

授業概要

前半は、海洋の具体的な循環構造とその力学を海洋観測の技術革新とともに説明する。

後半は、エルニーニョ予測や温暖化予測の進展を、特に大気と海洋の相互作用に焦点を当てて紹介する。

0. Overview

a. 海洋の構造

b. 海洋観測

3. 風成循環と熱塩循環

4. 波動と応答

5. エルニーニョと南方振動

6. 地球温暖化

海洋の炭素循環

参考書：

Ocean Circulation : The Open University, PERGAMON PRESS ***OC**

El Nino, La Nina, and the Southern Oscillation : S. G. H. Philander, Academic Press

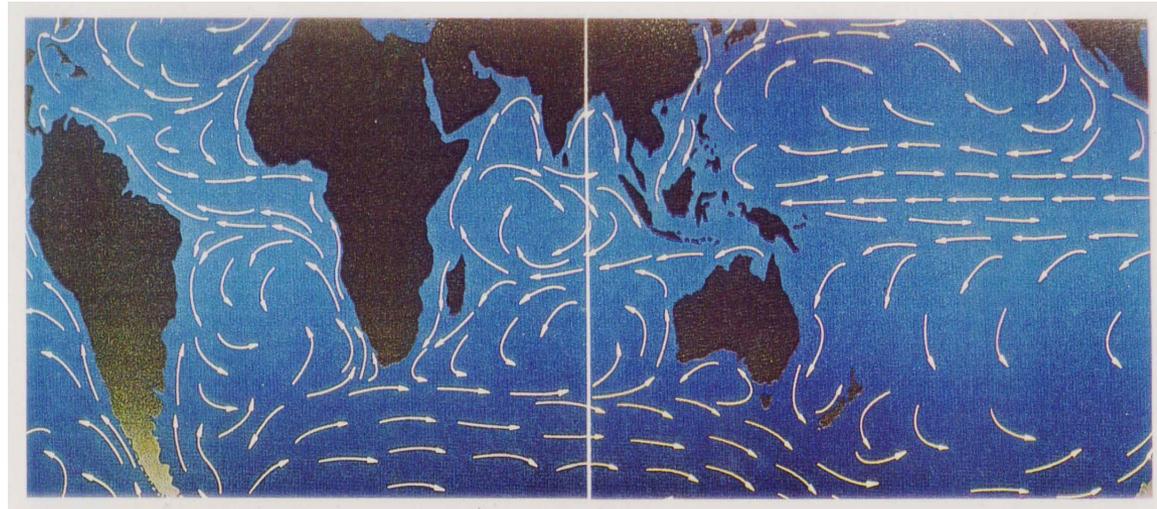
IPCC 第4次報告書(第1作業部会)：

http://www.ipcc.ch/publications_and_data/ar4/wg1/en/contents.html

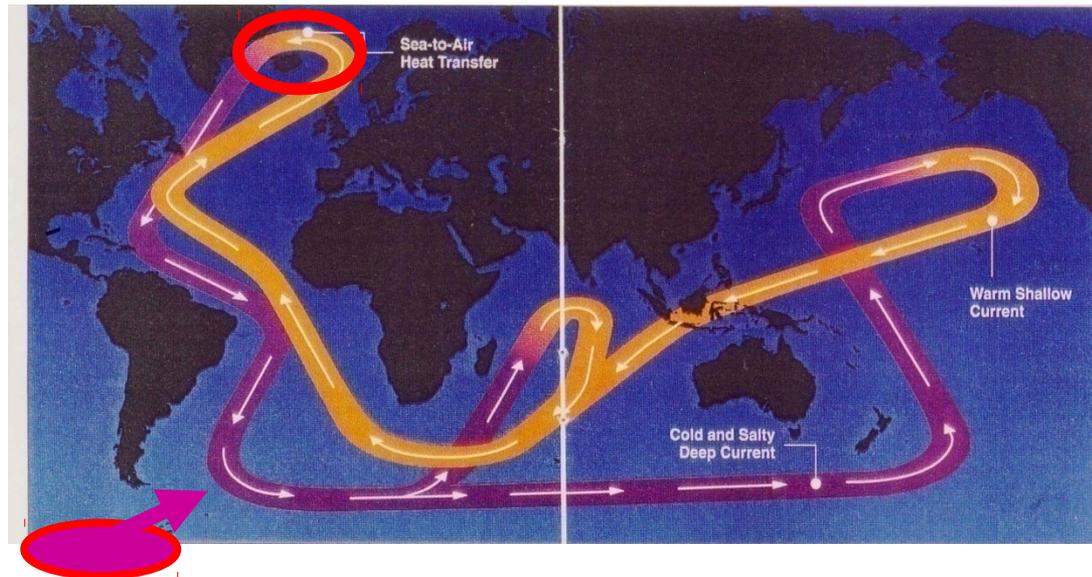
地球温暖化と海：野崎義行 東京大学出版会

3. 風成循環と熱塩循環

風成循環

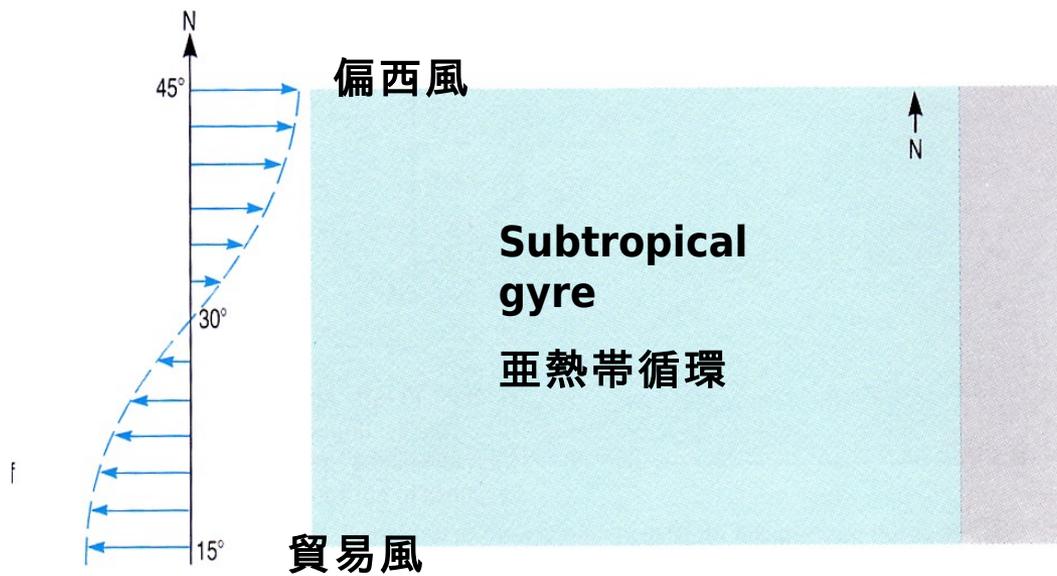
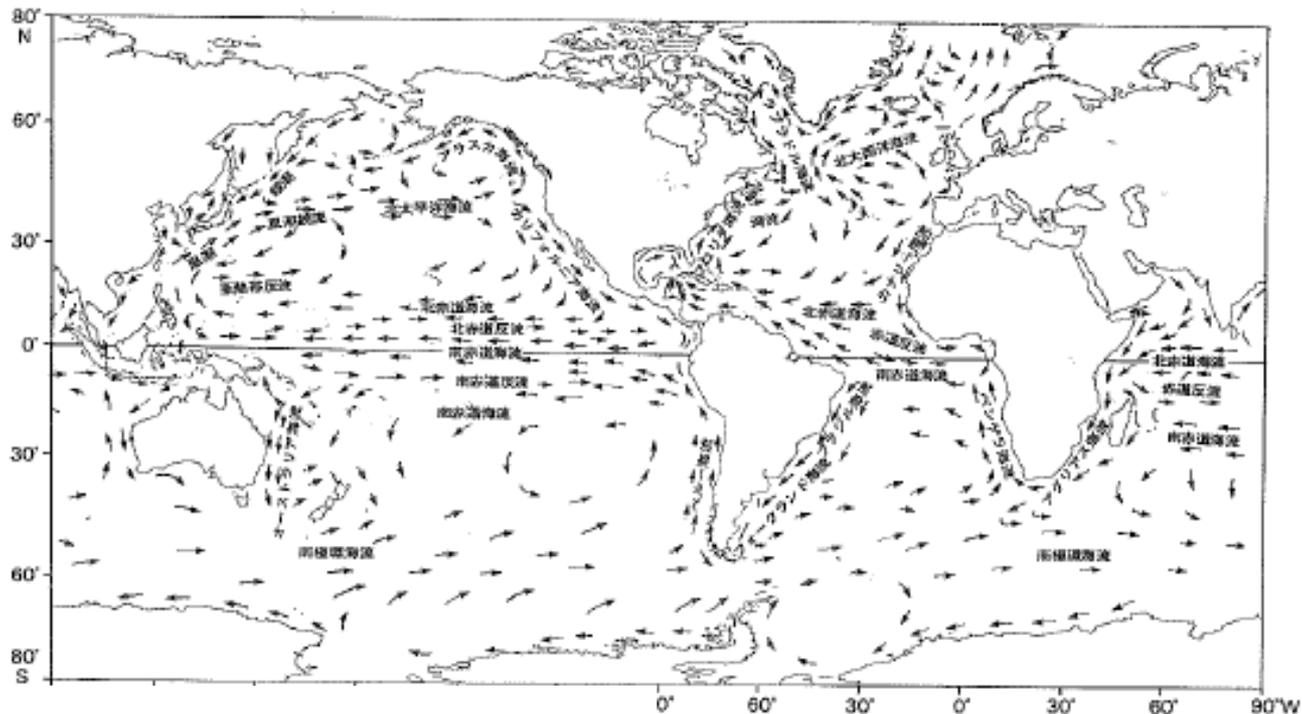


熱塩循環

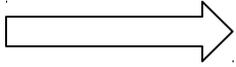


風成循環

表層で卓越



風応力 (τ_x, τ_y)



① 境界層

② 内部領域

① (エクマン層)

$$-fv = A_V \frac{\partial^2 u}{\partial z^2}$$

$$fu = A_V \frac{\partial^2 v}{\partial z^2}$$

②

$$0 = -\frac{1}{\rho} \frac{\partial p}{\partial x} + fv + A_H \Delta_H u \quad (1)$$

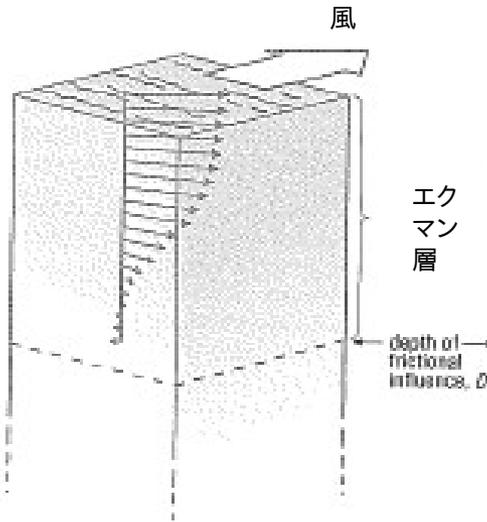
$$0 = -\frac{1}{\rho} \frac{\partial p}{\partial y} - fu + A_H \Delta_H v \quad (2)$$

$$0 = -\frac{1}{\rho} \frac{\partial p}{\partial z} - g \quad (3)$$

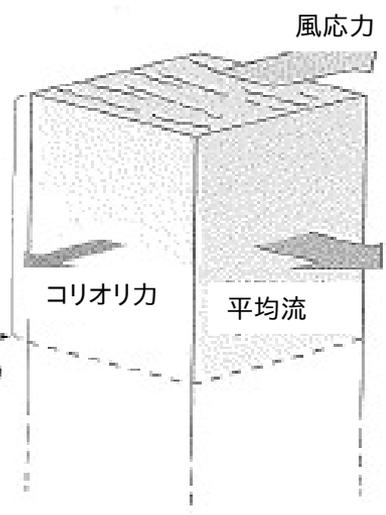
$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \quad (4)$$

$$\Delta_H = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}$$

エクマンらせん



エクマン輸送

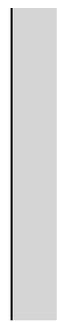
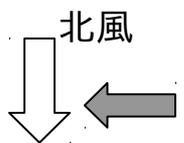


10~100m

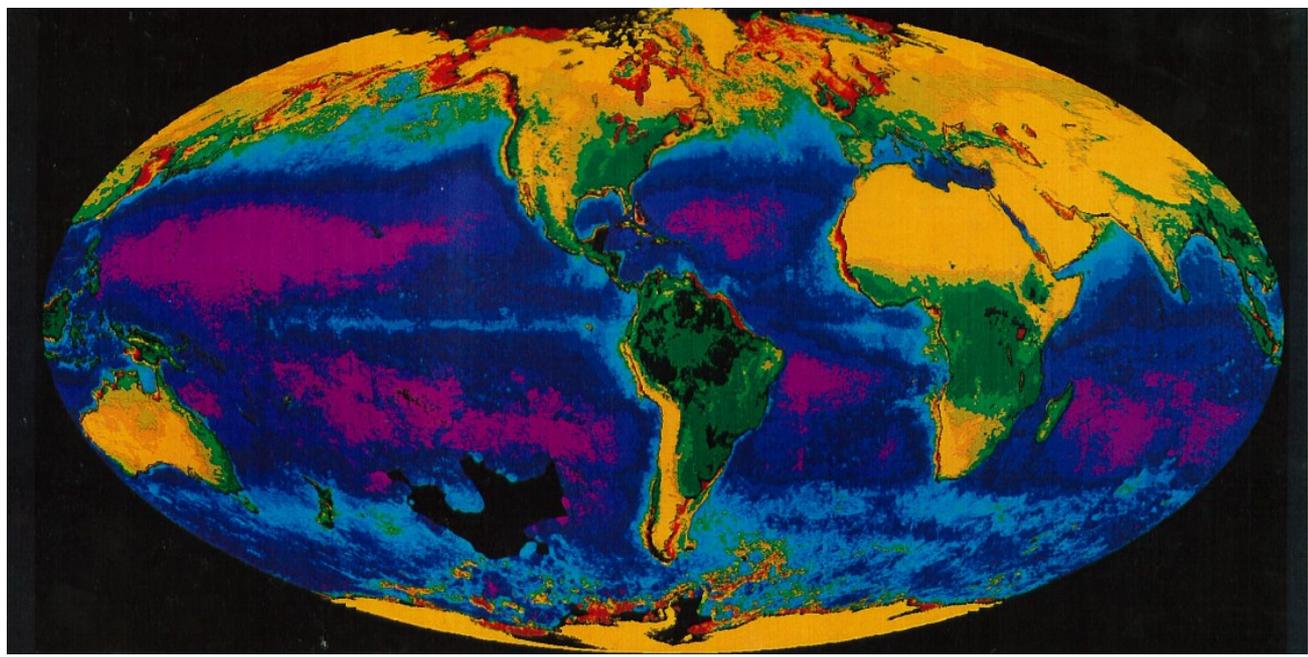
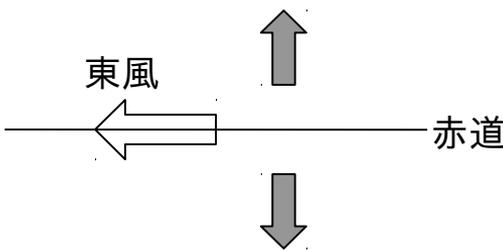
厚さ: $\sqrt{\frac{A_v}{f}}$

輸送量: $\frac{\tau}{\rho f}$

沿岸湧昇



赤道湧昇



渦度方程式 $\frac{\partial}{\partial x}(2) - \frac{\partial}{\partial y}(1)$

$$\beta v = -f \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right) + A_H \Delta \left(\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \right)$$

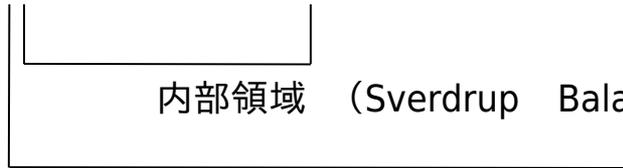
$$\frac{f}{D} w_E$$

$$\beta v = \frac{f}{D} \left(\frac{\partial}{\partial x} \left(\frac{\tau_y}{f} \right) - \frac{\partial}{\partial y} \left(\frac{\tau_x}{f} \right) \right) + A_H \Delta \left(\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \right)$$

惑星渦度

風の強制力

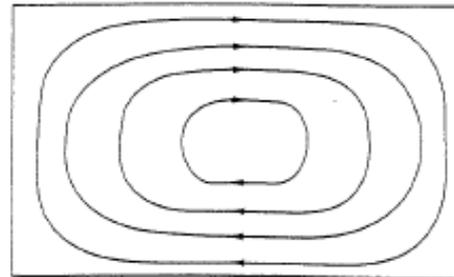
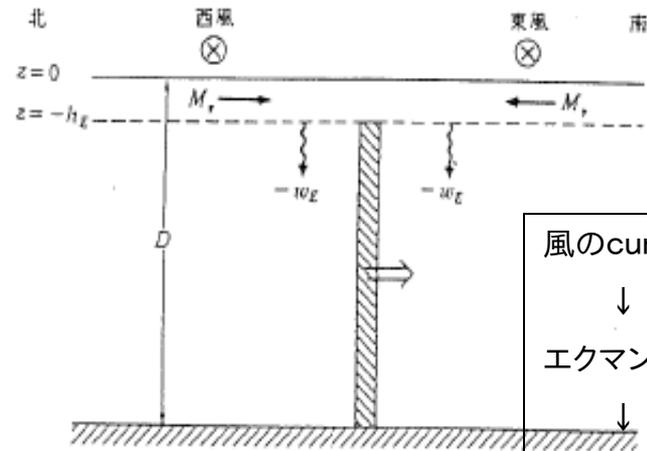
粘性



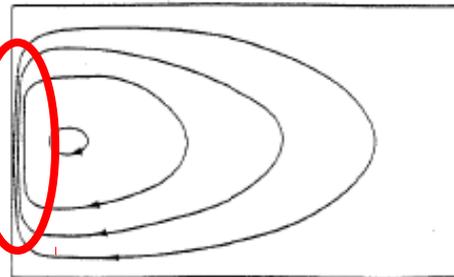
西岸境界流

総流量 $\iint v \, dx dz = \int \frac{1}{f} \text{curl}(\vec{\tau})$

$30 - 50 \text{ Sv } (10^6 \text{ m}^3/\text{s})$



$f = \text{一定}$

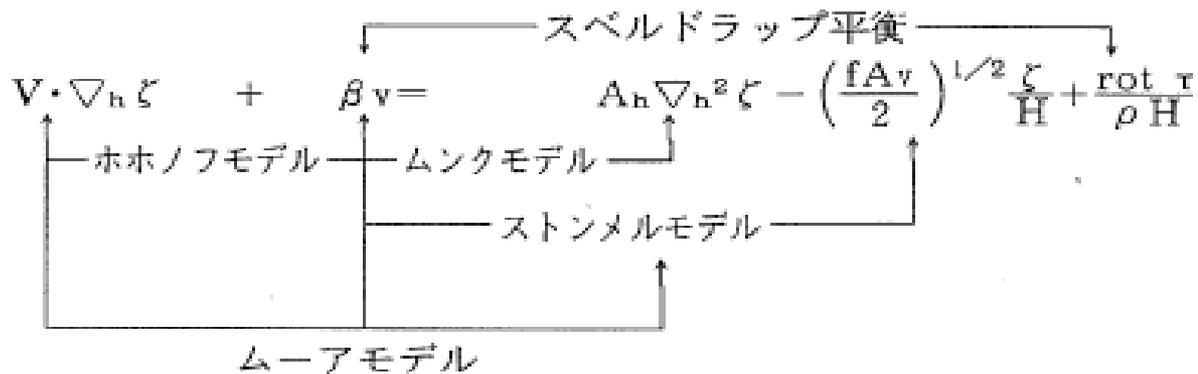


$f = f_0 + \beta y$

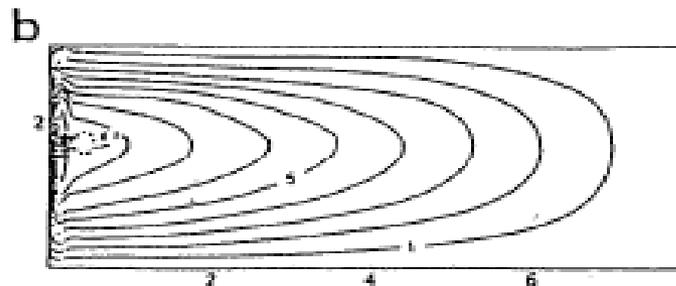
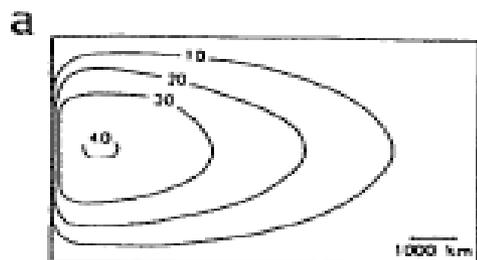
風のcurl
↓
エクマン層の収束・発散
↓
鉛直流 (Ekman pumping)
↓
内部領域の流れ

惑星ベータ
緯度による自転効果の違い
↓
西岸境界流の形成に本質的

様々な境界層モデル

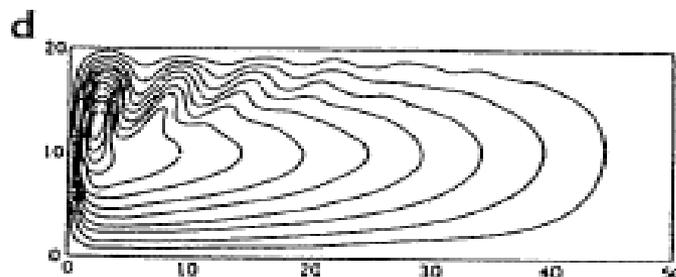
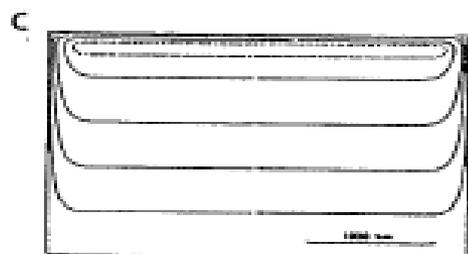


$$\sqrt[3]{\frac{\beta}{A_h}}$$

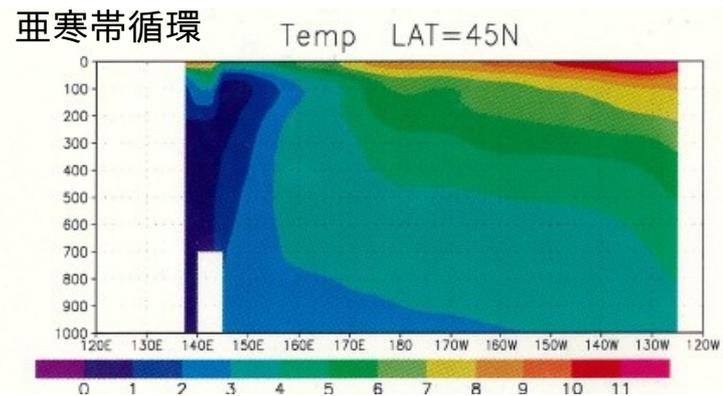
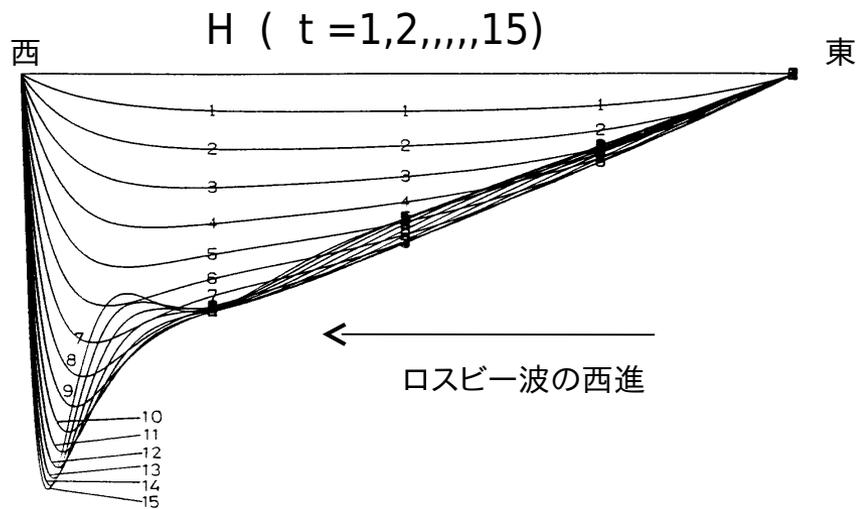


$$\sqrt{\frac{f A_V}{2}} \frac{1}{\beta H}$$

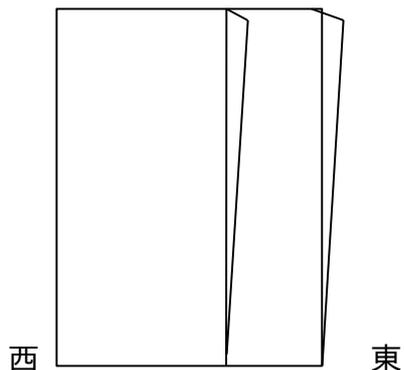
$$\sqrt{\frac{U}{\beta}}$$



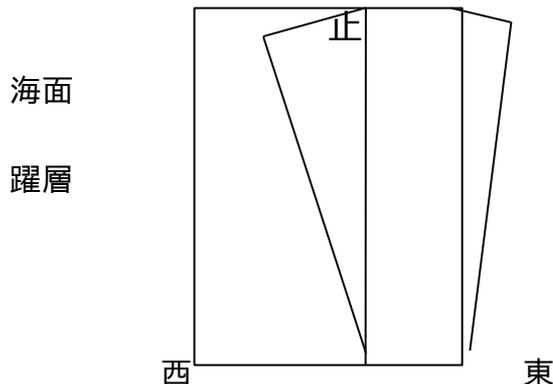
流線関数の等値線で示した解析解による海洋大循環の流線関数。(a)Stommel (1948), (b)Munk (1950), (c)Fofonoff(1954)および(d)Moore (1963)。



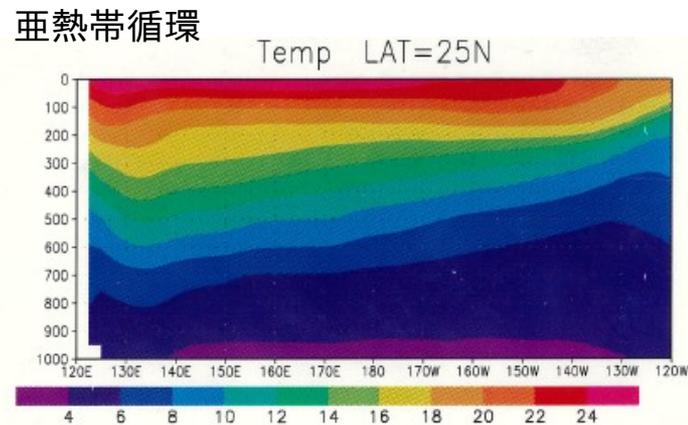
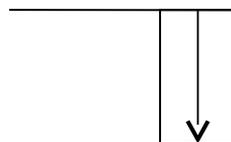
順圧応答の後
(~1か月)



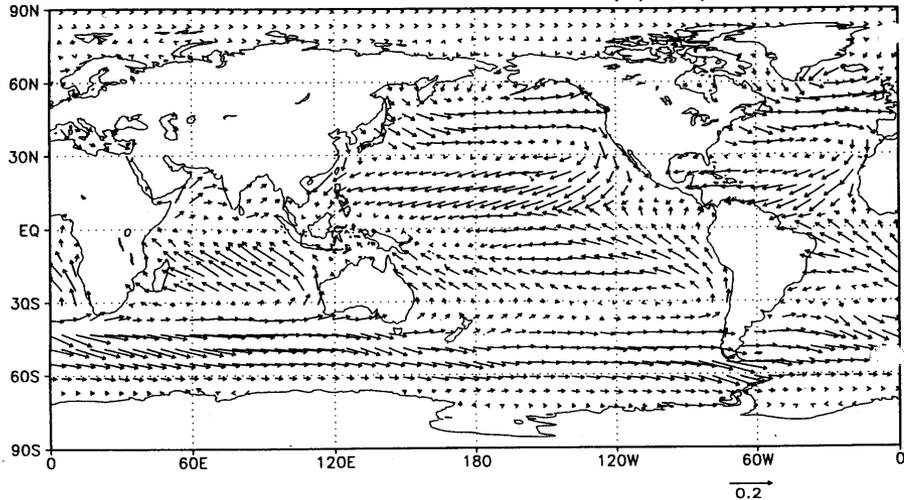
傾圧応答の後
(~10年) 下層静



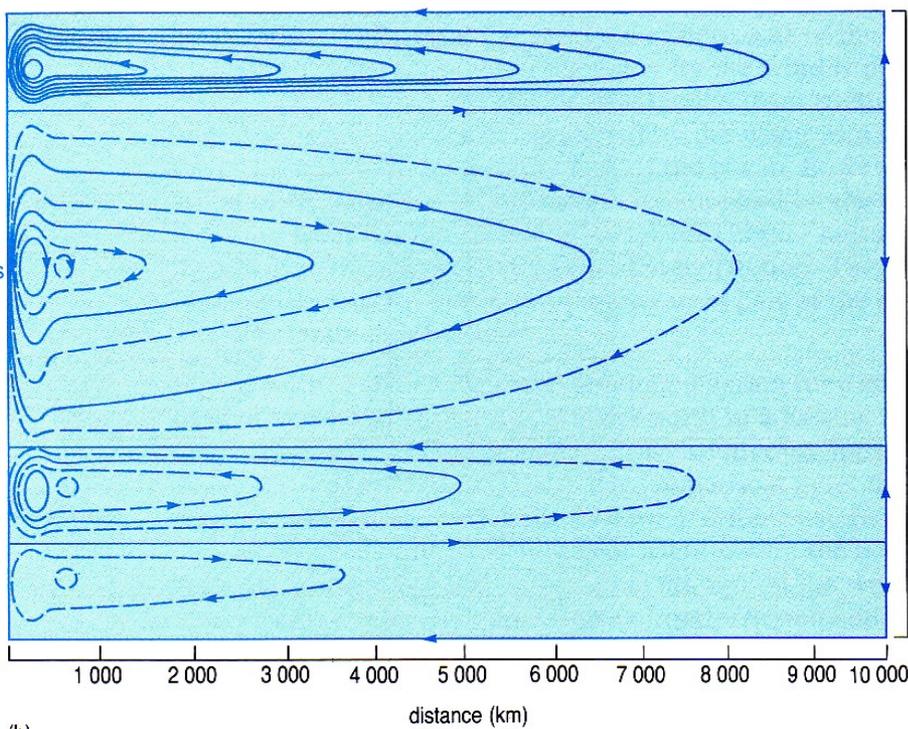
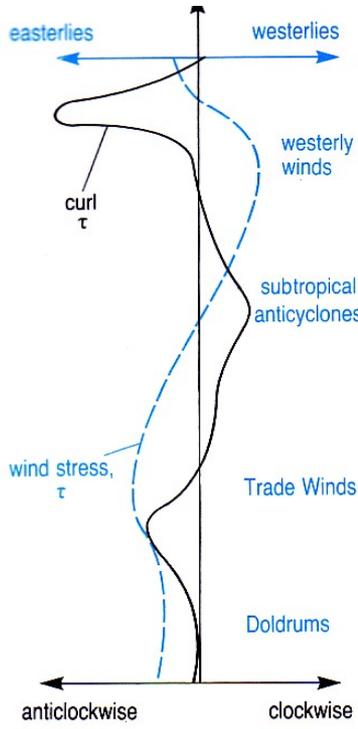
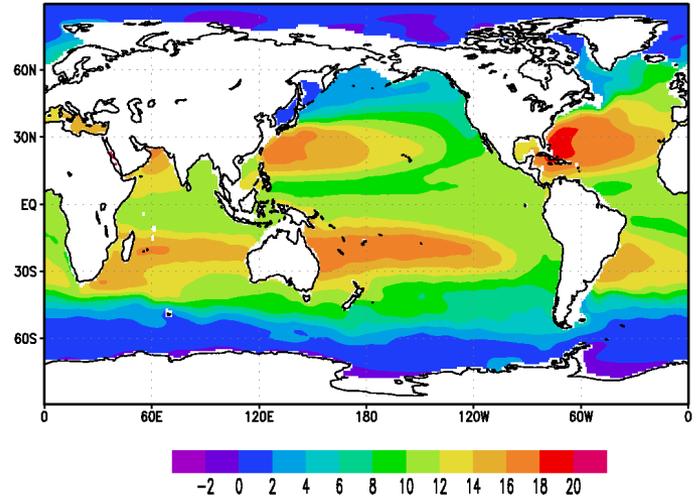
流れ



Annual Mean Wind Stress (N/m²)



Temp 300m



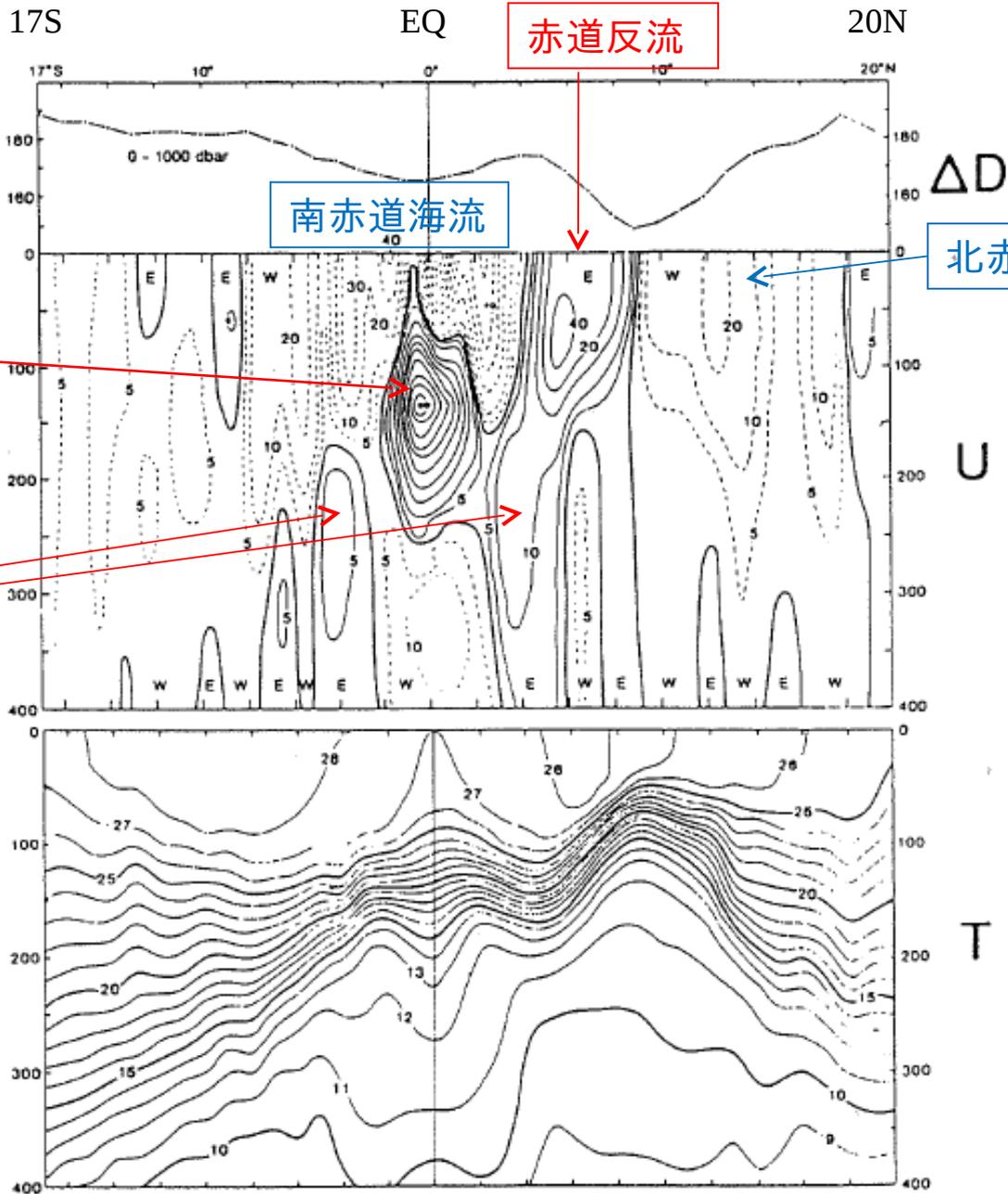
60° N
50° West Wind Drift
40°
30° subtropical gyre
20°
10° North Equatorial Current
0° Equatorial Counter-Current
South Equatorial Current

(a)

(b)

中部太平洋150W

南北断面



赤道反流

南赤道海流

北赤道海流

赤道潜流

亜表層反流

深度(m)

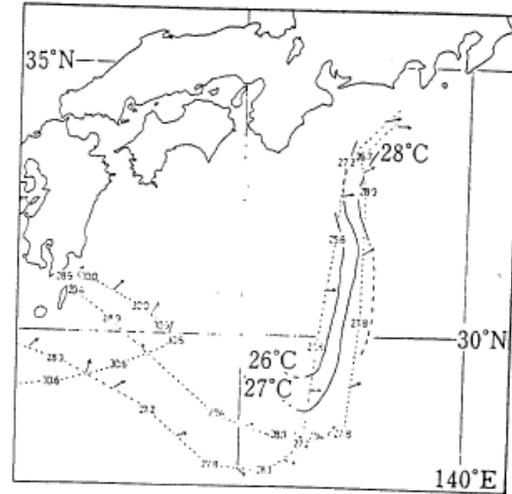
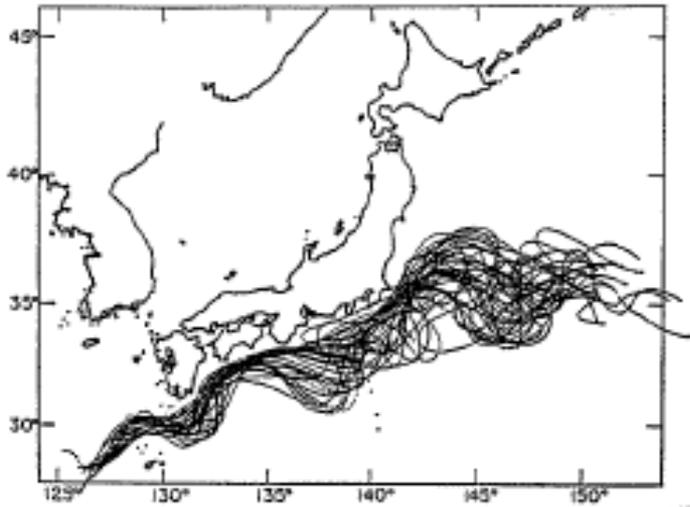
400

ΔD

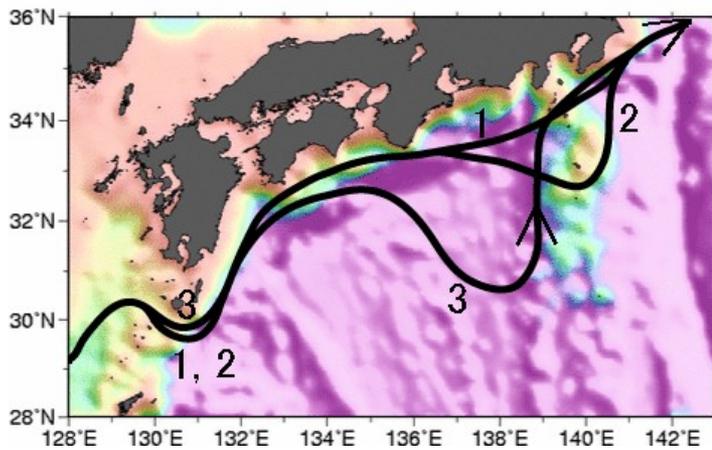
U

T

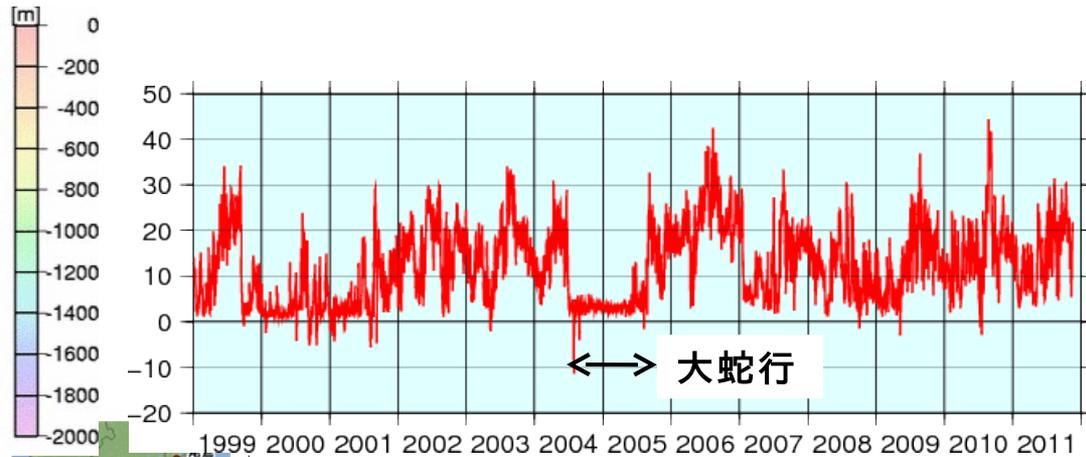
黒潮流路の Bimodality



1854年6月13日から7月13日の間にペリー艦隊が観測した表面水温分布。点線は航跡を示す



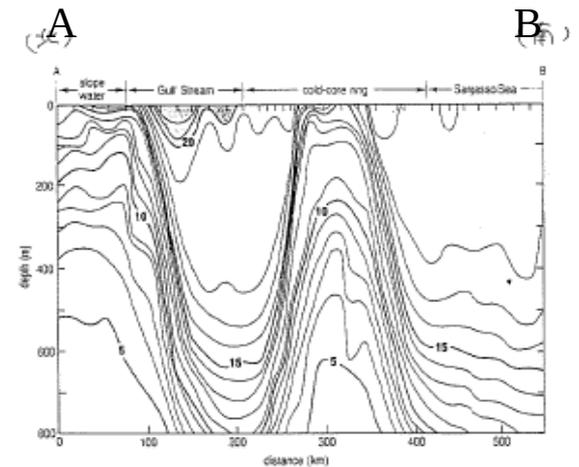
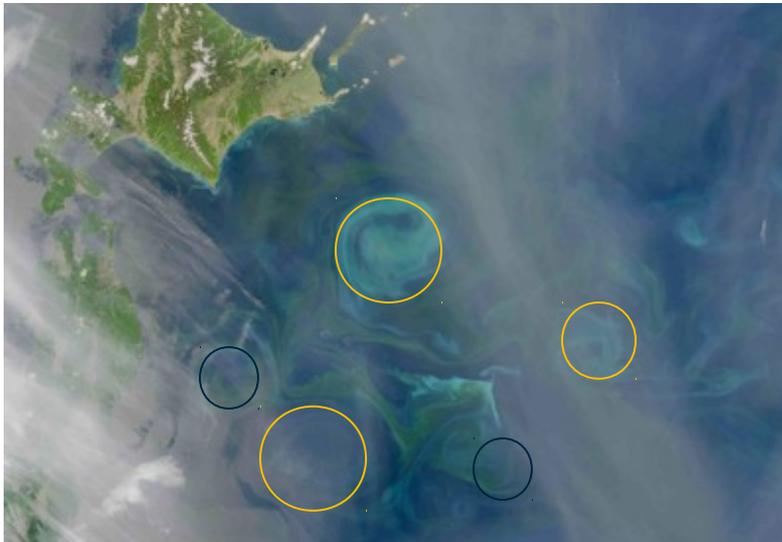
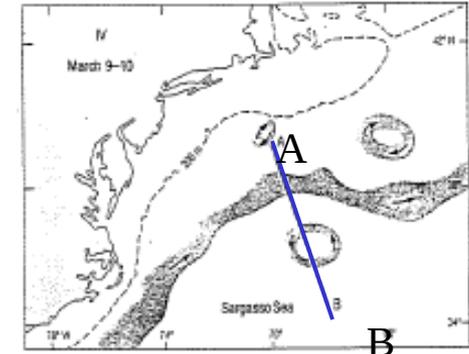
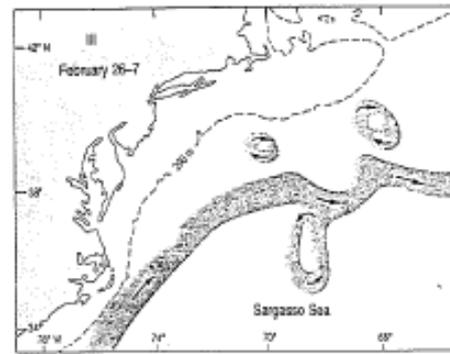
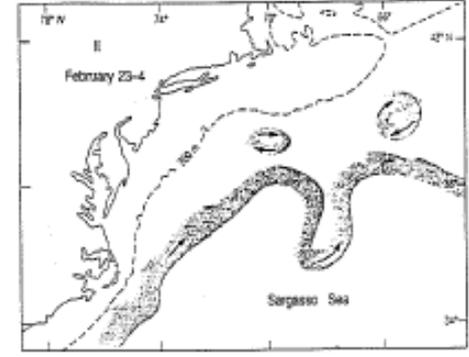
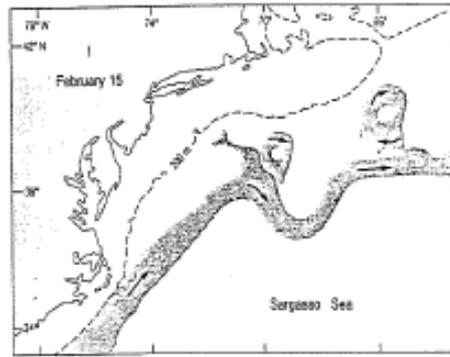
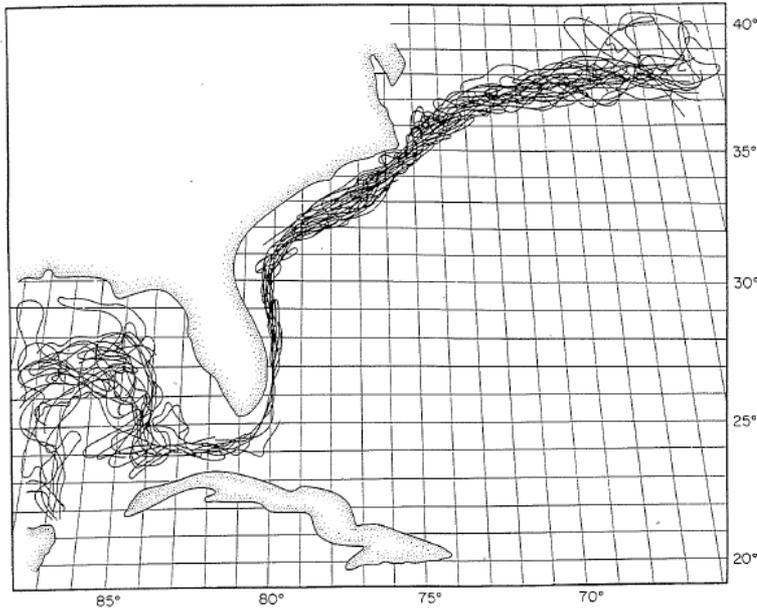
- 1: 非大蛇行接岸流路
- 2: 非大蛇行離岸流路
- 3: 大蛇行流路



潮位差(串本-浦神)

渦のcut-off

※黒潮でも見られる



(Aqua MODIS 2009 May 11a)

Stommel (1958) の回転水槽実験

渦度バランスに基づき、極向き流を説明

$$\beta v = f \frac{w}{H}$$

- ・ 深層水 局所的に沈降
→ 内部領域 上昇流 $w > 0$

- ・ 主躍層の維持には
鉛直移流と鉛直拡散がバランス $w \frac{dT}{dz} = \kappa \frac{d^2T}{dz^2}$

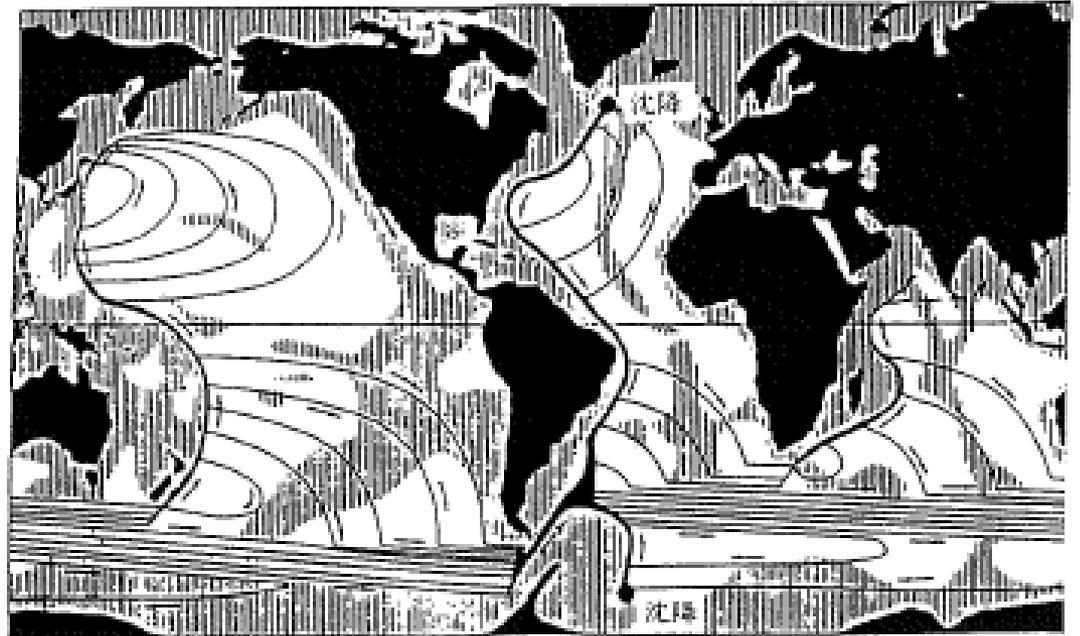
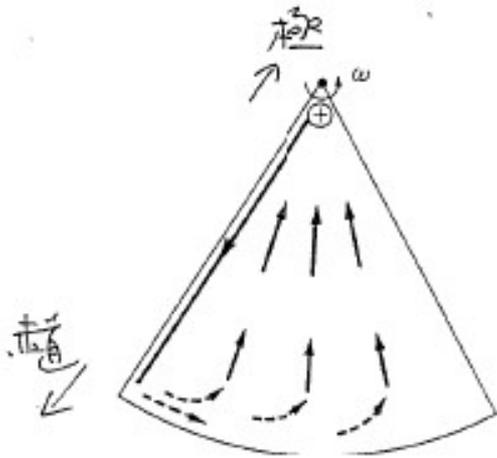
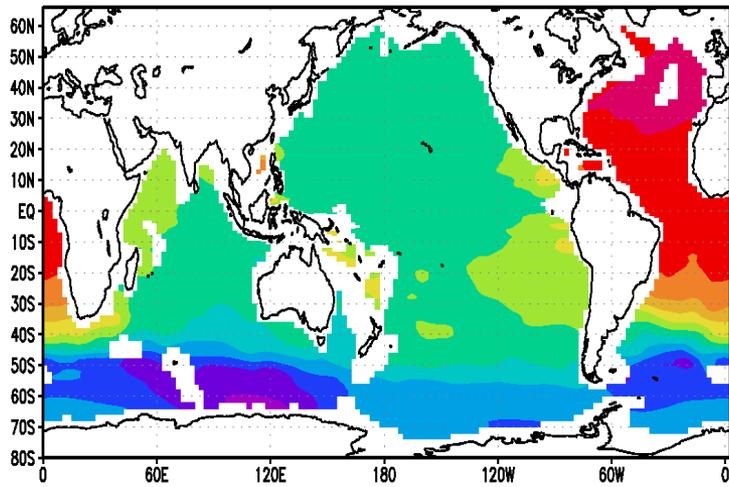
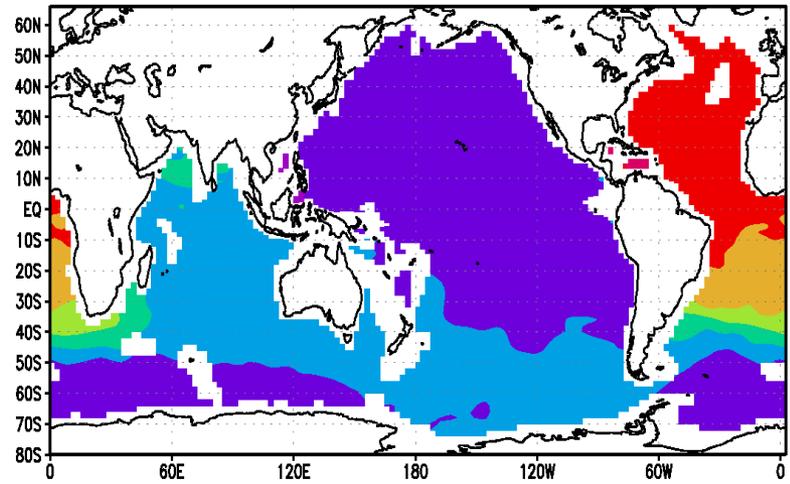


図 6-7 全球規模の深層循環の概念図 (Stommel, 1958)

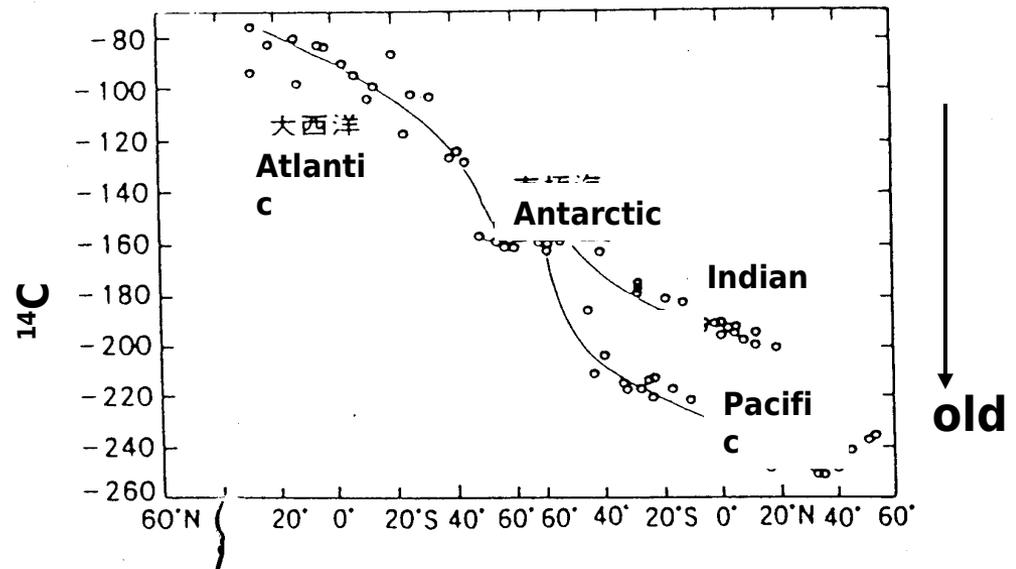
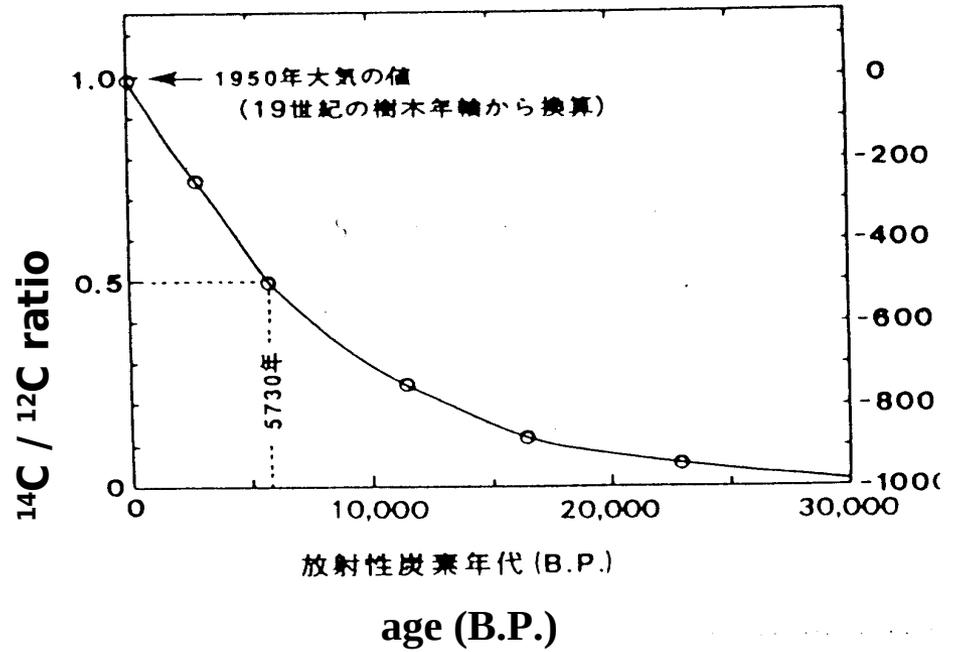
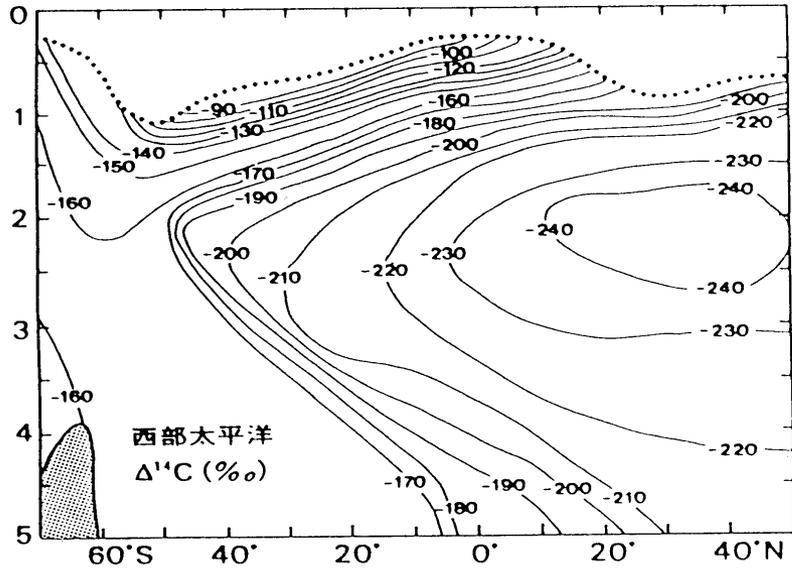
ann.mean T(3000m)



ann.mean S(3000m)



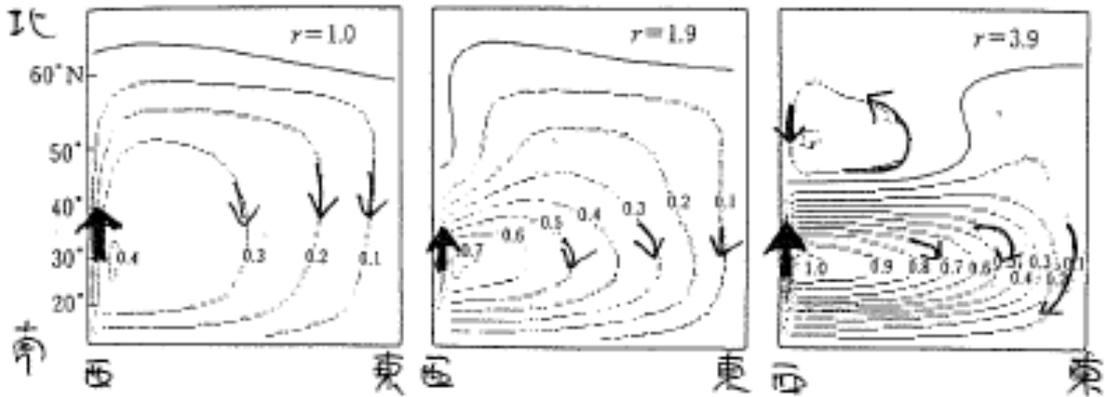
西部太平洋 ^{14}C



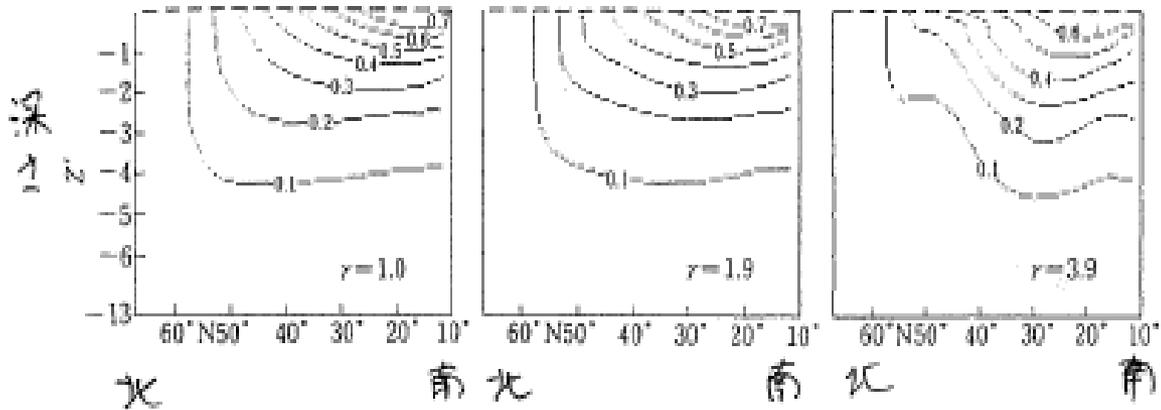
	風成循環	熱塩循環
駆動力	風 (curl)	密度差 (加熱・冷却) (蒸発・降水)
力のつり合い	地衡流	地衡流
西岸境界流	○	○
卓越深	表層	深層
	エクマン層での 収束・発散	限られた沈降域と 一様な上昇域
北半球中緯度	南向流	北向流

風成 vs 熱塩 数値シミュレーション

上層の流線の水平分布



水温の南北断面

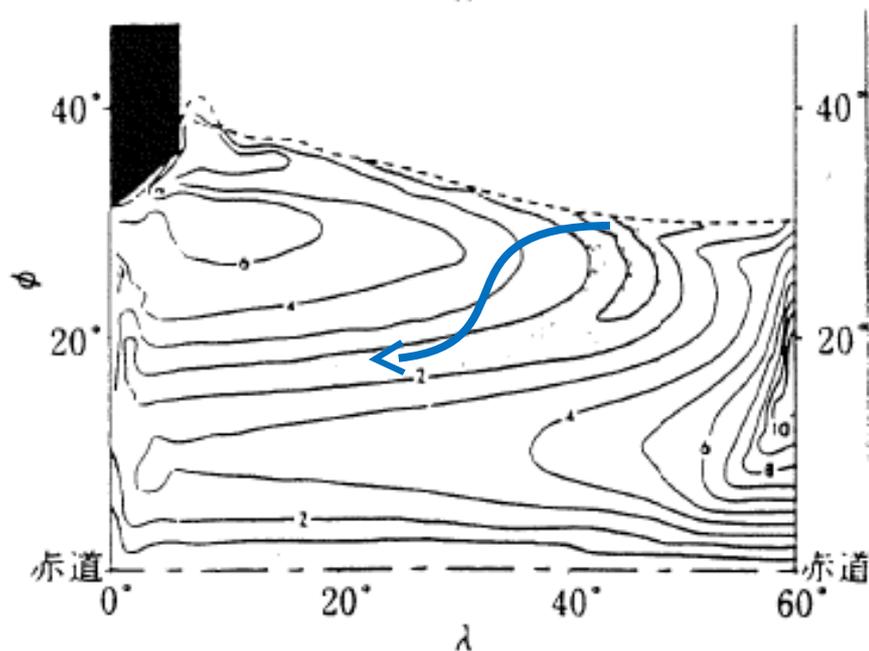
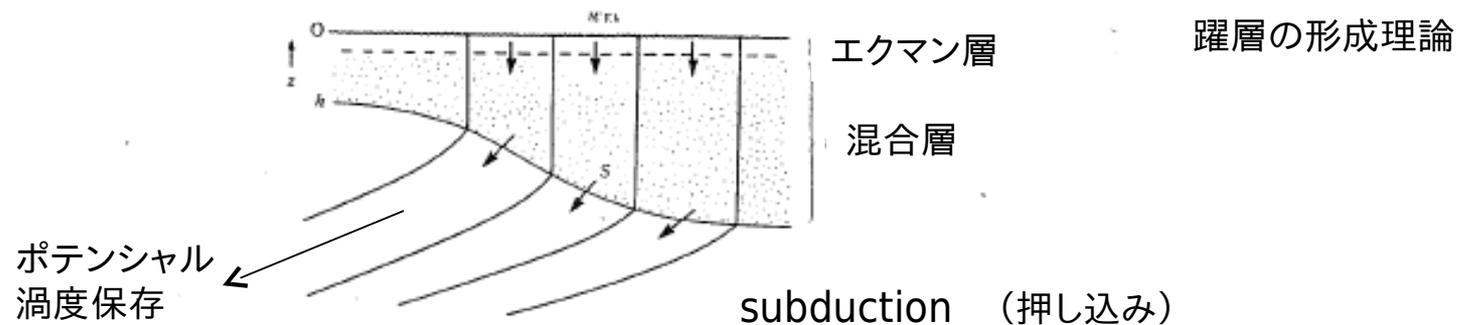


海面密度差

→
+風応力 (2gyre)

Ventilation (通気理論) : 中層水の形成

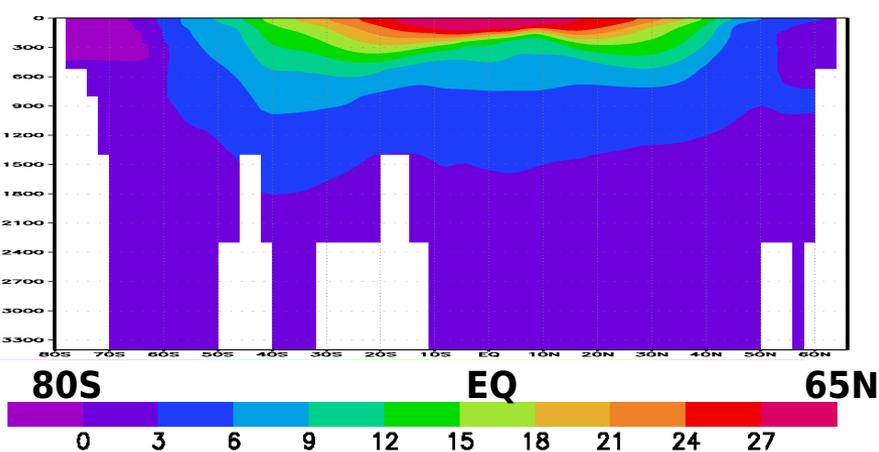
Luyten, Pedlosky and Stommel (1983)



等密度面上のポテンシャル渦度 (OGCM : Cox, 1985)

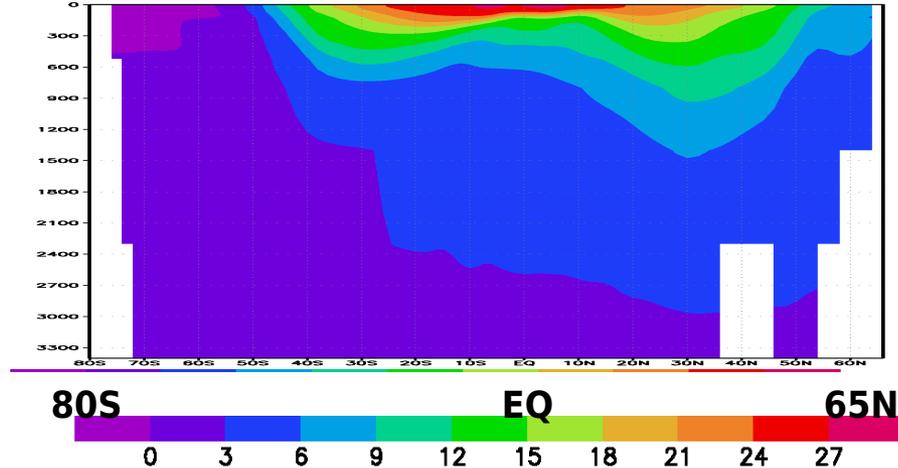
水温南北断面 (太平洋 180E)

80S-65N 0-3400m



水温南北断面 (大西洋 30W)

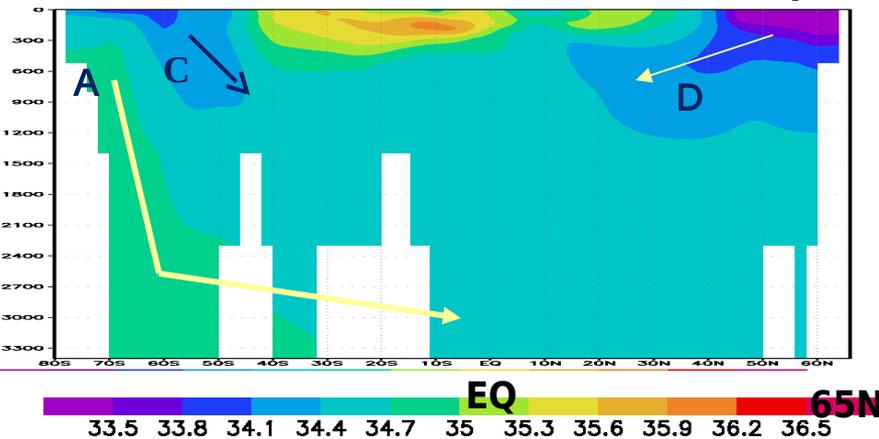
80S-65N 0-3400m



- A 南極低層水
- B 北大西洋深層水
- C 南極中層水
- D 北太平洋中層水

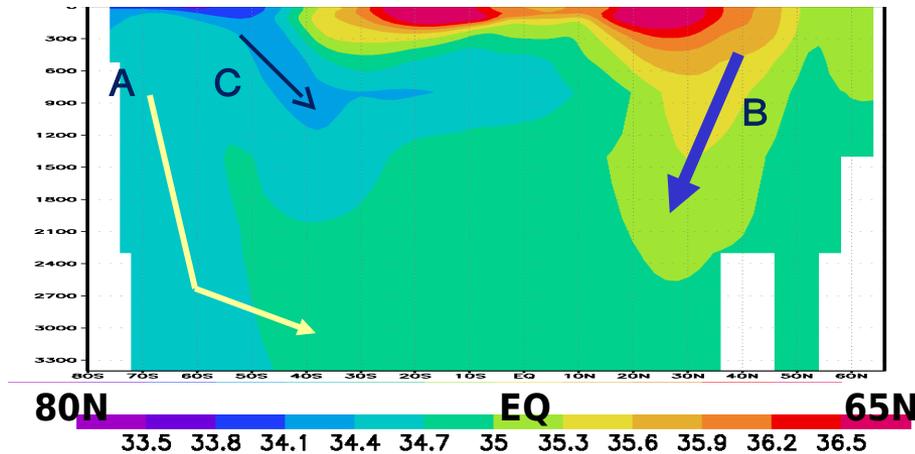
塩分南北断面 (太平洋180E)

80S-65N 0-3400m



塩分南北断面 (大西洋 30W)

80S-65N 0-3400m



4. 波動と応答

駆動力 (風応力、浮力) の変化



波動の伝播

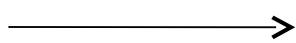


中緯度 数年~10年
赤道域 2~3年

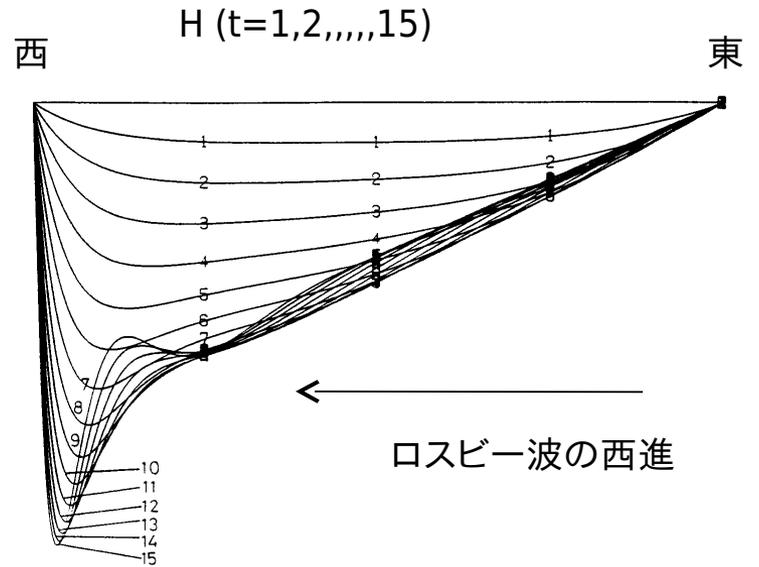
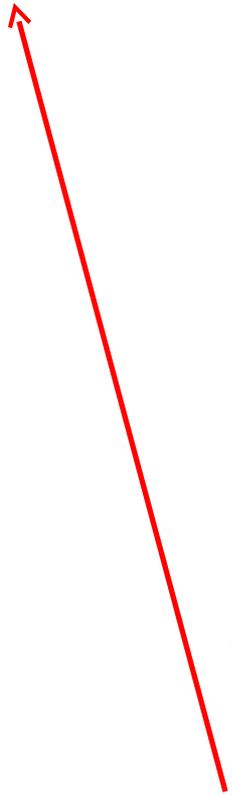
新たな圧力分布の形成



SST の変化



大気応答



正・負のフィードバック

浅水方程式

$$\frac{\partial u}{\partial t} - fv = -g \frac{\partial \eta}{\partial x} \quad (1)$$

$$\frac{\partial v}{\partial t} + fu = -g \frac{\partial \eta}{\partial y} \quad (2)$$

$$\frac{\partial \eta}{\partial t} + H \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right) = 0 \quad (3)$$

$$\eta = e^{i(kx + ly - \omega t)}$$

※ reduced gravity model

$$H_1 \ll H_2, \Delta\rho \ll \rho$$

$$\rightarrow H = H_1, g = g\Delta\rho$$

1 慣性重力波 $f = f_0$

$$\omega^2 = f_0^2 + (k^2 + l^2)gH$$

2 ロスビー波

・準地衡風近似 $V = V_g + V_a \quad (v_g \gg v_a)$

・ベータ近似 $f = f_0 + \beta y \quad (f_0 \gg \beta y)$

$$-f_0 v = -g \frac{\partial \eta}{\partial x}$$

$$f_0 u = -g \frac{\partial \eta}{\partial y}$$

$$(2) \times \frac{\partial}{\partial y} - (1) \times \frac{\partial}{\partial x} \quad (\text{圧力傾度項の消去})$$

$$\zeta \equiv \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} = \frac{g}{f_0} \left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} \right) \eta$$

ポテンシャル
渦度保存

$$\frac{\partial}{\partial t} \left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} - \frac{1}{\lambda^2} \right) \eta + \beta \frac{\partial \eta}{\partial x} = 0$$

$$\lambda = \frac{\sqrt{gH}}{f_0}$$

$$\omega = \frac{\beta}{k^2 + l^2 + \frac{1}{\lambda^2}}$$

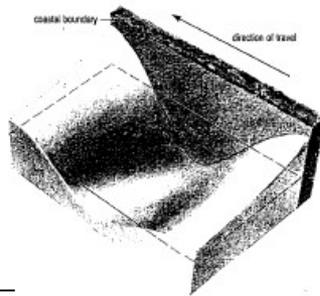
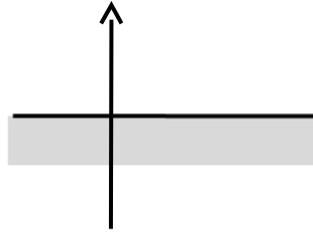
3 ケルビン波 南北に走る岸(x=0)に補足

(1)から(3)で $u \equiv 0$

$$-fv = -g \frac{\partial \eta}{\partial t} \quad (1)'$$

$$\frac{\partial v}{\partial t} = -g \frac{\partial \eta}{\partial y} \quad (2)'$$

$$\frac{\partial \eta}{\partial t} + H \frac{\partial v}{\partial y} = 0 \quad (3)'$$



$$\begin{pmatrix} \eta \\ v \end{pmatrix} = \begin{pmatrix} A \\ B \end{pmatrix} G(x) F(ky - \omega t)$$

(2)'、(3)'に代入

$$\omega^2 = gHk^2 \rightarrow \omega = \pm \sqrt{gH} \cdot k$$

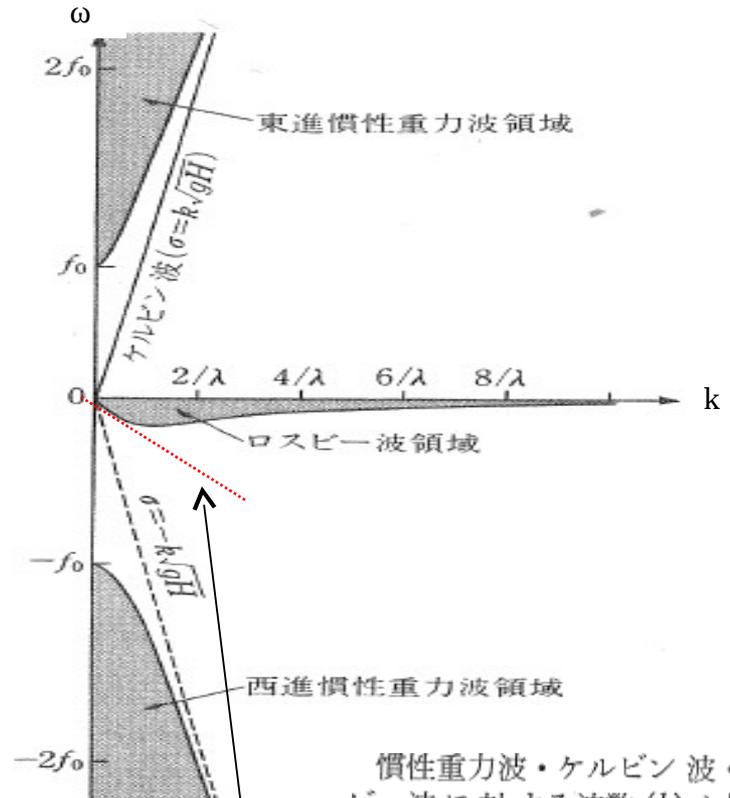
(1)'に代入

$$G(x) = \exp\left(\pm \frac{1}{\lambda} x\right)$$

$$\omega = -\sqrt{gH} \cdot k \quad \text{だと} \exp\left(-\frac{1}{\lambda} x\right) \quad \text{で発散}$$

とならぬ

$$\therefore \omega = -\sqrt{gH} \cdot k$$



慣性重力波・ケルビン波・ロスビー波に対する波数(k)と振動数(σ)の関係, $f_0 = 10^{-4} \text{ sec}^{-1}$, $\beta = 1.6 \times 10^{-18} \text{ cm}^{-1} \text{ sec}^{-1}$, $\lambda = 2,000 \text{ km}$ として計算してある

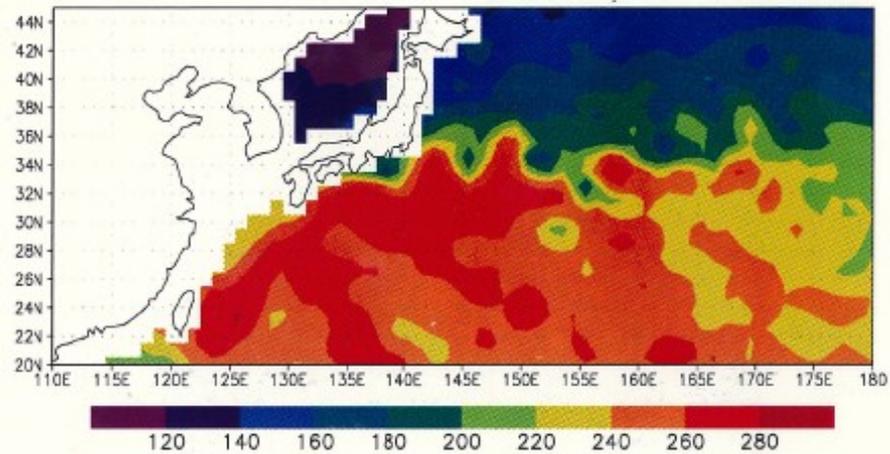
$$\omega = -\frac{\beta k}{k^2 + l^2 + \frac{1}{\lambda^2}} \rightarrow \omega = -\beta \lambda^2 k$$

非分散

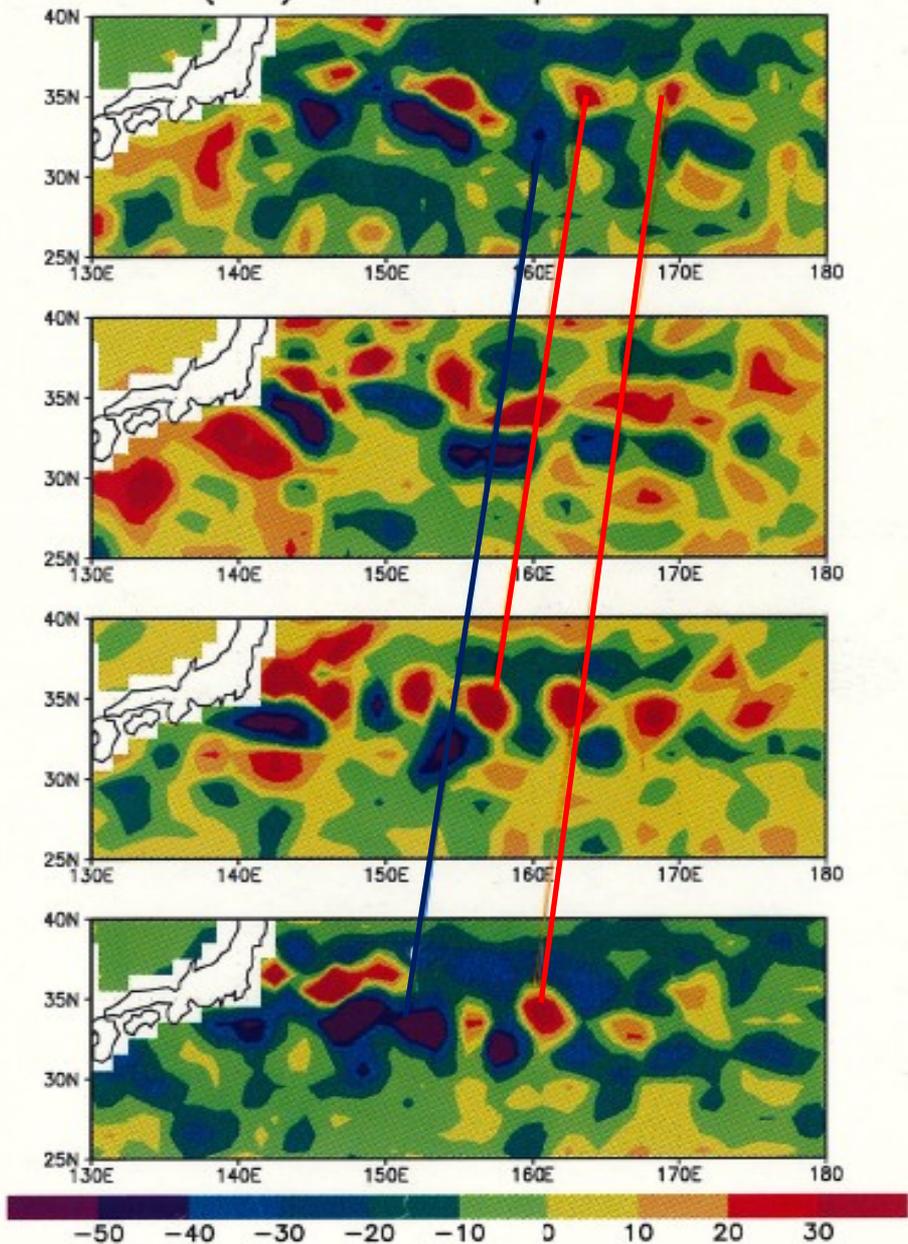
発散ロスビー波

$$c_p = c_g = -\beta \lambda^2 \sim 5 \text{ km/day}$$

SSH(cm) 1997DEC



SSHA(cm) 96Jun-Sep-Dec-97Mar



~ 3 km/day

連続成層の場合 → 鉛直モード展開

$$\frac{Du}{Dt} - fv + \frac{1}{\rho_0} P_x = (K_M u_z)_z$$

$$\frac{Dv}{Dt} + fu + \frac{1}{\rho_0} P_y = (K_M v_z)_z$$

$$-\rho g + P_z = 0$$

$$u_x + v_y + w_z = 0$$

$$\frac{D\rho}{Dt} = (K_H \rho_z)_z$$

基本成層

$$\rho = \rho_0 + \bar{\rho}(z) + \rho'(x, y, z, t)$$

$$\rho_t - N^2 w / g = (K_H \rho_z)_z$$

$$N = (-g\bar{\rho}_z / \rho_0)^{1/2}$$

$K_M = K_H = A/N^2$ であれば変数分離可能

$$u = \sum U_m(x, y, t) R_m(z)$$

$$v = \sum V_m(x, y, t) R_m(z)$$

$$\frac{p}{g} = \sum \eta_m(x, y, t) R_m(z)$$

$$w = \sum W_m(x, y, t) S_m(z)$$

$$S_{zz} + \frac{N^2}{gh} S = 0 \quad (\text{固有方程式})$$

h : equivalent depth

$$R = -ghS_z$$

$$U_t - fV + g\eta_x = -AU/gh$$

$$V_t + fU + g\eta_y = -AV/gh$$

$$\eta_t + h(U_x + V_y) = -A\eta/gh$$

浅水方程式と同じ形

具体的な例
(熱帯)

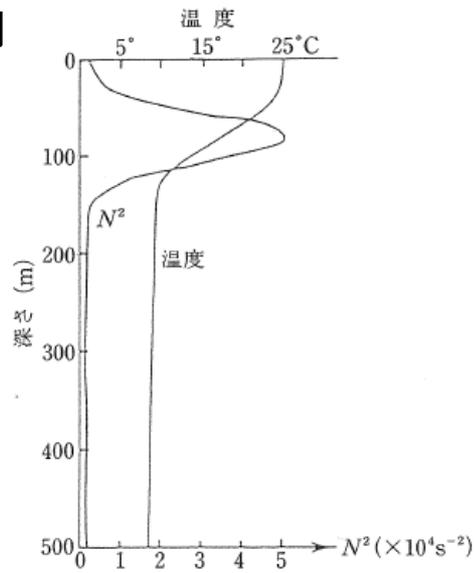


図 5-2 熱帯の代表的な温度とプラント・パイサラ振動数の鉛直分布 (Philander, 1990)

500 m 以下の温度分布は海底 4000 m まで、一定の割合でゼロまで減少させている。

m	$H_m(\text{cm})$	$C_m(\text{cm s}^{-1})$
0	400,000	20,000
1	60	240
2	20	140
3	8	88
4	4	63
5	2	44

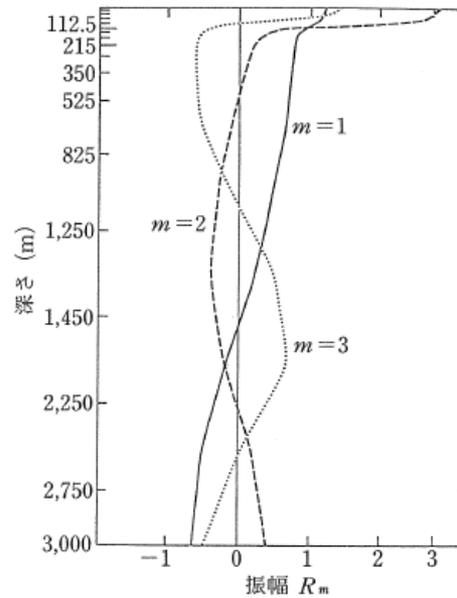


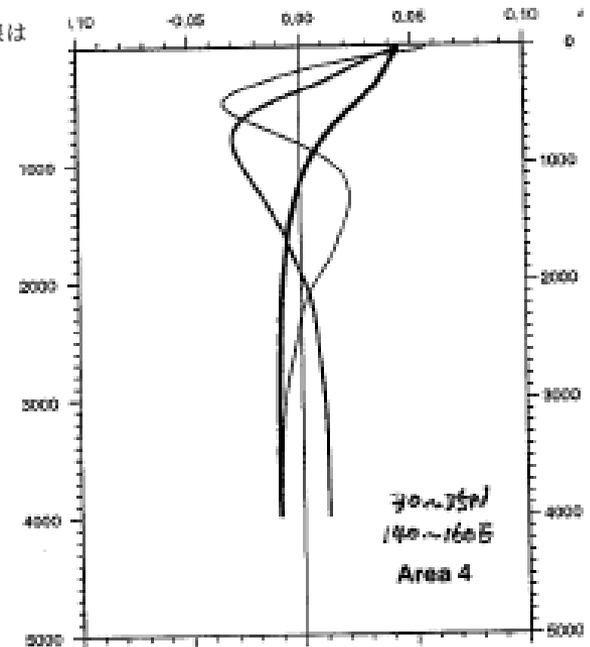
図 5-3 図 5-2 の温度分布から求められた、傾圧モードの鉛直構造 (Philander, 1990)

実線は $m=1$ 、破線は $m=2$ 、そして点線は $m=3$ である。

$$\lambda = C/f \text{ (km)}$$

3,000
350
200

別な事例
(中緯度)



赤道捕捉波 $\rightarrow f = \beta y$ (Matsuno, 1966)

$$\frac{\partial u}{\partial t} - fv = -g \frac{\partial \eta}{\partial x} \quad (1)$$

$$\frac{\partial v}{\partial t} + fu = -g \frac{\partial \eta}{\partial y} \quad (2)$$

$$\frac{\partial \eta}{\partial t} + H \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right) = 0 \quad (3)$$

1. ケルビン波

$$v \equiv 0 \quad c = \sqrt{gH}$$

$$u_{tt} - c^2 u_{xx} = 0$$

$$\beta y u_t - c^2 u_{xy} = 0$$

$$u = E(y)F(x \pm ct)$$

$$y \rightarrow \infty \text{ 有限} \\ F(x - ct) e^{-\frac{1}{2} \frac{y^2}{\lambda^2}}$$

$$\lambda = \sqrt{\frac{c}{\beta}}$$

2. ロスビー波・慣性重力波

(1)、(3)から v を η で表し、(2)に代入

$$(v_{xx} + v_{yy})_t + \beta v_x - \frac{1}{c^2} v_{ttt} - \frac{\beta^2 y^2}{c^2} v_t = 0$$

$$v \approx A(y) e^{i(kx - \omega t)}$$

$$\Psi_{m,yy} + (2m+1)\Psi_m - y^2 \Psi_m = 0$$

$$\Psi_m = \frac{e^{-\frac{y^2}{2}} H_m(y)}{\sqrt{2^m m!} \sqrt{\pi}} \quad H_m(y) \text{ エルミートの多項式}$$

$$\frac{c}{\beta} \left(\frac{\omega^2}{c^2} - k^2 - \frac{\beta k}{\omega} \right) = 2m + 1, \quad m = 0, 1, 2, \dots$$

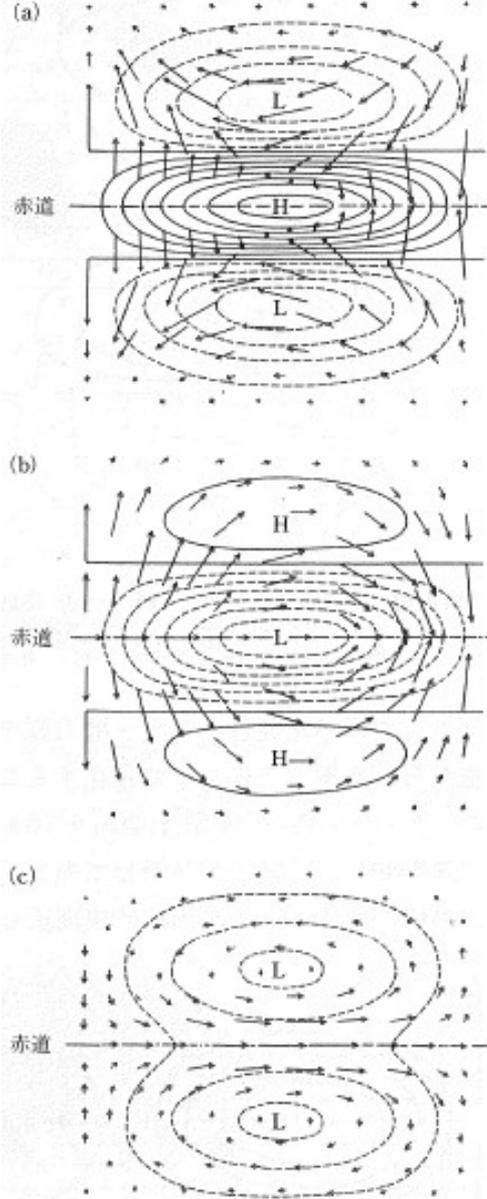


図 2.12 赤道付近における波動($n=1$). (a)東に伝播する慣性重力波, (b)西に伝播する慣性重力波, (c)ロスビー波. (Matsuno, 1966)

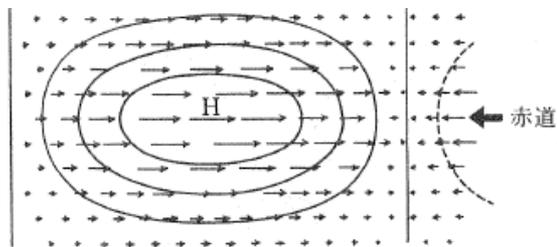
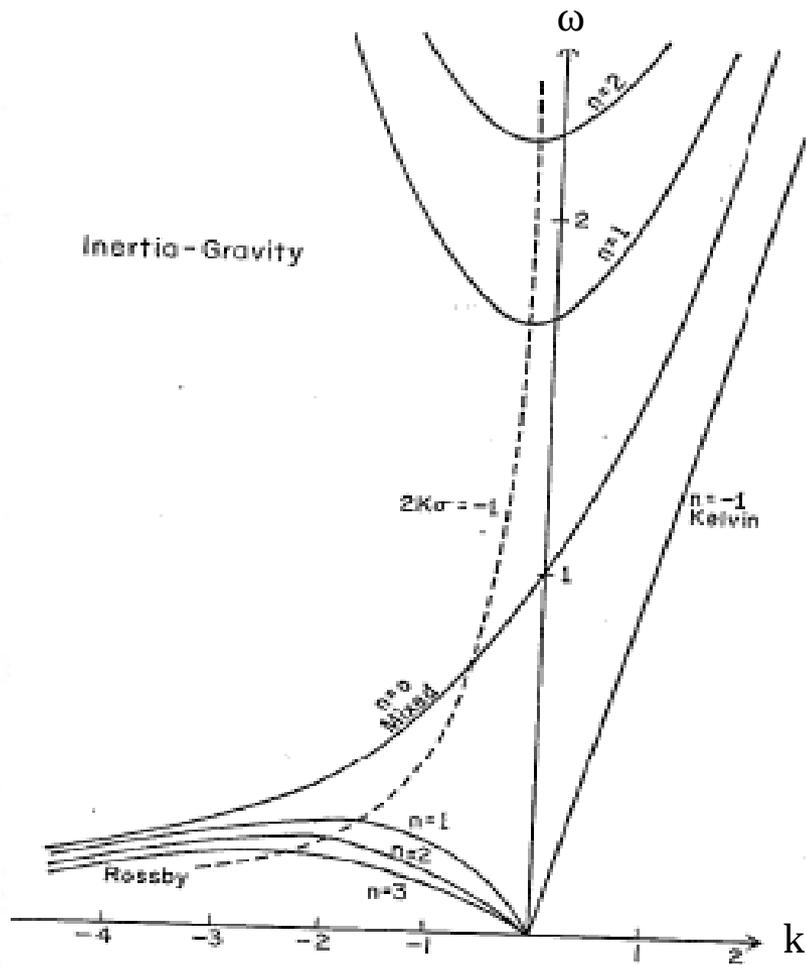


図 2.14 ケルビン波に伴う気圧場と風の間 (Matsuno, 1966).

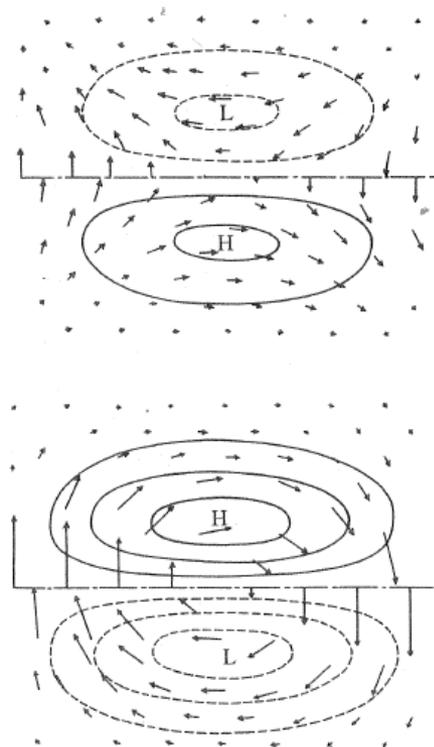
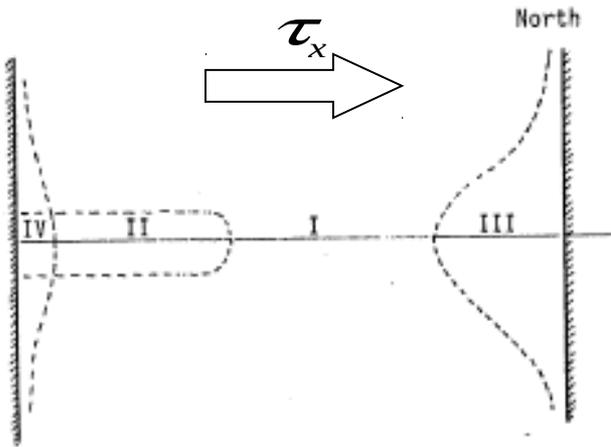


図 2.13 赤道付近における波動($n=0$) (Matsuno, 1966): (a)東に伝播する慣性重力波, (b)西に伝播する混合ロスビー重力波.

東風に対する応答

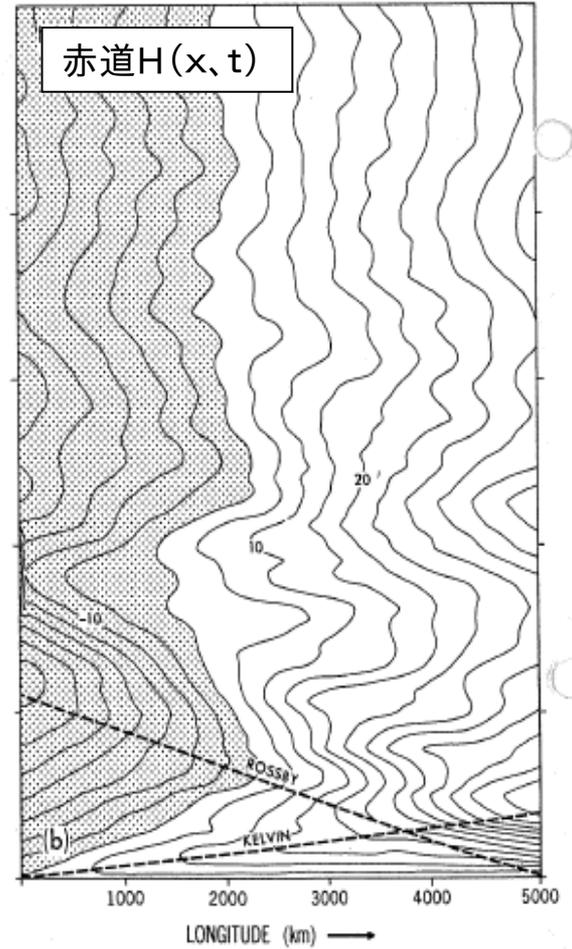
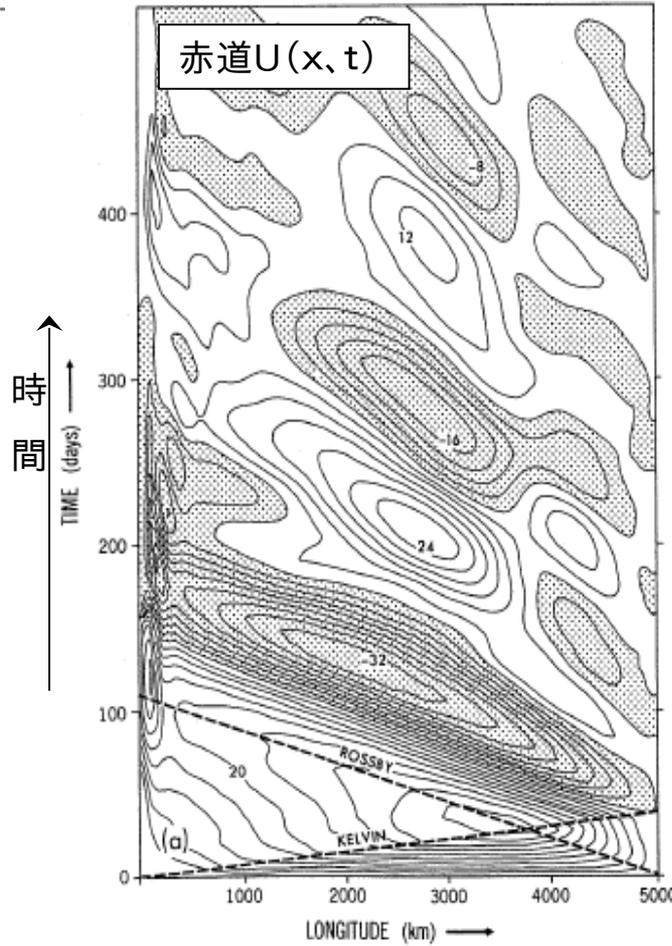
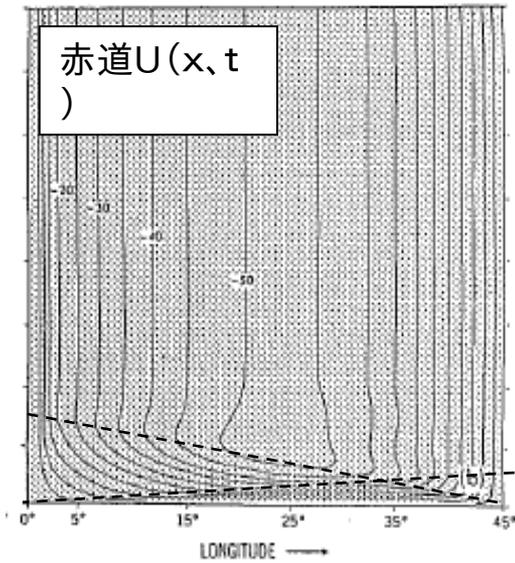


$$\frac{\partial u}{\partial t} + g \frac{\partial \eta}{\partial x} = \frac{\tau_x}{H} (-\alpha u)$$

I II · III

τ_x 一定 \rightarrow 静止

消散(粘性・拡散)が効く場合



$$\left(\frac{\partial}{\partial t} + \frac{\alpha}{\lambda}\right)U - yV + \frac{\partial \eta}{\partial x} = \tau \quad (1)$$

$$yU + \frac{\partial \eta}{\partial y} = 0 \quad (2)$$

$$\left(\frac{\partial}{\partial t} + \frac{\alpha}{\lambda}\right)\eta + \frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} = 0 \quad (3)$$

長波近似、 Gill(1980)より

$$q = \eta + U, \quad r = \eta - U$$

$$(q, r, V) = \sum_{m=0}^M (Q^m, R^m, V^m) \Psi_m(y)$$

$$\tau = \sum_{m=0}^M F^m \Psi_m(y)$$

$$\Psi_{m,yy} + (2m+1)\Psi_m - y^2\Psi_m = 0$$

$$\Psi_m = \frac{e^{-\frac{y^2}{2}} H_m(y)}{\sqrt{2^m m!} \sqrt{\pi}}$$

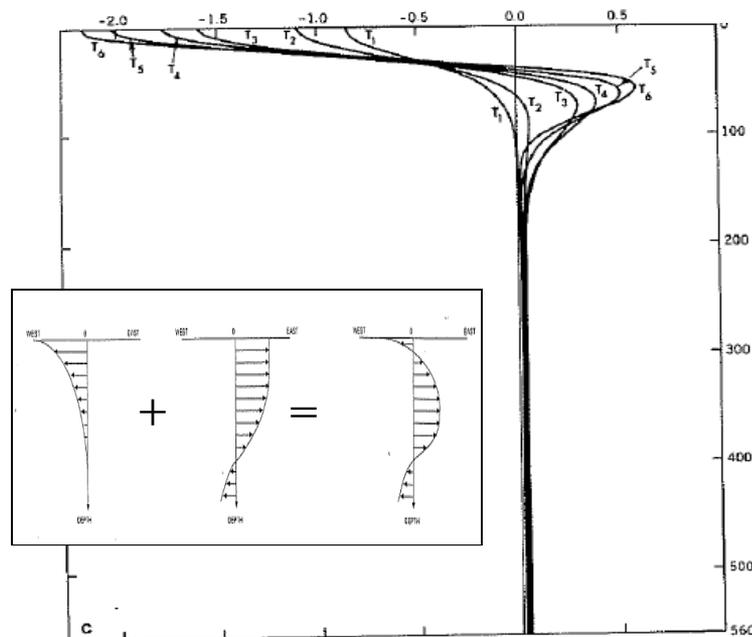
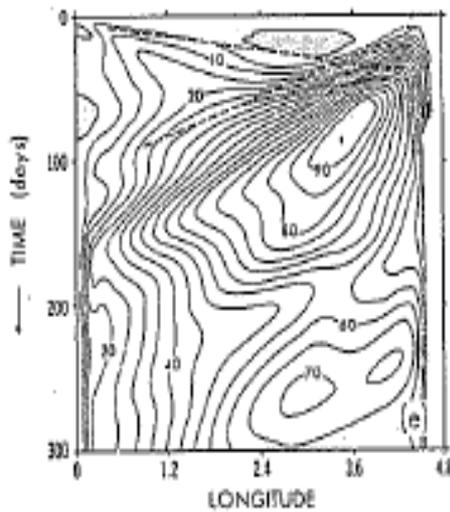
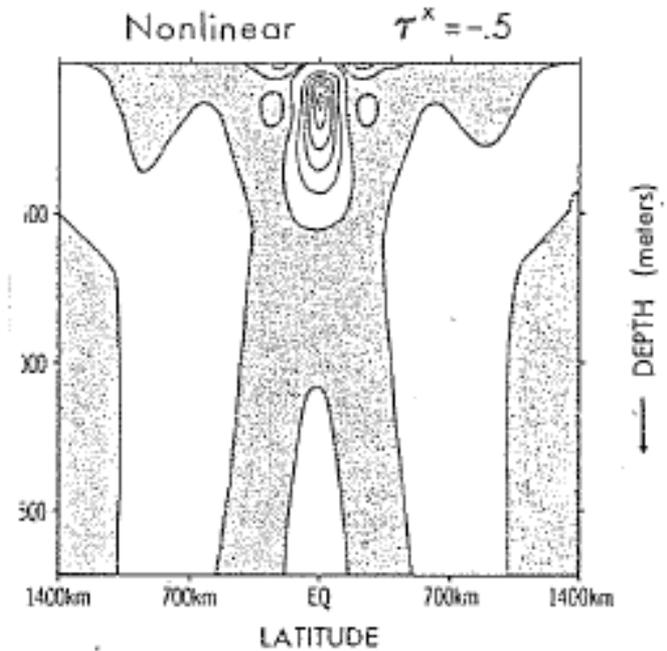
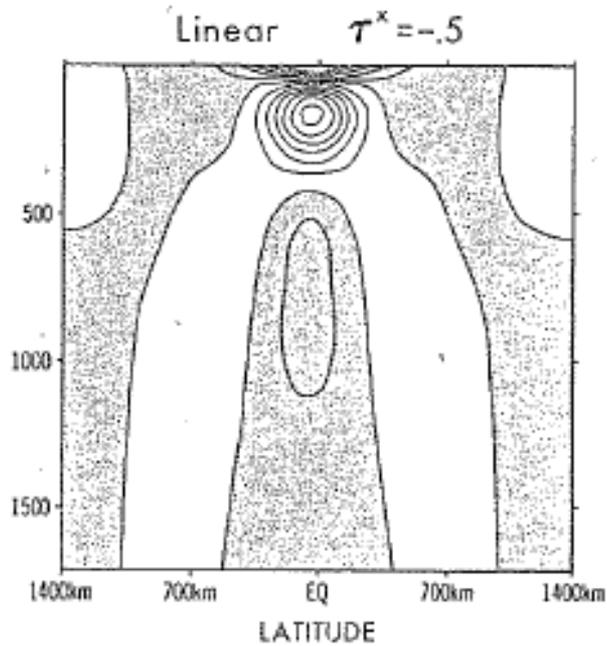
Kelvin mode $\left(\frac{\partial}{\partial t} + \delta + \frac{\partial}{\partial x}\right) Q^0 = F^0$

Rossby mode $\left(\frac{1}{c_m} \left(\frac{\partial}{\partial t} + \delta\right) - \frac{\partial}{\partial x}\right) \begin{pmatrix} V^m \\ Q^{m+1} \\ R^{m-1} \end{pmatrix} = \begin{pmatrix} -\left(\frac{\partial}{\partial t} + \delta\right) \sqrt{2m} F^{m-1} \\ -F^{m+1} \\ -F^{m-1} \end{pmatrix} \quad c_m = \frac{1}{2m+1}$
 $(m = 1, 3, 5, \dots)$

B.C.

$x = x_W \quad \int_{-\infty}^{\infty} u \, dy = 0$ 西岸 ロスビー波 → ケルビン波

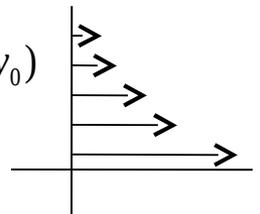
$x = x_E \quad u = 0 \quad (q = r)$ 東岸 ケルビン波 → ロスビー波



東西圧力勾配にともなう子午面循環

渦度保存

$$-\frac{dU}{dy} = -\beta(y - y_0)$$



東向き運動量 赤道へ

湧昇で上向き移流

表層の西向き運動量は極方向へ

Figure 4.11 (Continued)