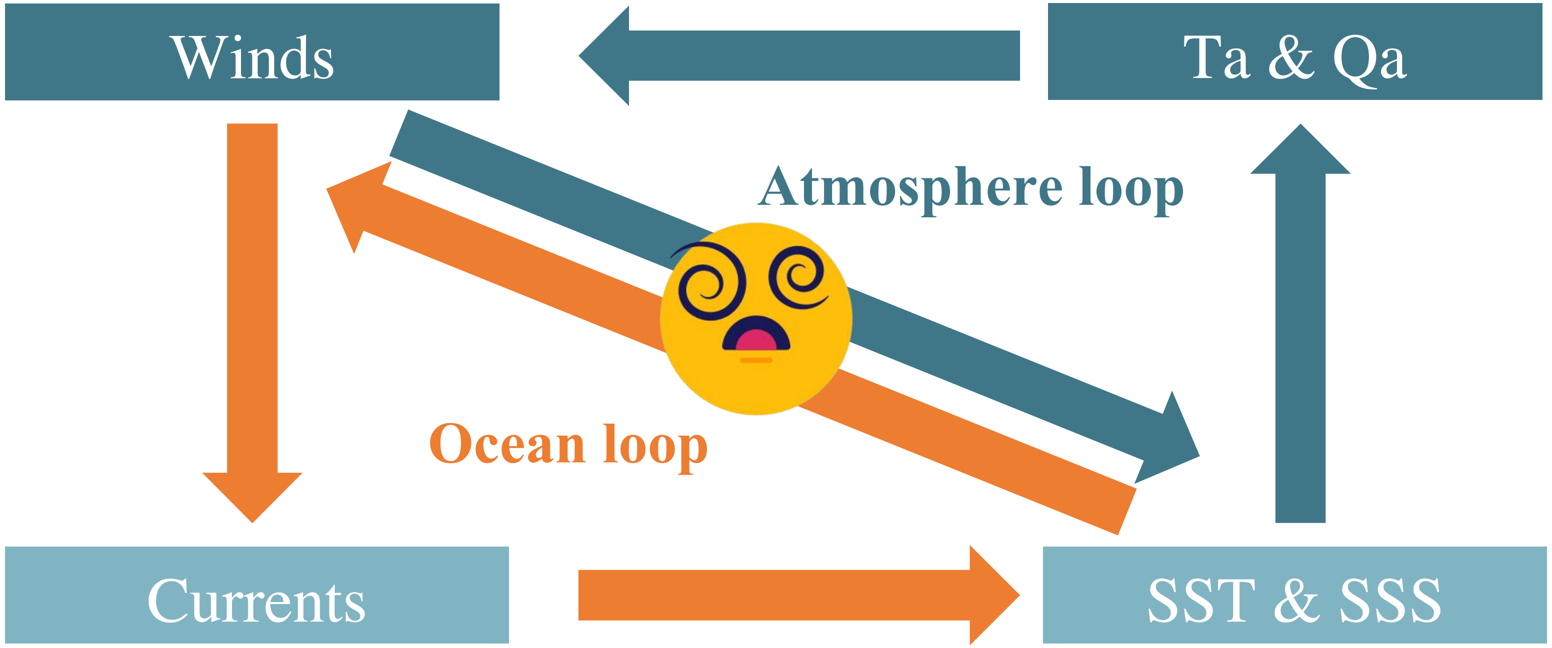
Air-sea coupling from the big picture

From the ocean side



Air-sea coupling from the big picture

From the atmosphere side



Causation issues???

Current feedback to the momentum budget

a. Current feedback

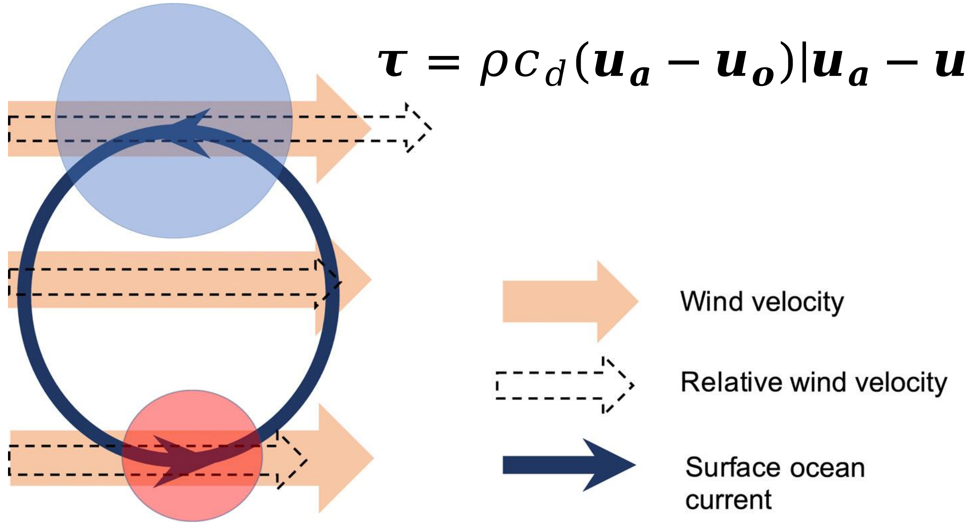
How ocean eddies lose/gain energy to/from the atmosphere.

$$\boldsymbol{\tau} = \rho c_d \boldsymbol{u_a} |\boldsymbol{u_a}|$$

$$\boldsymbol{\tau} = \rho c_d (\boldsymbol{u_a} - \boldsymbol{u_o}) |\boldsymbol{u_a} - \boldsymbol{u_o}|$$

Regime of eddy killing

$$\boldsymbol{\tau} = \rho c_d (\boldsymbol{u_a} - \boldsymbol{u_o}) |\boldsymbol{u_a} - \boldsymbol{u_o}|$$



Rai et al., 2021

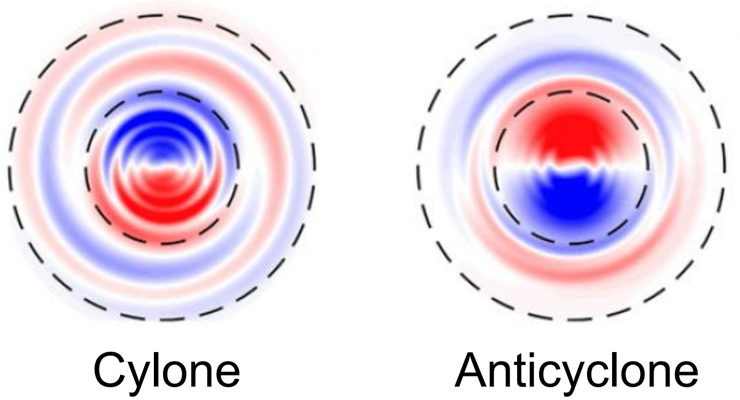
b. Nonlinear Ekman theory

$$\boldsymbol{U_{Ek}} \cdot \nabla \boldsymbol{u} + \boldsymbol{u} \cdot \nabla \boldsymbol{U_{Ek}} + \boldsymbol{U_{Ek}} \cdot \nabla \boldsymbol{U_{Ek}} + f \hat{\boldsymbol{z}} \times \boldsymbol{U_{Ek}} = \boldsymbol{\tau}/\rho$$

ocean current   Ekman flow

Or simply: $w_{Ek} = \frac{1}{\rho} \frac{\nabla \times \boldsymbol{\tau}}{f + \zeta}$ **Basically, what matters is ζ.**

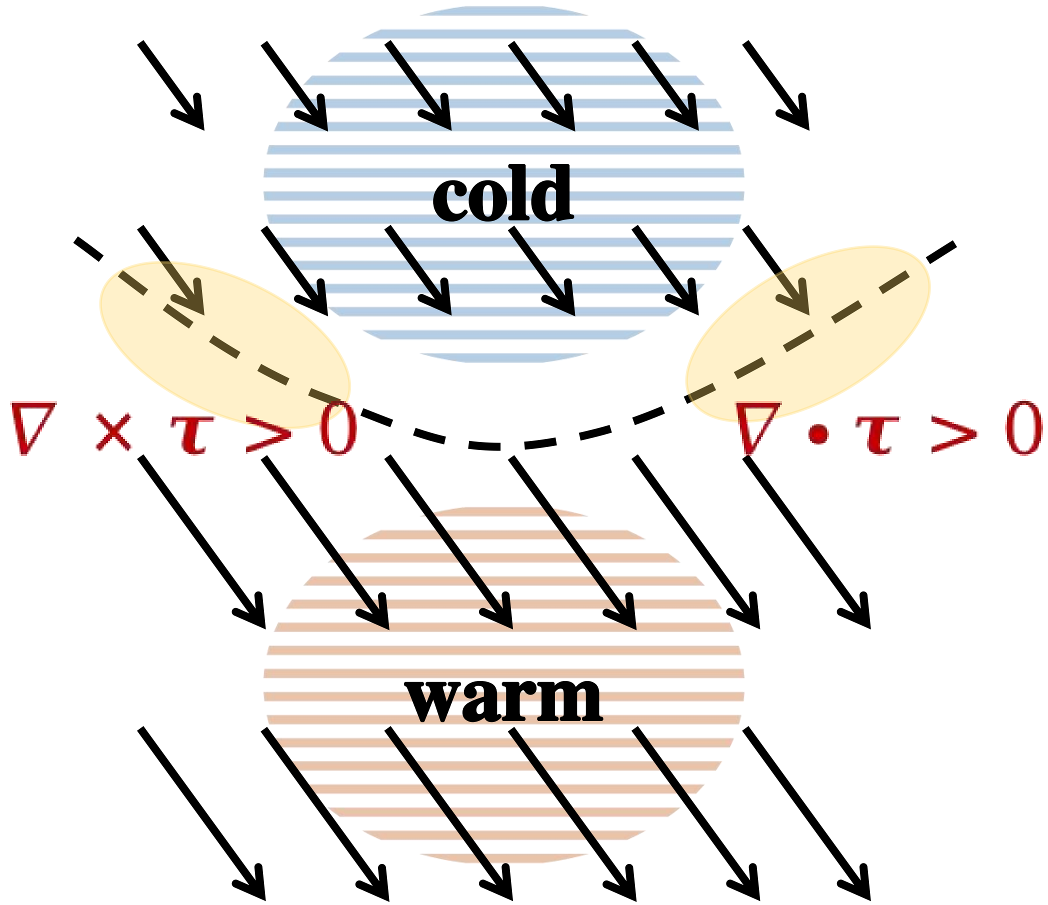
Eddy-induced Ekman pumping



Chen et al., 2021

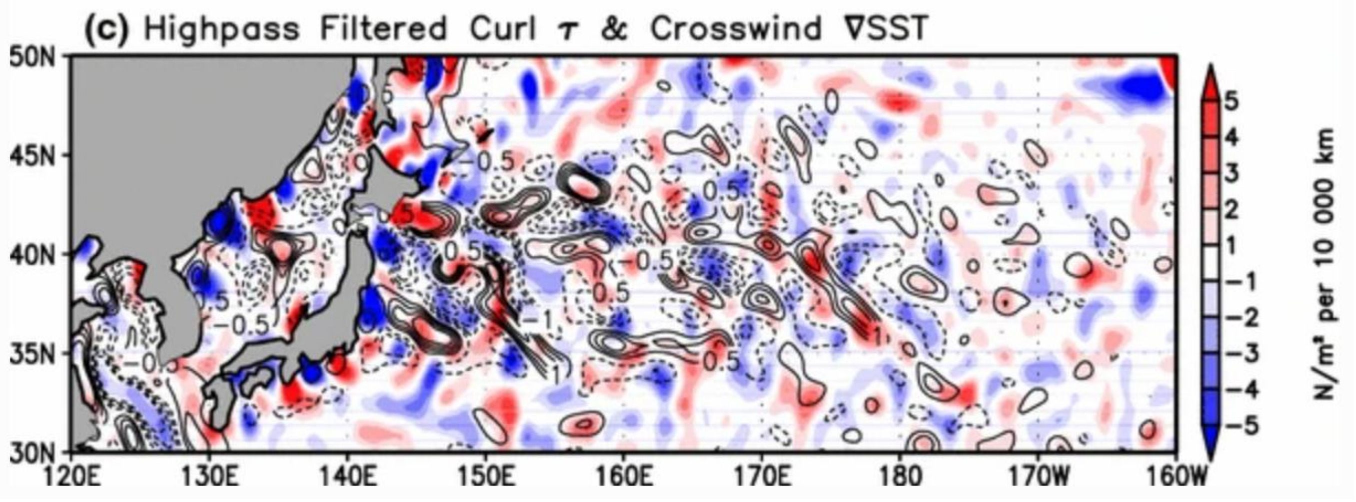
Thermal feedback to the momentum budget

Oceanic thermal feedback to wind stress

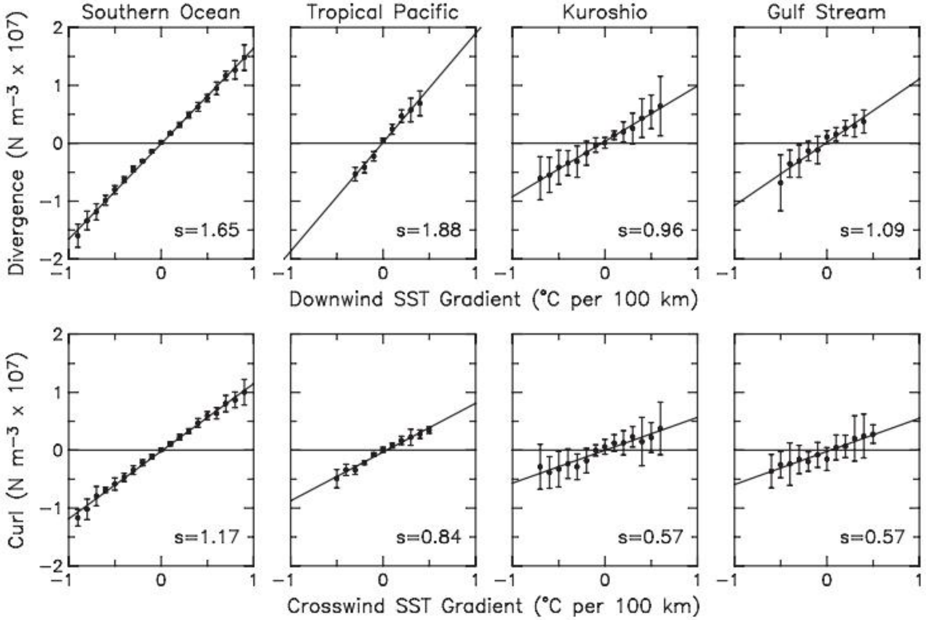


Crosswind SST gradient: wind vorticity
Downwind SST gradient: wind divergence

revised from Chelton et al., 2010

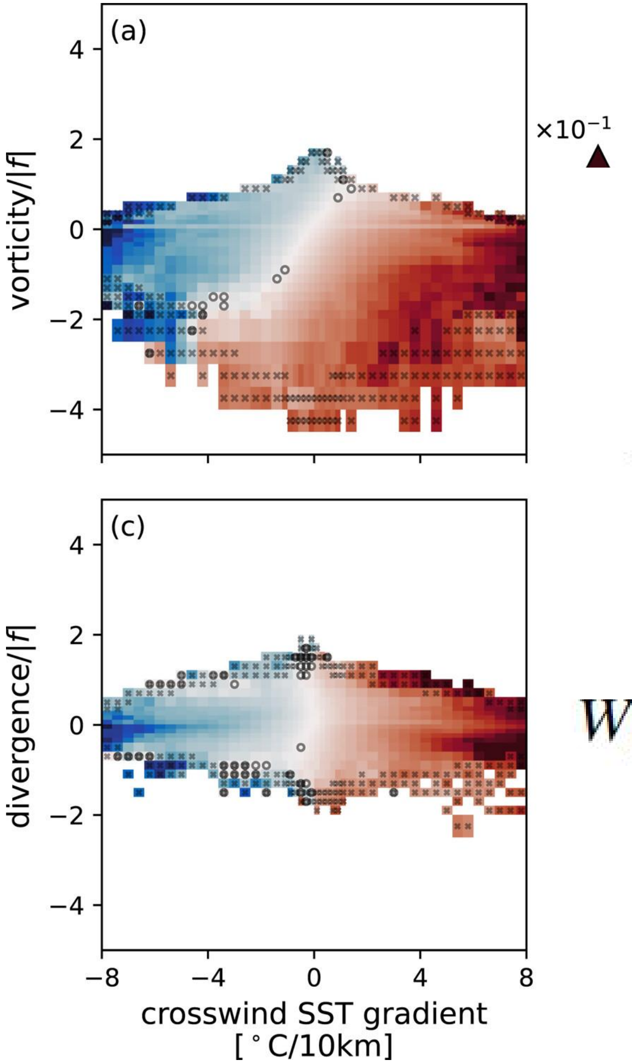


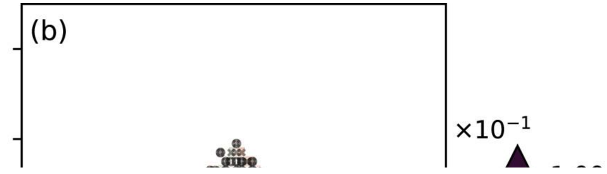
Wei et al., 2017



Chelton et al., 2004

Total feedback to the momentum budget

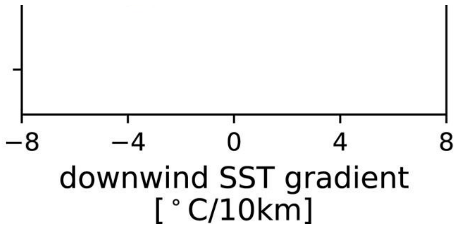




$$W_c = \frac{\nabla \times \tilde{\boldsymbol{\tau}}}{\rho_o(f+\zeta)},$$

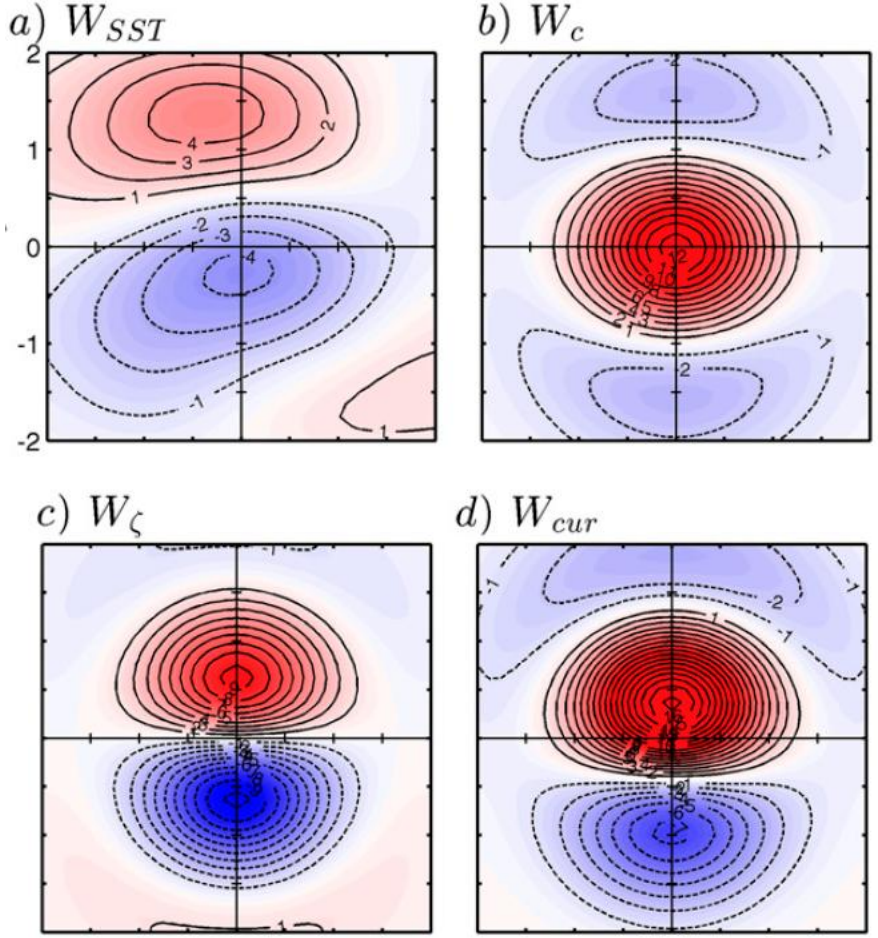
$$W_\zeta = \frac{1}{\rho_o(f+\zeta)^2}\left(\tilde{\tau}^x\frac{\partial \zeta}{\partial y} - \tilde{\tau}^y\frac{\partial \zeta}{\partial x}\right),$$

$$W_{\mathrm{SST}} = \frac{\nabla \times \boldsymbol{\tau}'_{\mathrm{SST}}}{\rho_o(f+\zeta)}.$$



Bai et al., 2024

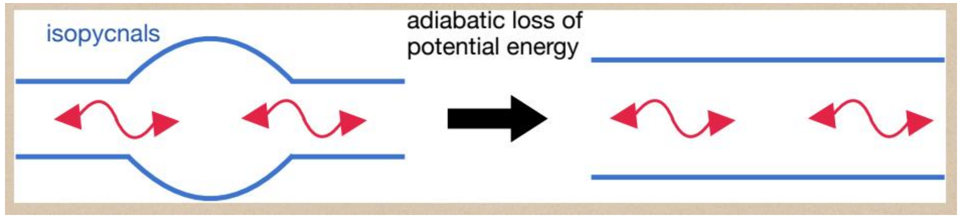
Westerly wind over anticyclonic eddies in the Northern Hemisphere



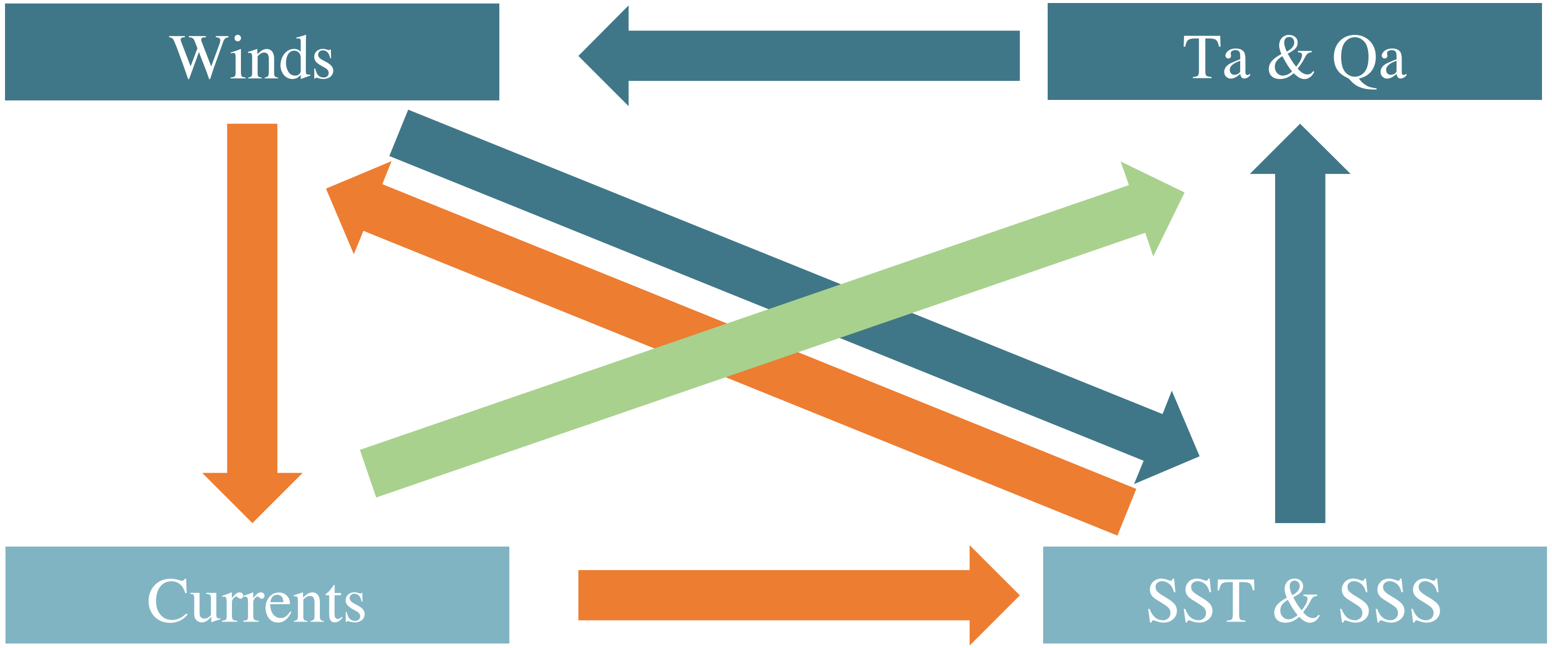
Gaube et al., 2015

How do ocean currents interact with air stability?

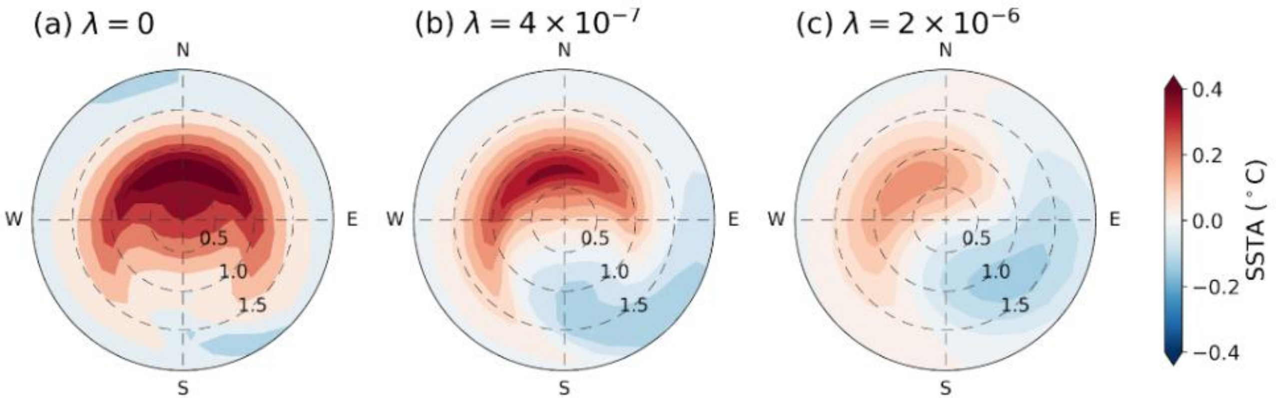
1) Regime of eddy parameterization



$$\overline{u'b'} = -\kappa_{GM} \nabla \bar{b}$$



2) SSH-SST inconsistency

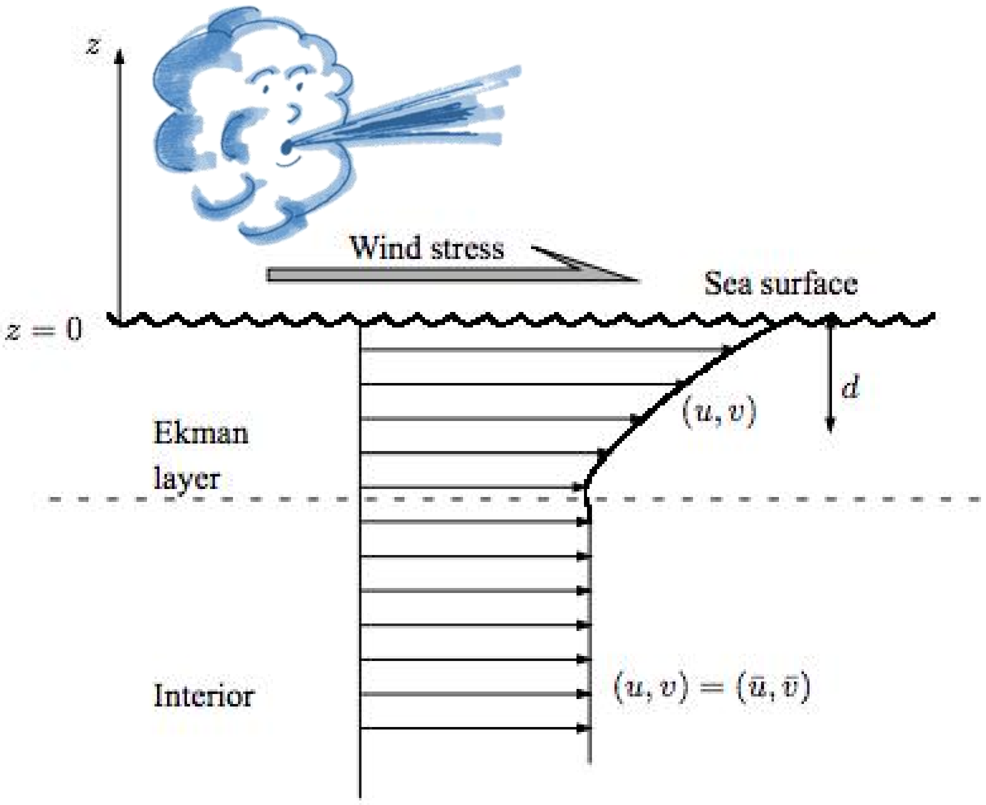


Wu and Mahadevan, submitted

Forcing: background SST gradient
Damping: air-sea heat flux

$$\frac{\partial T'}{\partial t} = -\tilde{u}' \cdot \nabla T' - v' \frac{dT_b}{dy} - \lambda T'$$

Nonlinear Ekman theory



Classic Ekman-layer regime:

$$f\hat{k} \times \boldsymbol{u} = \frac{1}{\rho_0}\nabla p + A_z \frac{\partial^2 \boldsymbol{u}}{\partial z^2}$$

$$\boldsymbol{u} = \boldsymbol{u}_g + \boldsymbol{u}_{Ek}$$

$$f\hat{k} \times (\boldsymbol{u}_g + \boldsymbol{u}_{Ek}) = \frac{1}{\rho_0}\nabla p + A_z \frac{\partial^2 (\boldsymbol{u}_g)}{\partial z^2} + A_z \frac{\partial^2 (\boldsymbol{u}_{Ek})}{\partial z^2}$$

Ekman balance (surface layer)

Geostrophic balance
(interior ocean)

However, observations depart significantly from this simple theory.

Development of the flow-dependent Ekman theory

	Ekman (1905)	Stern and Niiler (1960s)	Wenegrat and Thomas (2017)
Contents	Horizontal transport depends on the stress and Coriolis parameter f only.	Allows for shear of the surface velocity field to affect the transport.	Extends early results to better account for curvature in the surface flow path.
Ekman Transport	$U_{Ek} = \frac{\tau_y}{f}$ $V_{Ek} = -\frac{\tau_x}{f}$	$U_{Ek} \approx \frac{\tau_y}{f + \zeta}$ $V_{Ek} \approx -\frac{\tau_x}{f + \zeta}$	$R_0 \bar{u} \frac{\partial V_{Ek}}{\partial s} + (1 + R_0 2\Omega) U_{Ek} = \tau_n$ $R_0 \bar{u} \frac{\partial U_{Ek}}{\partial s} - (1 + R_0 \zeta) V_{Ek} = \tau_s$
Assumptions	Homogeneous deep stationary ocean.	Valid for plane parallel flows (e.g., straight jets); however, not explicitly solved for flows with curvature.	Curvilinear flows, with $R_{oe} \ll 1$ and $R_o < 1$; however, not easily applicable to complicated flow fields.

Flow-dependent Ekman layer

$$\frac{\partial \boldsymbol{u}_{Ek}}{\partial t} + \underbrace{(\boldsymbol{u}_{Ek} \bullet \nabla)\boldsymbol{u}_0}_{\text{advection 1}} + \underbrace{(\boldsymbol{u}_0 \bullet \nabla)\boldsymbol{u}_{Ek}}_{\text{advection 2}} + \underbrace{(\boldsymbol{u}_{Ek} \bullet \nabla)\boldsymbol{u}_{Ek}}_{\text{nonlinear (advection 3)}} + f\hat{k} \times \boldsymbol{u}_{Ek} = \frac{\partial \boldsymbol{\tau}}{\partial z} - A_h \nabla^4 \boldsymbol{u}_{Ek} \ldots$$

1. The time-dependent term has been added for simplifying the calculation.

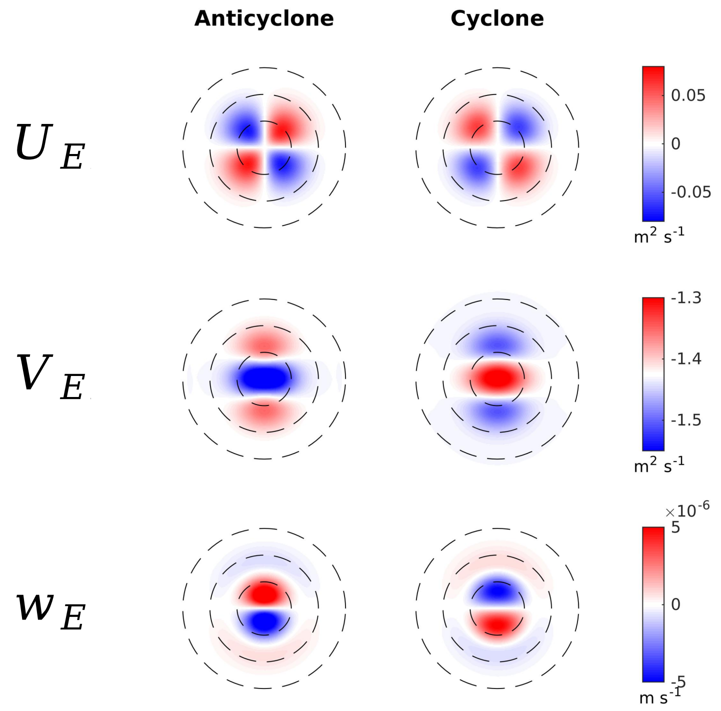
2. Scale analysis of the three advection terms: R_o, R_o^2 and $R_o \bullet R_{oe}$.
   (Assumptions used here: $R_{oe} \ll 1$ and $R_o < 1$.)

3. Advection 1 has been widely used (or added) to study wind-induced near-inertial oscillations.

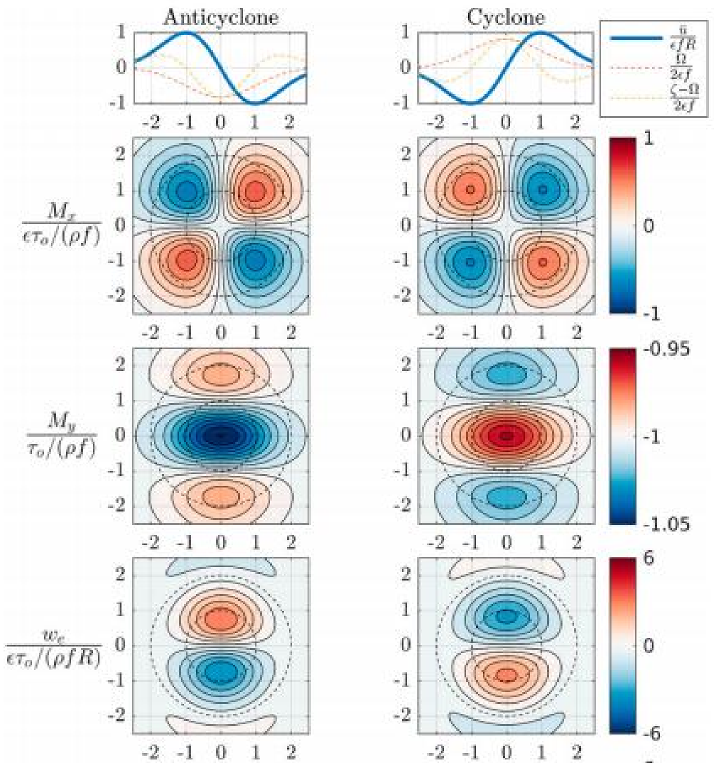
4. Vertical integration leads to the transport equation.

Ekman-layer response to prescribed vortices

Our simulations



Wenegrat & Thomas simulations



The zonal transport develops a quadrupole pattern, emphasizing that the flow-dependent Ekman transport is not strictly perpendicular to the wind stress, and more complicated than the linear Ekman theory :)

The meridional transport converges (diverges) on the north (south) side of the cyclonic vortex, with the pattern reversed for the vortex with anticyclonic flow.

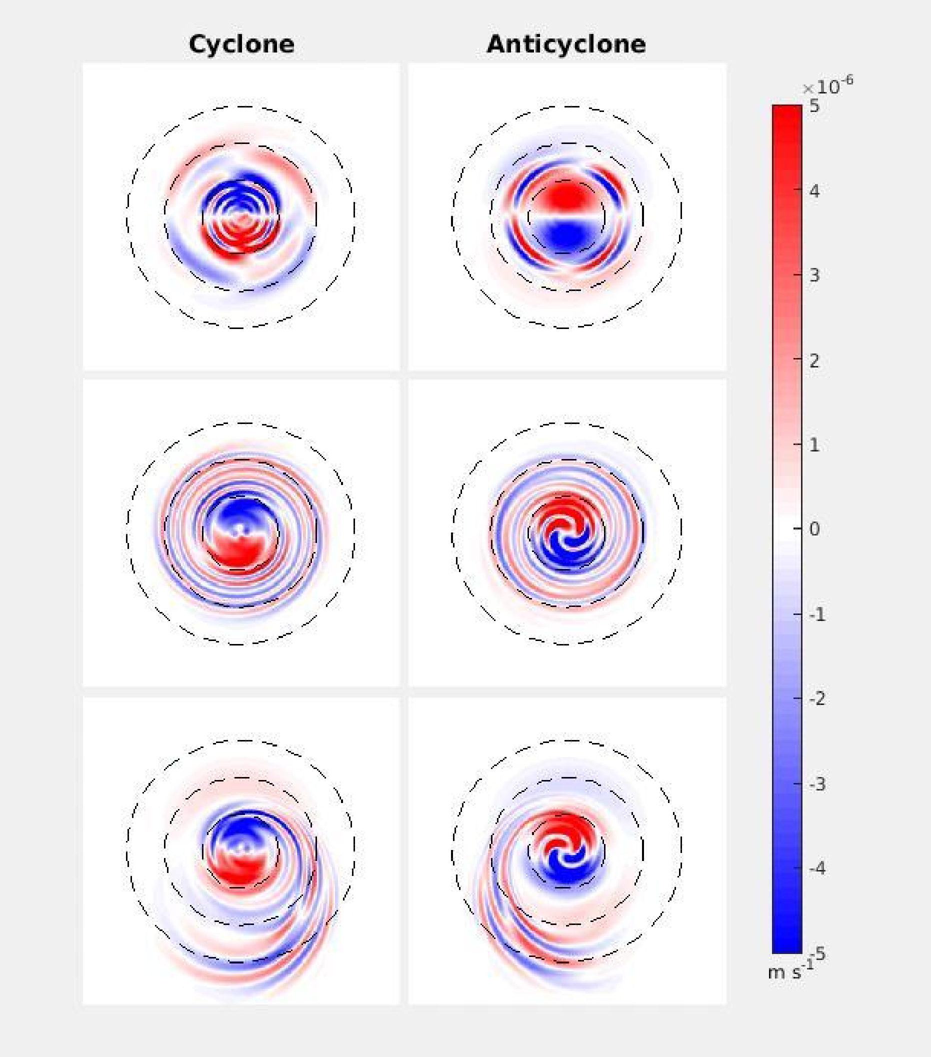
Ekman-layer response to prescribed vortices

Ekman pumping response with different regimes

Advection 1

Advection 1 + Advection 2

Advection 1 + Advection 2 + Nonlinear

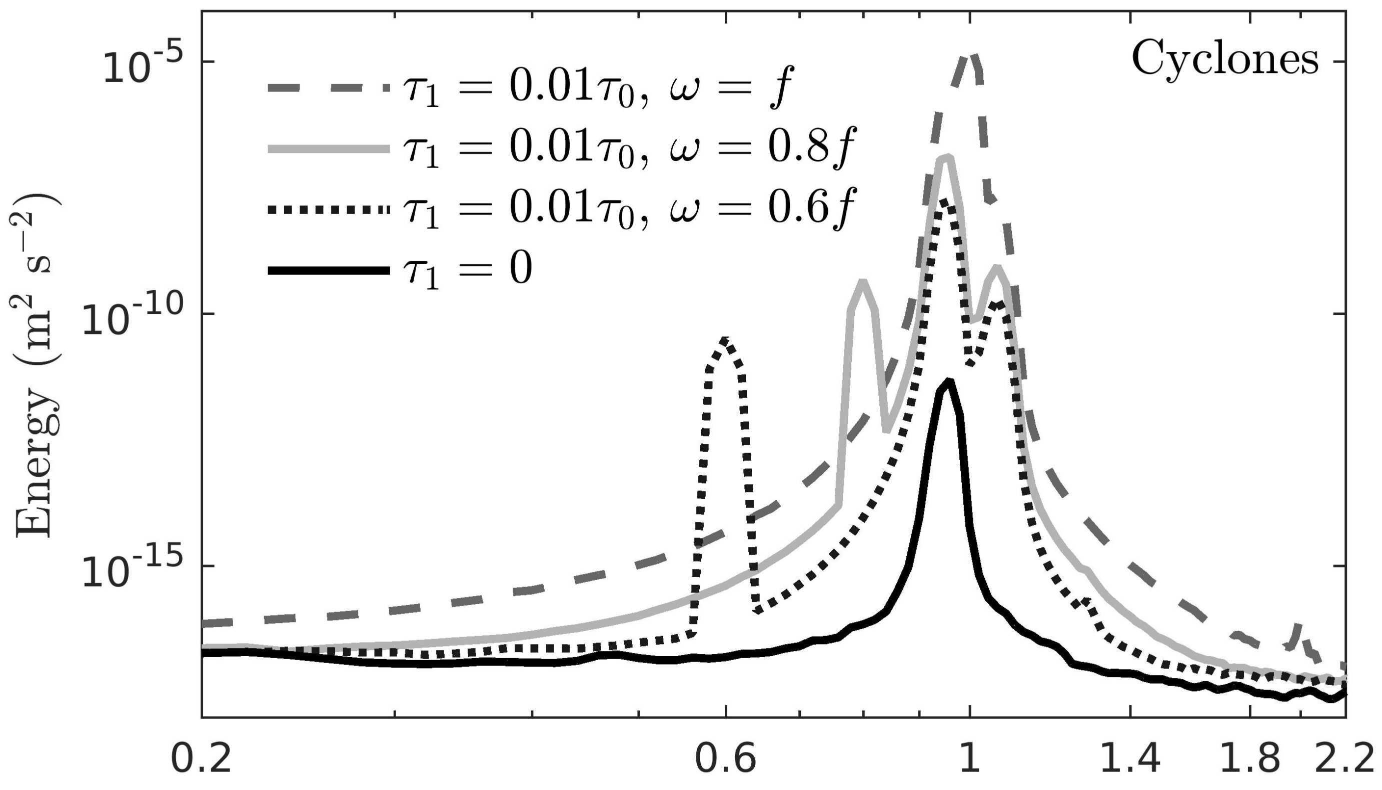


Recap:

- Interesting differences :)
- The time dependence introduces a near-inertial (high-frequency) component to the pumping velocities.

Ekman-layer response to prescribed vortices

Frequency spectra of pumping velocities with forcing at different frequencies



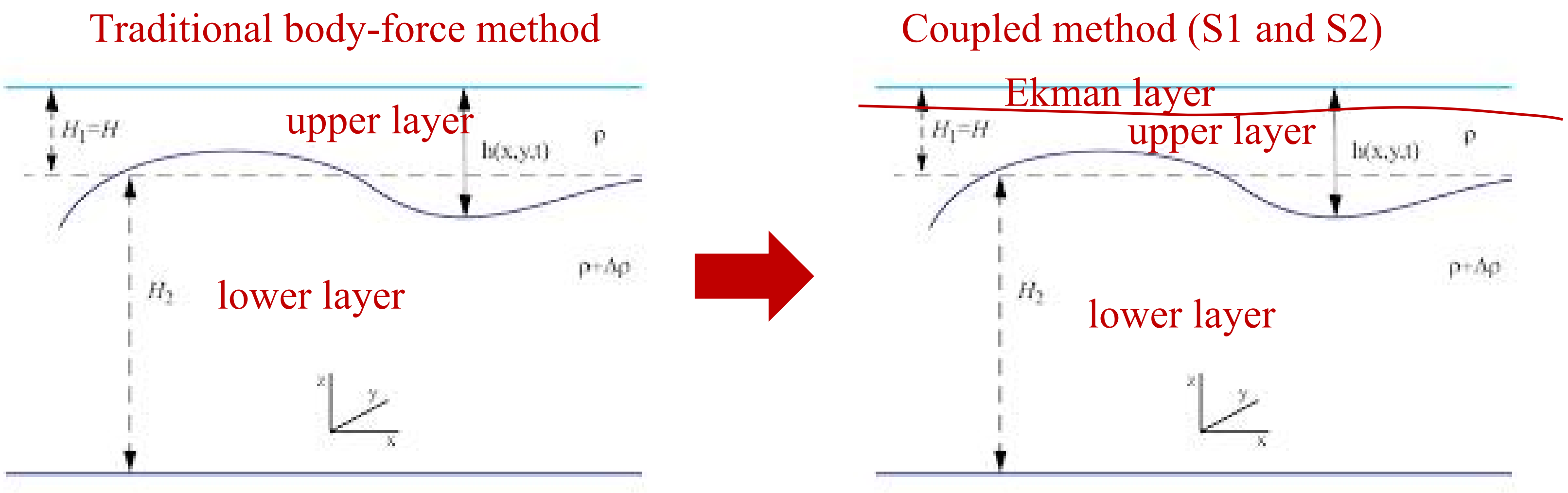
$$\tau_{total} = \tau_0 + \tau_1 \bullet \sin(\omega t)$$

- High-frequency winds lead to responses at the same frequency, plus a component at f.
- Synoptic scale winds with large enough amplitude can be a forcing at f.
- Presence of a secondary peak on the right hand side of the inertial peak.

Ekman-interior coupled model

Two different regimes

1. Wind stress is applied as a body force in the upper-layer momentum equation (traditional)
2. Use an explicit Ekman layer to force the upper-layer mass equation (coupled)



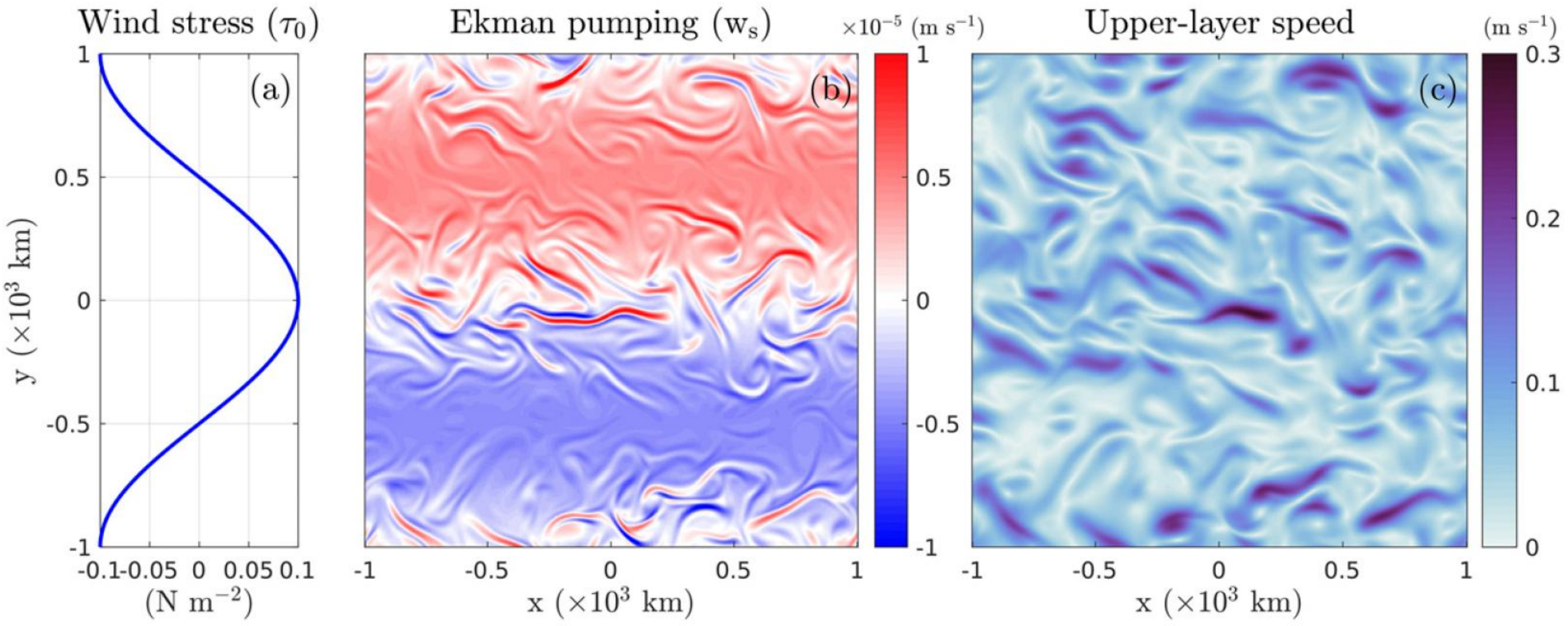
We consider a two-layer shallow water model with a slab Ekman layer in the top layer. Thus, we can use "Ekman pumping" as a forcing in the upper layer mass equation.

Model setup: two-layer rigid lid, domain size (2000km × 2000km), resolution (512 grid points × 512 grid points), wind forcing τ is a cosine function of latitude.

Ekman-interior coupled model

Simulations		Traditional body-force method	Coupled method (S1 and S2)
Processes		Wind forcing → upper layer	Wind forcing → modified Ekman layer → upper layer
Equations	Ekman layer		Many options as described in model formulation (S1 model: advection1+2; S2 model: advection1+2+3)
	Upper-layer momentum	$\frac{\partial}{\partial t}\vec{u}_1 + (\vec{u}_1 \bullet \nabla)\vec{u}_1 + f\hat{z} \times \vec{u}_1 = \frac{\vec{\tau}}{h_1} - A_h \nabla^4 \vec{u}_1$	$\frac{\partial}{\partial t}\vec{u}_1 + (\vec{u}_1 \bullet \nabla)\vec{u}_1 + f\hat{z} \times \vec{u}_1 = - A_h \nabla^4 \vec{u}_1$
	Upper-layer mass	$\frac{\partial}{\partial t}h_1 + \nabla \bullet (h_1 \vec{u}_1) = 0$	$\frac{\partial}{\partial t}h_1 + \nabla \bullet (h_1 \vec{u}_1) = - w_E$ $(w_E = \nabla \bullet (\vec{U}_E))$

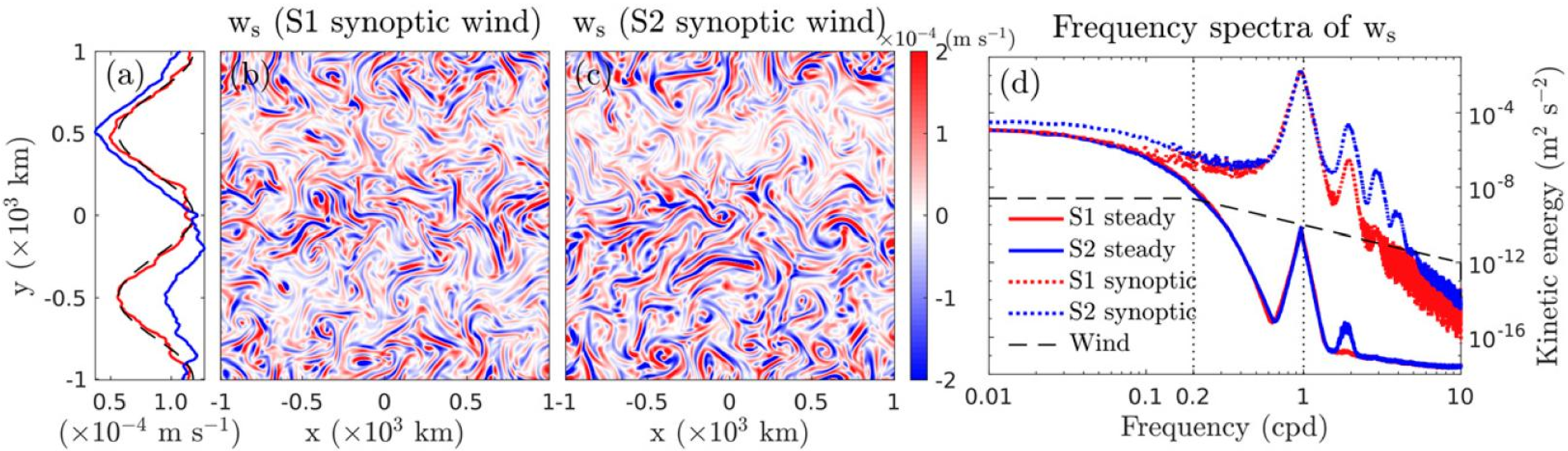
Ekman-interior coupled model



S1 simulation with steady wind

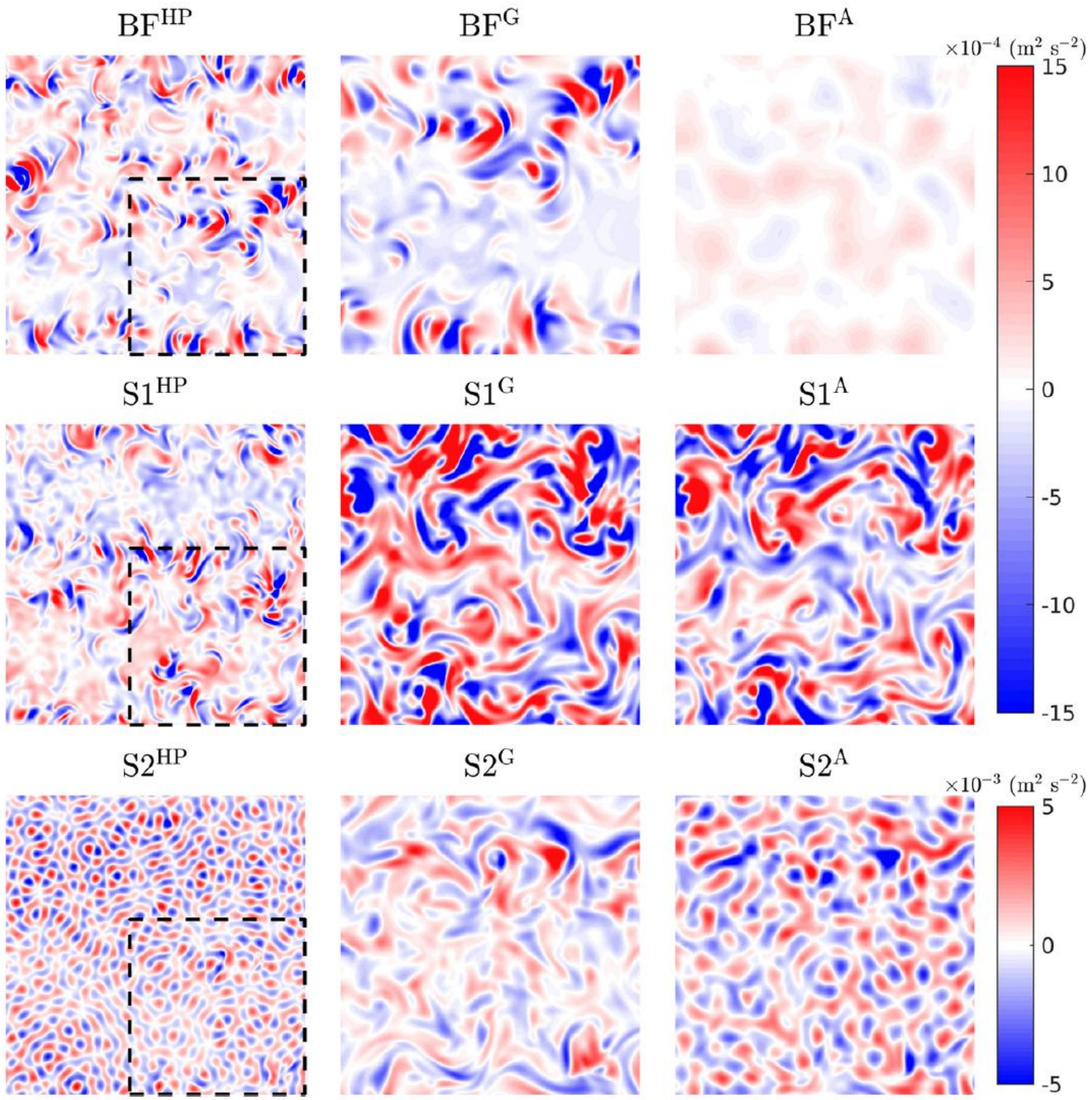
(a) wind structure; (b) Ekman pumping; (c) the upper-layer speed

Ekman-interior coupled model



Ekman pumping velocity with synoptic wind

Ekman-interior coupled model



High-pass fields of surface pressure

1. For BF forcing, surface pressure is dominated by fast timescale geostrophic modes.

2. For S1, geostrophic and ageostrophic modes are comparable.

3. For S2, ageostrophic modes are larger at small scales.

Unbalanced contributions to surface pressure appear sensitive to how surface-layer dynamcis is presented.

Summary

- Flow-dependent Ekman layer can result in a transport that is not perpendicular to the wind.
- Synoptic wind can be a near-inertial forcing for the flow-dependent Ekman layer.
- With steady wind stress, the Ekman-interior coupled model is almost identical to the traditional (body-force) two-layer shallow water model.
- For the coupled model, high-pass pressure fields appear sensitive to how surface-layer Ekman dynamcis is presented.
- More in: Chen, Straub and Nadeau (2021). Interaction of nonlinear Ekman pumping, near-inertial oscillations, and geostrophic turbulence in an idealized coupled model.

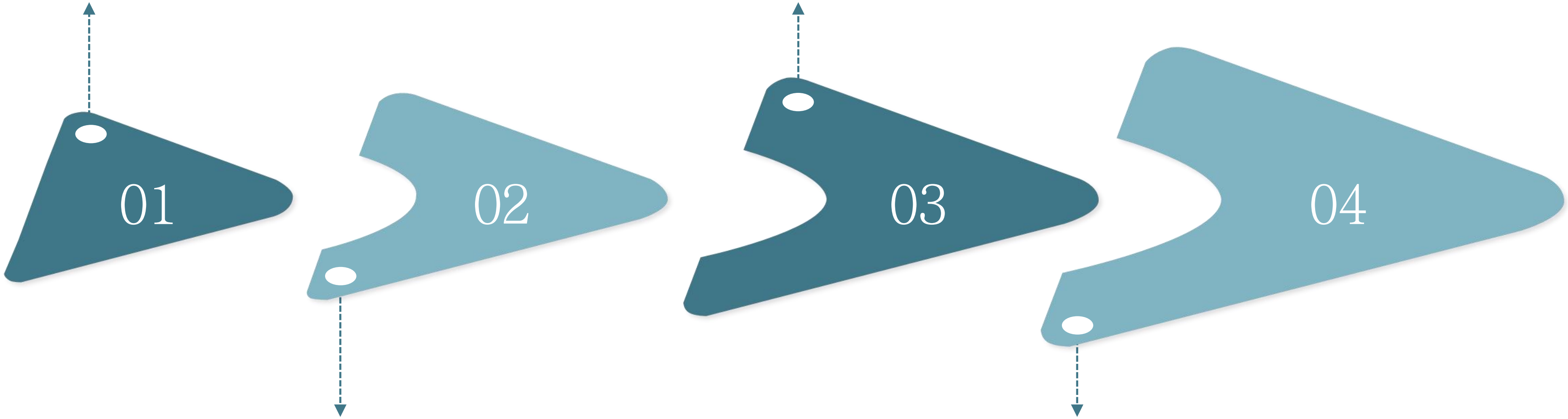
SSH-SST inconsistency in mesoscale eddies

OAFlux2 (Yu, 2023)

The second generation of OAFlux sponsored by NASA’s MEaSUREs program. (Yu, 2023)

META3.2 eddy atlas

Derived from the altimetric absolute dynamic topography (ADT) (Pegliasco et al., 2022)



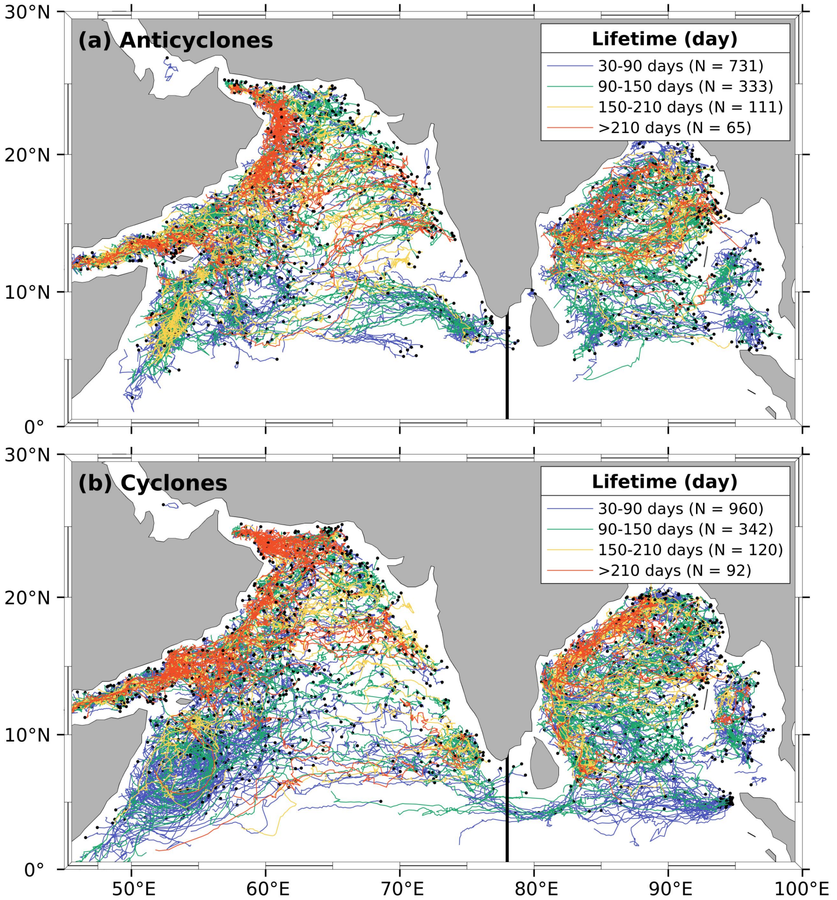
Filtering processes

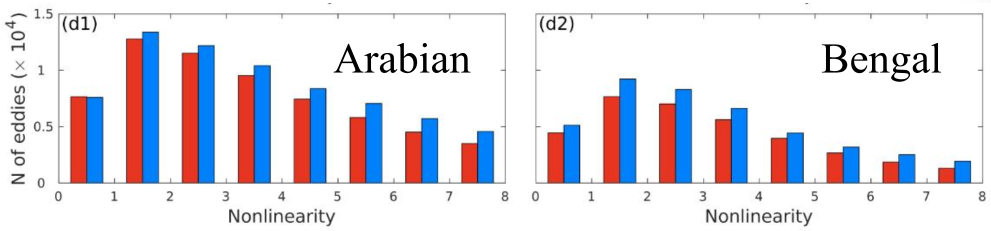
1) Time: bandpass Butterworth window to preserve 7-90 days;
2) Space: moving average Hann window to remove scales larger than 600 km.

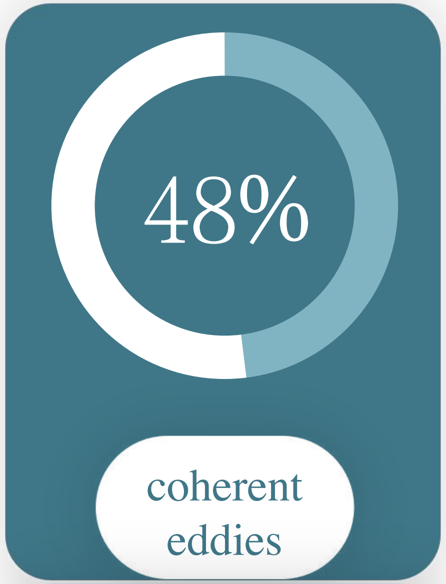
Co-location

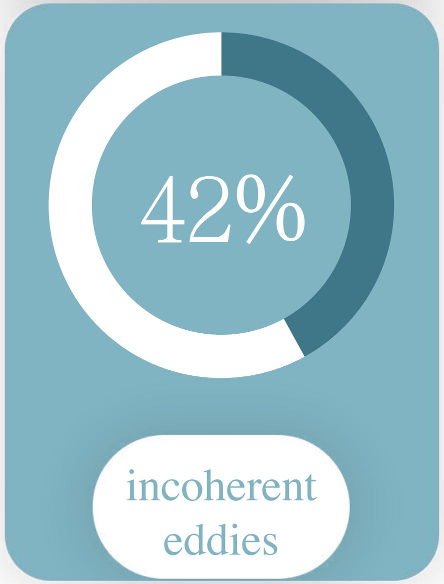
1) Extract air-sea variables within eddy contours;
2) We focus on the North Indian Ocean as one example and extend to the global ocean.

SSH-SST coherent and incoherent eddies in NIO





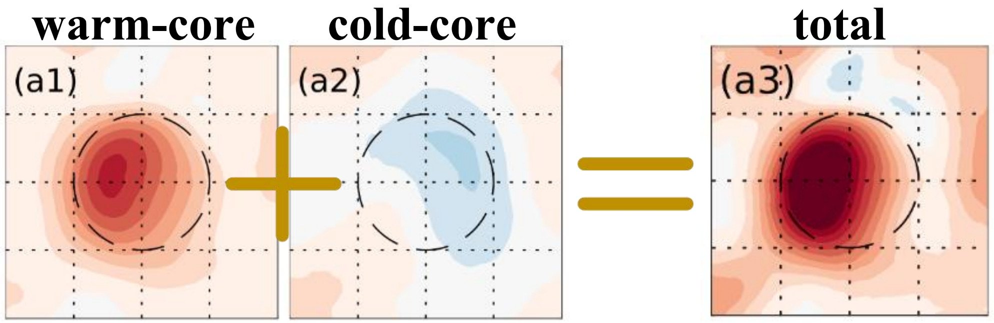




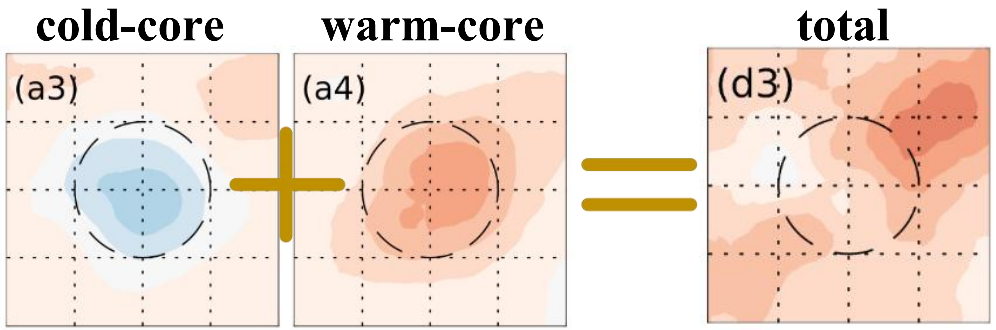
Coherent: AEs ---> SSHA+ ---> SSTA+
CEs ---> SSHA- ---> SSTA-

Incoherent: AEs ---> SSHA+ ---> SSTA-
CEs ---> SSHA- ---> SSTA+

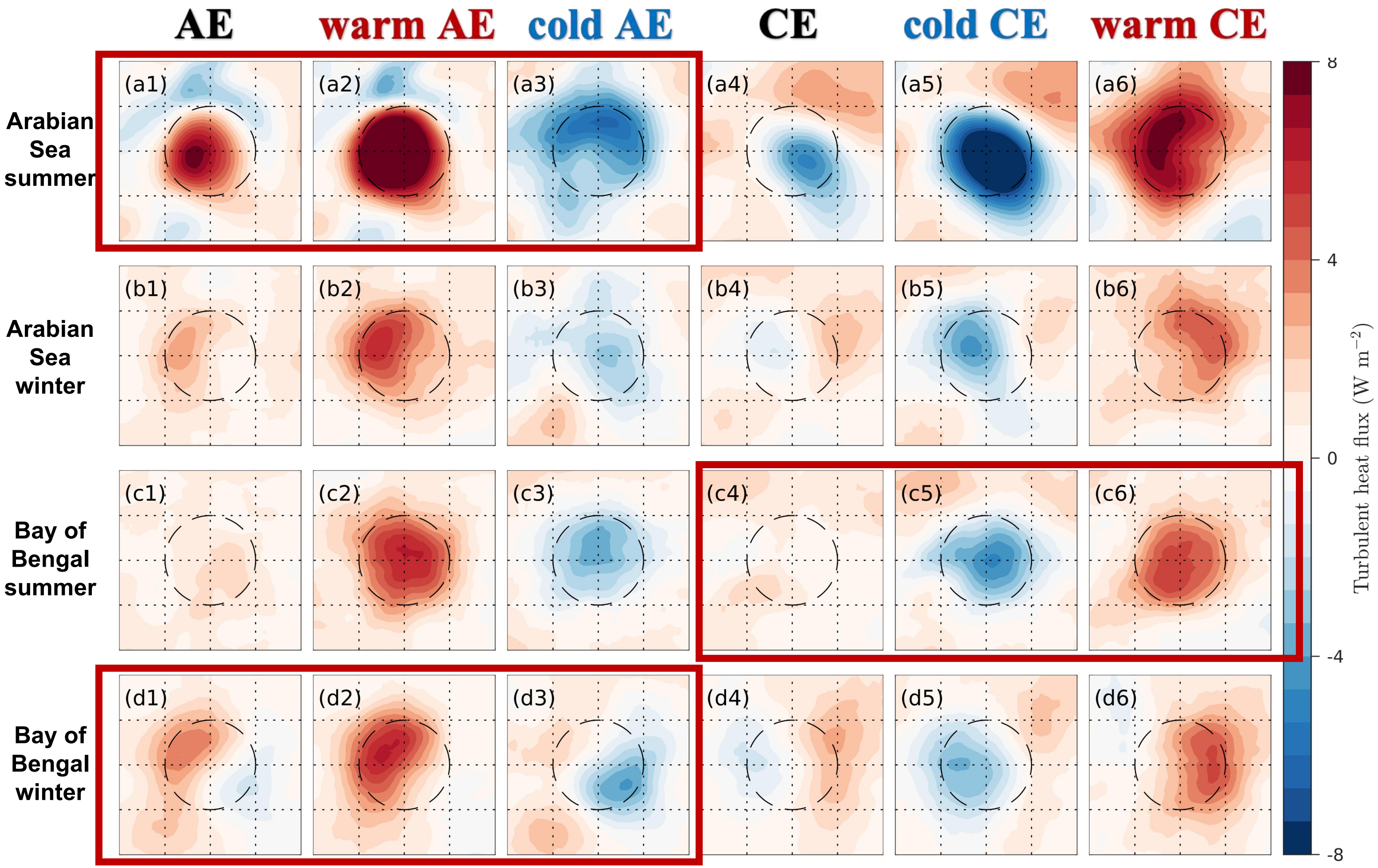
Example 1: Arabian Sea AEs



Example 2: Bay of Bengal CEs



Seasonality of eddy-induced turbulent heat flux in NIO



Monopole (shifted)

Coherent eddies dominate the total pattern. (**eddy-trapping effect**)

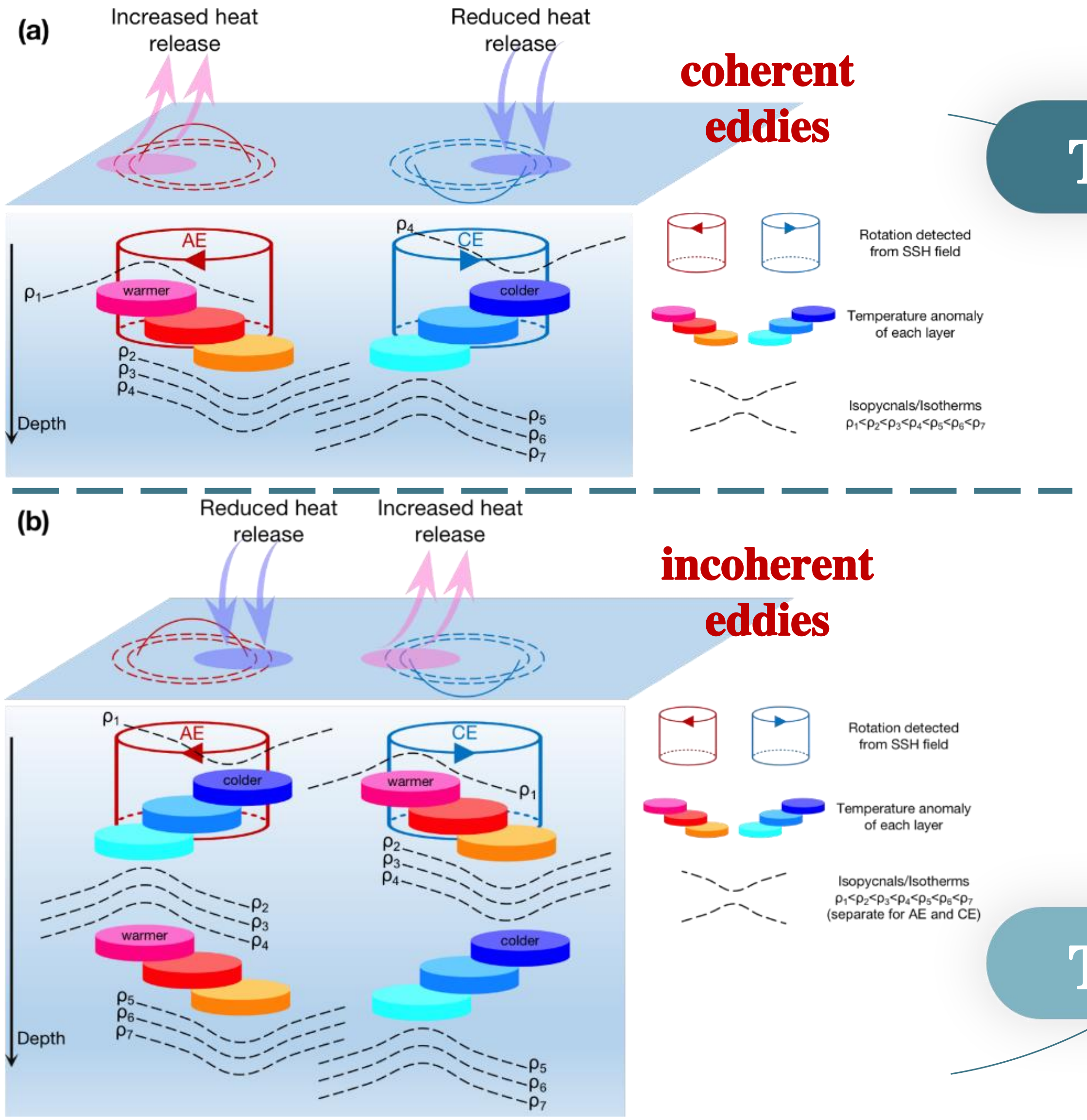
Cancellation

Coherent and incoherent eddies have inseparable magnitudes.

Dipole

Incoherent eddies shift in an opposite direction from coherent eddies. (**eddy-stirring effect**)

Paradigms of eddy-flux interaction



THM 1

Eddy-induced SST-THF coefficients could go up to 30 W/m²/K (in contrast with the large-scale 1 W/m²/K).

THM 2

The combination of SSH-SST coherent and incoherent eddies leads to monopoles, dipoles and cancellation.

THM 3

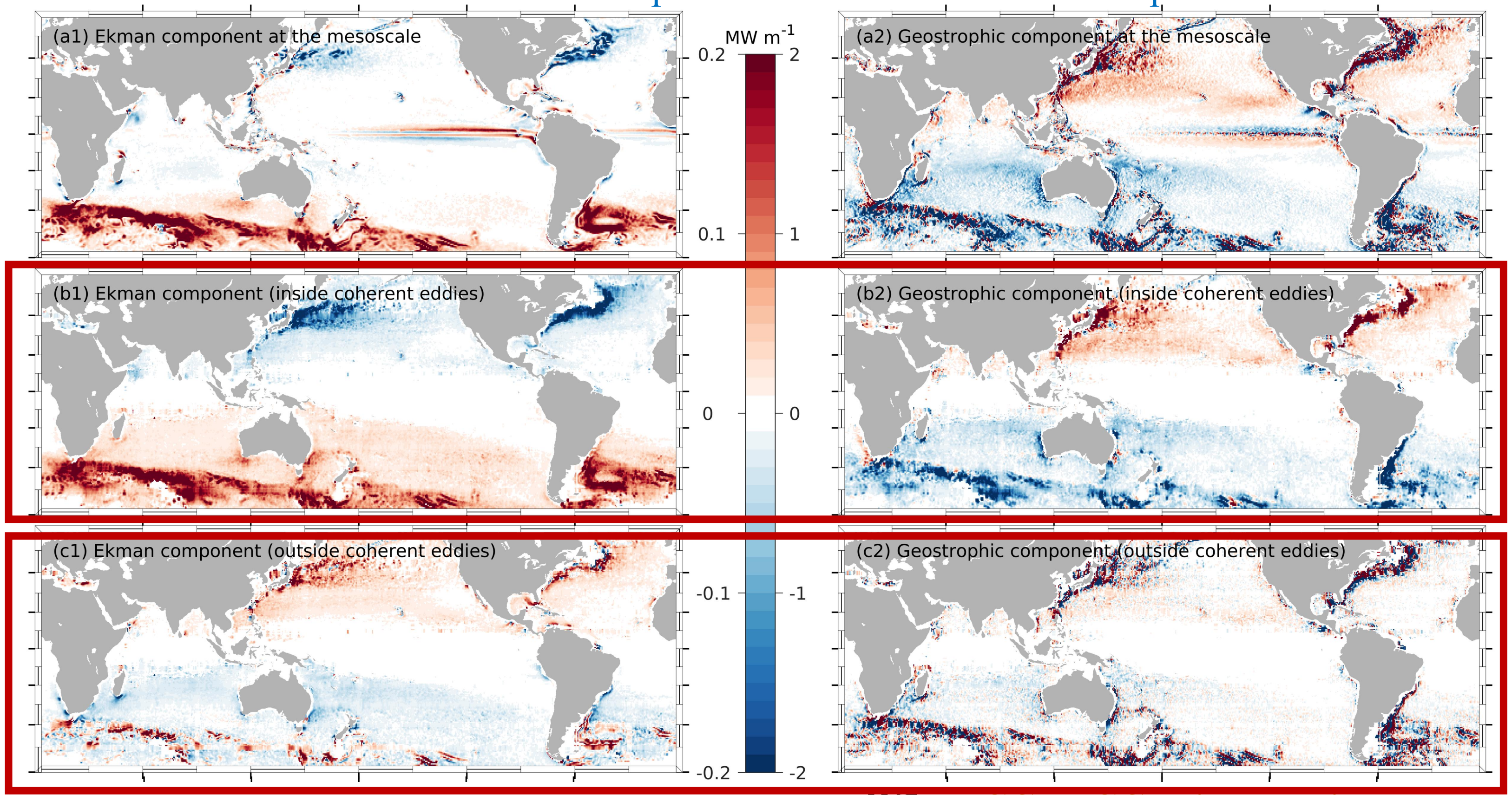
Mechanisms of incoherent eddies: vertical tilting of isopycnal surfaces which might be related to water mass subduction and mixing (e.g., creation of mode waters).

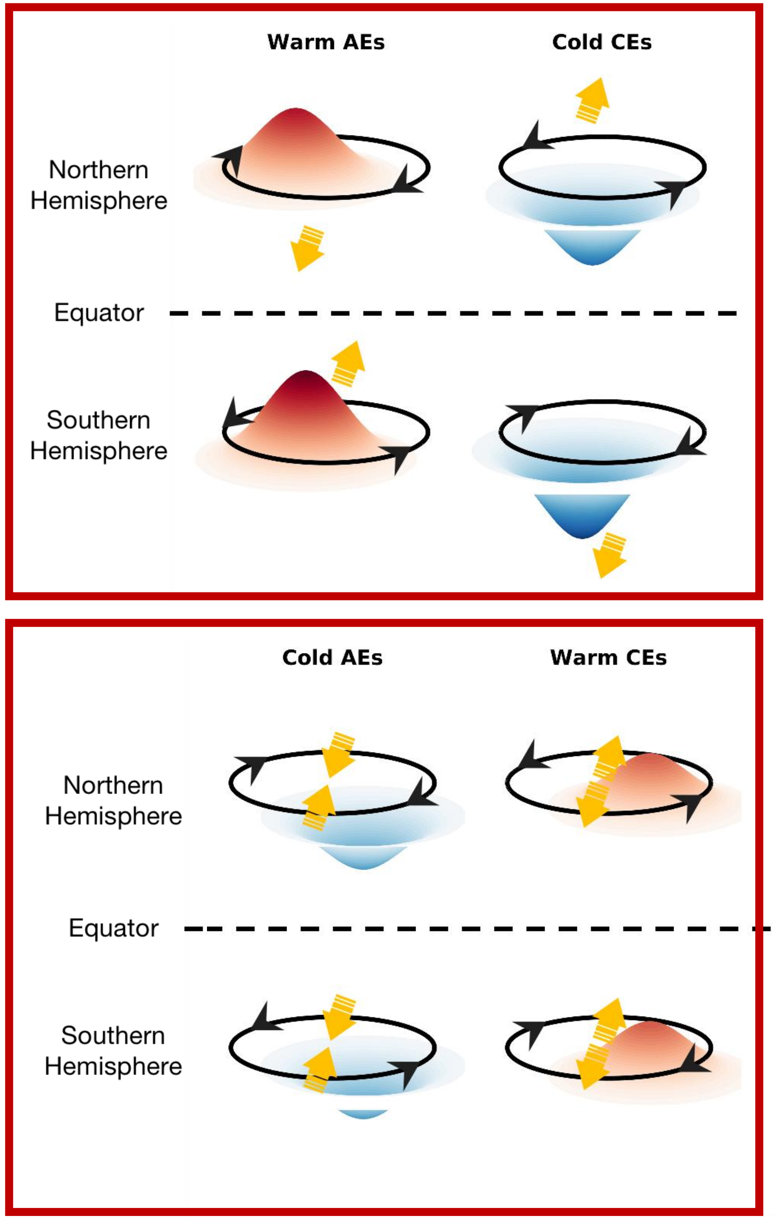
Meridional heat transport for the global ocean

Comparison between the geostrophic and Ekman contributions to ocean heat transport: $OHT = \rho C_p h \int Tv\, dx.$

Red indicates: northward SSTA+ transport or southward SSTA- transport

Blue indicates: northward SSTA- transport or southward SSTA+ transport





Summary

- The geostrophic component of MHT at the mesoscale is 10 times larger than the Ekman component.

- SSH-SST coherent eddies dominate the spatial patterns of MHT at the mesoscale.

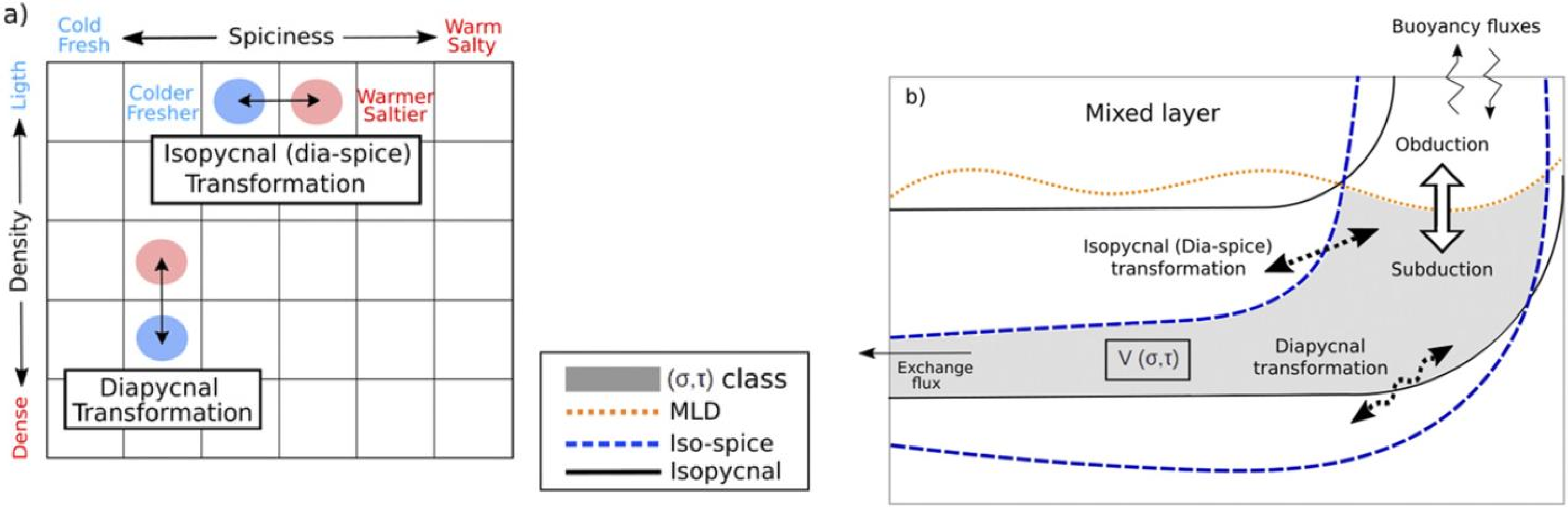
- Though incomparable in magnitude with the large scale MHT, mesoscale eddies can still transport 30 TW of heat near sea surface.

- More in:
  Chen and Yu (2024). Signature of mesoscale eddies on air-sea heat fluxes in the North Indian Ocean.
  Chen and Yu (2024). Mesoscale meridional heat transport inferred from sea surface observations.

Isopycnic water mass subduction

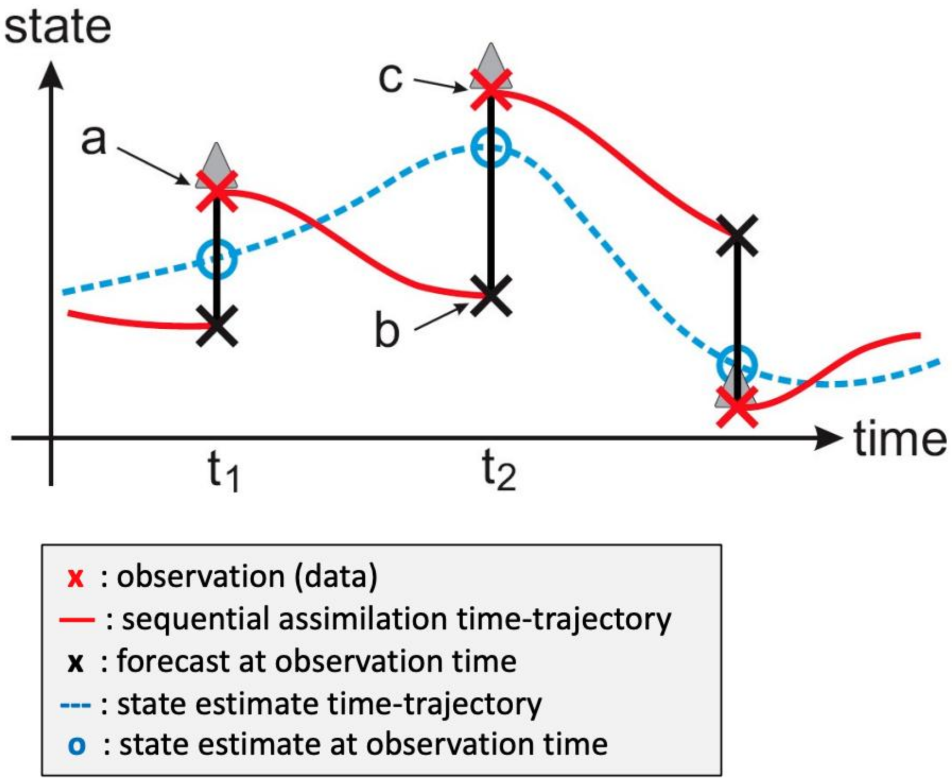
(Trans)formation:
The mixing of two or more different water masses.

Subduction:
The transfer of fluid from the mixed layer into the stratified thermocline.

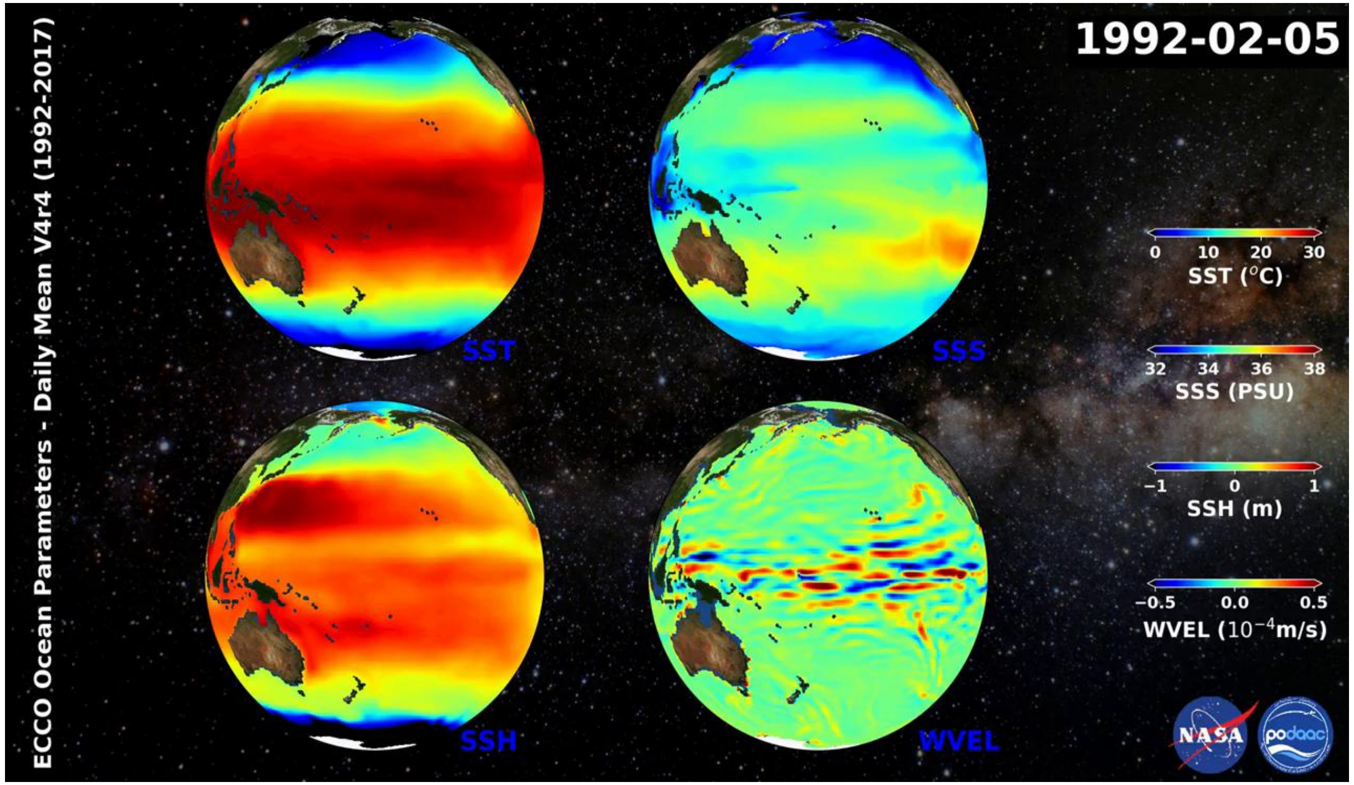


Portela et al., 2020

Approach: revisiting the subduction using ECCO



Four variables in ECCO simulations 1992-2017

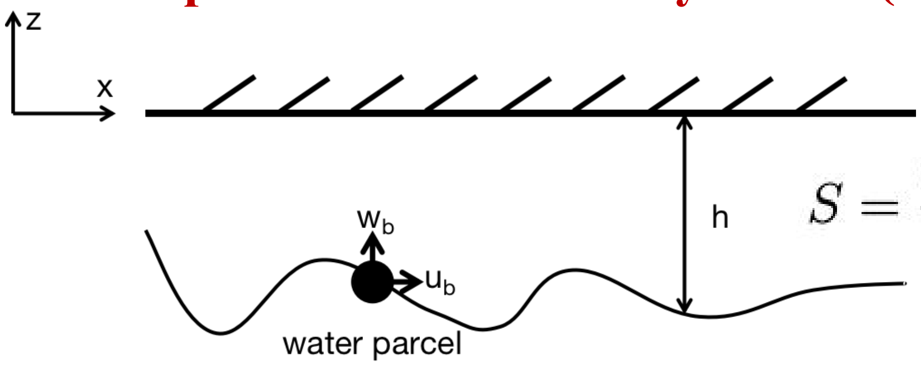


Continuous Assimilation: "ocean state estimation"

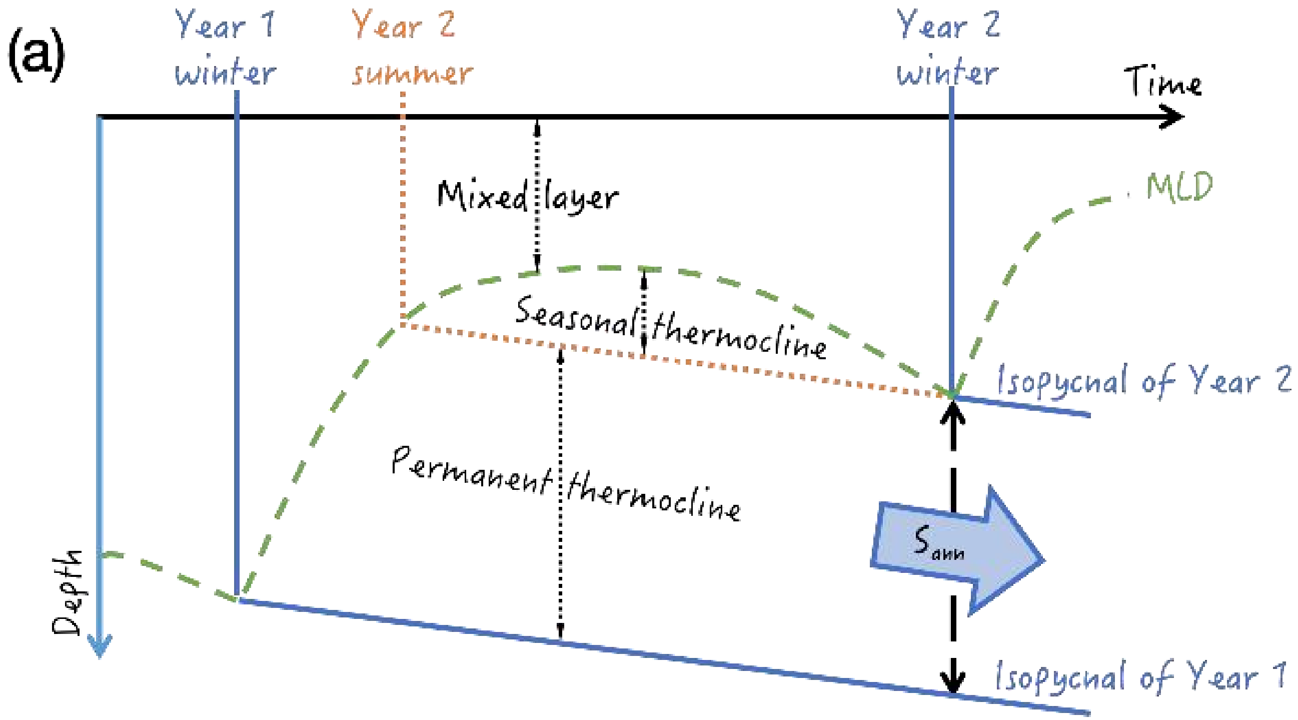
- Best fit to observations over entire simulation window;
- Conservation laws are implicitly respected: time trajectories are physically-consistent;
- Resolution in space: 0.5 degree regular latitude-longitude grid, and 50 levels in depth.
- Temporal resolution for outputs: monthly and daily.

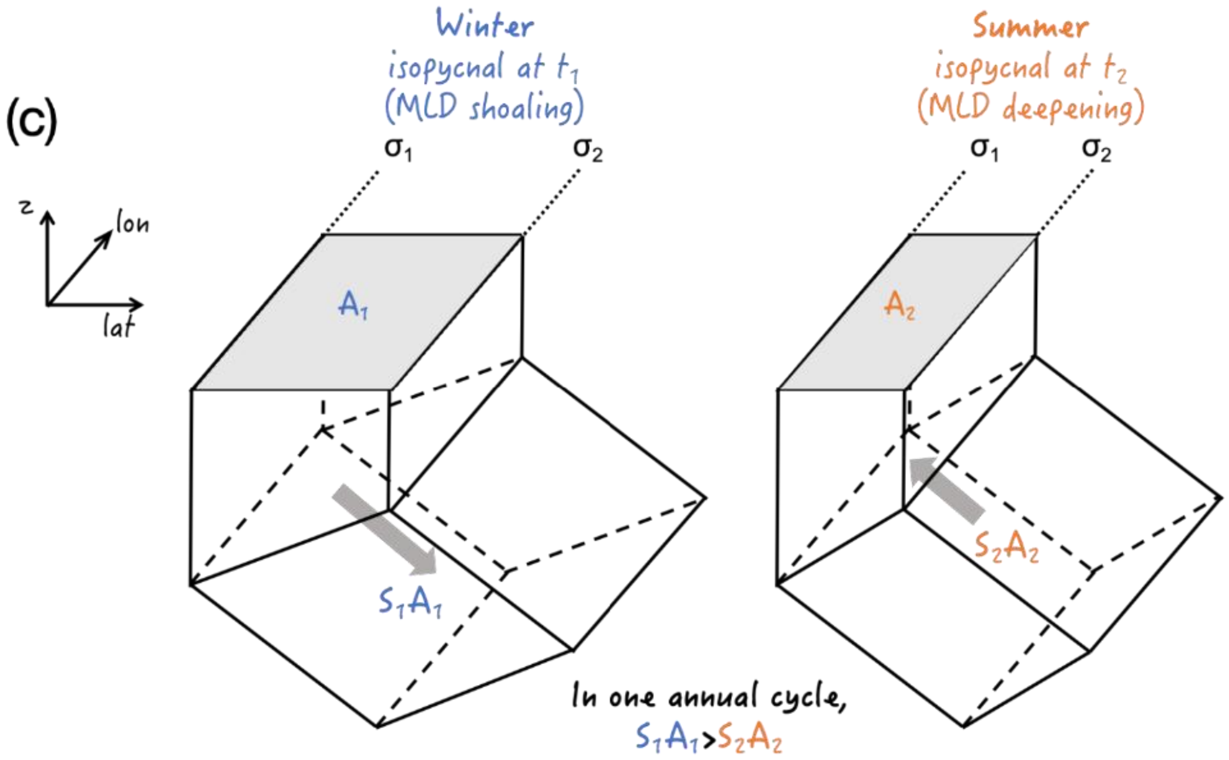
Theories of subduction

Water parcel at the mixed layer base (laterally fixed)



$$S = \frac{\partial h}{\partial t} + \boldsymbol{u}_b \cdot \nabla h + w_b$$

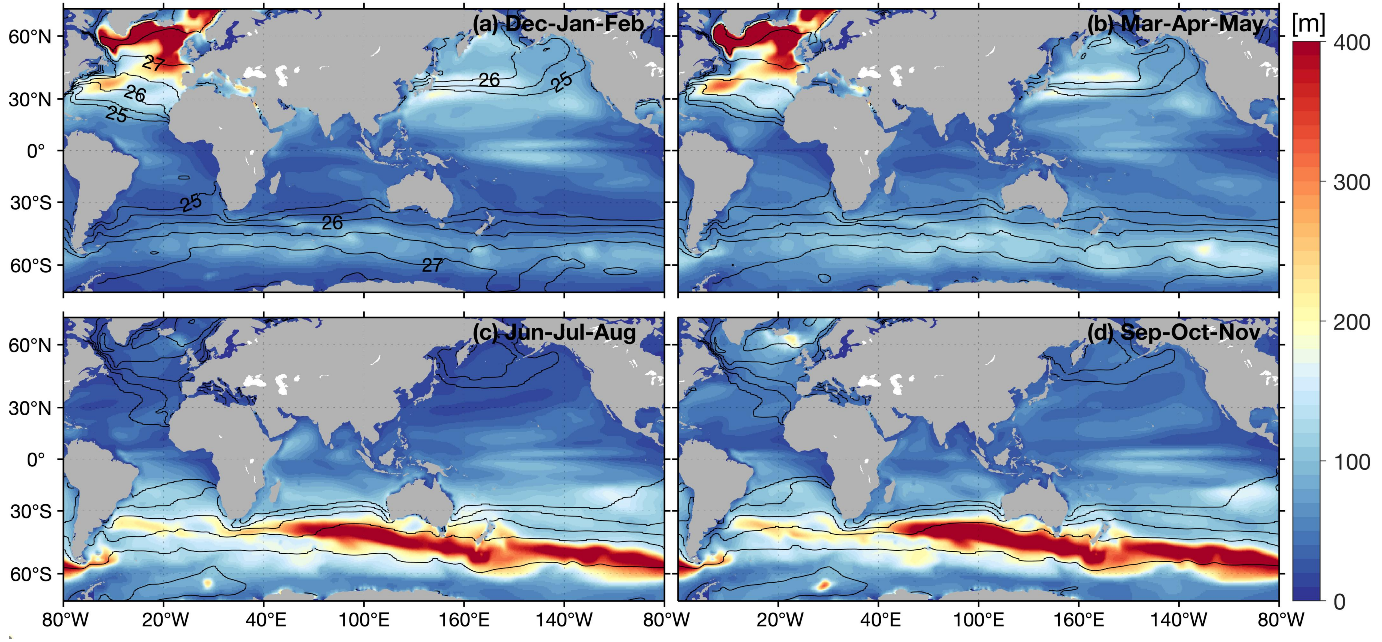




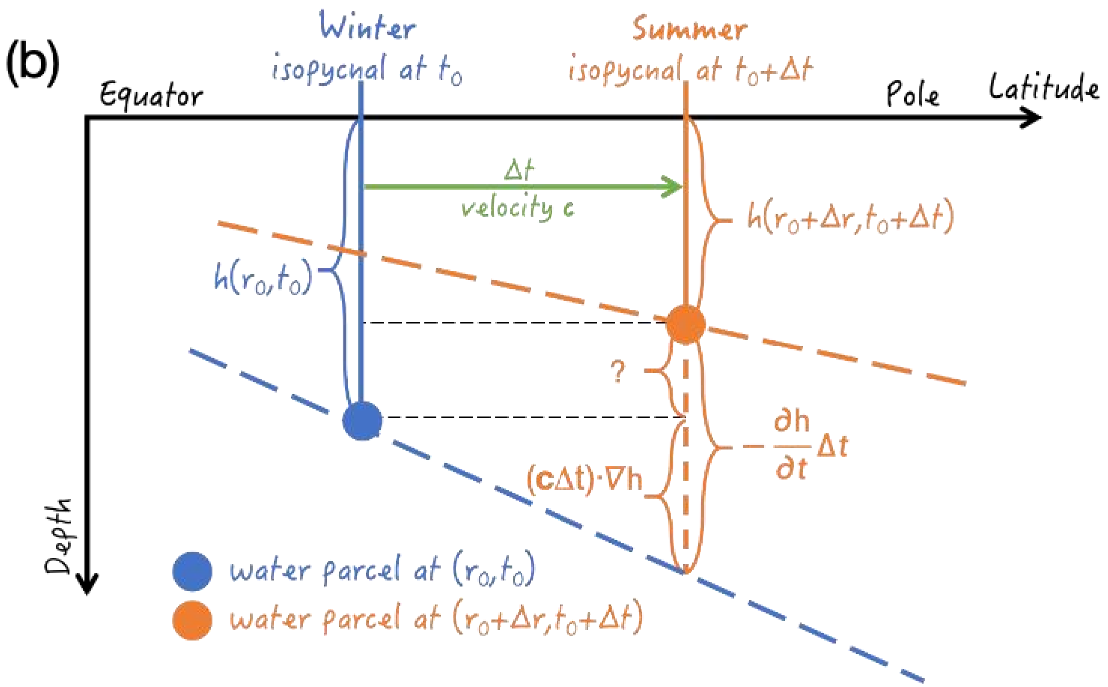
04 – Isopycnic water mass subduction

Meridional migration of isopycnals

Seasonal mixed layer depths



Schematic of one water parcel at the ML base

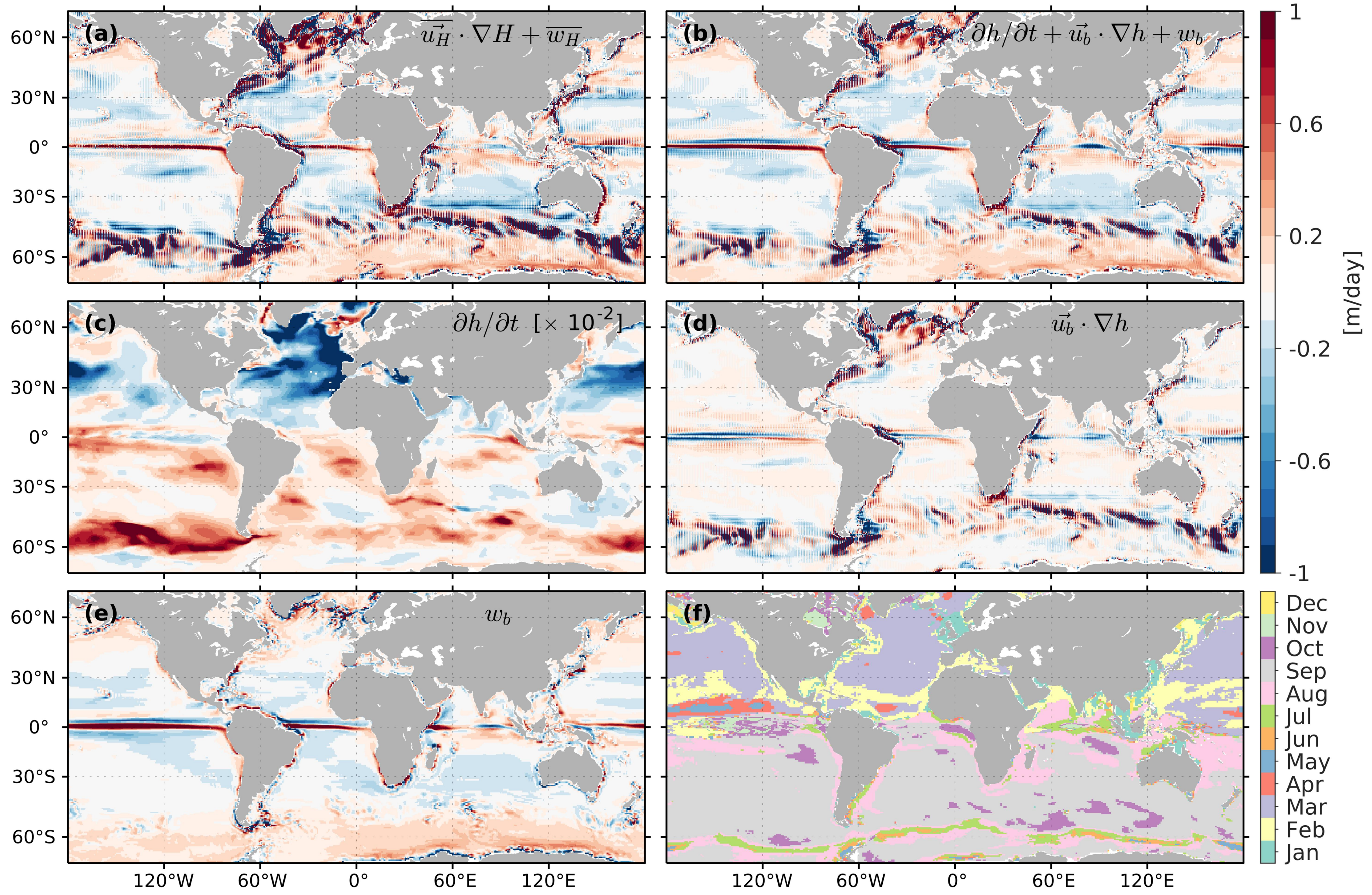


Classic subduction $$S = \frac{\partial h}{\partial t} + \boldsymbol{u}_b \cdot \nabla h + w_b \qquad (1)$$

Switch of the temporal term $$\left.\frac{\partial h}{\partial t}\right|_\sigma \Delta t = h(r_0 + \Delta r, t_0 + \Delta t) - h(r_0, t_0) = \left.\frac{\partial h}{\partial t}\right|_r \Delta t + (\mathbf{c}\Delta t)\cdot\nabla h \qquad (2)$$

New expression of subduction $$S = \left.\frac{\partial h}{\partial t}\right|_\sigma + \left.\boldsymbol{u}_b\right|_\sigma \cdot \nabla h + w_b = \left.\frac{\partial h}{\partial t}\right|_r + \mathbf{c}\cdot\nabla h + (\boldsymbol{u}_b - \mathbf{c})\cdot\nabla h + w_b \qquad (3)$$

Stommel's demon?



Subduction estimated at the migrating isopycnals

New expression of subduction

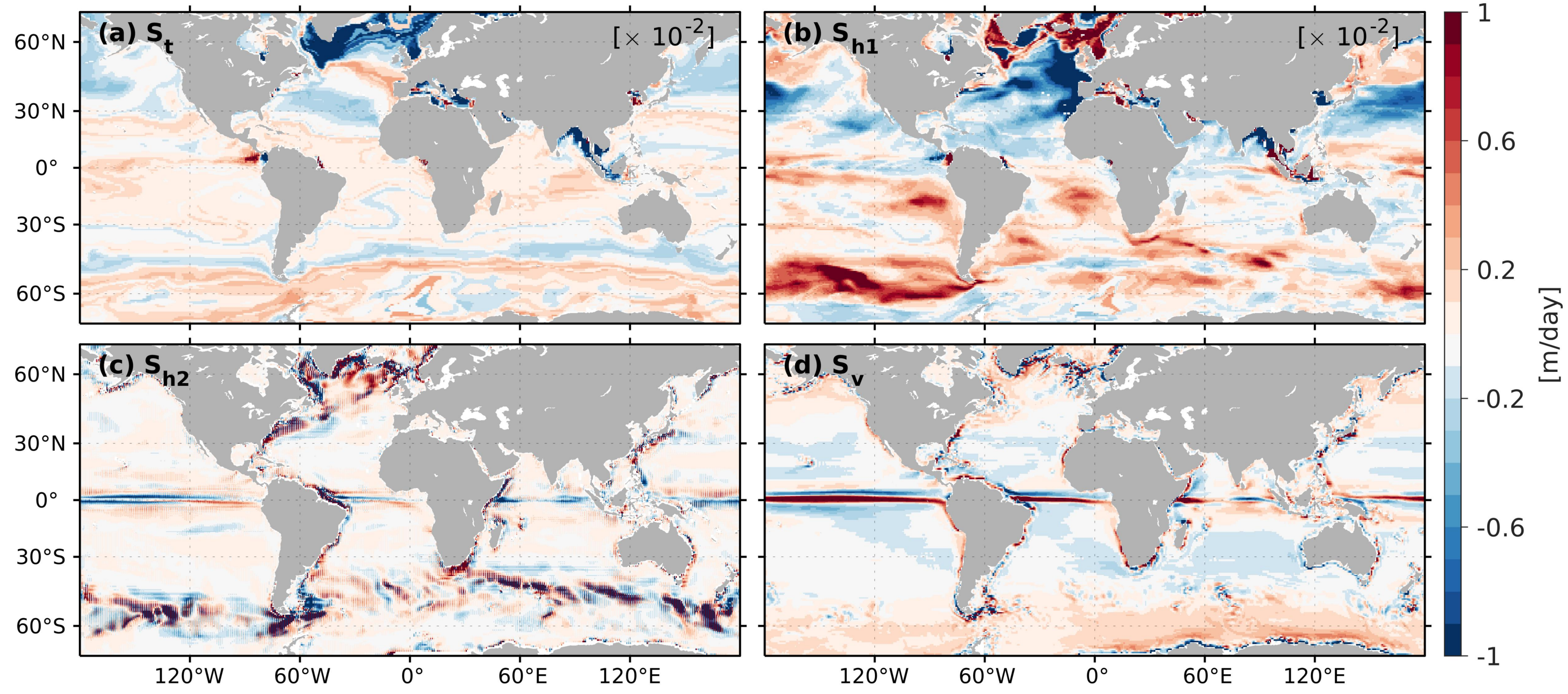
$$S = \left.\frac{\partial h}{\partial t}\right|_{\sigma} + \left.\boldsymbol{u}_b\right|_{\sigma} \cdot \nabla h + w_b = \underbrace{\left.\frac{\partial h}{\partial t}\right|_{r}}_{\text{temporal term } S_t} + \boldsymbol{c} \cdot \nabla h + (\boldsymbol{u}_b - \boldsymbol{c}) \cdot \nabla h + w_b$$

vertical velocity S_v

migration of isopycnal S_{h1}

lateral induction S_{h2}

Four terms of the instantaneous subduction rate



Summary:

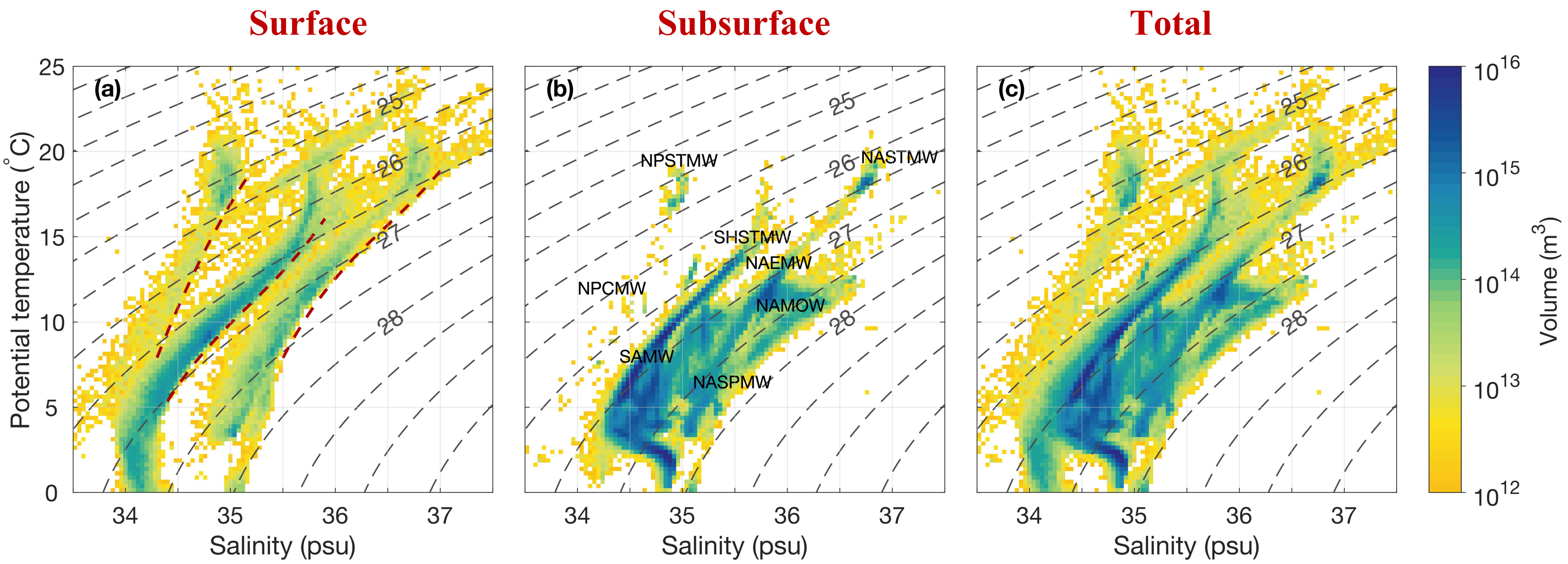
1) Large scale is dominated by Ekman pumping.

2) Spatial patterns along the ACC and in the polar North Atlantic are controlled by lateral induction.

3) Migration of isopycnals matters especially at mid to high latitudes.

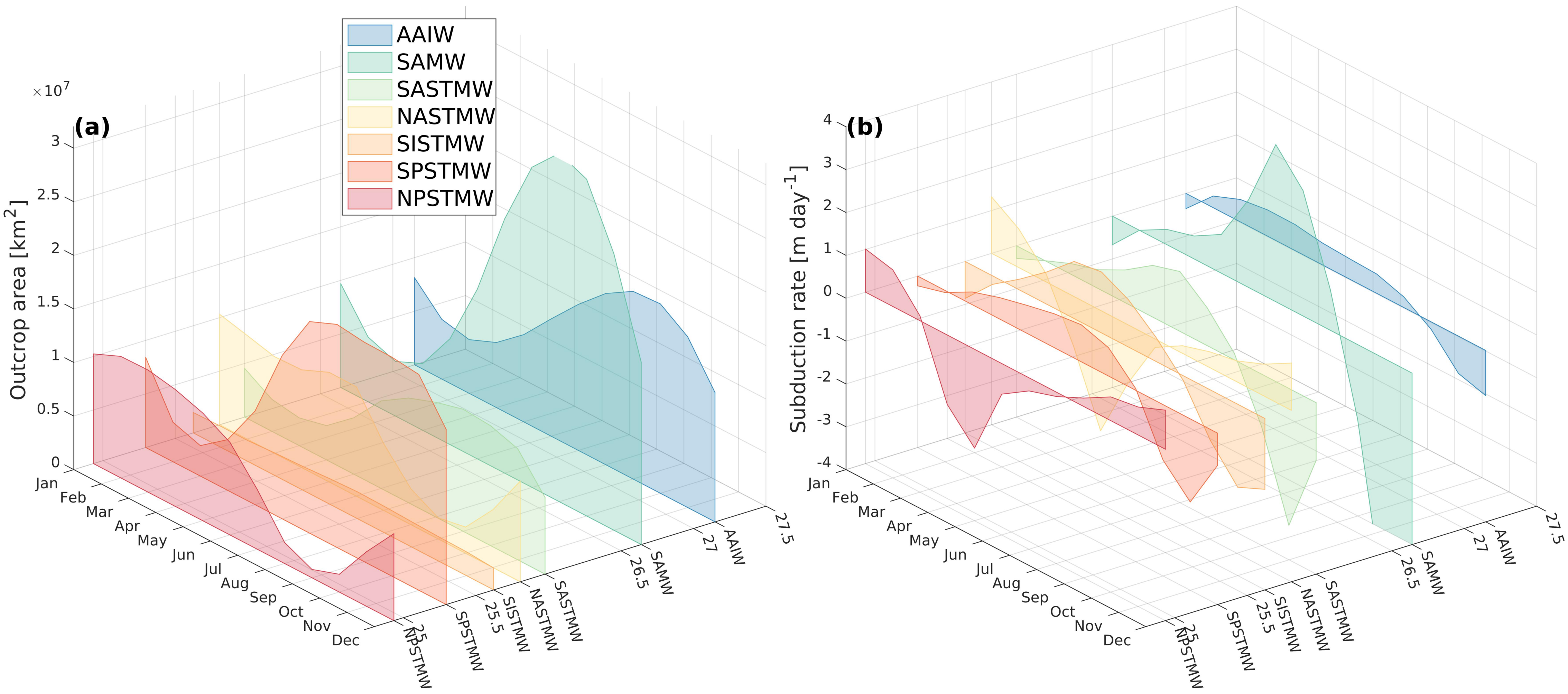
4) The temporal term does not vanish to zero as assumed in the theory of Stommel's demon.

T-S diagram of water masses



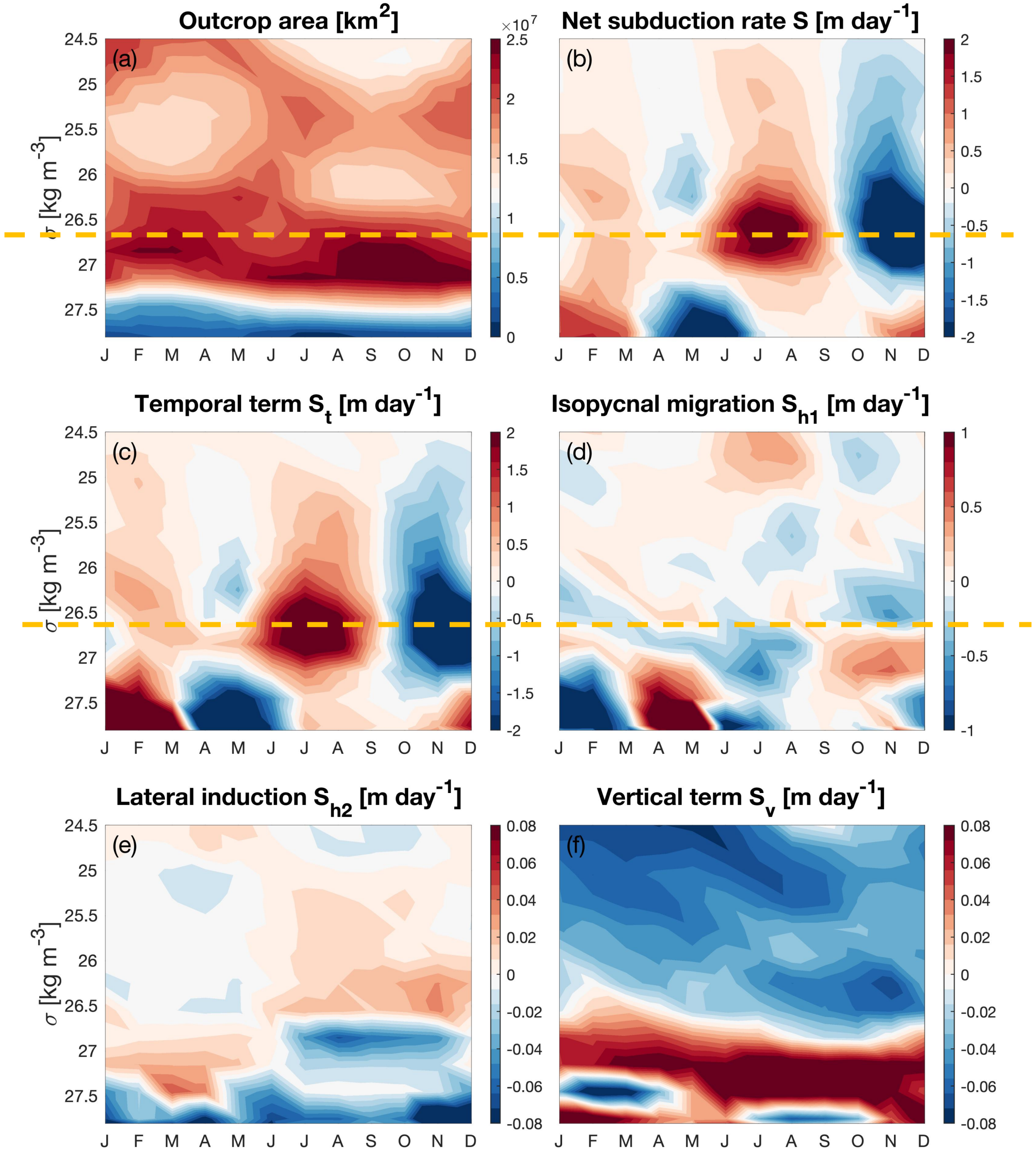
T-S diagram of surface and subsurface water masses detected from global Argo data.

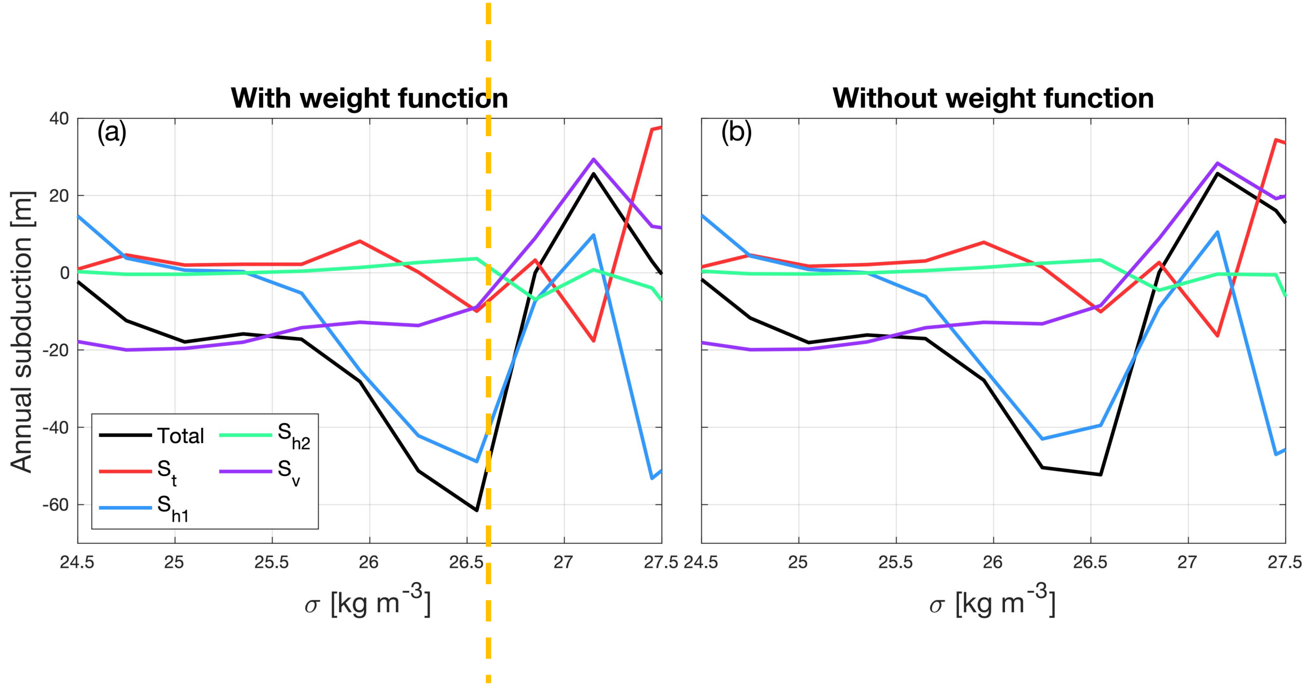
Subduction for global water masses



04 – **Isopycnic water mass subduction**

Nonlinearity in annual subduction





1. The outcropping area is dependent on time and density.

2. Nonlinearity leads to modifications of volume subduction at different isopycnals.

3. Net volume subduction is resulted from the expansion of outcrop area and subduction rate increment.

Summary

- The results suggest that to switch to the isopycnic coordinate is a better framework for studying the water mass subduction.

- Net volume subduction is greatly modified by the nonlinearity between the time dependence of outcropping area and instantaneous subduction rate.

- More in: My PhD thesis. Water mass subduction in an isopycnic coordinate.

Prospectives

Nonlinear Ekman theory

- Include eddy killing regime.
- Compare with Ekman pumping induced from thermal feedback.

SSH-SST inconsistency in mesoscale eddies

- Connection with subsurface structures following eddy trajectories.
- Connection with atmospheric stability following eddy trajectories.

Isopycnic water mass subduction

- An interesting calculation will be to connect water mass subduction to transformation at the surface.
- A comparison to Lagrangian estimate will be optimal.
- PV perspective of water mass subduction.

Thanks!