

論文紹介（17/11/17 EOASセミナー）

Eddy Generation and Jet Formation via Dense Water Outflows across the Antarctic Continental Slope

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JPO, 2016

南極の陸棚斜面における高密度水流出に伴う
渦の生成とジェットの形成

山崎 開平

私の研究テーマ・・・

南極海陸棚域の水塊交換

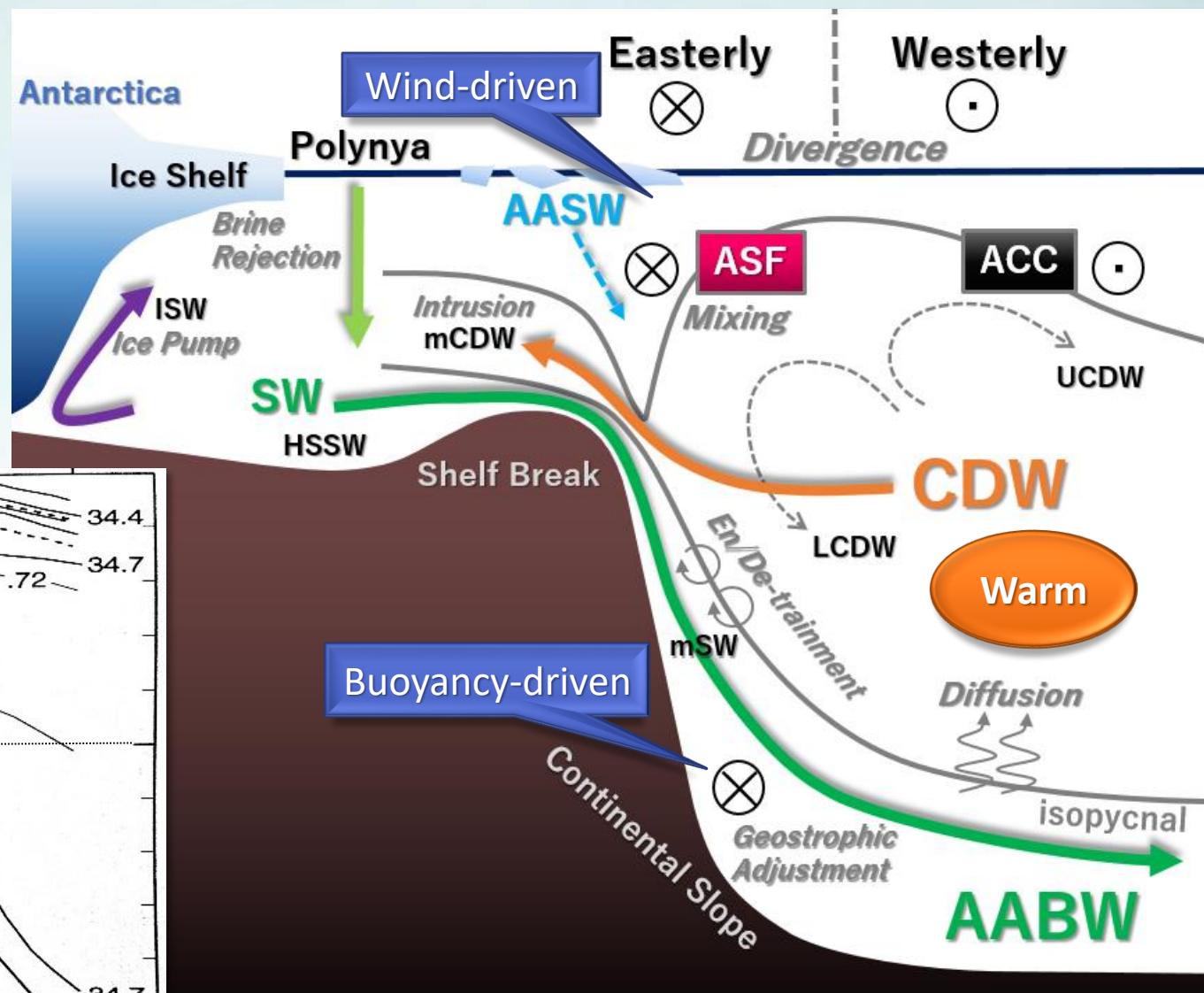
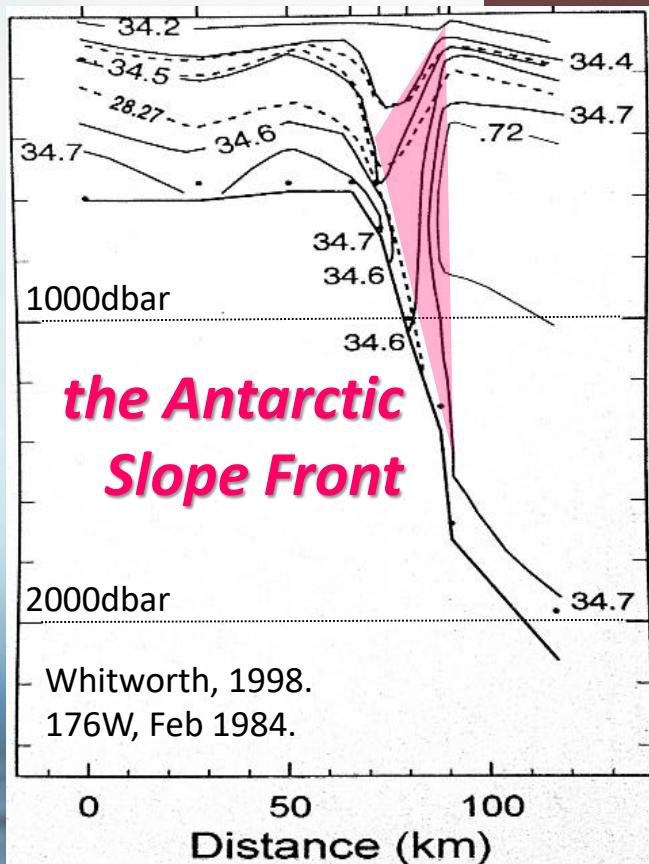
Exchanges associated with the Antarctic Slope Front

Contents

1. Introduction
 2. Model configuration
 3. Role of eddies in cross-slope exchange
 4. Dynamics of along-slope jets
 5. Mixing length theory for cross-slope eddy transfer (時間の都合上カット)
 6. Discussion and conclusions → **Summary**
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- ```
graph LR; A[1. Introduction
2. Model configuration
3. Role of eddies in cross-slope exchange
4. Dynamics of along-slope jets] --> B[Model configuration]; C[5. Mixing length theory for cross-slope eddy transfer
6. Discussion and conclusions] --> D[Dynamics of eddies and jets]; C --> E[Summary]
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# **Introduction**

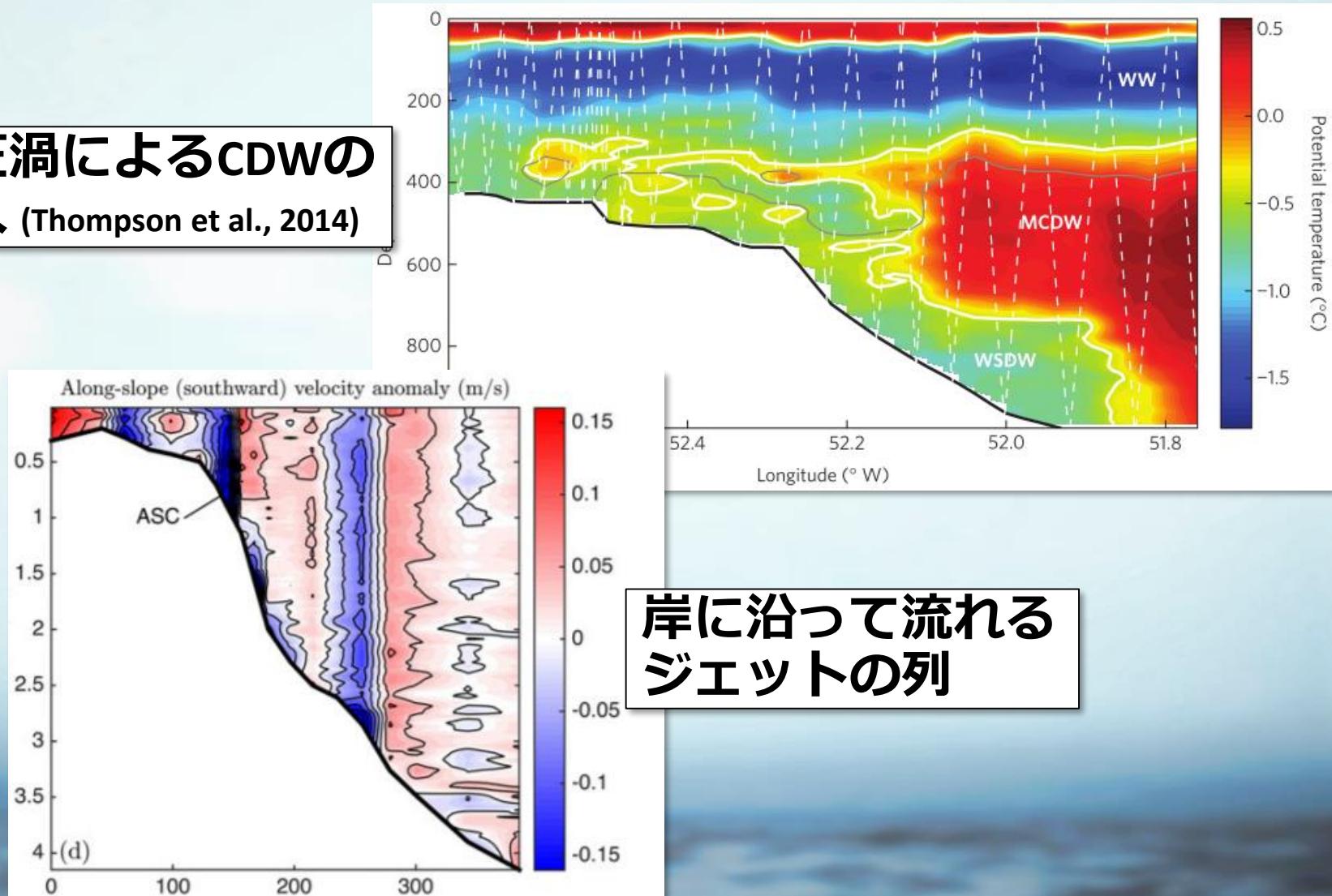
# 南極海陸棚域の 力学過程



# Cross slope/shelf exchange?

# 渦とジェットの観測例 (Weddell海の西部)

傾圧渦によるCDWの流入 (Thompson et al., 2014)



# 議論の流れ

ターゲット：

渦 ⇄ ジェット

CDW ⇄ 底層水

CDWの流入に対する渦の寄与は？

渦輸送の定量化

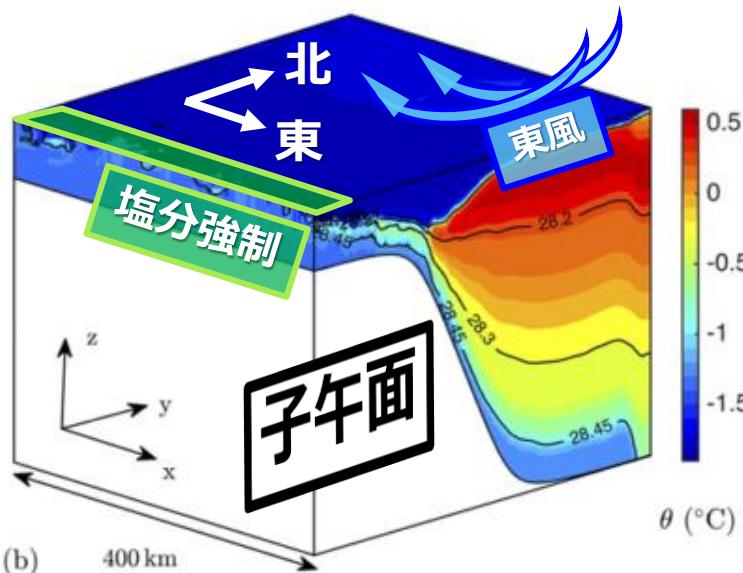
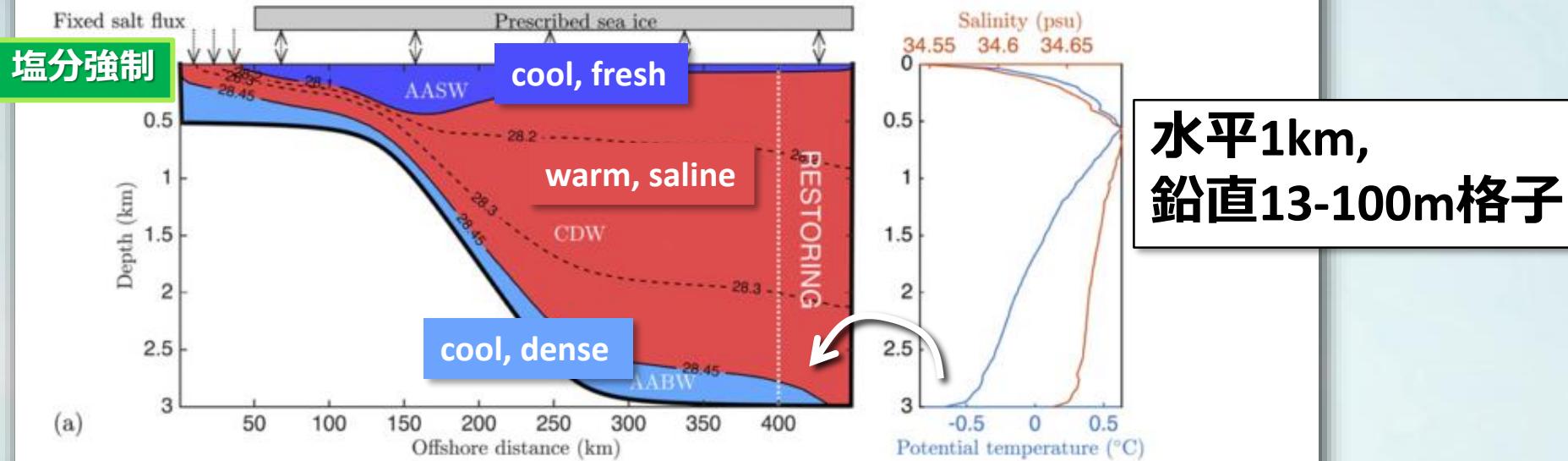
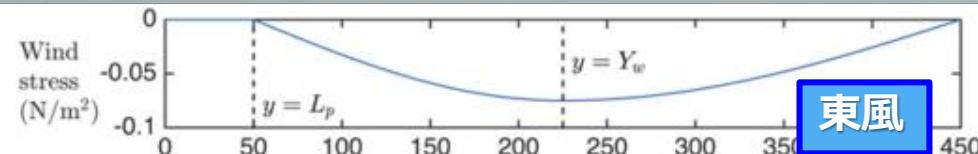
なぜ渦は岸へと移流する？

運動量バランス(TEM)

渦の生成を制御するものは？

遷移するジェット

# **Model configuration**



- ✓ Boussinesq momentum and tracer conservation equations (MITgcm)
- ✓ Nonlinear equation of state

- constant AABW export
- neutral density  $\gamma_n$  layering

# ※Transformed Eulerian Mean (TEM)について

## 渦移流をあわせた流れ（残差流）の運動方程式

東西一様の場合に適用しやすいので、主に大気で用いられるが…  
海洋でも、南大洋の子午面循環に対して適用

★Boussinesq流体・QG近似・  
平均的に東西一様な擾乱場で  
考えると…

子午面上の残差流線関数  $\chi^\dagger = \chi_a + \chi_c$ .  
 $(\bar{v}_a, \bar{w}_a) = (-\partial_z \chi_a, \partial_y \chi_a)$  : 非地衡流  $\chi_c = \frac{\bar{v} \bar{b}}{N^2}$  : 渦

渦流線関数  $\propto$  浮力偏差の南北フラックス

$$\text{E-P flux : } \nabla \cdot \mathbf{F} = \nabla \cdot \begin{pmatrix} F_y \\ F_z \end{pmatrix} = \nabla \cdot \begin{pmatrix} -\bar{u}' \bar{v}' \\ \frac{f_0}{N^2} \bar{v}' \bar{b}' \end{pmatrix}$$

渦と平均流の相互作用の式

$$\partial_t \bar{u} - f_0 \bar{v}_a = \bar{\mathcal{G}}_x - \partial_y (u' v'),$$

$$f_0 \partial_z \bar{u} = -\partial_y \bar{b}, \text{ : 温度風}$$

$$\partial_y \bar{v}_a + \partial_z \bar{w}_a = 0,$$

$$\partial_t \bar{b} + \bar{w}_a N^2 = \bar{\mathcal{B}} - \partial_y (v' b')$$

渦拡散 “symmetric”

渦移流 “skew”

↓ 「渦による駆動」をE-P fluxで表す

$$\partial_t \bar{u} - f_0 \bar{v}^\dagger = \bar{\mathcal{G}}_x + \nabla \cdot \mathbf{F},$$

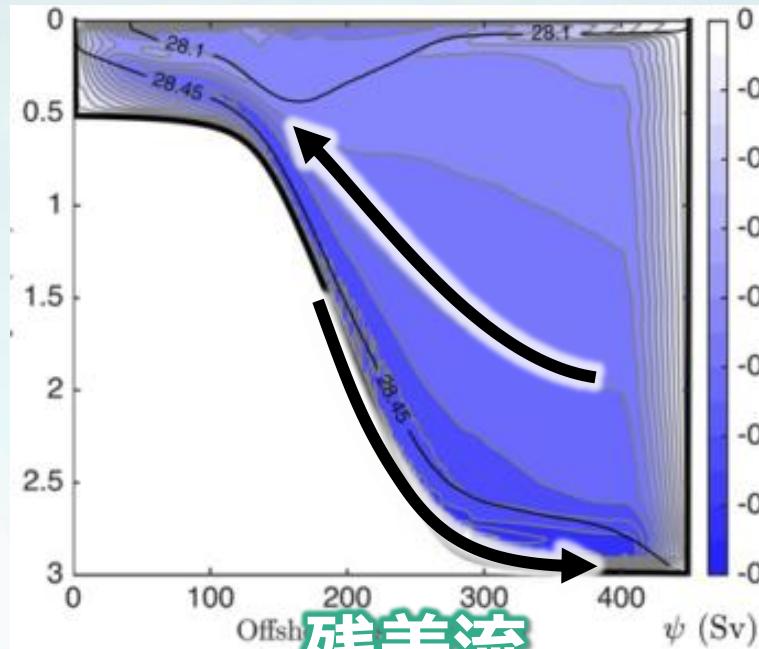
$$f_0 \partial_z \bar{u} = -\partial_y \bar{b},$$

$$\partial_y \bar{v}^\dagger + \partial_z \bar{w}^\dagger = 0,$$

$$\partial_t \bar{b} + \bar{w}^\dagger N^2 = \bar{\mathcal{B}},$$

TEM方程式系

# 子午面上の流線関数



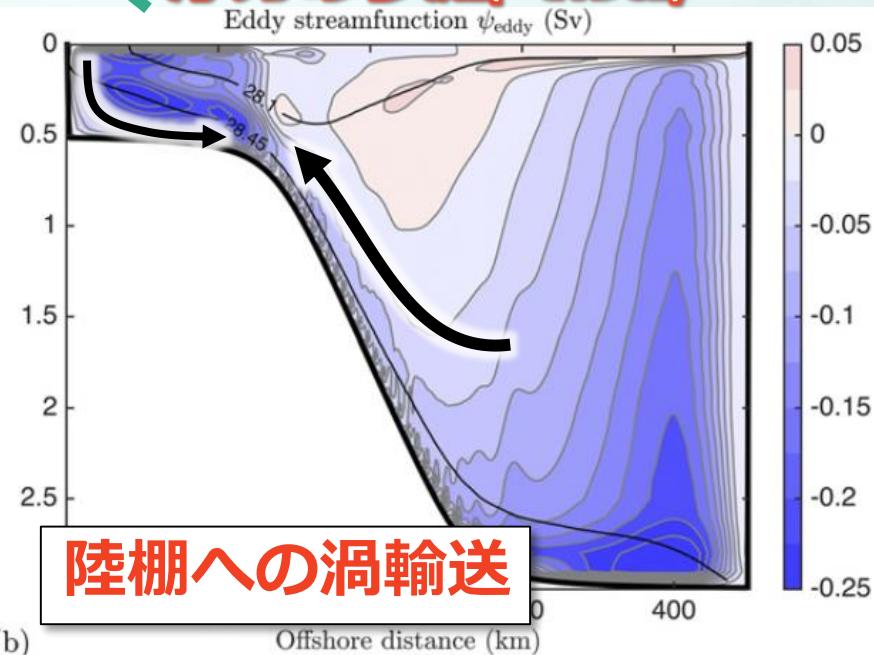
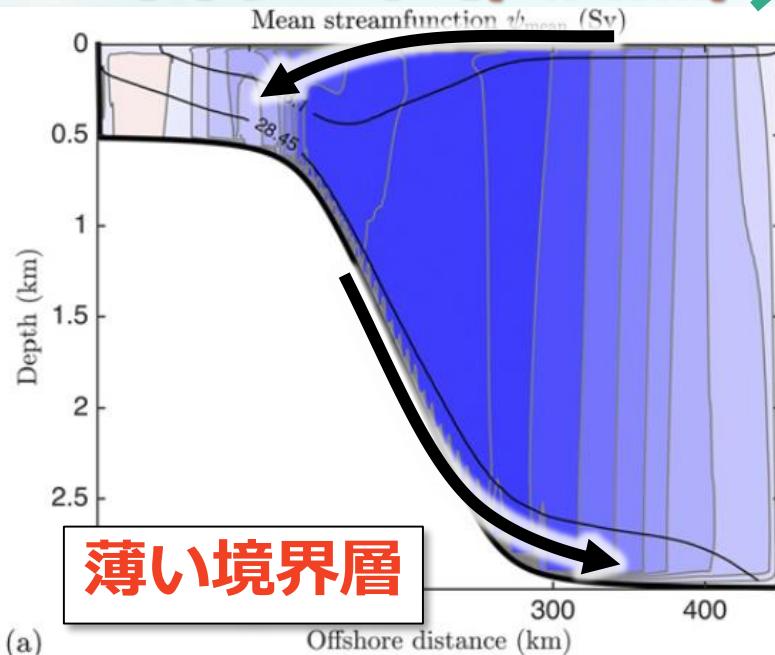
Neutral Density  
Transformed Eulerian Mean  
(Stewart and Thompson 2015b)

$$\begin{aligned}\psi &= \psi_{\text{mean}} + \psi_{\text{eddy}}, \\ \psi_{\text{mean}} &= \int_z^0 \bar{v} dz, \quad \text{and} \\ \psi_{\text{eddy}} &= \frac{\beta(\bar{S}, \bar{\theta}, z) \bar{v}' \bar{S}' - \alpha(\bar{S}, \bar{\theta}, z) \bar{v}' \bar{\theta}'}{\beta(\bar{S}, \bar{\theta}, z) \bar{S}_z - \alpha(\bar{S}, \bar{\theta}, z) \bar{\theta}_z}.\end{aligned}$$

残差流

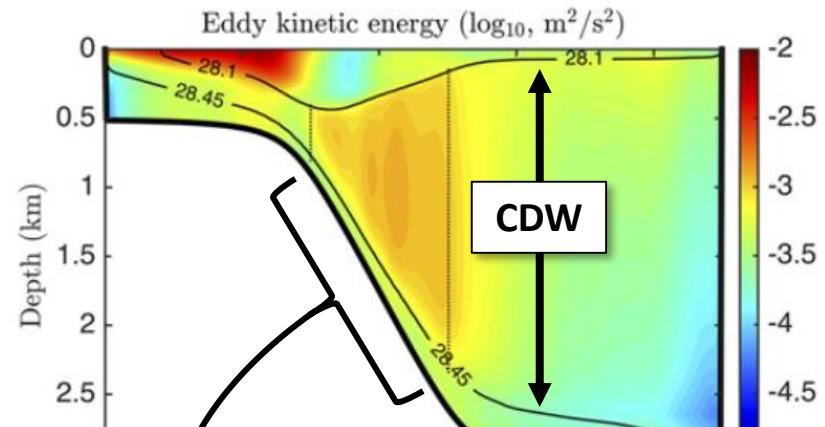
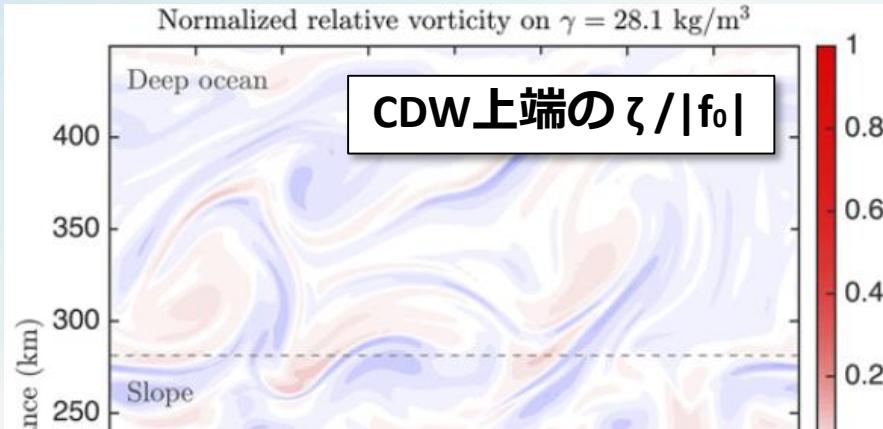
オイラー平均(=非地衡流)

浮力の移流(=渦移流)



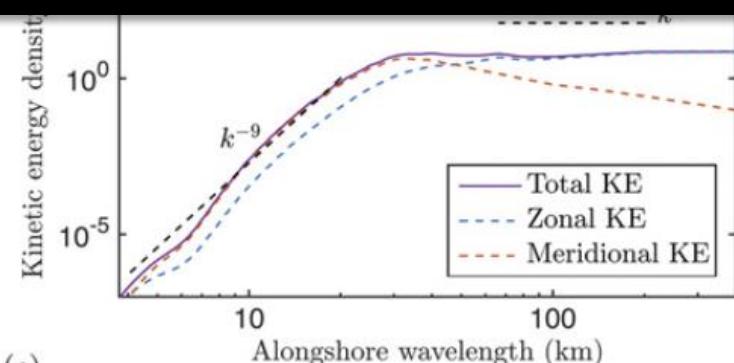
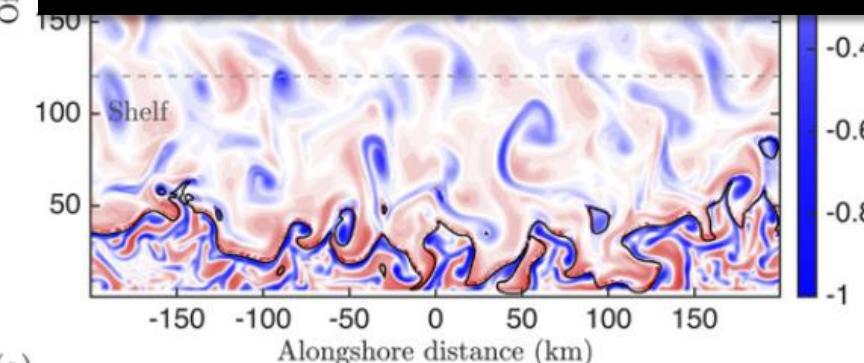
# **Dynamics of eddies and jets**

# 渦活動の様子



**Baroclinic instability isn't suppressed over steep topography?**

(e.g. Pennel et al. 2012; Isachsen 2011; Stewart and Thompson 2013)



(a)

(c)

外洋 :  $O(100) \text{ km}$ ,  $\text{Ro} < 0.1$

“mesoscale eddies”

斜面 :  $O(30) \text{ km}$ ,  $\text{Ro} = 0.2\text{-}0.3$

“small eddies”

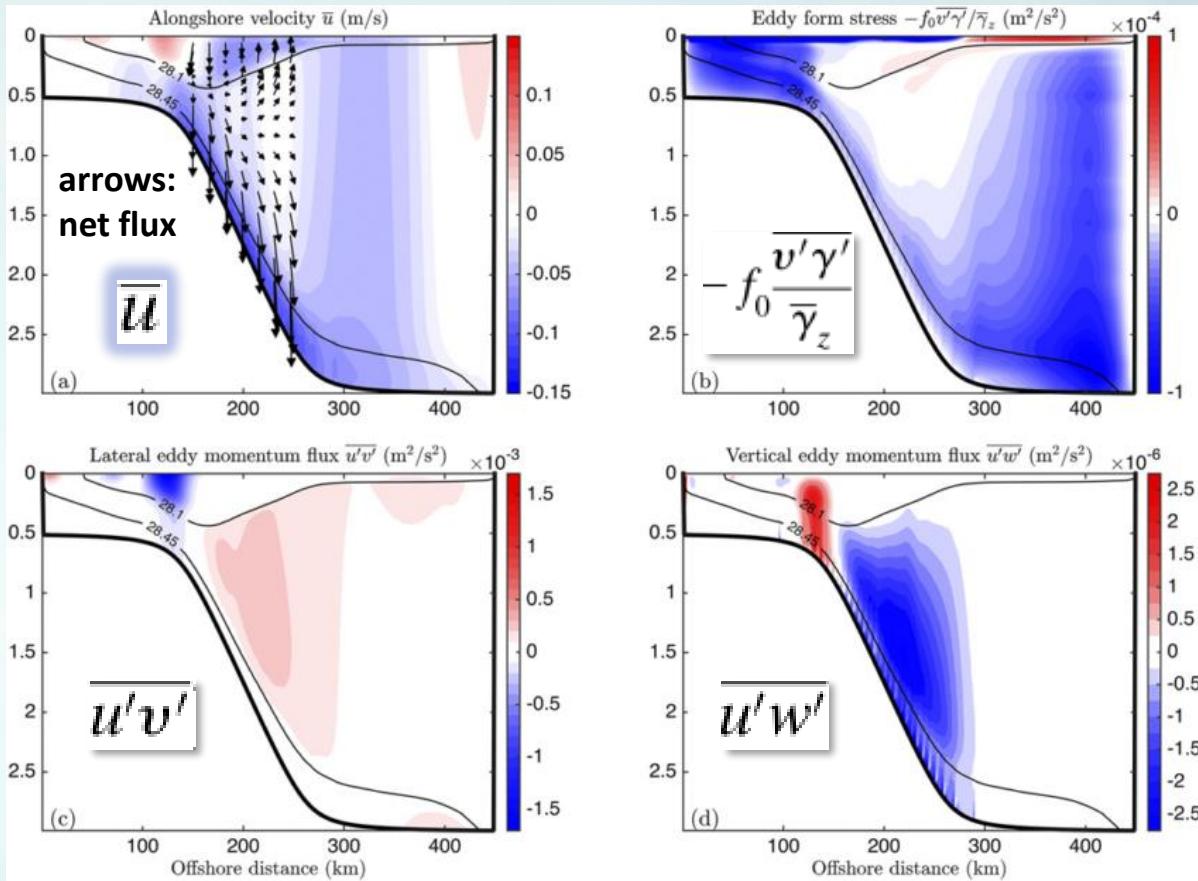
陸棚 :  $O(10) \text{ km}$ ,  $\text{Ro} = 1\text{-}2$

“submesoscale features”

# 渦による東向き運動量フラックス

TEM along-slope momentum balance

$$\frac{\partial \bar{u}}{\partial t} + \frac{\partial}{\partial y} (\bar{u}' v') + \frac{\partial}{\partial z} \left( \bar{u}' w' - f_0 \frac{v' \gamma'}{\bar{\gamma}_z} \right) \approx f v^\dagger.$$



●南北残差流によるコリオリカ

● **eddy form stress** ⇔ 涡流線関数

※form stress : レイヤー間の平均圧力応力

$$\tau_i = -\overline{\eta_i \frac{\partial p_i}{\partial x}}, \quad \rho f v' = \frac{\partial p'}{\partial x}, \quad \eta' \approx -b' / (\partial b / \partial z)$$

- 表層と底層の西向流が、CDWに「西向き運動量」を供給  
⇒ 西向き運動量の収束で、CDWの岸向き残差流が駆動
- 底層からのeddy form stressが鉛直フラックスで卓越  
⇒ 底層の傾圧不安定が残差流を駆動

What's a control factor for the momentum supply?

# \*ジェットの形成について

## 【成層流体のエネルギークスケード】

2-D乱流  $\Rightarrow$  運動エネルギーは**低波数**へ散逸

**“inverse cascade”**

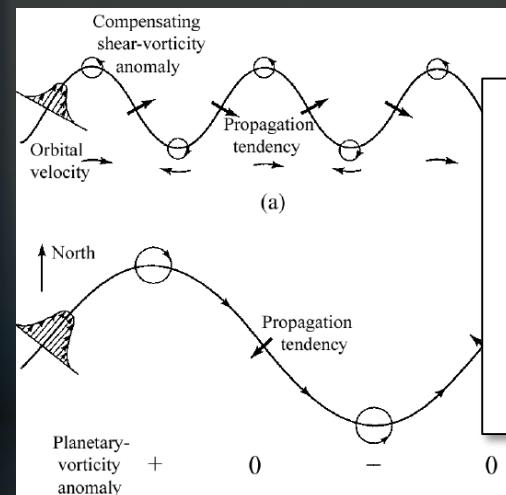
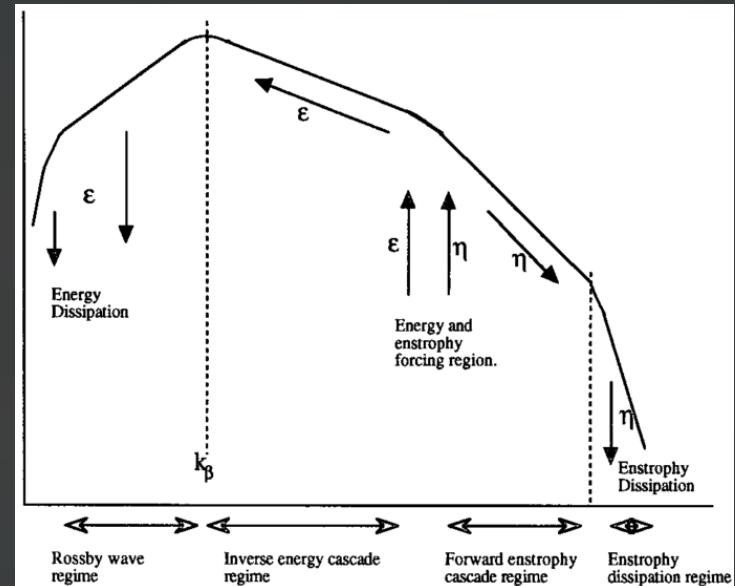
∴ エンストロフィー Z の保存

ある波数のエネルギーが与えられたとき、

$$E = \int E(k) dk, \quad Z = \int k^2 E(k) dk$$

に対して、

$E(k)$  が**平均的に**高波数にカスケードすると  
 $Z$ は保存しない！



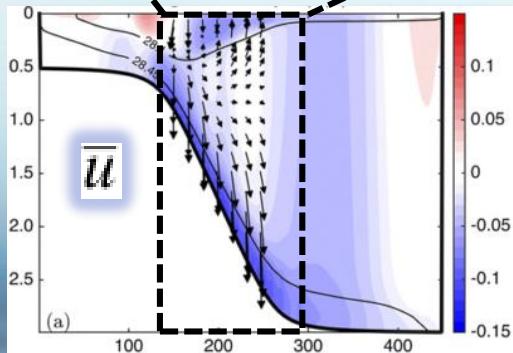
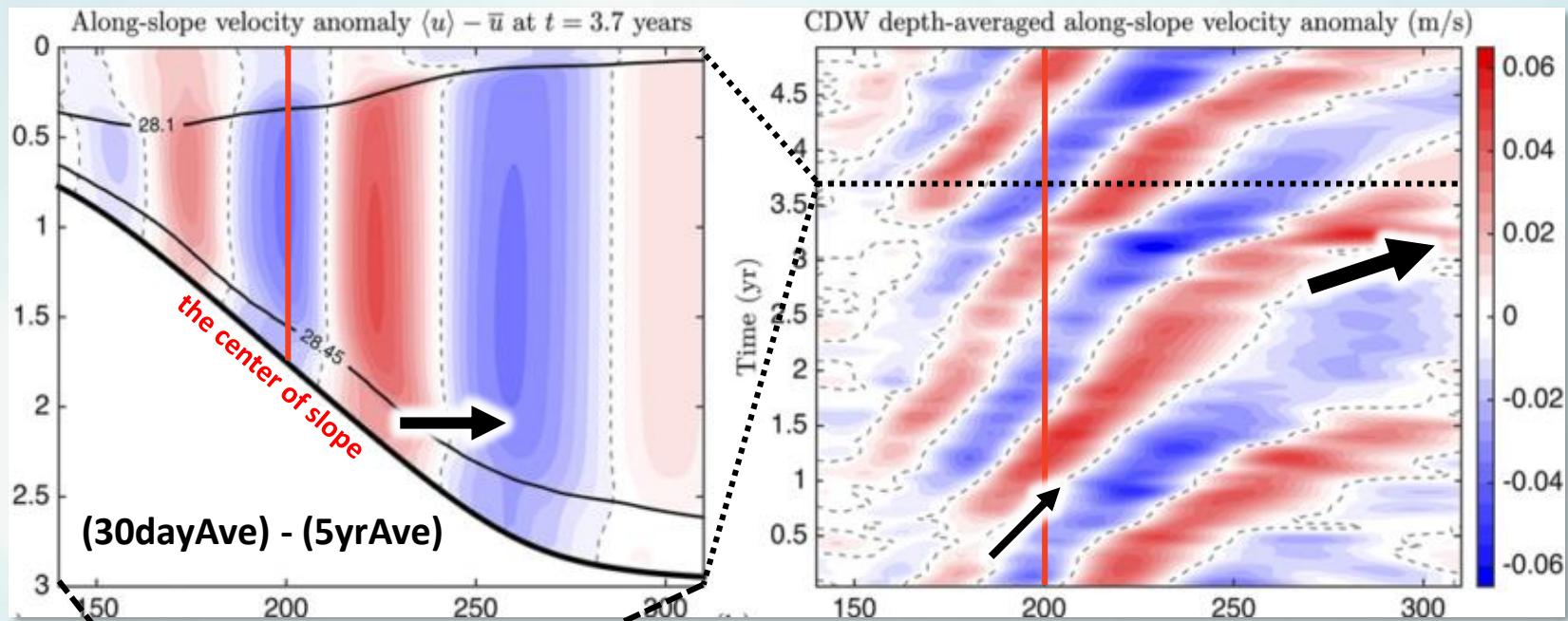
## 【β効果が大きい場合】

**“wave turbulence boundary”** (e.g. Vallis and Maltrud 1993)

渦位の勾配はRossby波や蛇行流meanderをつくる

- … 蛇行流の波長：カスケードできるスケールの上限
- … 運動エネルギーが一定の波数に集積、**ジェット形成**

# 東西流速のアノマリー



ジェットの列が沖へ遷移

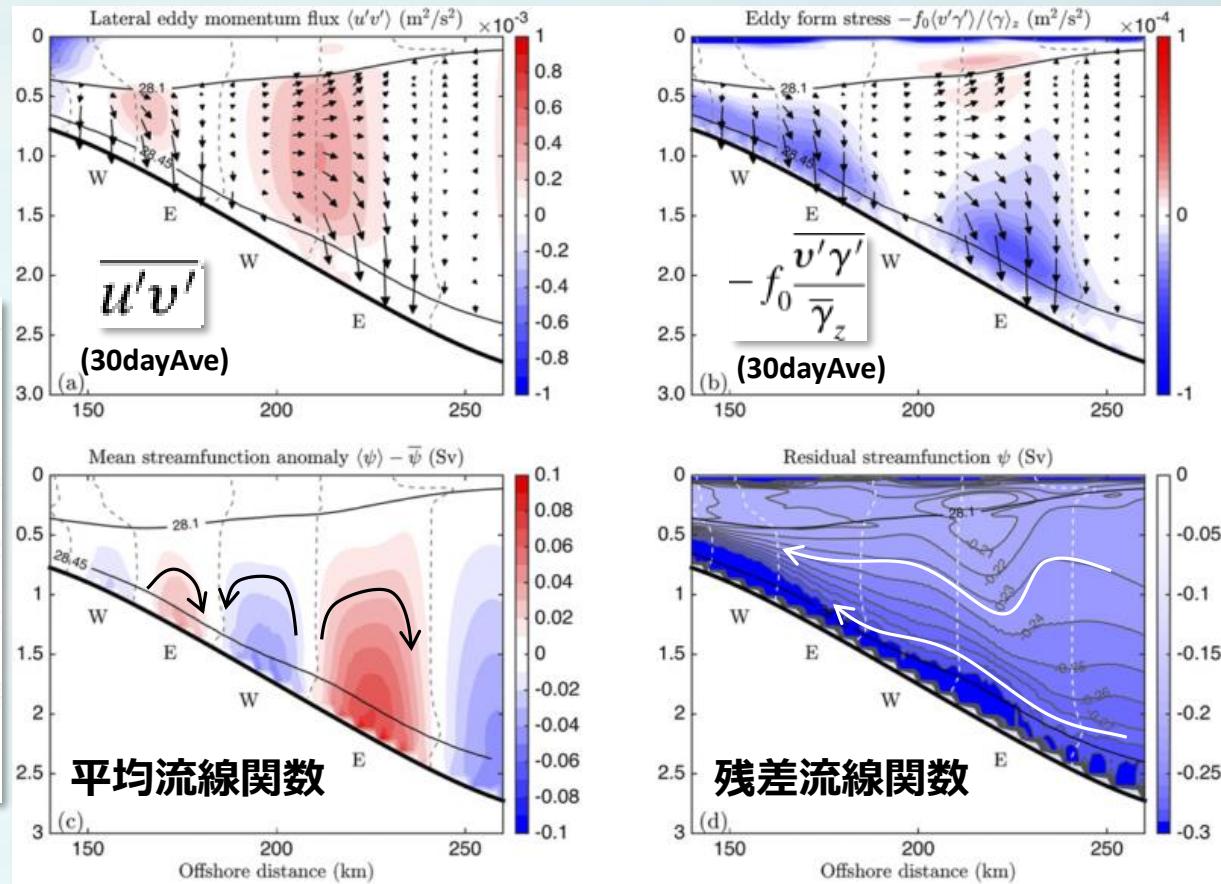
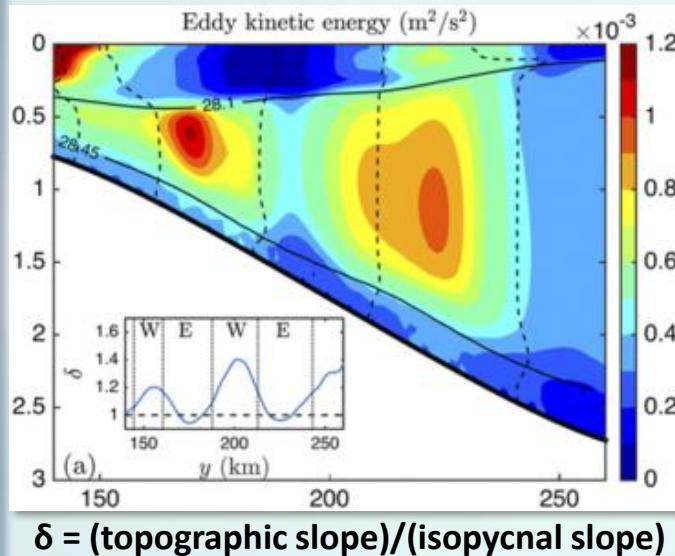
@shelf break

幅: 30km, 速さ: 25km/yr

@continental rise

幅: 50km, 速さ: 50km/yr

# 再び東向き運動量



- 東向ジェットでの渦輸送、岸向き残差流の駆動  
…表層/底層との強いシアに伴う傾圧不安定
- 水平渦フラックスによりジェットが沖へ遷移

# **Summary**

# 今回わかったこと

- ✓ CDWの渦移流が陸棚への熱輸送を担う
- ✓ 表層・底層からCDWへの西向き運動量
- ✓ 「西向き運動量の収束」 ⇒ 「岸向き残差流」
- ✓ 混合距離によるフラックス推定スキル

CDW flux  $\propto$   
DSW outflow!

## メカニズムについて

Baroclinic instability isn't suppressed over steep topography?



浮力強制に伴う底層流が渦活動をアシスト

What's a control factor for the momentum supply?



沖へ遷移するジェット；鉛直シア ⇔ 不安定

JPO, 2016

**Eddy Generation and Jet Formation via Dense Water Outflows across  
the Antarctic Continental Slope**

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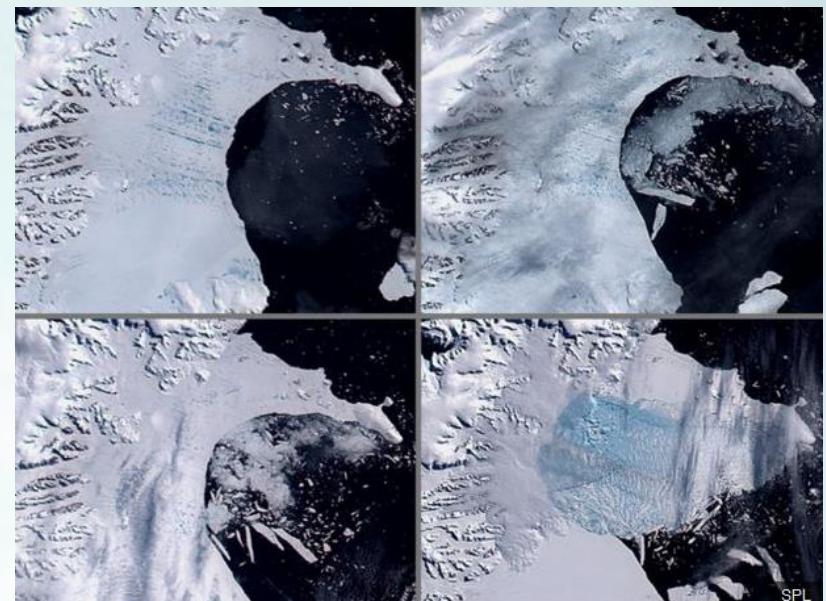
*Environmental Sciences and Engineering, California Institute of Technology, Pasadena, California*

ありがとうございました

# なぜ南極海？

## □ 海氷 *sea ice*

- アルベド調節
- 大気との物理量交換
- 熱塩輸送
- 一次生産



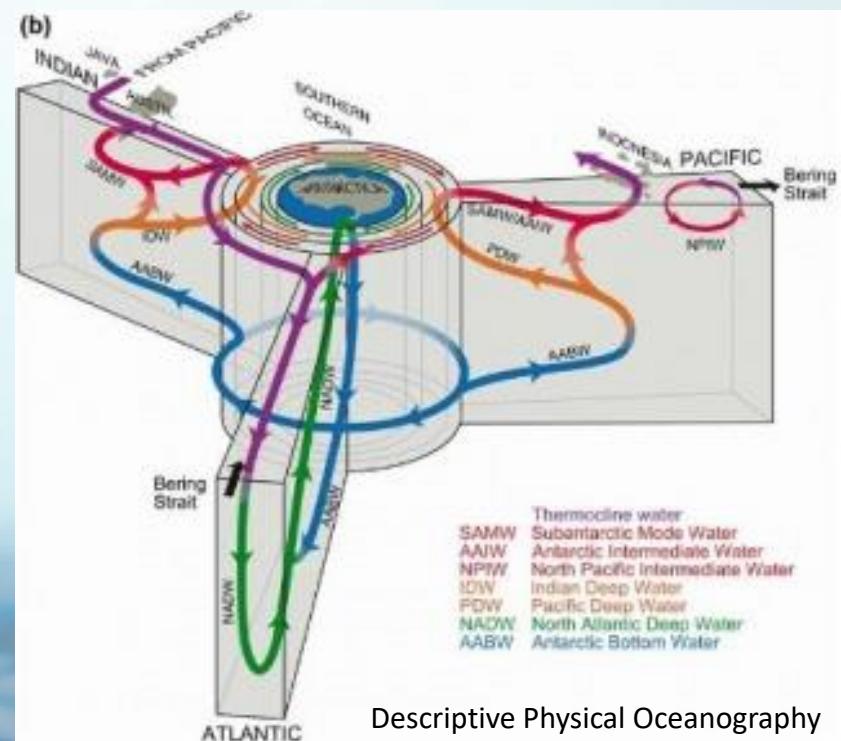
2002年の西南極Larsen B棚氷の崩壊

## □ 棚氷 *ice shelf*

- 海洋との相互作用
- 海水位上昇

## □ 深層循環 *meridional overturning*

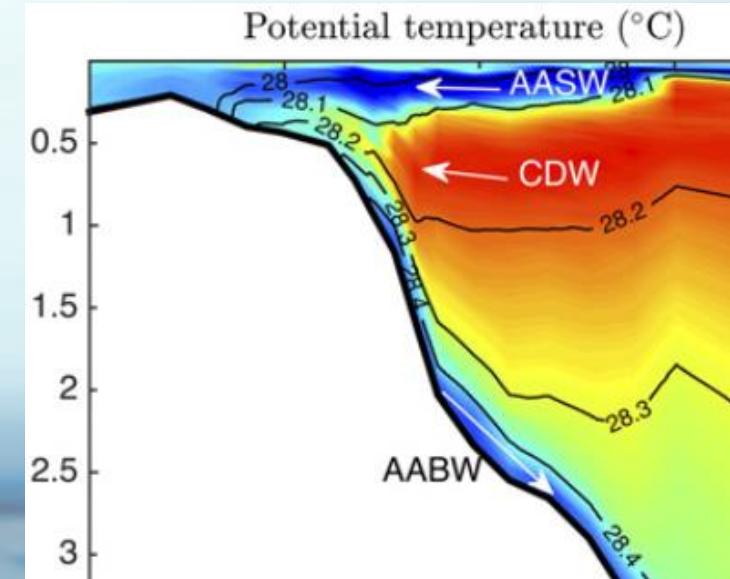
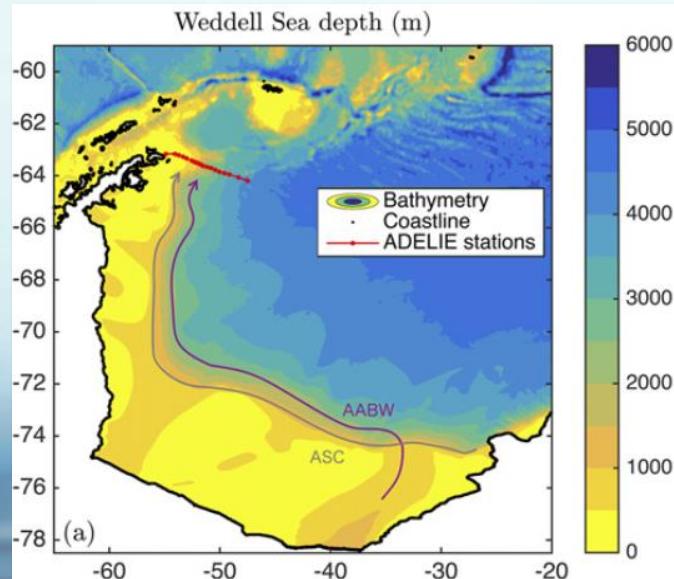
- 地球の恒温機能
- 物質循環



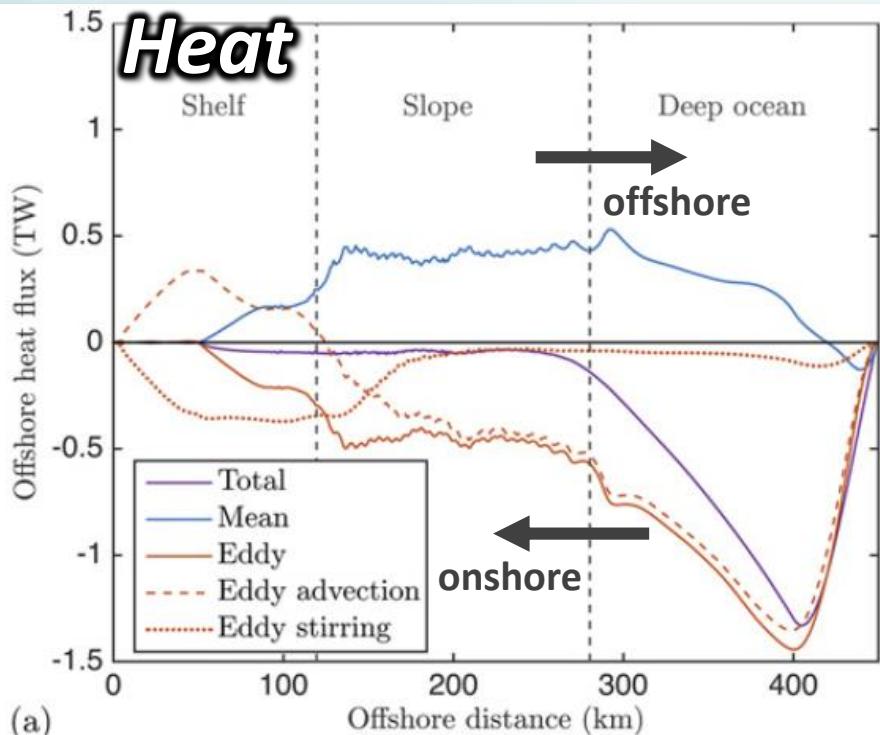
# 議論のポイント

- CDWの陸棚への渦輸送 eddy transport
  - …  $NH/f = 5-10\text{km}$  (亜熱帯の傾圧渦の1/10)
- CDW flux  $\propto$  Dense Shelf Water ?
  - vs. 地形性β効果によるジェット形成 jet formation

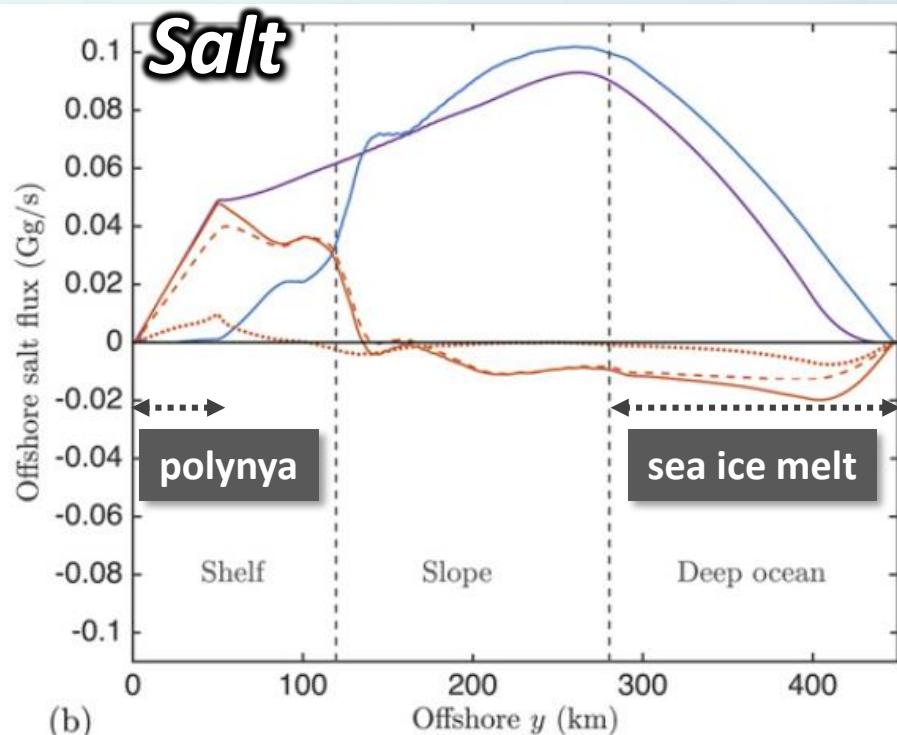
参考海域→



# 沖向き熱塩フラックス



(a)



(b)

$$F^{(\phi)} = F_{\text{mean}}^{(\phi)} + F_{\text{eddy}}^{(\phi)},$$

$$F_{\text{mean}}^{(\phi)} = L_x \int_{-h}^0 \bar{v} \bar{\phi} dz, \quad \text{and}$$

$$F_{\text{eddy}}^{(\phi)} = L_x \int_{-h}^0 \bar{v}' \bar{\phi}' dz,$$
  

$$F_{\text{eddy}}^{(\phi)} = F_{\text{adv}}^{(\phi)} + F_{\text{stir}}^{(\phi)}, \quad \text{and}$$

$$F_{\text{adv}}^{(\phi)} = L_x \int_{-h}^0 v_{\text{eddy}} \bar{\phi} dz;$$

【平均流】 (= 非地衡流)  
 低温・低塩なAASWの岸向きEkman輸送  
 【渦による移流】 (= 渦による体積輸送)  
 傾圧は「陸棚で塩分勾配」「沖合で水温勾配」  
 【渦による搅拌】 (= 渦フラックスの剩余)  
 热は陸棚に入ると“passive tracer”

# for reference simulation

| Parameter            | Value                                         | Description                         |
|----------------------|-----------------------------------------------|-------------------------------------|
| $L_x$                | 400 km                                        | Zonal domain size                   |
| $L_y$                | 450 km                                        | Meridional domain size              |
| $H$                  | 3000 m                                        | Maximum ocean depth                 |
| $H_s$                | 500 m                                         | <i>Continental shelf depth</i>      |
| $Y_s$                | 200 km                                        | Slope center position               |
| $W_s$                | 75 km                                         | <i>Slope half-width</i>             |
| $L_p$                | 50 km                                         | Width of shelf polynya              |
| $\Sigma$             | $2.5 \text{ mg m}^{-2} \text{ s}^{-1}$        | <i>Polynya salt forcing</i>         |
| $Y_w$                | 225 km                                        | <i>Peak wind stress position</i>    |
| $L_r$                | 50 km                                         | Width of northern relaxation region |
| $T_r$                | 8 weeks                                       | Northern relaxation time scale      |
| $\tau_{\max}$        | $0.075 \text{ N m}^{-2}$                      | <i>Wind stress maximum</i>          |
| $\rho_0$             | $999.8 \text{ kg m}^{-3}$                     | Reference density                   |
| $g$                  | $9.81 \text{ m}^2 \text{ s}^{-1}$             | Gravitational constant              |
| $f_0$                | $-1.31 \times 10^{-4} \text{ s}^{-1}$         | Reference Coriolis parameter $f$    |
| $A_h$                | $12 \text{ m}^2 \text{ s}^{-1}$               | Horizontal viscosity                |
| $A_v$                | $3 \times 10^{-4} \text{ m}^2 \text{ s}^{-1}$ | Vertical viscosity                  |
| $A_{4\text{grid}}$   | 0.1                                           | Grid-dependent biharmonic viscosity |
| $C_{4\text{leith}}$  | 1.0                                           | Leith vortical viscosity            |
| $C_{4\text{leithD}}$ | 1.0                                           | Leith solenoidal viscosity          |
| $\kappa_v$           | $5 \times 10^{-6} \text{ m}^2 \text{ s}^{-1}$ | Vertical diffusivity                |
| $r_b$                | $1 \times 10^{-3} \text{ m s}^{-1}$           | Bottom friction                     |
| $\Delta_x, \Delta_y$ | 1 km                                          | Horizontal grid spacing             |
| $\Delta_z$           | 13–100 m                                      | Vertical grid spacing               |
| $\Delta_t$           | 179 s                                         | Time step size                      |

for sea ice (thermodynamic forcing only)

| Parameter          | Value                                                | Description                                    |
|--------------------|------------------------------------------------------|------------------------------------------------|
| $L_0$              | $3.34 \times 10^5 \text{ J kg}^{-1}$                 | Latent heat of melting                         |
| $C_i$              | $2060 \text{ J kg}^{-1} \text{ }^\circ\text{C}^{-1}$ | Ice heat capacity                              |
| $C_p$              | $3994 \text{ J kg}^{-1} \text{ }^\circ\text{C}^{-1}$ | Ocean heat capacity                            |
| $\rho_i$           | $920 \text{ kg m}^{-3}$                              | Ice reference density                          |
| $\kappa_i$         | $1.14 \times 10^{-6} \text{ m}^2 \text{ s}^{-1}$     | Ice thermal diffusivity                        |
| $\gamma_T$         | $6 \times 10^{-5} \text{ m s}^{-1}$                  | Thermal turbulent exchange velocity            |
| $H_i$              | 1 m                                                  | Ice thickness                                  |
| $\phi_{\text{fr}}$ | 0.14                                                 | Salinity retention fraction on freezing        |
| $\mu$              | $0.054 \text{ }^\circ\text{C psu}^{-1}$              | Linear saline freezing temperature coefficient |
| $T_i$              | $-5^\circ\text{C}$                                   | Ice temperature                                |
| $S_i$              | 5 psu                                                | Ice salinity                                   |

# Transformed Eulerian Mean (TEM)について

渦輸送と非地衡流の「残差」として生じる流れを記述する方程式

★ Boussinesq流体・QG近似・平均的に東西一様な渦擾乱場で考えると…

$$\begin{aligned}\psi &= \frac{p - p_0(z)}{\rho_0 f_0} \quad \frac{\partial \psi}{\partial z} = \frac{b}{f_0} \quad \text{流線関数と浮力} \\ D_g u - \beta y v - f_0 v_a &= \mathcal{G}_x, \\ D_g v + \beta y u + f_0 u_a &= \mathcal{G}_y, \quad \text{運動方程式} \\ \partial_x u_a + \partial_y v_a + \partial_z w_a &= 0, \quad \cdot \text{連続の式} \\ D_g b + N^2 w_a &= \mathcal{B},\end{aligned}$$

  $D_g q = \chi$ , PV方程式  
 $q = f_0 + \beta y + \partial_x v - \partial_y u + f_0 \partial_z (b/N^2)$ ,  
 $\chi = \partial_x \mathcal{G}_y - \partial_y \mathcal{G}_x + f_0 \partial_z (\mathcal{B}/N^2)$ .

  $\psi' = \psi - \bar{\psi}$ , 摶乱成分の分離  
 $q' = q - \bar{q} = \partial_x^2 \psi' + \partial_y^2 \psi' + \partial_z \left( \frac{f_0^2}{N^2} \partial_z \psi' \right)$

 Eliassen-Palm fluxによるPV収支  
 $\partial_t \bar{q} + \partial_y (\bar{v}' q') = \bar{\chi}$ .  
 $\bar{v}' q' = \nabla \cdot \mathbf{F} = \nabla \cdot \begin{pmatrix} F_y \\ F_z \end{pmatrix} = \nabla \cdot \begin{pmatrix} -\bar{u}' \bar{v}' \\ \frac{f_0}{N^2} \bar{v}' \bar{b}' \end{pmatrix}$

渦と平均流の相互作用の式

$$\begin{aligned}\partial_t \bar{u} - f_0 \bar{v}_a &= \bar{\mathcal{G}}_x - \partial_y (u' v'), \\ f_0 \partial_z \bar{u} &= -\partial_y \bar{b}, \quad : \text{温度風} \\ \partial_y \bar{v}_a + \partial_z \bar{w}_a &= 0, \\ \partial_t \bar{b} + \bar{w}_a N^2 &= \bar{\mathcal{B}} - \partial_y (v' b')\end{aligned}$$

渦拡散 “symmetric”

渦移流 “skew”

◎ 「渦による駆動」をE-P fluxで表す

子午面上の残差流線関数  $\chi^\dagger = \chi_a + \chi_c$ .  
 $(\bar{v}_a, \bar{w}_a) = (-\partial_z \chi_a, \partial_y \chi_a)$  : 非地衡流  $\chi_c = \frac{\bar{v}' \bar{b}'}{N^2}$  : 渦

渦流線関数  $\propto$  浮力偏差の南北フラックス

$$\begin{aligned}\partial_t \bar{u} - f_0 \bar{v}^\dagger &= \bar{\mathcal{G}}_x + \nabla \cdot \mathbf{F}, \\ f_0 \partial_z \bar{u} &= -\partial_y \bar{b}, \\ \partial_y \bar{v}^\dagger + \partial_z \bar{w}^\dagger &= 0, \\ \partial_t \bar{b} + \bar{w}^\dagger N^2 &= \bar{\mathcal{B}},\end{aligned}$$

TEM方程式系

# 渦エネルギー収支 (Boussinesq)

- baroclinic conversionが卓越
- 風応力 vs. 浮力強制
 

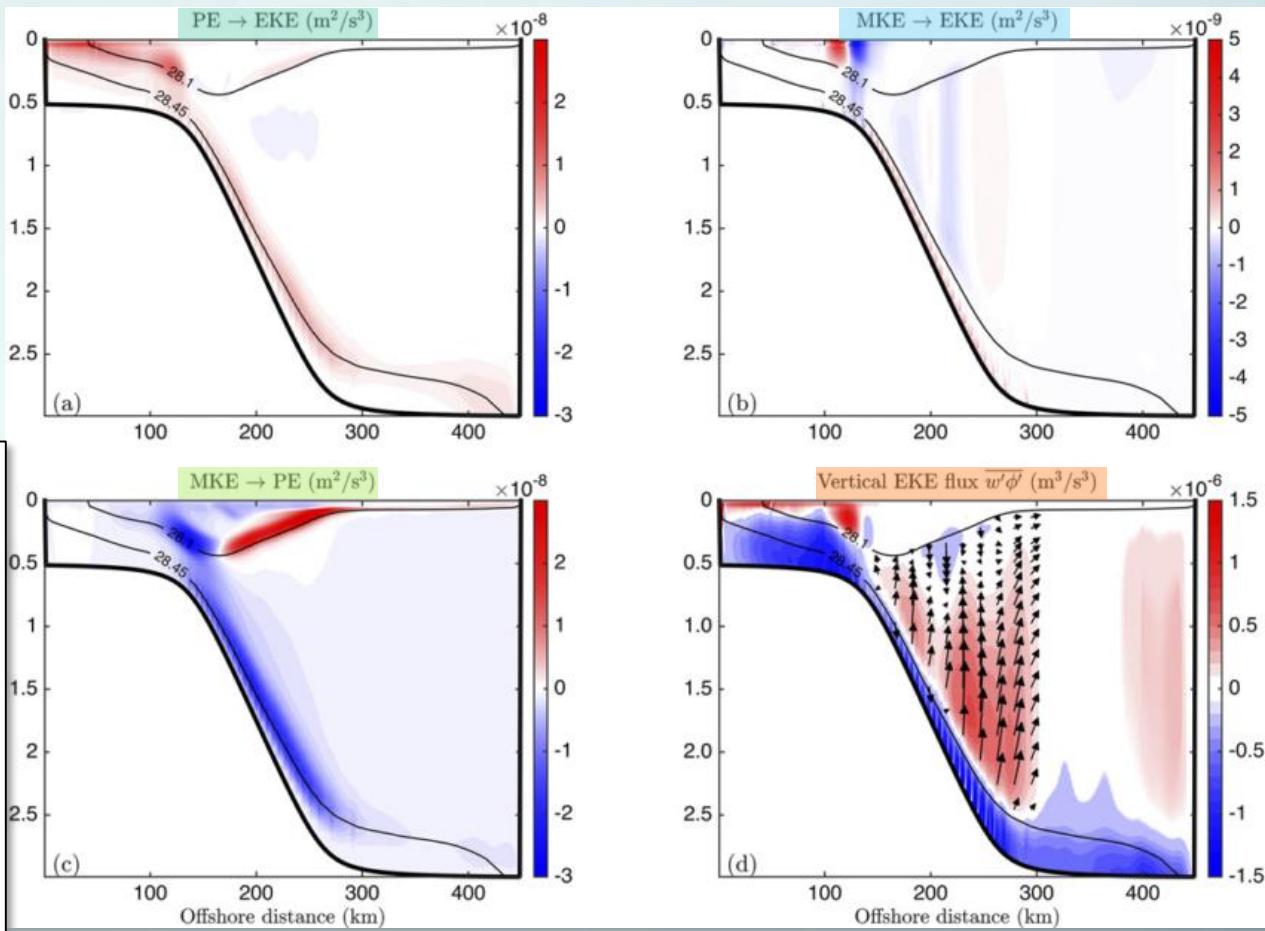
風応力 $\Rightarrow$ MKE $\Rightarrow$ PE $\Rightarrow$ EKE

浮力 $\Rightarrow$ PE $\Rightarrow$ MKE $\Rightarrow$ 摩擦

浮力 $\Rightarrow$ PE $\Rightarrow$ EKE ※小規模
- 風による陸棚の密度勾配低減
 

…深層での渦生成を抑制
- 準地衡鉛直フラックスの卓越
 

…傾圧不安定の関与



$$\frac{\partial}{\partial t} \text{EKE} + \nabla \cdot \mathbf{F}_{\text{EKE}} = (\text{MKE} \rightarrow \text{EKE}) + (\text{PE} \rightarrow \text{EKE}) : \text{EKEの収支}$$

$$\mathbf{F}_{\text{EKE}} = \frac{1}{2} \overline{\mathbf{u}_h'^2 (\bar{\mathbf{u}} + \mathbf{u}')} + \overline{\mathbf{u}' \phi'} \quad (\text{MKE} \rightarrow \text{EKE}) = -\overline{\mathbf{u}_h' \cdot (\mathbf{u}' \cdot \nabla) \mathbf{u}_h},$$

$$(\text{PE} \rightarrow \text{EKE}) = \overline{w' b'},$$

$$(\text{MKE} \rightarrow \text{PE}) = \psi_{\text{mean}} \frac{\partial b}{\partial y} = -\overline{w} \overline{b} - \nabla \cdot (\psi_{\text{mean}} b \hat{\mathbf{y}}) \quad \text{isopycnal tilting}$$

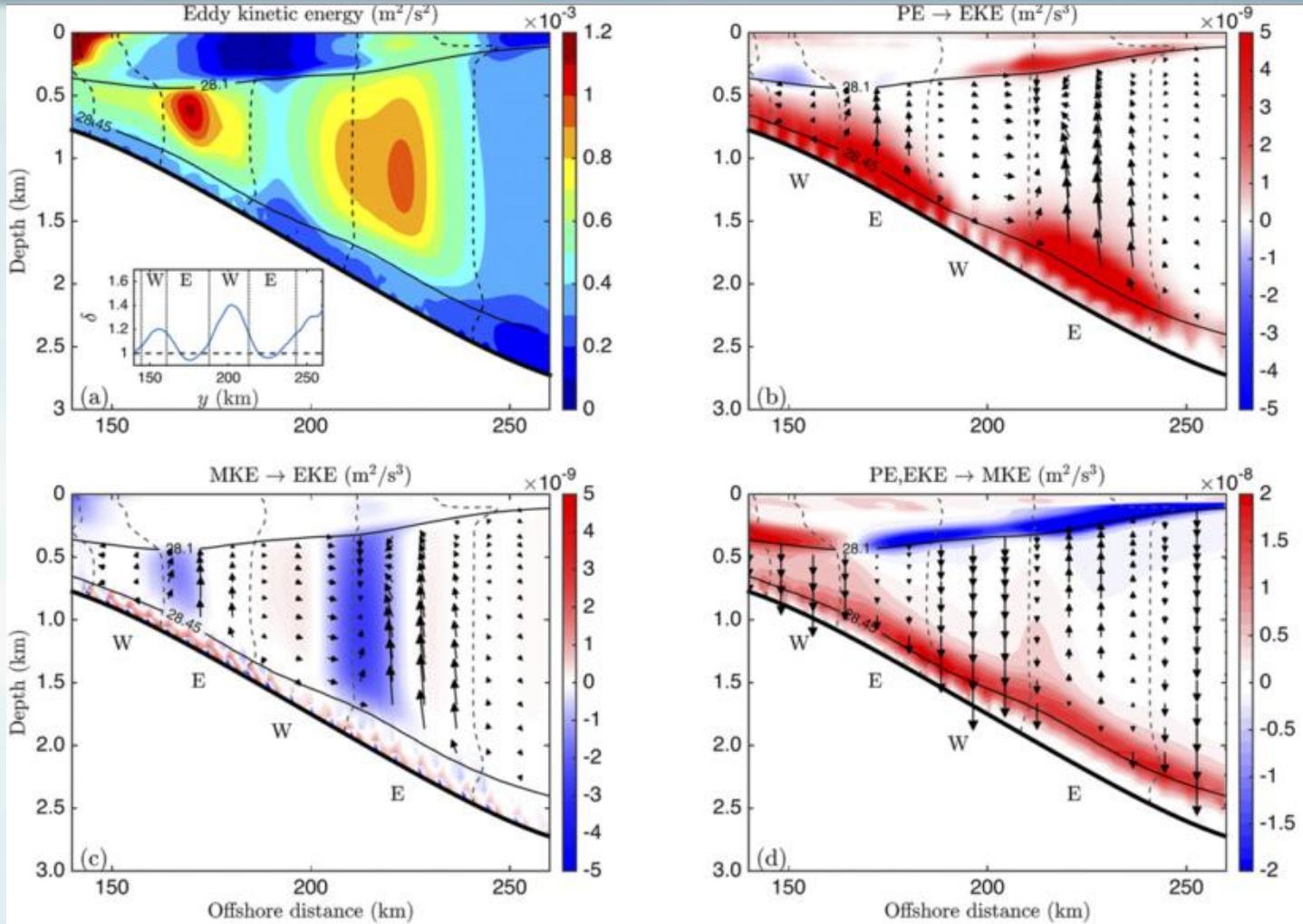
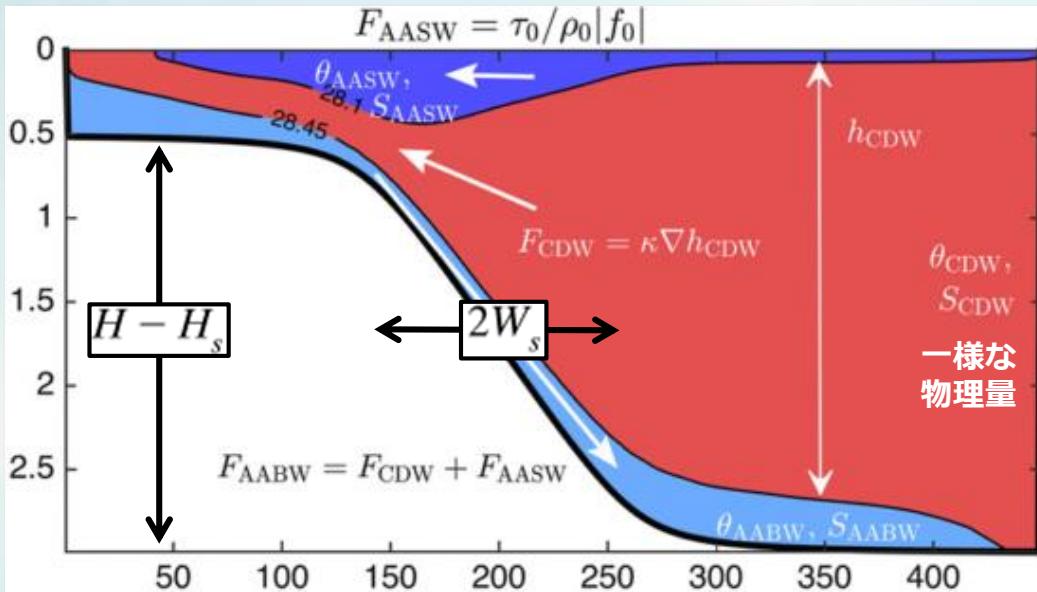


FIG. 10. Energy fluxes and transformations within continental slope jets at  $t = 3.7$  yr (cf. with Fig. 8). In each panel the black contours show the neutral density and the dashed gray contours show the jet boundaries, each averaged over 30 days and along the continental slope. The labels W and E indicate whether the jets are directed westward or eastward. (a) EKE. (b) Baroclinic conversion from PE to EKE. (c) Barotropic conversion from MKE to EKE. (d) Combined production of MKE via conversion from PE and EKE. In (b) and (c), the arrows indicate the direction of the net EKE flux vector within the CDW density range. In (d), the arrows indicate the direction of the net MKE flux within the CDW density range. The inset in (a) shows the topographic parameter  $\delta = (\text{topographic slope})/(\text{isopycnal slope})$  as a function of offshore distance for the  $\gamma = 28.45 \text{ kg m}^{-3}$  isopycnal. The isopycnal slope was smoothed using a Gaussian kernel regression filter with a width of 3 km in order to remove small-scale noise due to steps in the topographic slope on the model's  $z$ -coordinate grid.

# 混合距離でパラメトライズ



フラックスが知りたい ↓

$$F_{AABW} = F_{AASW} + F_{CDW}$$

$$F_{AASW} = \tau_{\max} / \rho_0 |f_0|, \text{ Ekman 輸送}$$

$$F_{CDW} = \kappa \frac{\partial h_{CDW}}{\partial y} \quad \text{「厚さの拡散」}$$

$$\propto \text{海底傾斜 } s_b \quad \frac{\partial h_{CDW}}{\partial y} \approx s_b = \frac{H - H_s}{2W_s}$$

**thickness diffusivity**

$$\kappa = C u_{\text{eddy}} l_{\text{mix}}$$

# mixing length theory

$$u_{\text{eddy}} = \sqrt{\frac{2}{A_{\text{slope}}} \iint_{\text{slope}} dy dz \text{ EKE}}$$

Case1

$$\kappa_{\text{Rh}} = \frac{1}{2} C_{\text{Rh}} u_{\text{eddy}} L_{\text{Rh}}$$

$$C_{\text{Rh}} = C_{\text{V97}} = 0.015 : \text{eddy transfer coefficient}$$

Rhines scale  
βジェットの波長

$$L_{\text{Rh}} = \pi \sqrt{\frac{2u_{\text{eddy}}}{\beta_t}}$$

$$\beta_t = \frac{|f_0|}{h_{\text{CDW}}} \left| \frac{\partial h_{\text{CDW}}}{\partial y} \right|$$

Case2

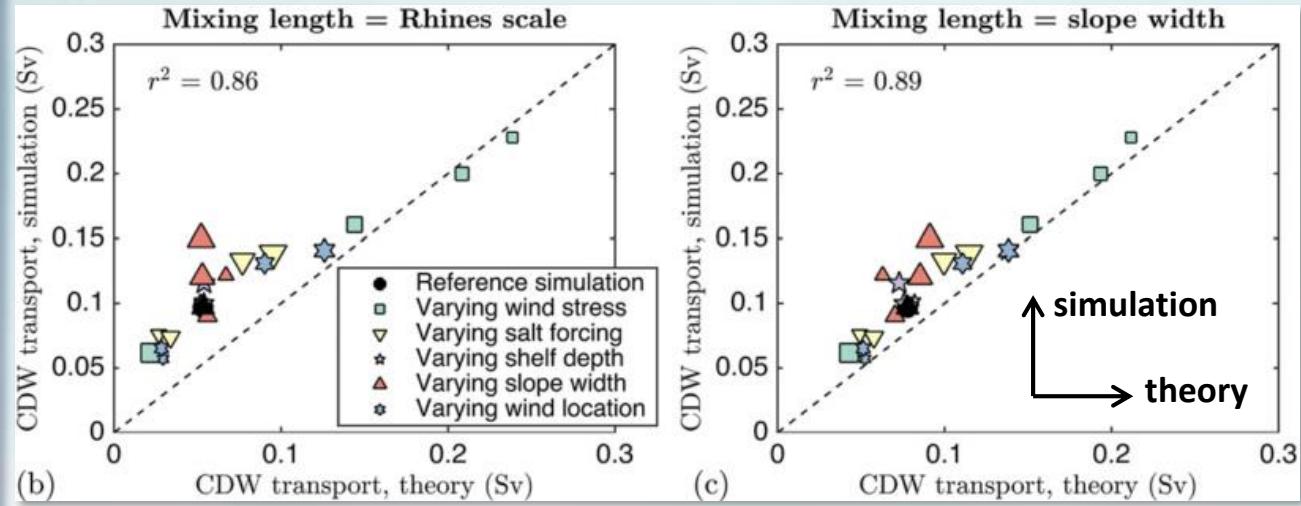
$$\kappa_s = C_s u_{\text{eddy}} (2W_s)$$

$$C_s = (1/8) C_{\text{V97}}$$

※再現性高めるように調節

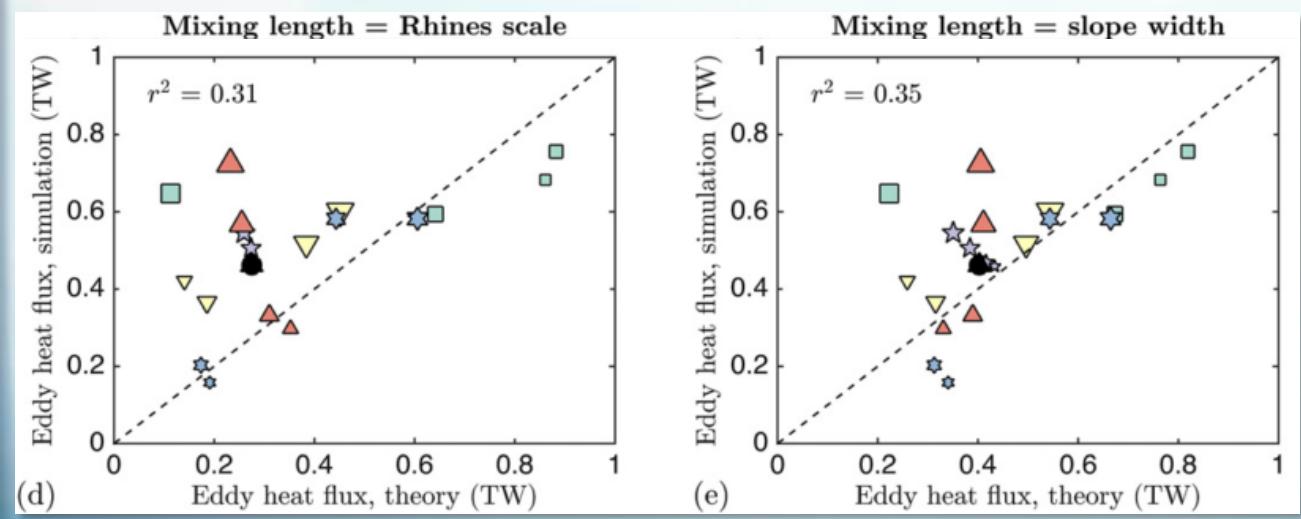
slope width 傾圧の領域

$$\kappa_s \propto (\text{EKE})^{1/2} s_b^{-1}$$



## ◎ CDW transport

- $L_{mix} = \text{slope width}$ が優位
  - $\propto \text{wind stress/location}$
  - $\propto \text{salt forcing}$
- (→ 先行研究と符合)



## ◎ eddy heat flux

- 理論値での予測難しい
  - 涡活動が高いと良好
- Ex.) wind stressの増加**
- AABWとの境界で PE  $\Rightarrow$  MKE 増  
→ その分 PE  $\Rightarrow$  EKE 減  
→ 涡輸送減少、精度低下
- Ex.) slope widthの増加**
- 斜面の勾配減  
→ PE  $\Rightarrow$  EKE 減  
→ 涡輸送減少、精度低下

# 感度実験；理論値 vs. 計算値

# Caveats and outlook : 今後考えるべきこと

- 非対称な地形 *topographic asymmetry*
- 潮汐混合 *tidal mixing*
- 季節性 *seasonality*
- 棚氷の融解水 *Ice Shelf Water*
- 海氷と運動量 *momentum from sea ice*
- 高周波の強制 *high frequency forcing*

BTW, ACC?