Equatorial dynamics:
a 25-year perspective

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Myrl Hendershott Symposium

Scripps Institution of Oceanography
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INTERNATIONAL PACIFIC RESEARCH CENTER

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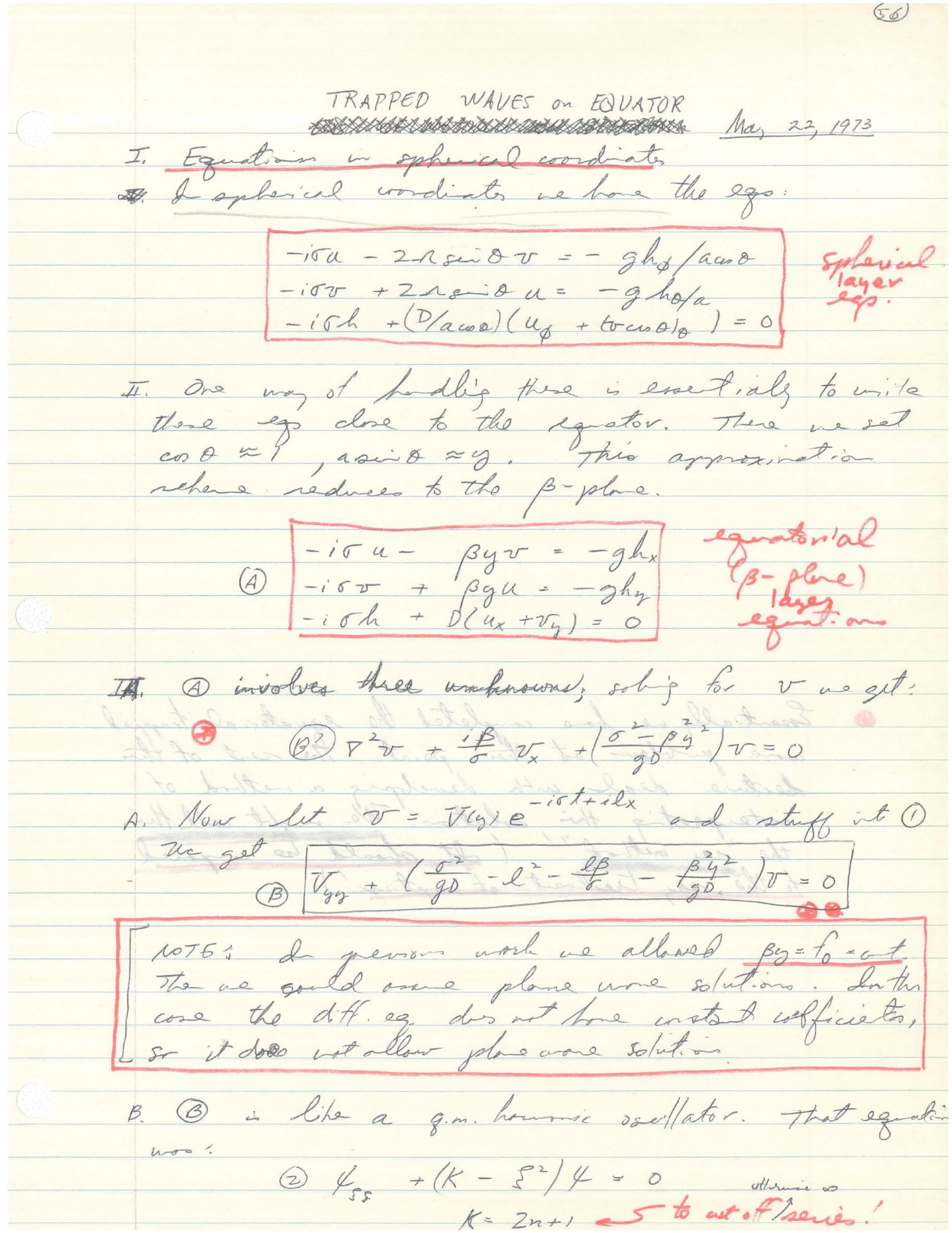
Talents

1) Teaching

ACTUAL NOTES from a Myrl Hendershott class! I learned my first **equatorial dynamics** in this class!!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TRAPPED WAVES on EQUATOR

May 22, 1973

I. Equations in spherical coordinates

In spherical coordinates we have the eqs:

$$\boxed{\begin{aligned} -i\sigma u - 2\Omega\sin\theta\, v &= -g h_\phi / a\cos\theta \\ -i\sigma v + 2\Omega\sin\theta\, u &= -g h_\theta / a \\ -i\sigma h + (D/a\cos\theta)(u_\phi + (v\cos\theta)_\theta) &= 0 \end{aligned}}$$

spherical layer eqs.

II. One way of handling these is essentially to write these eqs close to the equator. There we set $\cos\theta \approx 1$, $a\sin\theta \approx y$. This approximation scheme reduces to the β-plane.

(A)
$$\boxed{\begin{aligned} -i\sigma u - \beta y v &= -g h_x \\ -i\sigma v + \beta y u &= -g h_y \\ -i\sigma h + D(u_x + v_y) &= 0 \end{aligned}}$$

equatorial (β-plane) layer equations

III. (A) involves three unknowns; solving for v we get:

(B') $$\nabla^2 v + \frac{i\beta}{\sigma} v_x + \left(\frac{\sigma^2 - \beta^2 y^2}{gD}\right) v = 0$$

A. Now let $v = V(y)e^{-i\sigma t + ilx}$ and stuff it ① we get

(B) $$\boxed{V_{yy} + \left(\frac{\sigma^2}{gD} - l^2 - \frac{l\beta}{\sigma} - \frac{\beta^2 y^2}{gD}\right) V = 0}$$

NOTE: In previous work we allowed $\beta y = f_0 = $ const. Then we could assume plane wave solutions. In this case the diff. eq. does not have constant coefficients, so it does not allow plane wave solutions.

B. (B) is like a q.m. harmonic oscillator. That equation was:

② $$\psi_{\xi\xi} + (K - \xi^2)\psi = 0$$

$K = 2n+1$ otherwise, to cut off series!

Talents

1) Teaching

2) Students

Talents

1) Teaching

2) Students

3) Wine

4) Women

5) Song

Talents

1) Teaching

2) Students

3) Wine

4) Women

5) Song

6) Sports

Talents

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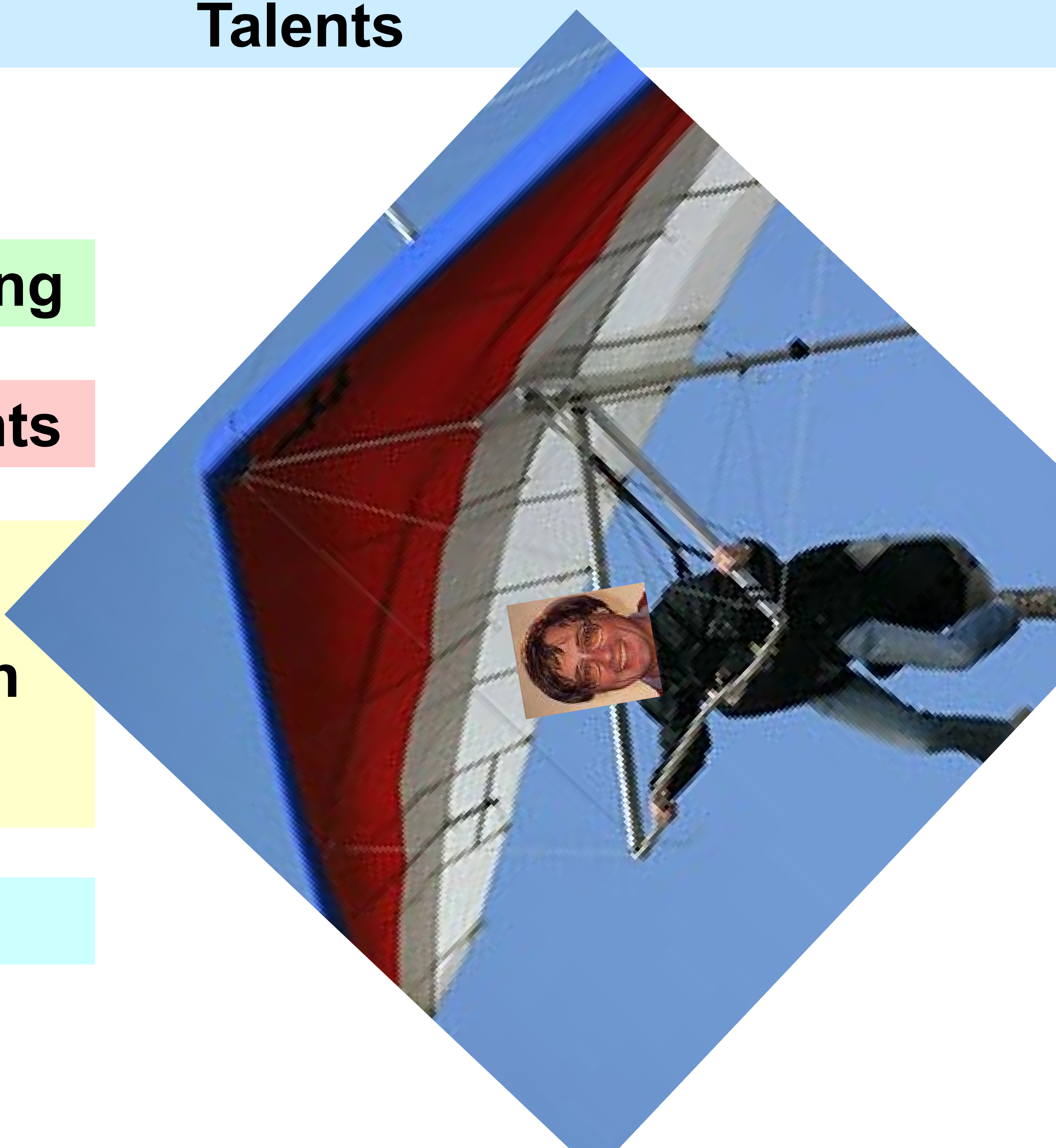

Talents

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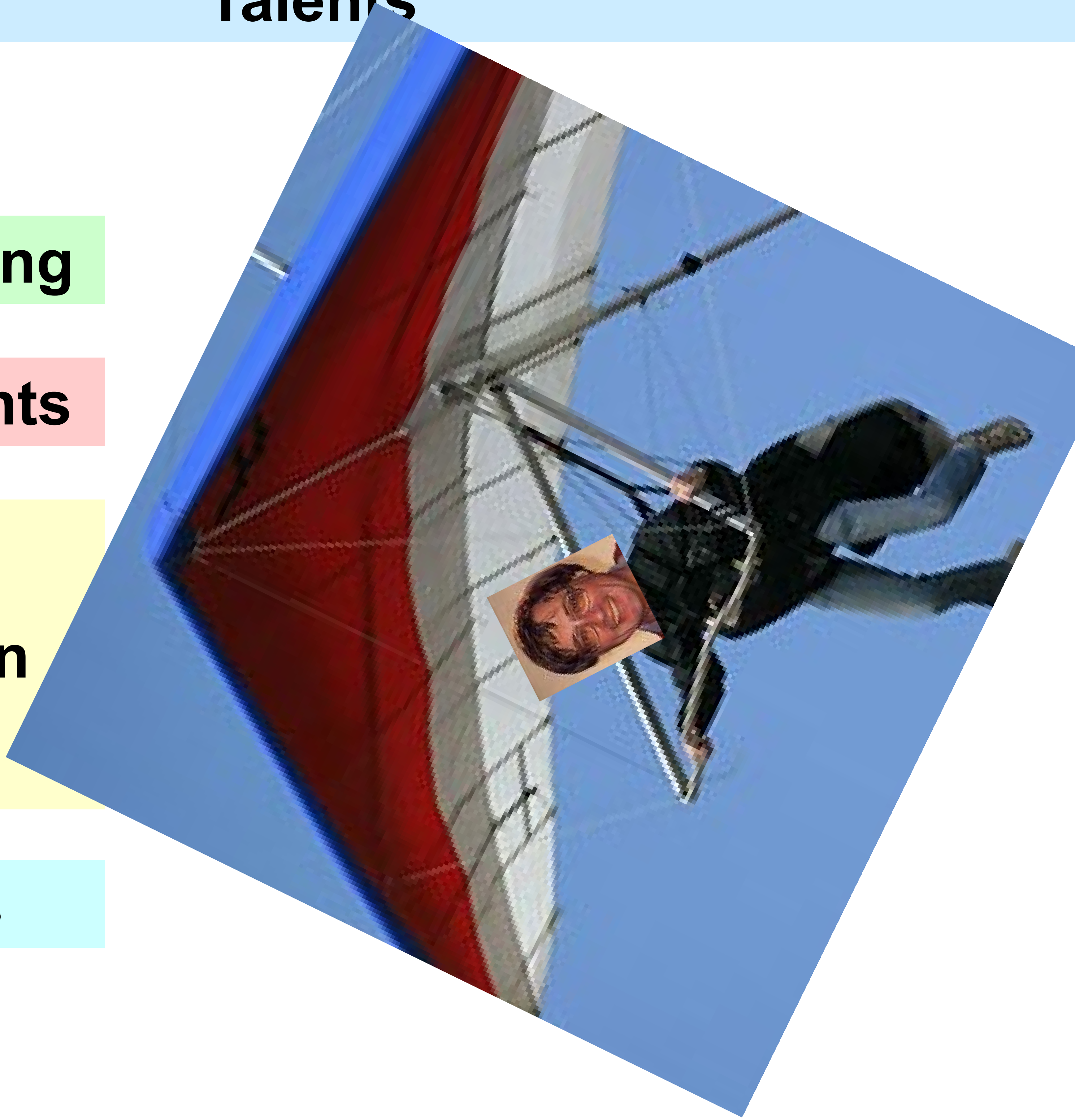

Talents

1) Teaching

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Talents

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6) Sports

Talents

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2) Students

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4) Women

5) Song

6) Sports

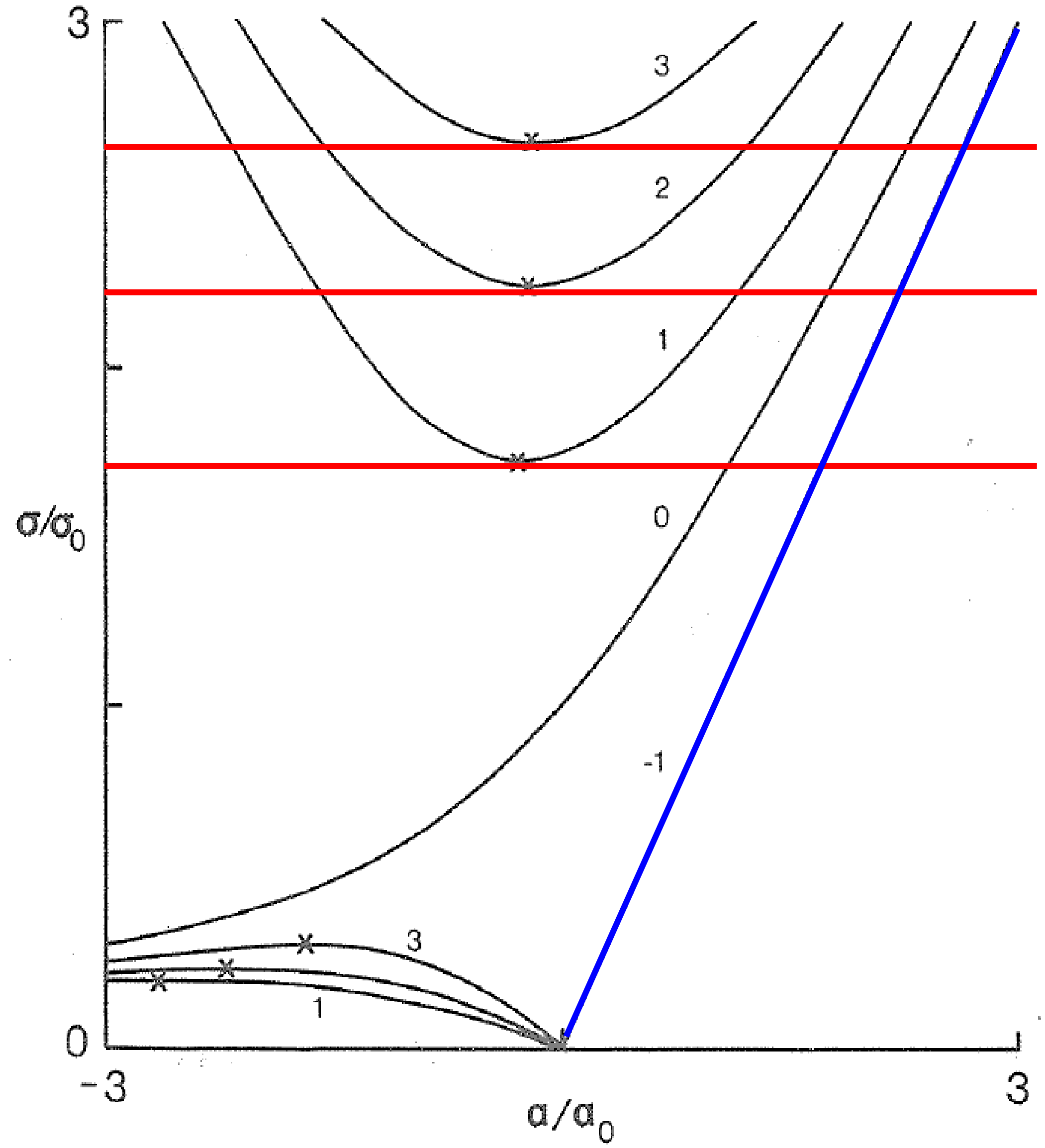
Equatorial dynamics

Topics

1) Equatorially trapped waves

The first equatorially trapped waves to be discovered were **gravity-wave resonances** with periods of O(10 days) (Wunsch and Gill, 1976; *Deep-Sea Res.*). There are no publications that explore the possibility of **Rossby-wave resonances**.

The **equatorial Kelvin wave** was **discovered after it was predicted** to be dynamically important in El Nino (Knox and Halpern, 1982, *JMR*). **Equatorial Rossby waves** were detected even later.

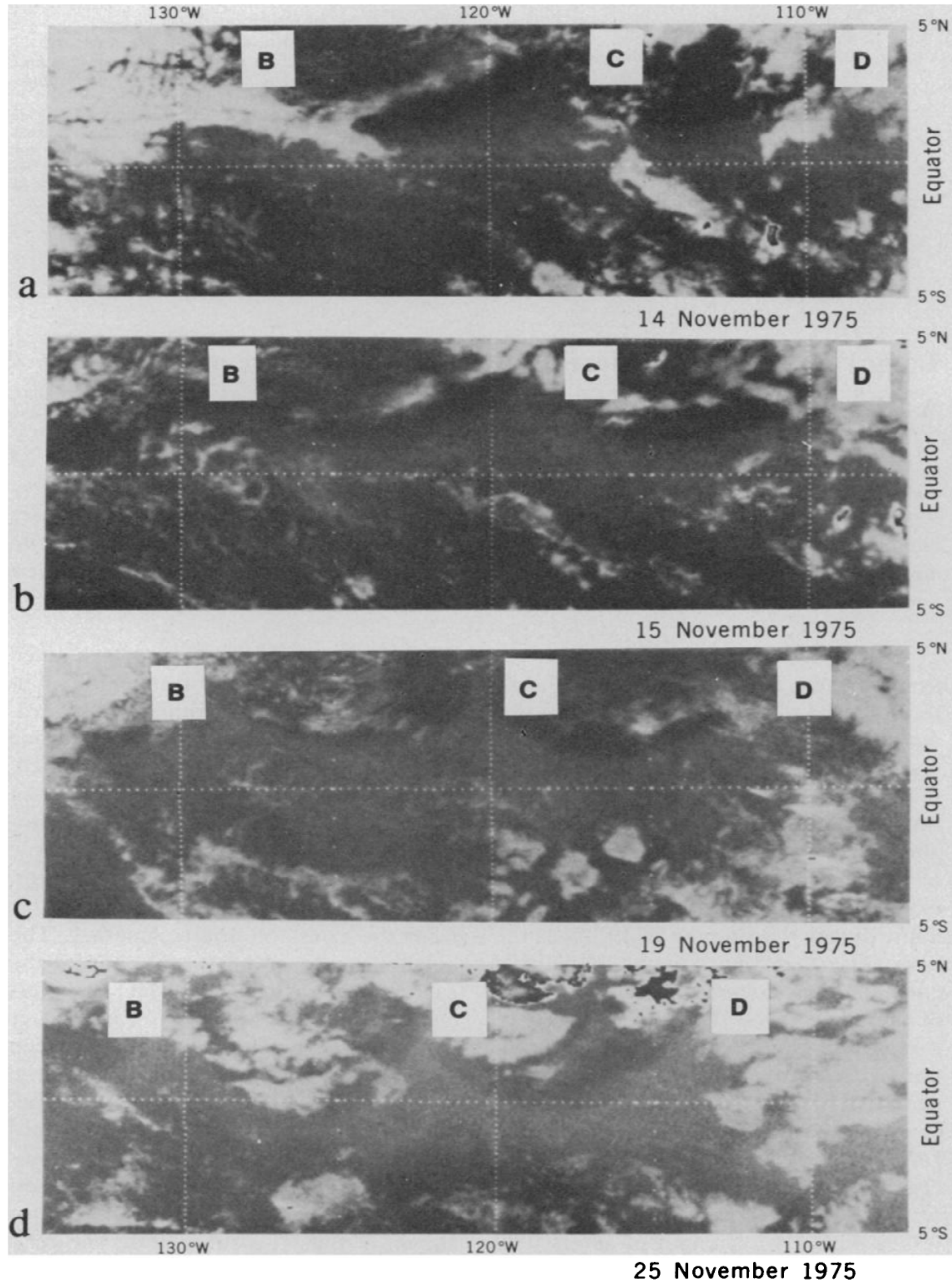


Topics

1) Equatorially trapped waves

2) TIWs

Legeckis (1977, *Science*) first reported the presence of TIWs in the eastern, tropical Pacific. TIWs were soon shown to have a **large impact on the momentum and heat fluxes** in the region. Philander (1976, 1978, *JGR*) argued that TIWs were caused by **barotropic instability**. Yu *et al.* (1992, *Prog.* Oceanogr.) later suggested that an **instability of the temperature front** was involved. Luther and Johnson (1990) suggested that there was **more than one type of TIWs**.



Topics

1) Equatorially trapped waves

2) TIWs

3) El Nino

Father of El Nino

Dan Rather, CBS News

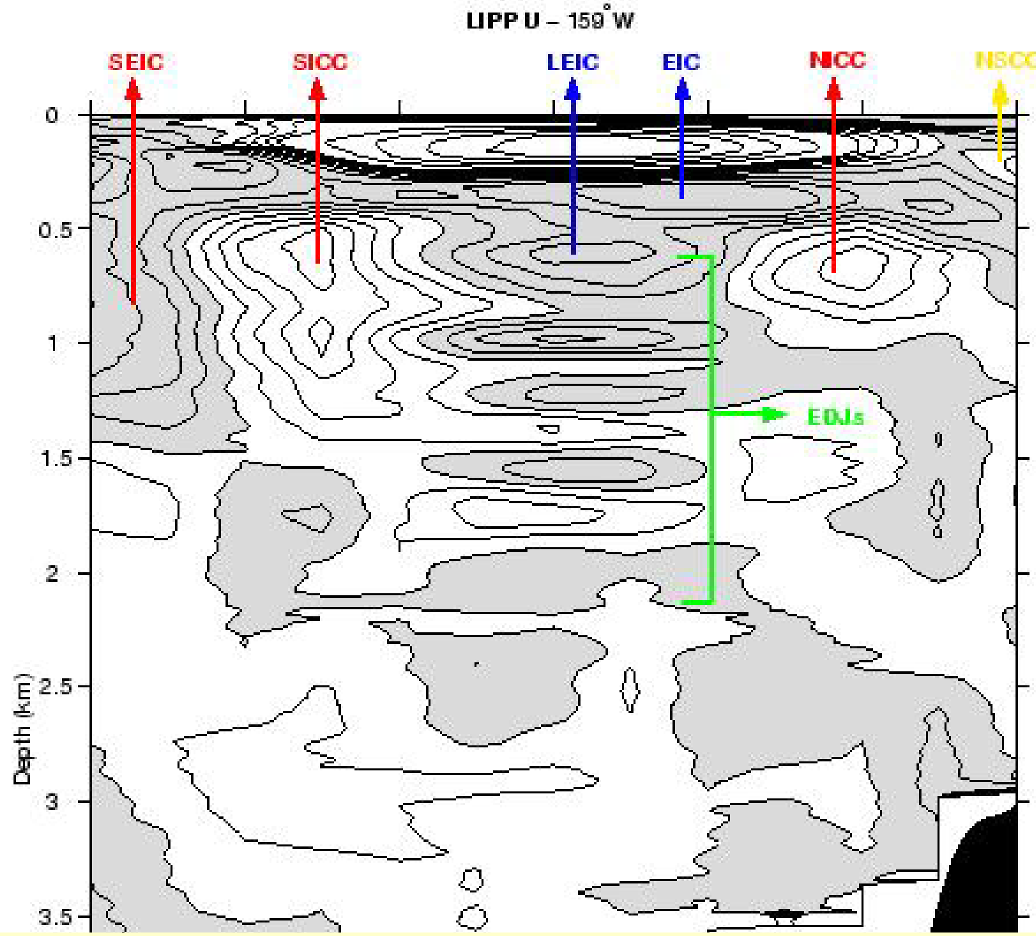
Topics

1) Equatorially trapped waves

2) TIWs

3) El Nino

4) Deep Equatorial Jets



Wunsch (1977, *JPO*) suggested that DEJs were **vertically-propagating, annual waves**, but that idea **proved incorrect** with the discovery that **DEJs are quasi-stationary**. Recently, Zhang & McPhaden have suggested that DEJs exhibit **a very slow vertical displacement** in the Atlantic and Pacific (periods of 5 years to decades). Hua & coworkers and Firing & Ascani have considered the excitation of **basin modes, wave-wave interactions and instabilites** as possible generation mechanisms. Anther possibility is that DEJs are an equatorial extension of **geostrophic turbulence**, as suggested by (Salmon, 1982).

Topics

1) Equatorially trapped waves

2) TIWs

3) El Nino

4) Deep Equatorial Jets

5) Equatorial Undercurrent

6) Subtropical Cells

7) Tsuchiya Jets

1) What are the **basic dynamics of the EUC**?

2) How is the **EUC linked to** the general ocean circulation at **higher latitudes**?

3) What processes set the **strength of the Subtropical Cells**, that is, of tropical/subtropical exchange?

4) What are the **basic dynamics of the Tsuchiya Jets**? What are the **sources and sinks** of the water that flows in them? What role do they play in the **general ocean circulation**? Are they part of the **IT-associated circulation**? Are they part of an **overturning cell deeper** than the STCs?

Linear, continuously stratified (LCS) model

Equations: A useful set of simpler equations is a version of the GCM equations linearized about a stably stratified background state of no motion. The resulting equations are

$$u_t - fv + \frac{1}{\bar{\rho}} p_x = \tau^x Z(z) + (\nu u_z)_z + \nu_h \nabla^2 u,$$

$$v_t + fu + \frac{1}{\bar{\rho}} p_y = \tau^y Z(z) + (\nu v_z)_z + \nu_h \nabla^2 v,$$

$$u_x + v_y + w_z = 0,$$

$$\rho_t - \frac{\bar{\rho} N_b^2}{g} w = (\kappa \rho_z)_z,$$

$$p_z = -\rho g,$$

where $N_b^2 = -g\rho_{bz}/\rho$ is assumed to be a function only of z. Vertical mixing is retained in the interior ocean.

As noted later, though, a serious limitation of the LCS model is that mixing is on perturbation density, ρ, not the total density field, $\rho + \rho_b$.

Equatorial Undercurrent

Vertical modes: With the assumptions that $\nu = \kappa = A/N_b^2(z)$, the ocean has a flat bottom, and convenient surface and bottom boundary conditions, solutions can be represented as expansions in the normal (barotropic and baroclinic) modes, $\psi_n(z)$, of the system. Expansions for the u, v, and p fields are

$$u = \sum_{n=0}^{N} u_n \psi_n, \quad v = \sum_{n=0}^{N} v_n \psi_n, \quad p = \sum_{n=0}^{N} \bar{\rho} p_n \psi_n,$$

where the expansion coefficients are functions of only x, y, and t. The resulting equations for u_n, v_n, and p_n are

$$\left(\partial_t + \frac{A}{c_n^2}\right) u_n - f v_n + p_{nx} = \tau^x Z_n + \nu_h \nabla^2 u_n,$$

$$\left(\partial_t + \frac{A}{c_n^2}\right) v_n + f u_n + p_{ny} = \tau^y Z_n + \nu_h \nabla^2 v_n,$$

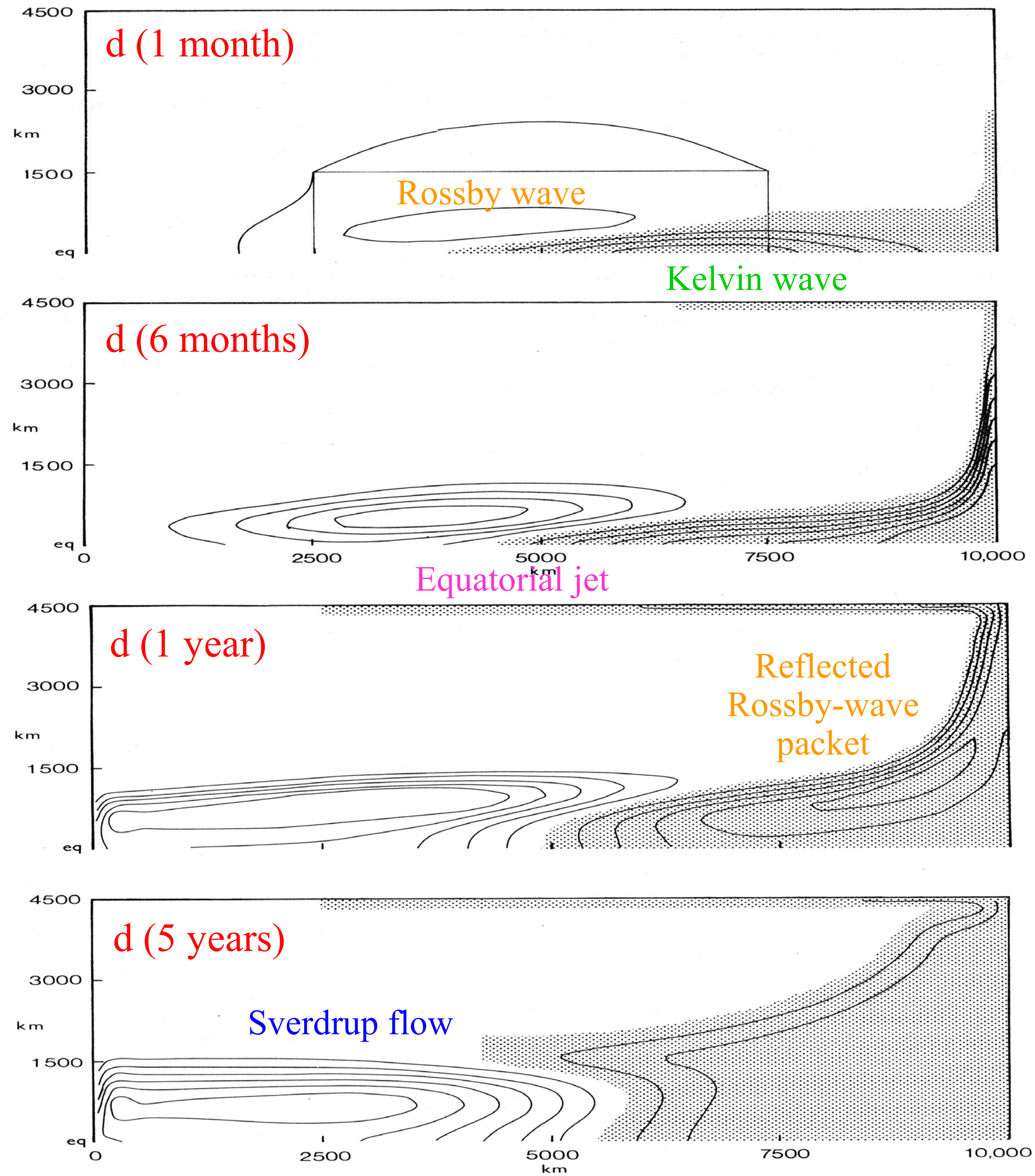
$$\left(\partial_t + \frac{A}{c_n^2}\right) \frac{p_n}{c_n^2} + u_{nx} + v_{ny} = 0,$$

The **basic dynamics of equatorial circulations were studied** using this simple system (*e.g.*, Moore, 1968, Ph.D. thesis; Cane and Sarachik, 1976, 1977, 1979, and 1981, *JMR*; McCreary, 1981, 1984).

Spin-up of an inviscid, baroclinic mode

LCS model

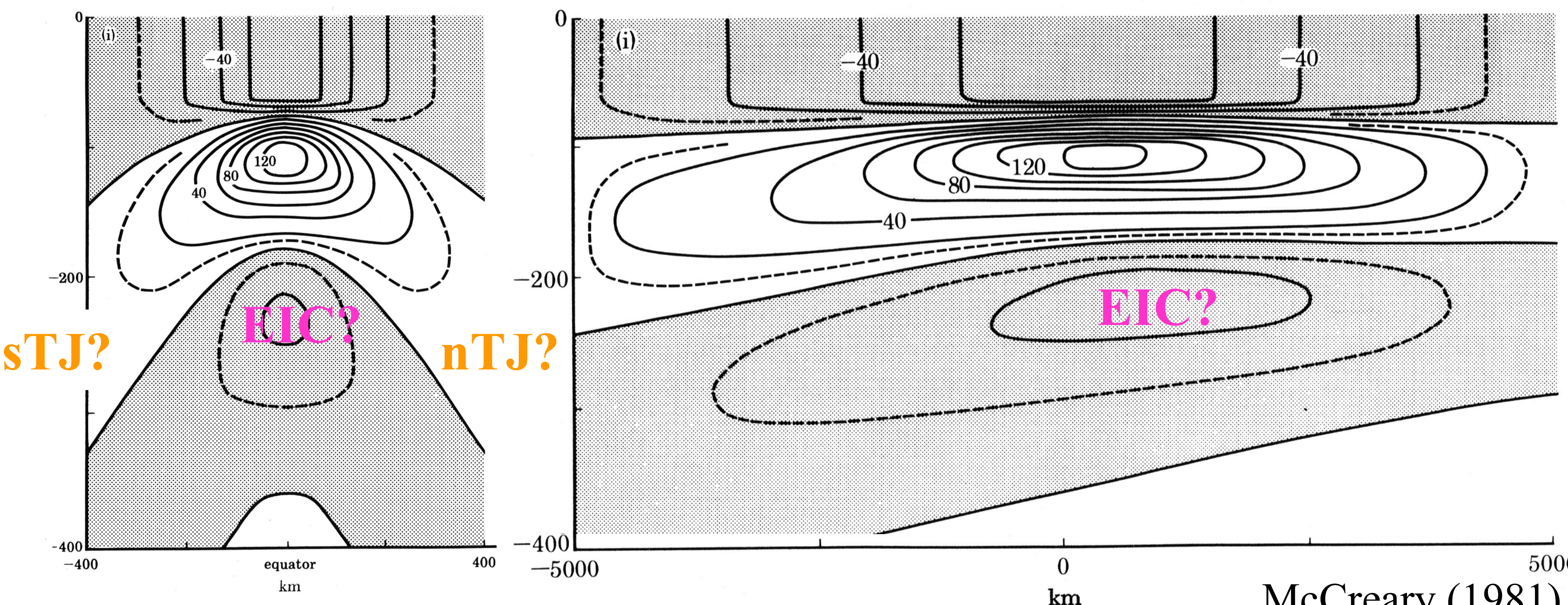
In response to forcing by a **patch of easterly winds, Kelvin and Rossby waves** radiate from the forcing region, reflect from basin boundaries, and eventually **adjust the system to a state of Sverdrup balance**.



Steady, linear response

Without diffusion: When the LCS model is inviscid, baroclinic waves associated with **all** modes are undamped. As a result, the steady-state response is a surface-trapped Sverdrup flow with a vertical structure, Z(z).

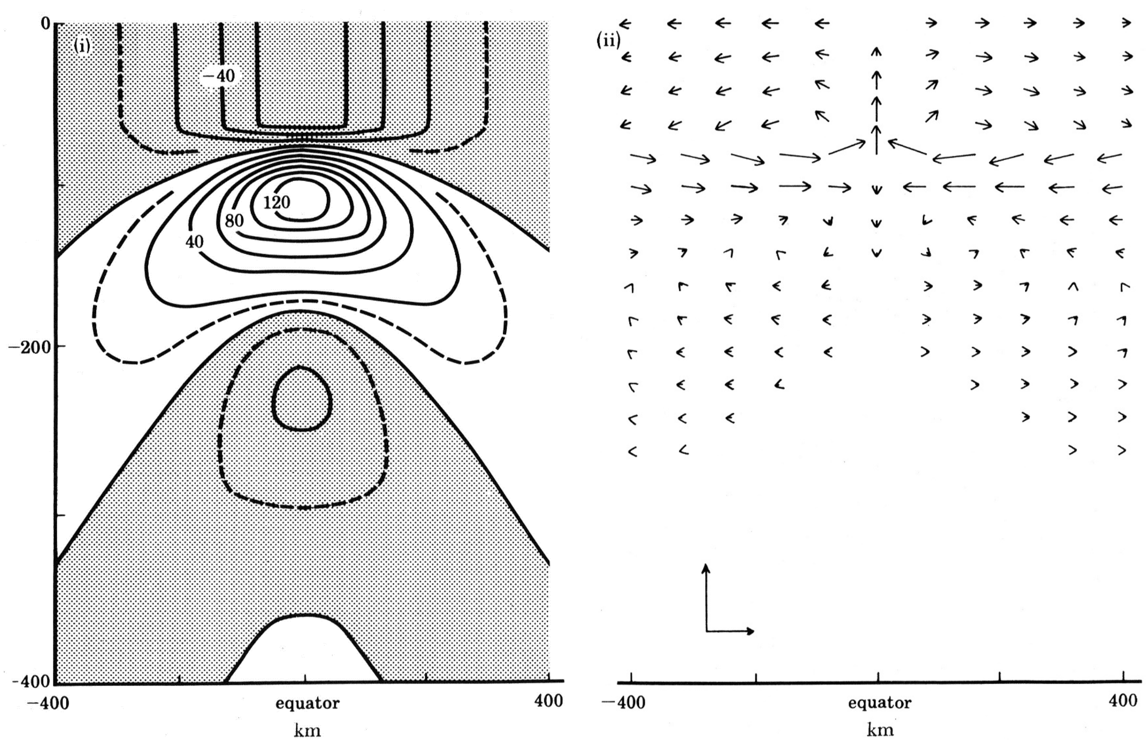
With diffusion: When the LCS model includes diffusion, realistic steady flows can be produced near the equator. A very nice solution, **but**…



McCreary (1981)

Steady, linear response

…in the LCS model, equatorial upwelling is balanced by downwelling **near the equator**. Water is warmed as it upwells, which is physically realistic. Because density diffusion is on perturbation density, ρ, not the total density field, $\rho + \rho_b$, water is cooled when it downwells, which is not realistic.



The **LCS model lacks a fundamental cooling process**, that is, **advection of cool subtropical water into the tropics** by the STCs.

Subtropical Cells

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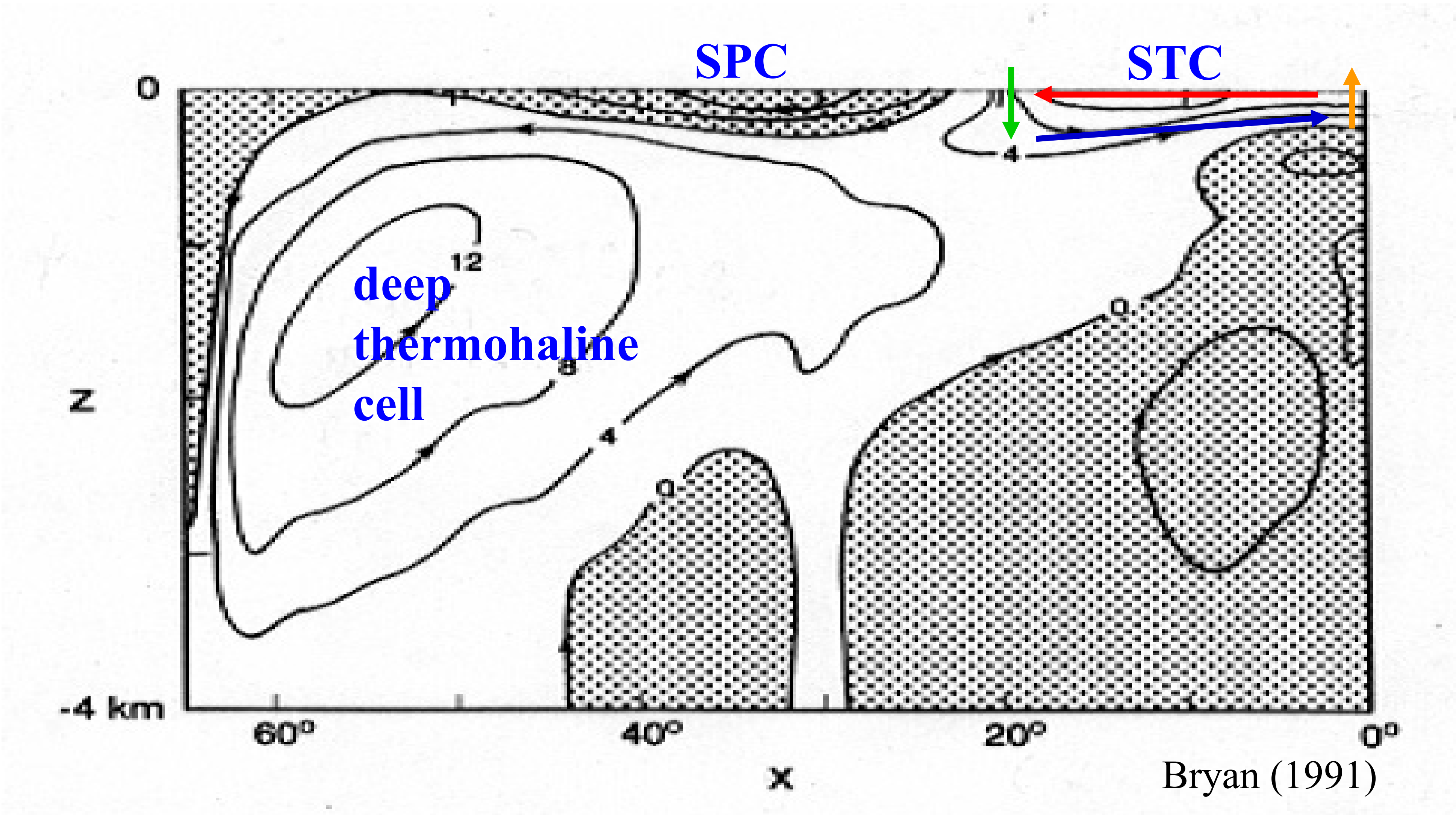
2-d overturning cells in a GCM solution



The overturning cells have much more complex 3-d structures.
What is the **3-d flow field associated with the STC**?

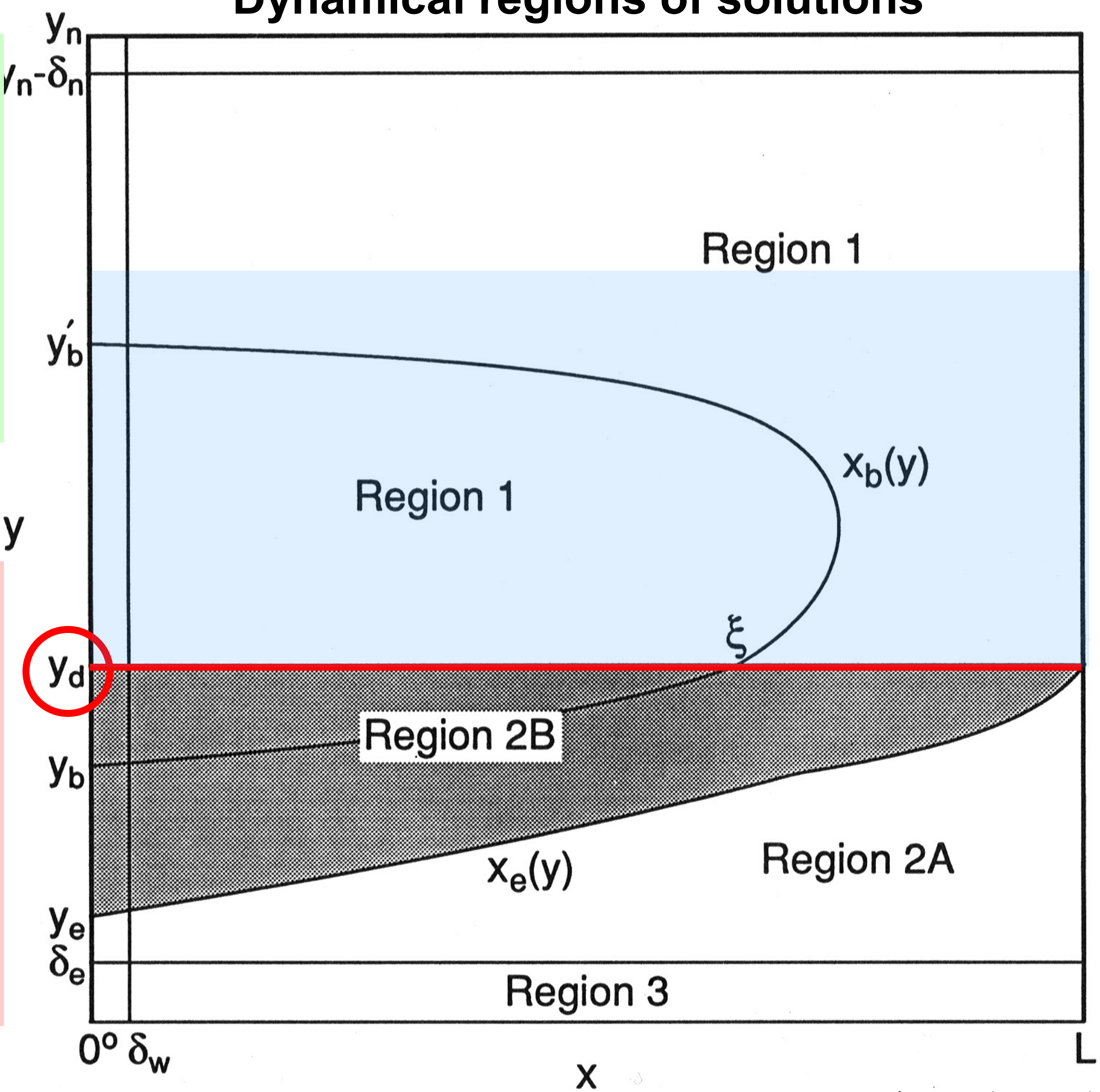
Subtropical Cells

2½-layer model

Subduction of water from layer 1 into layer 2occurs in Region 1 from the line of zero Ekman pumping by τ^x to y_d, **the latitude where subduction is assumed to cease in the model.**

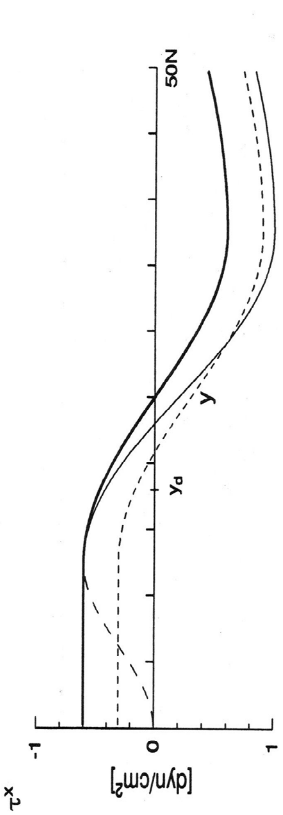
Layer-2 water flows across y_d, **the subduction cutoff latitude into the tropics within Region 2B**, a consequence of n = 2 Rossby waves propagating along characteristics. **Region 2A (the LPS Shadow Zone) is motionless**.

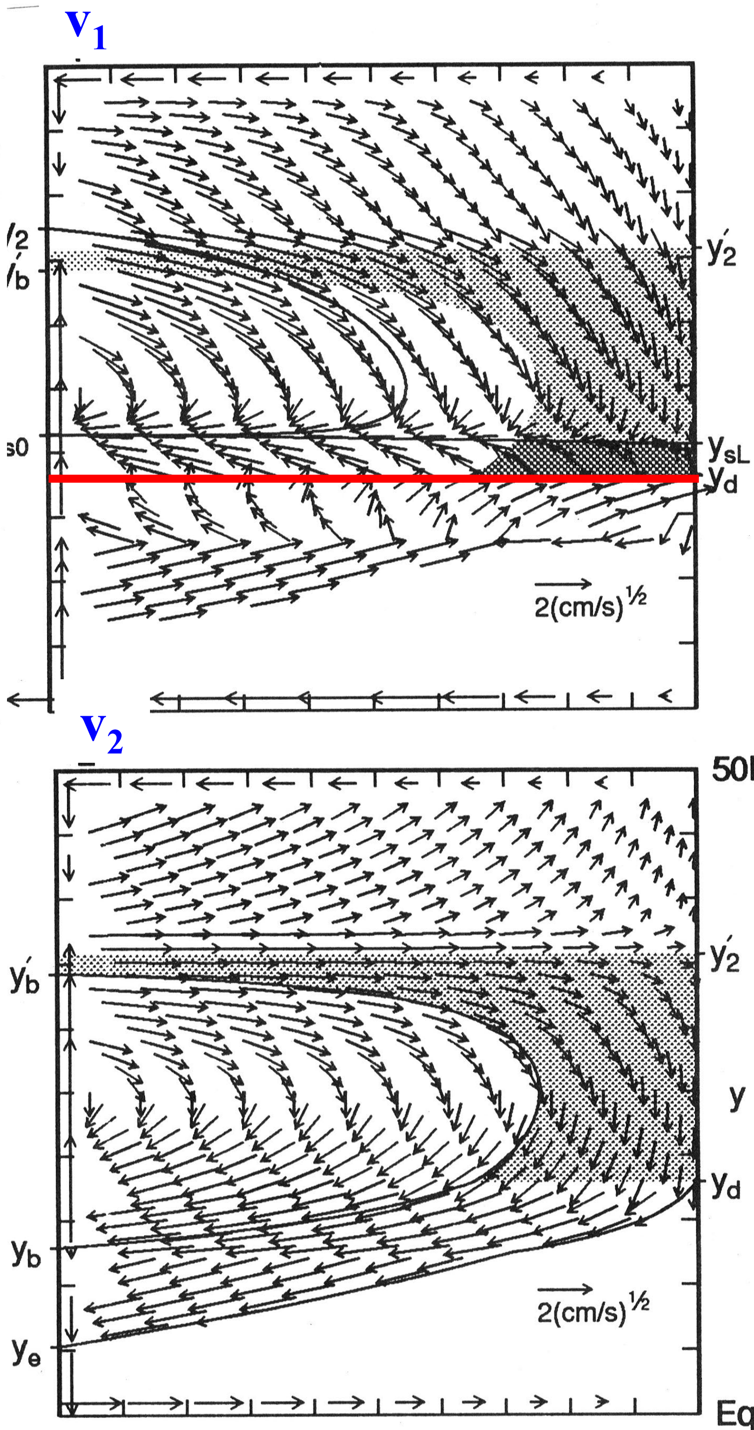
Dynamical regions of solutions

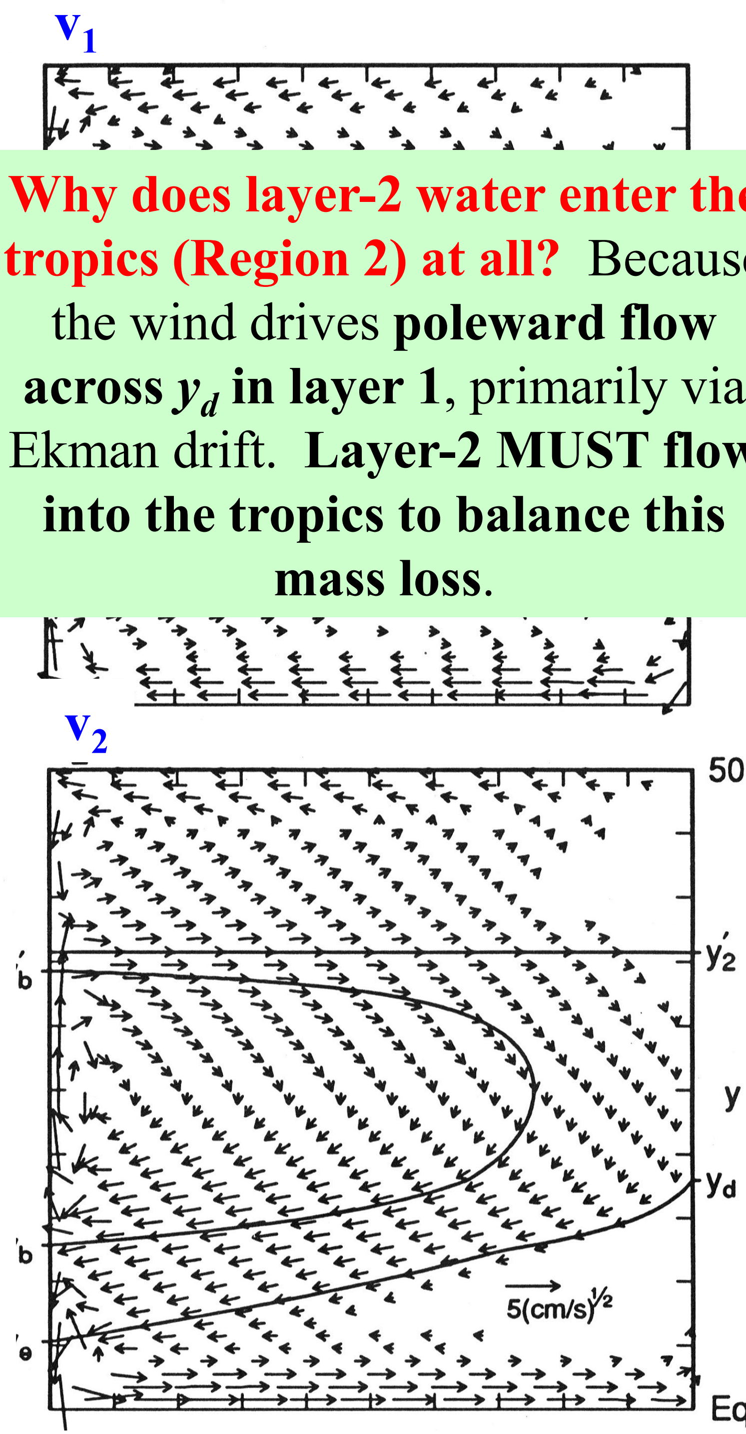


McCreary and Lu (1994)

Analytic solution   Numerical solution

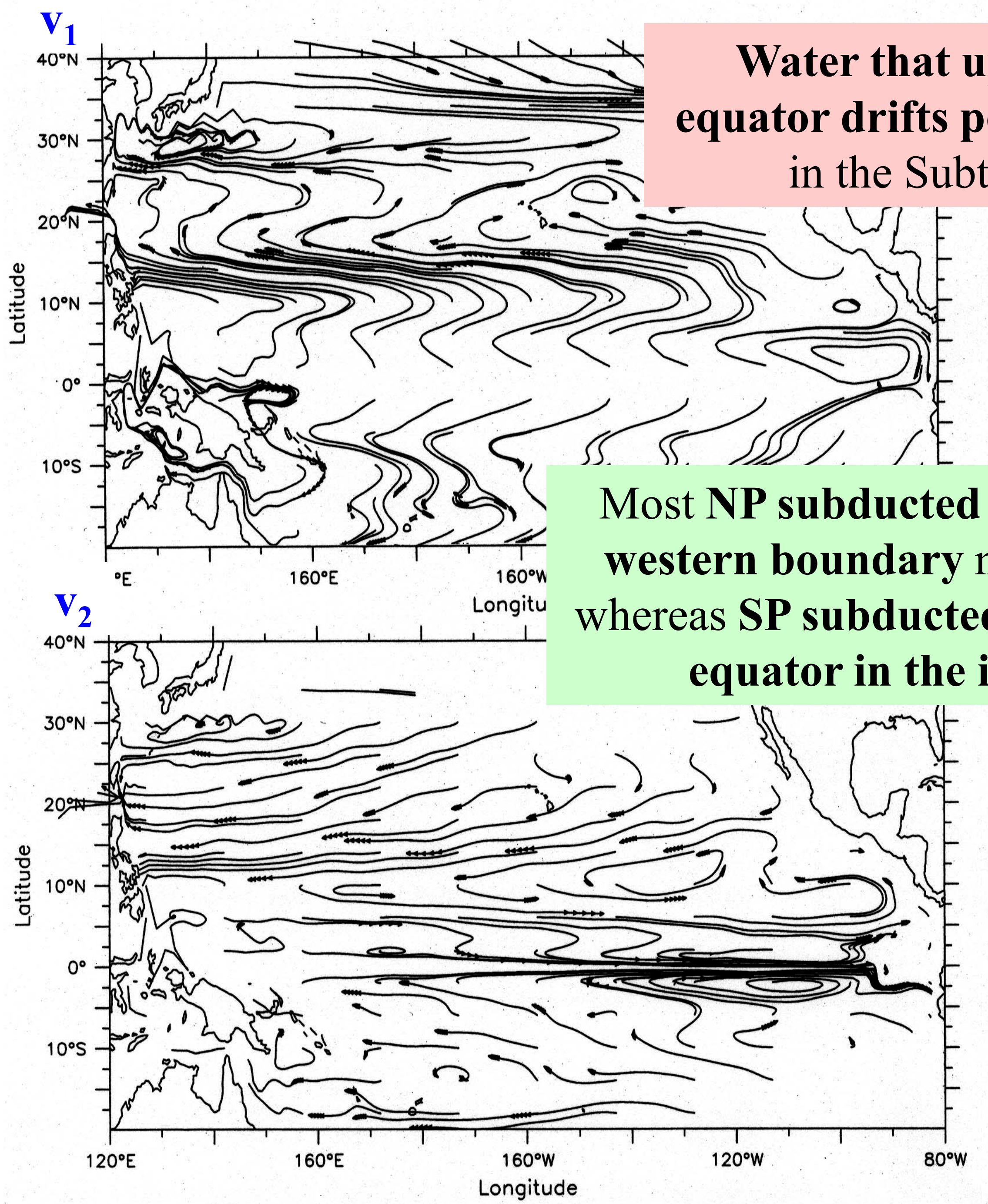






Why does layer-2 water enter the tropics (Region 2) at all? Because the wind drives **poleward flow across y_d in layer 1**, primarily via Ekman drift. **Layer-2 MUST flow into the tropics to balance this mass loss**.

Continuously stratified model



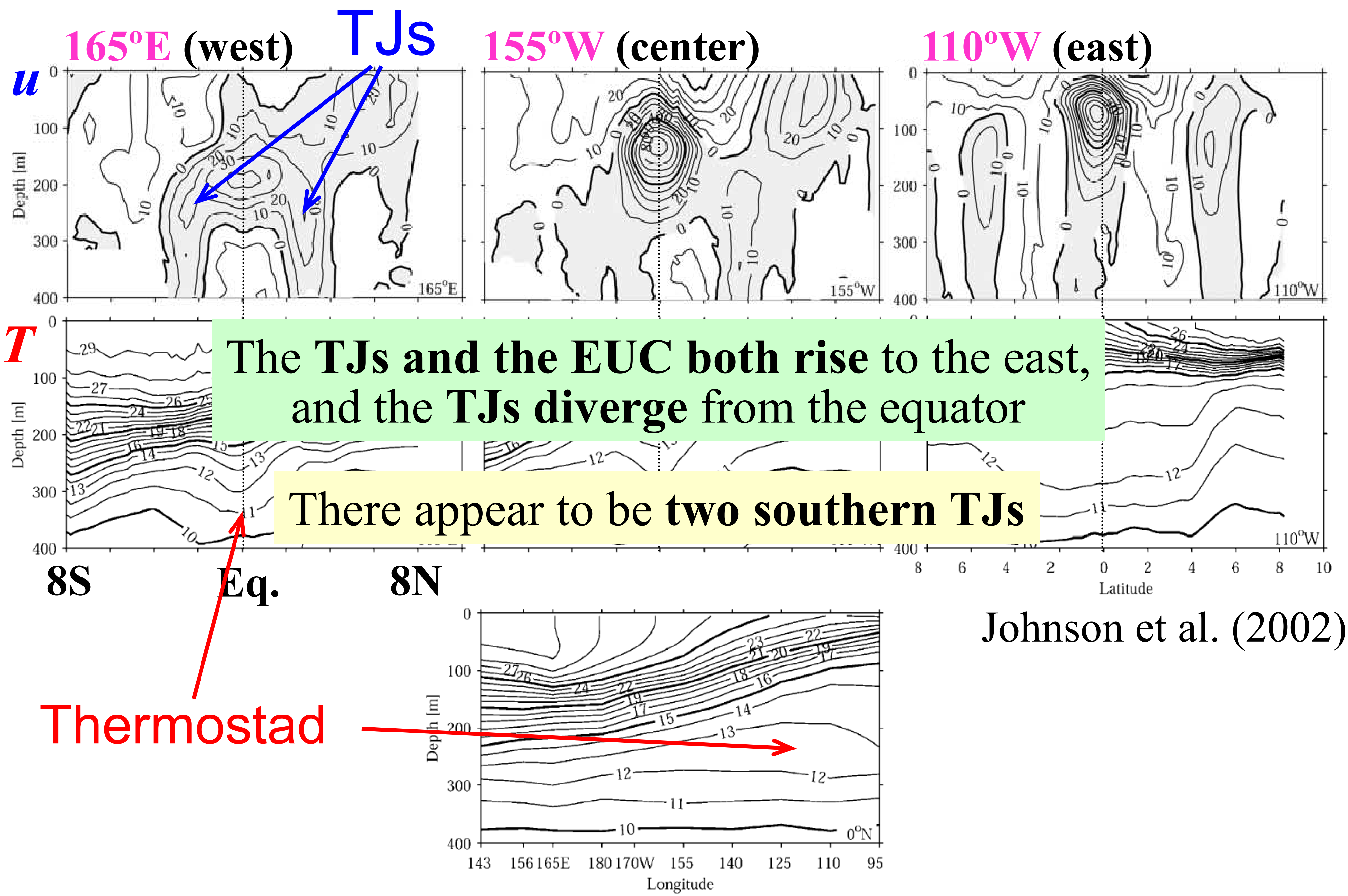
Water that upwells along the equator drifts poleward to circulate in the Subtropical Gyres.

Most **NP subducted water flows to the western boundary** north of the NECC, whereas **SP subducted water flows to the equator in the interior ocean**

Rothstein et al. (1998)

Tsuchiya Jets

Observed Tsuchiya Jets



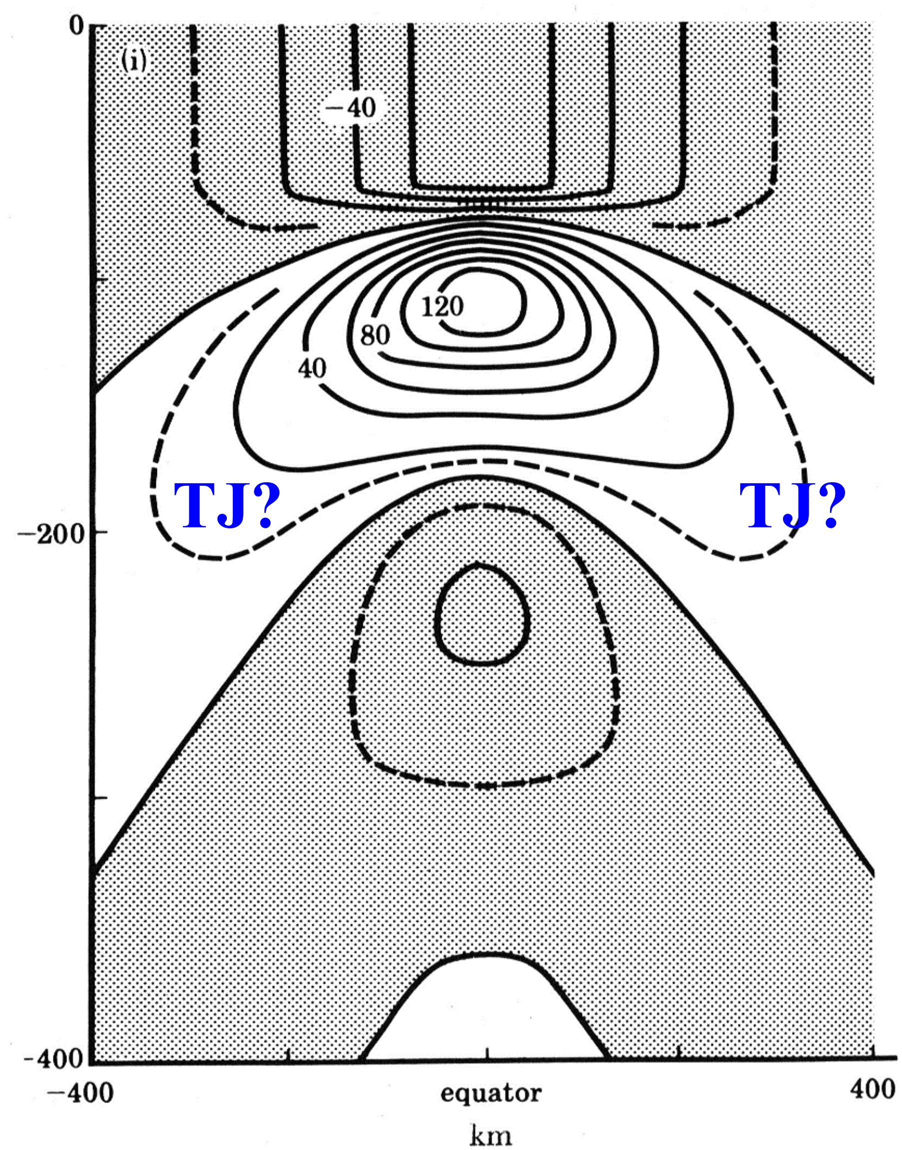
Theories

Local (y-z) forcing

- **Conservation of angular momentum** (Marin et al. 2000, 2003; Hua et al. 2003)
- **Eddy forcing** (Jochum & Malanotte-Rizzoli 2004; Ishida et al. 2005)

Remote forcing

- **Linear wave dynamics** (McPhaden 1984)
- **Inertial jet** (Johnson & Moore 1997)
- **Arrested front** (McCreary et al. 2002).

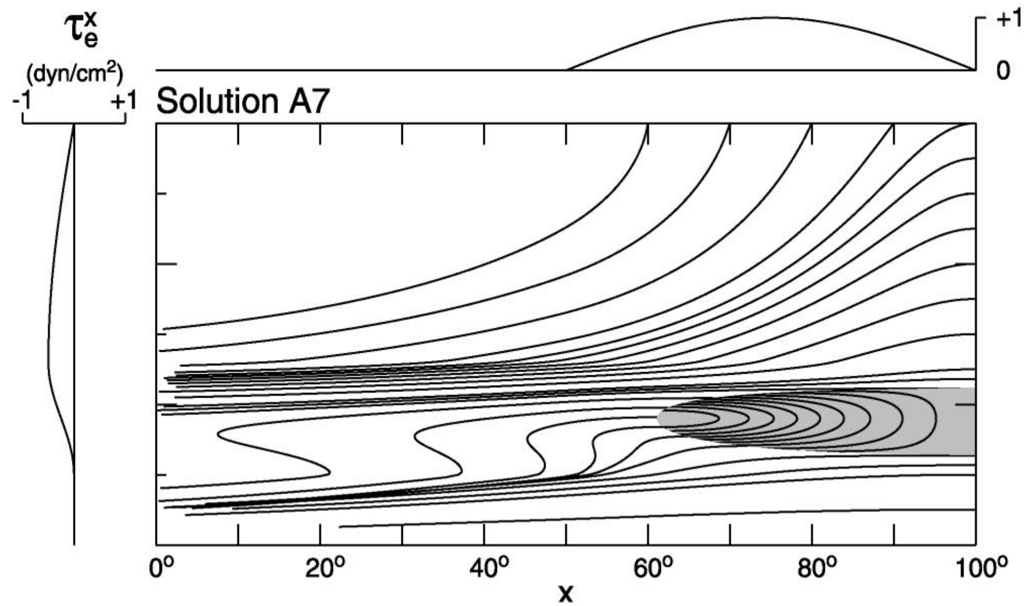


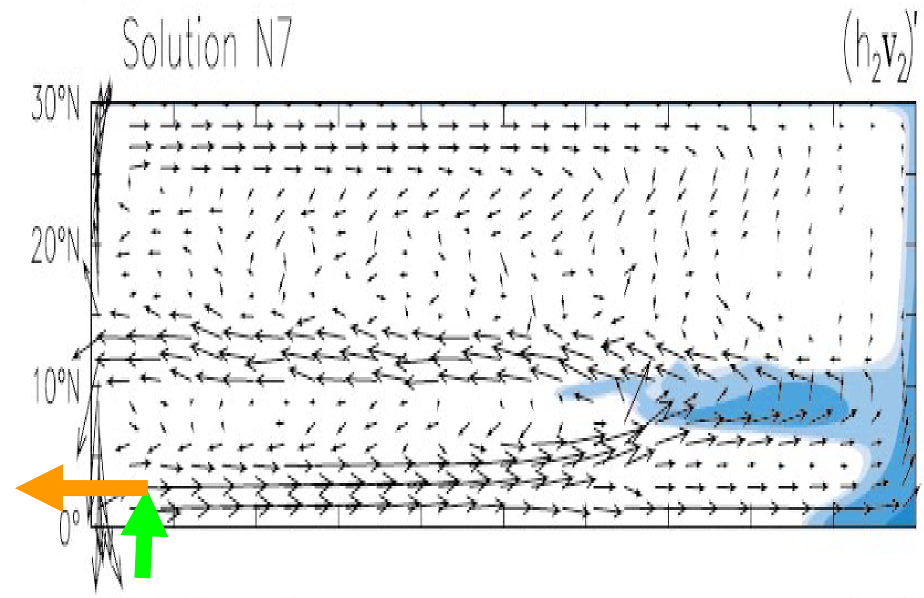
Arrested fronts in a 2½-layer model

In steady state, the total thickness field, $h = h_1 + h_2$, satisfies

$$\boxed{\left(\bar{u}_g - c_r\right) h_x + \bar{v}_g h_y = 0}$$

where u_g and v_g are geostrophic components of Sverdrup flow and c_r is the speed on a non-dispersive, $n = 2$, Rossby wave.





An analogous solution exists for the northern TJ. In this case, **there is upwelling in the Costa Rica dome**.

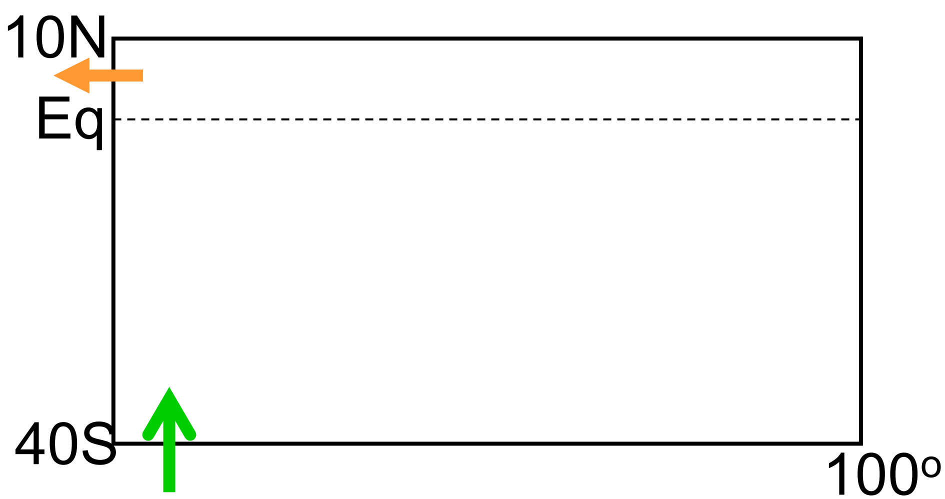
Arrested fronts in a GCM

Configuration

- **COCO 3.4** (Hasumi at CCSR, U Tokyo): level model; primitive equations on spherical coordinates.
- **$2^o \times 1^o \times 36$** levels → no eddies
- Constant salinity
- Box ocean: **$100^o \times (40^oS–10^oN)$ × 4000 m** for southern TJ

Forcing

- Idealized $\boldsymbol{\tau}^x$, $\boldsymbol{\tau}^y$
- **Inflow** of cool water (7.5 Sv; **$6^oC–14^oC$**) thru s.b.
- **Outflow** of warm water from $2^oN–6^oN$ thru w.b.
- Relax SST to **$T^*(y)$ = $15^oC–25^oC$**.



A hierarchy of solutions

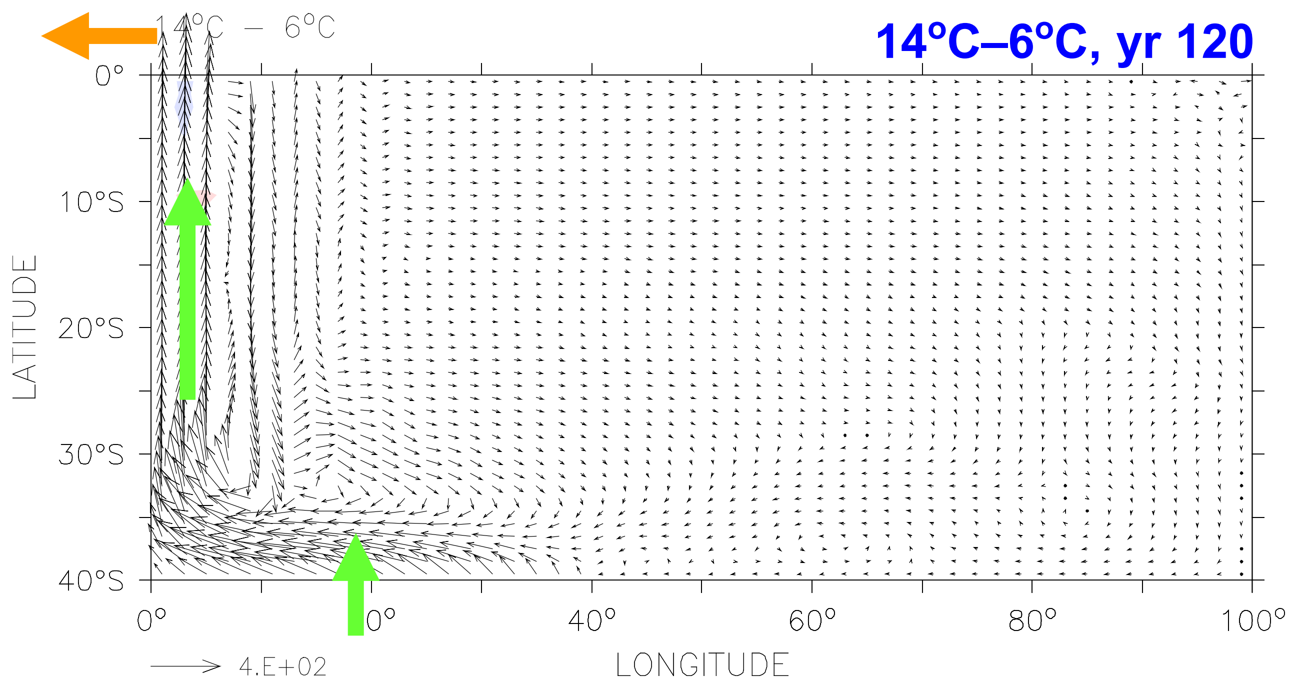
No wind

- Without wind, there is no interior Sverdrup flow. As a result, water flows directly from the inflow to the outflow port

Layer 2 is defined by the integral

$$\int_{6^\circ C}^{14^\circ C} dz\,(u, v)$$

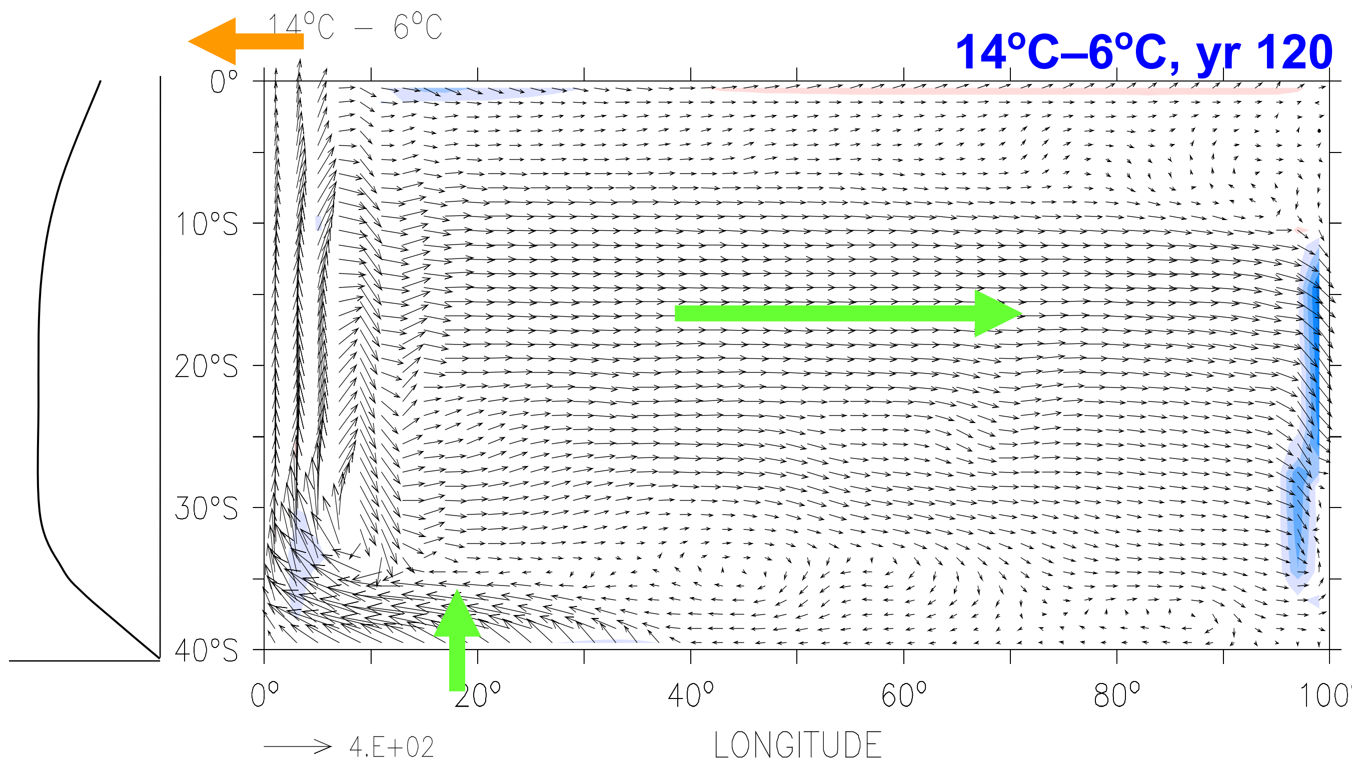
14°C–6°C, yr 120



τ^y **without curl** (zonally uniform)

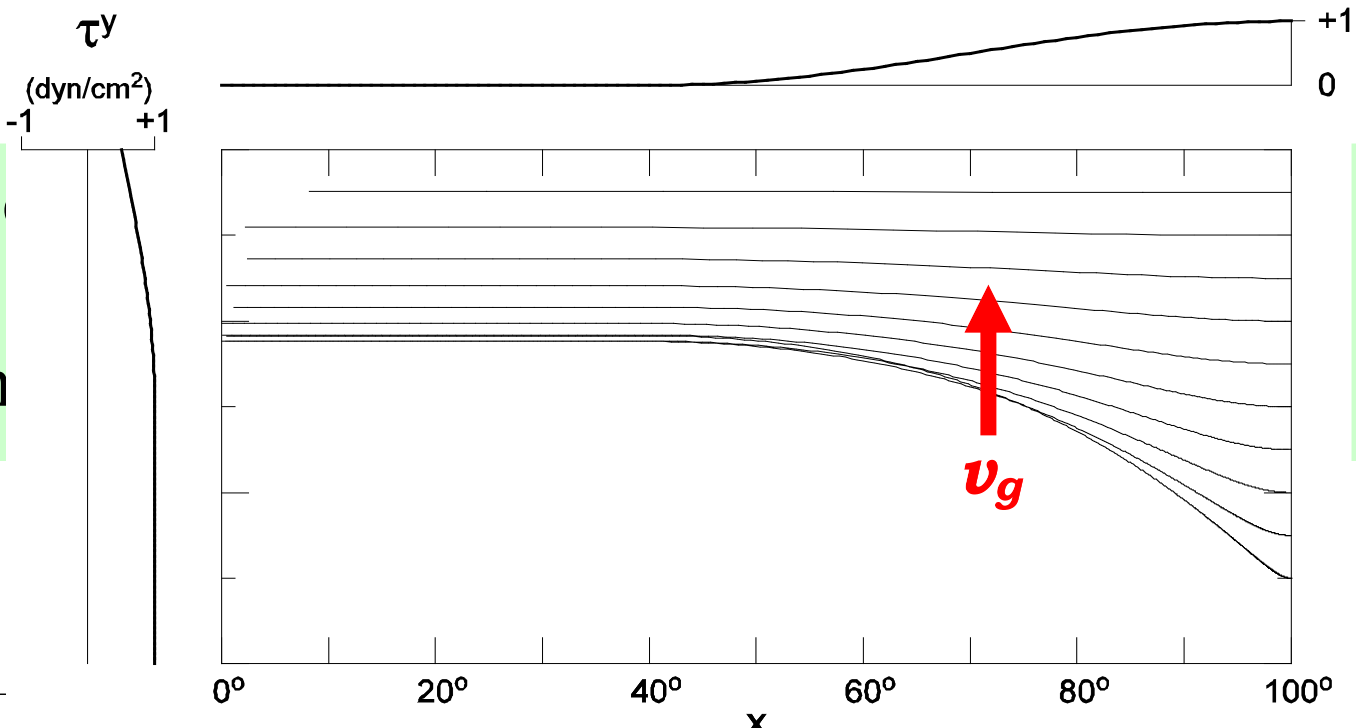
- Because of τ^y, upwelling shifts to the eastern boundary
- Because τ^y has no curl, there is still no interior Sverdrup flow and hence no v_g. So, layer-2 water flows zonally across the basin to supply water for the upwelling

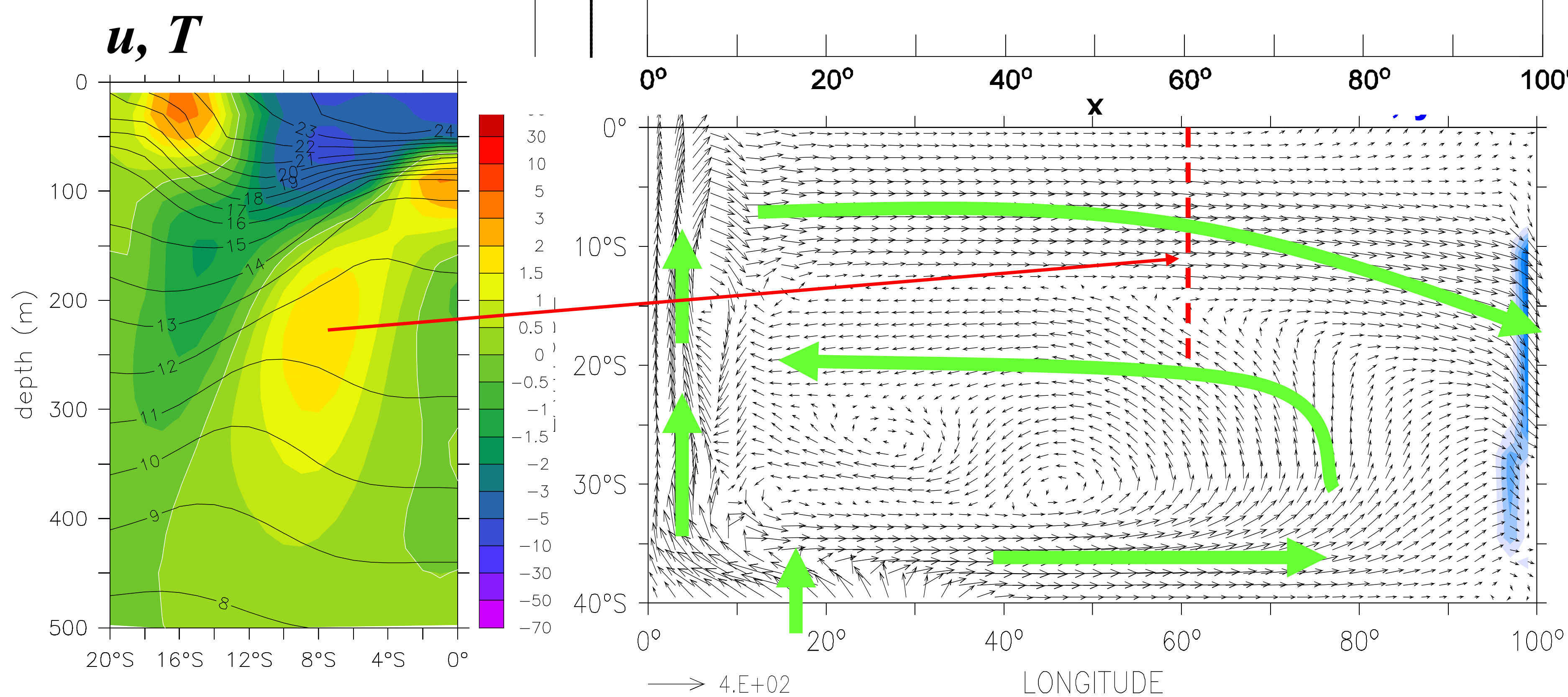
$$\tau^y = \tau_0 Y(y)$$
$$\tau_0 = 1 \text{ dyn/cm}^2$$



τ^y with curl

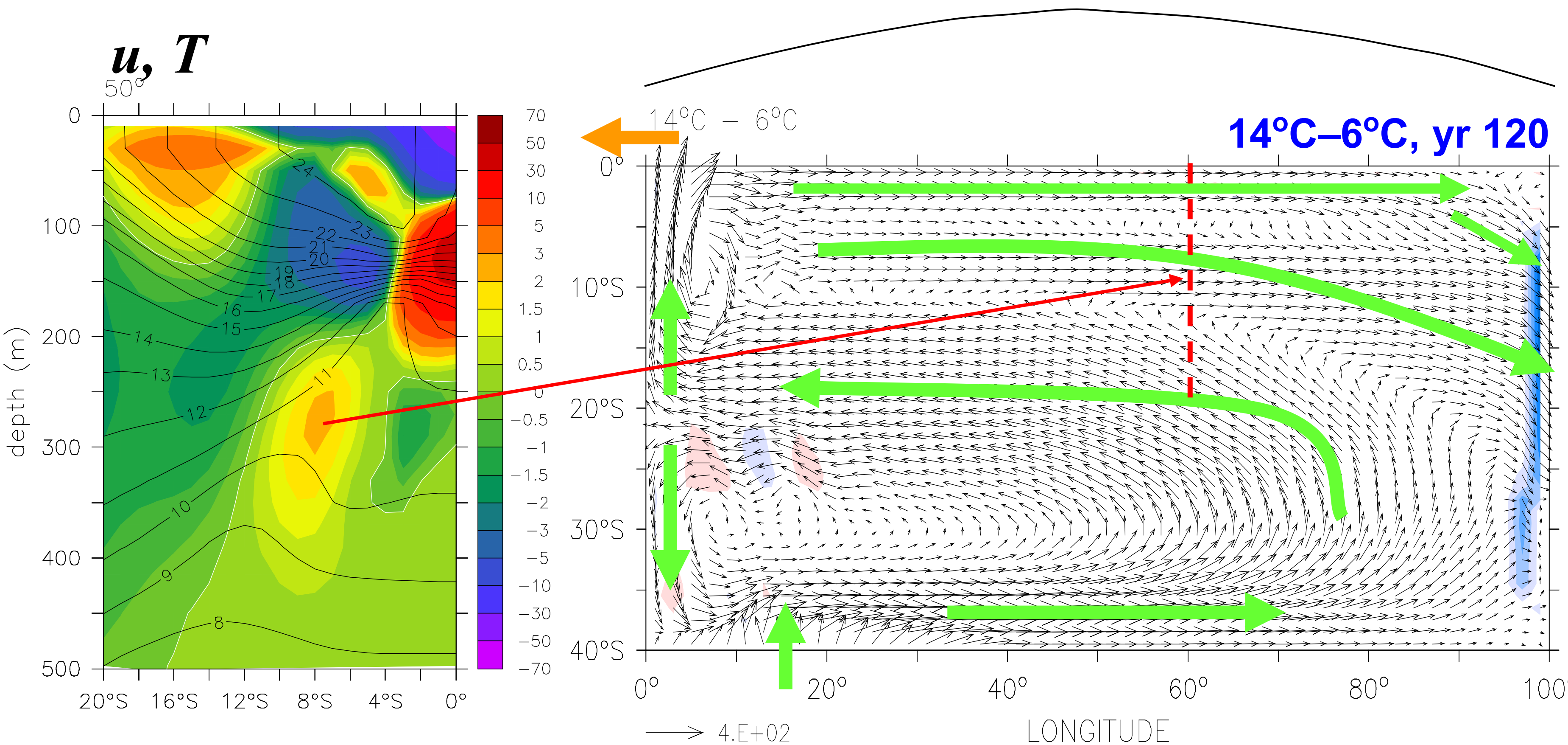
- Because τ^y has
a northward v_g.
the west to form



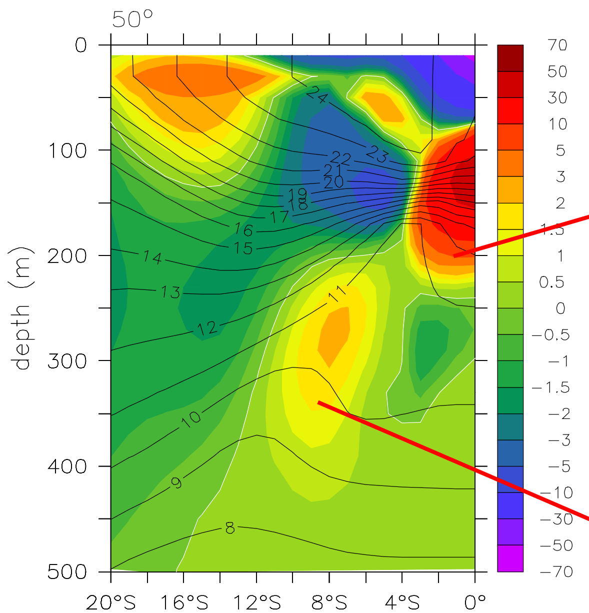


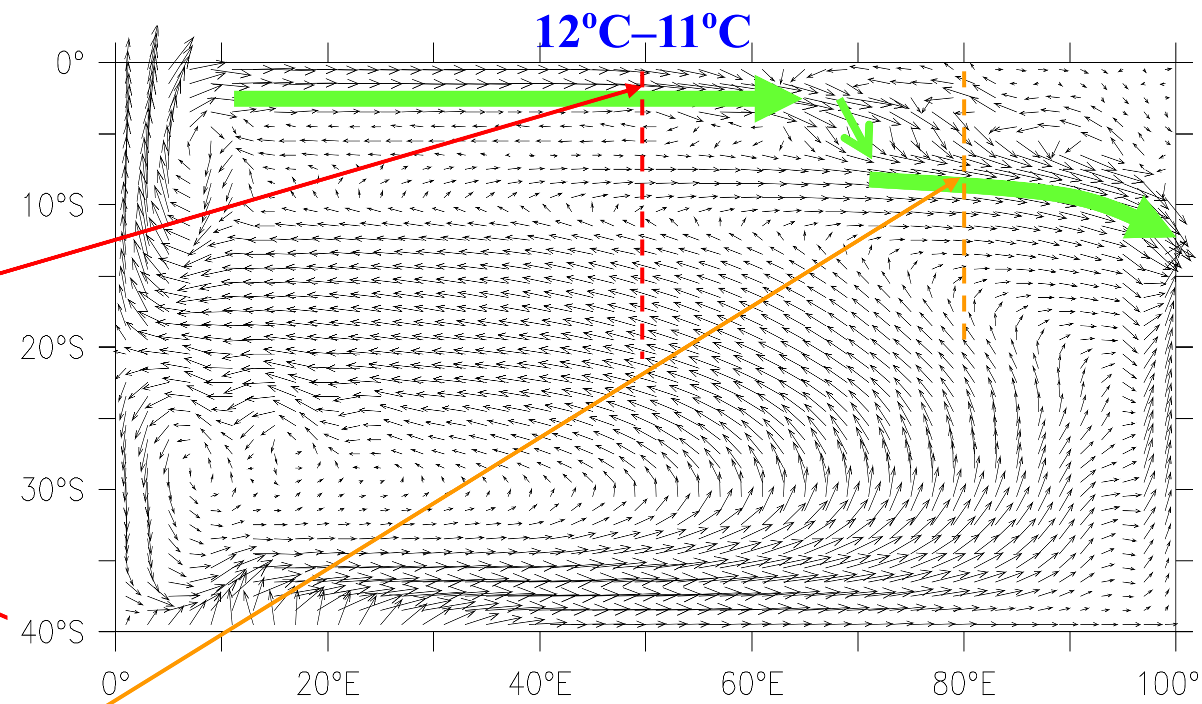
$\tau^x + \tau^y$ (control run)

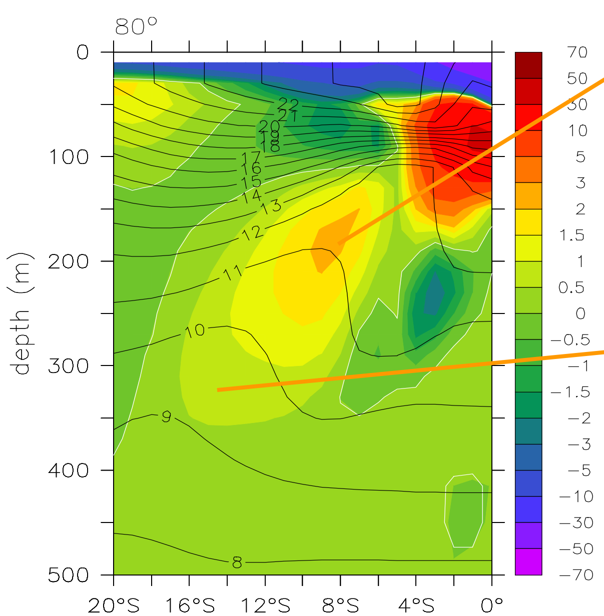
- Because of the additional zonal wind, v_g increases. As a result, the model TJ bends more equatorward, narrows, and strengthens



TJ pathways (control run)



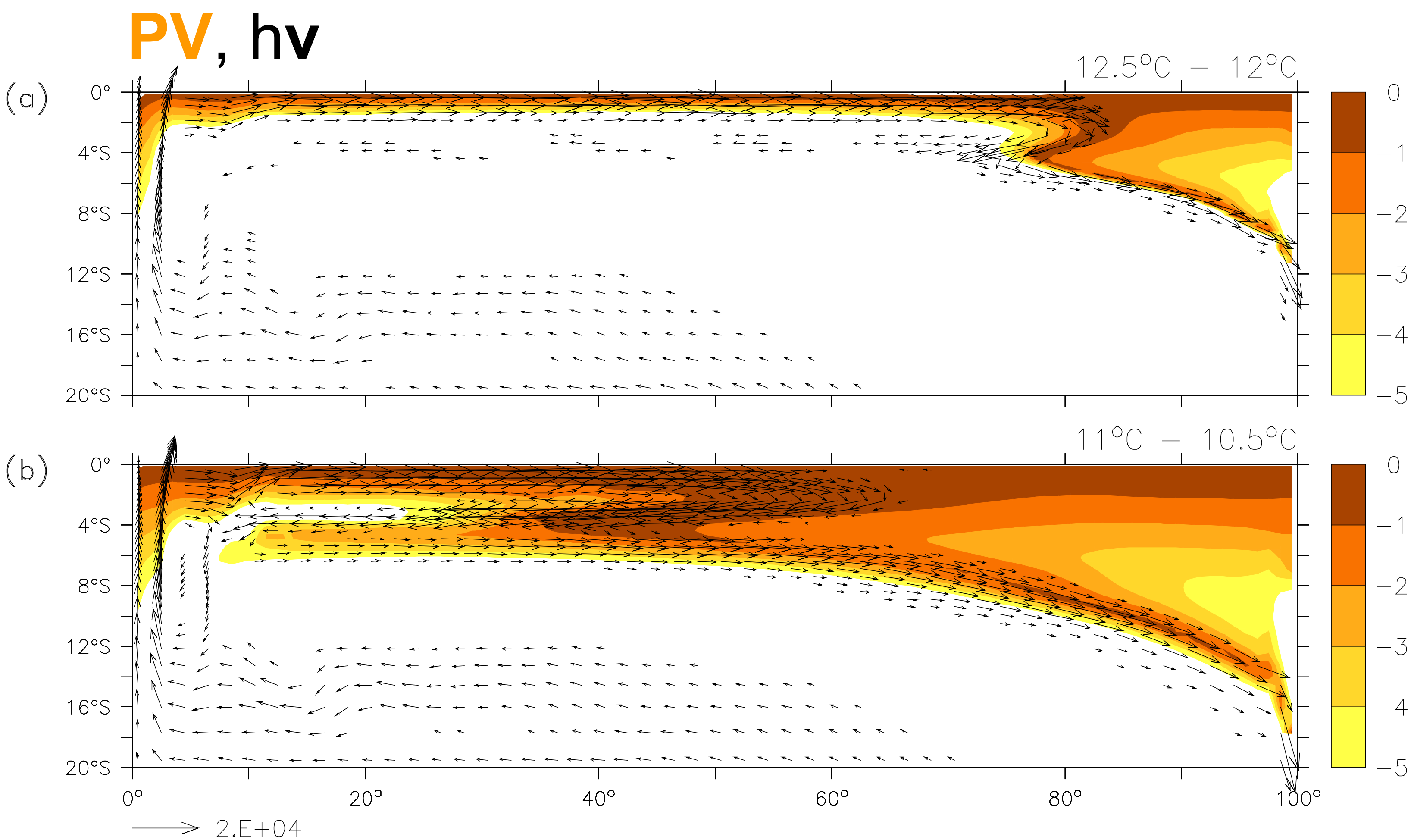




Due to these processes,
both **the TJ and EUC rise and warm to the east**,
consistent with the observed TJ.

TJ pathways (higher resolution run)

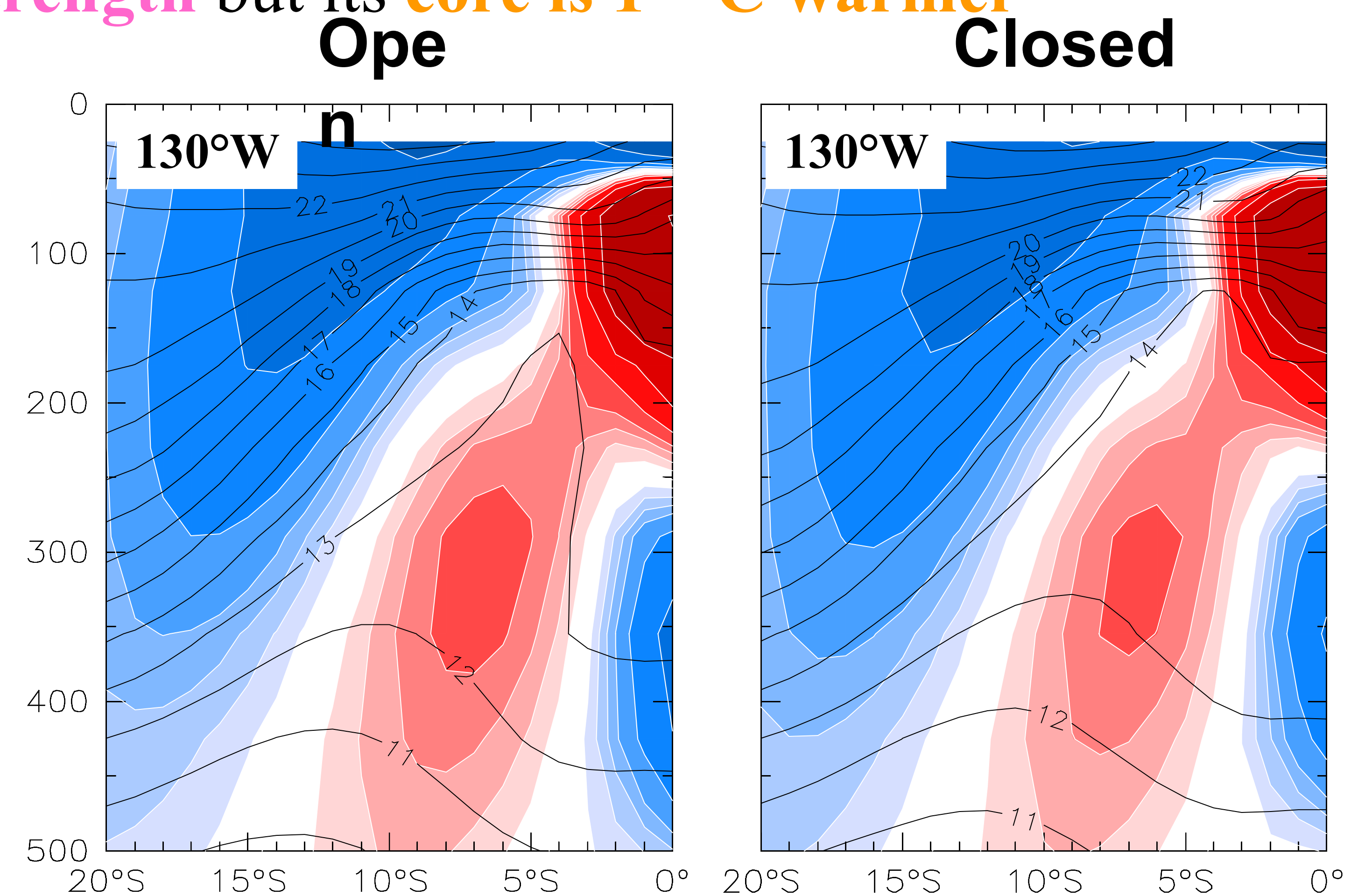
What happens as **resolution is increased further**, and the system enters an **eddy-resolving regime**?



Southern TJ in a global model

These properties suggest that the **model TJ is supplied primarily by an overturning cell internal to the Pacific**, one that is somewhat broader and deeper than the STCs.

strength but its core is 1˚ C warmer



Future

Topics

1) Equatorially trapped waves and TIWs

2) El Nino and other climate modes

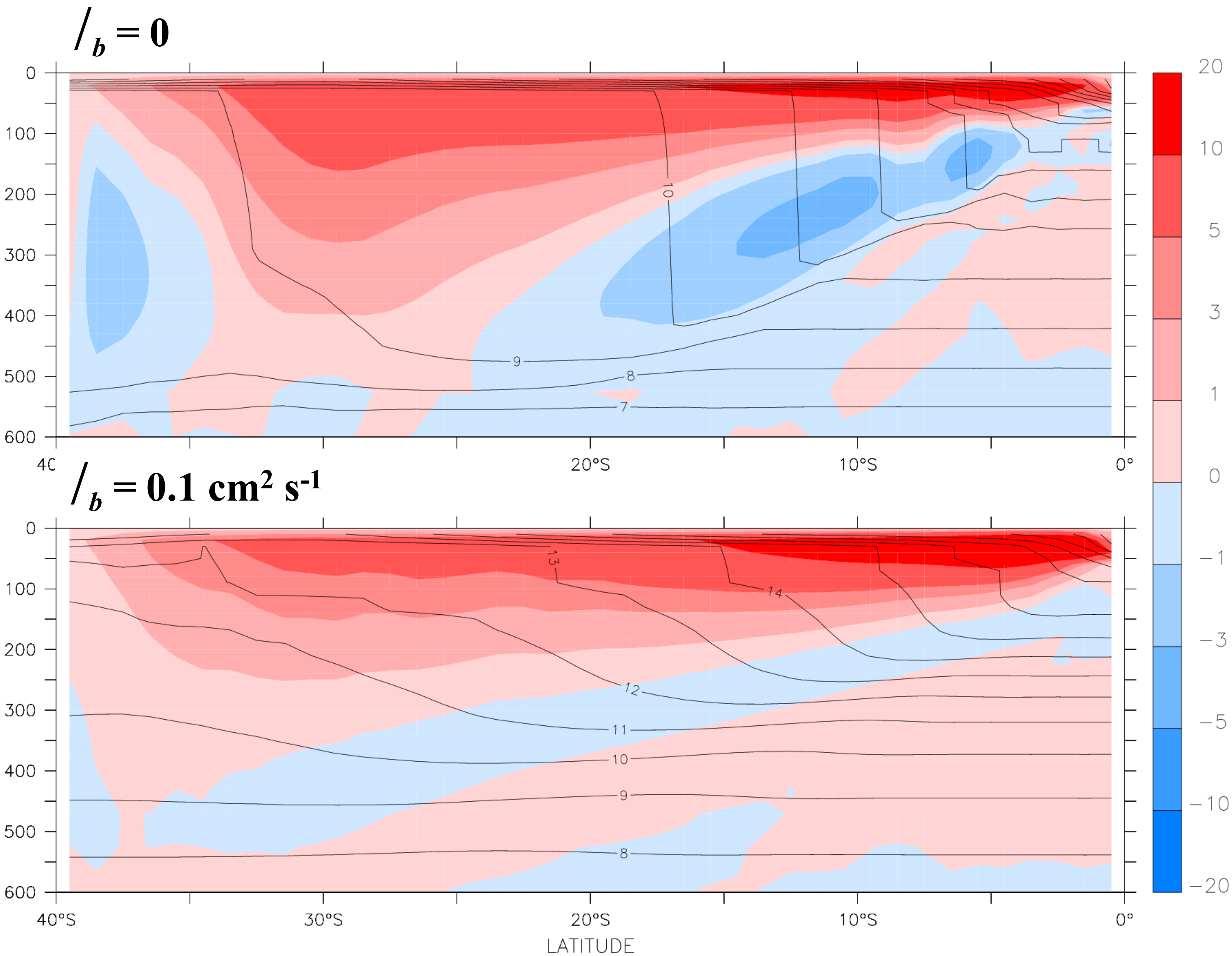
3) Deep Equatorial Jets and other deep currents

4) Equatorial Undercurrent, Tsuchiya Jets, and other near-surface currents

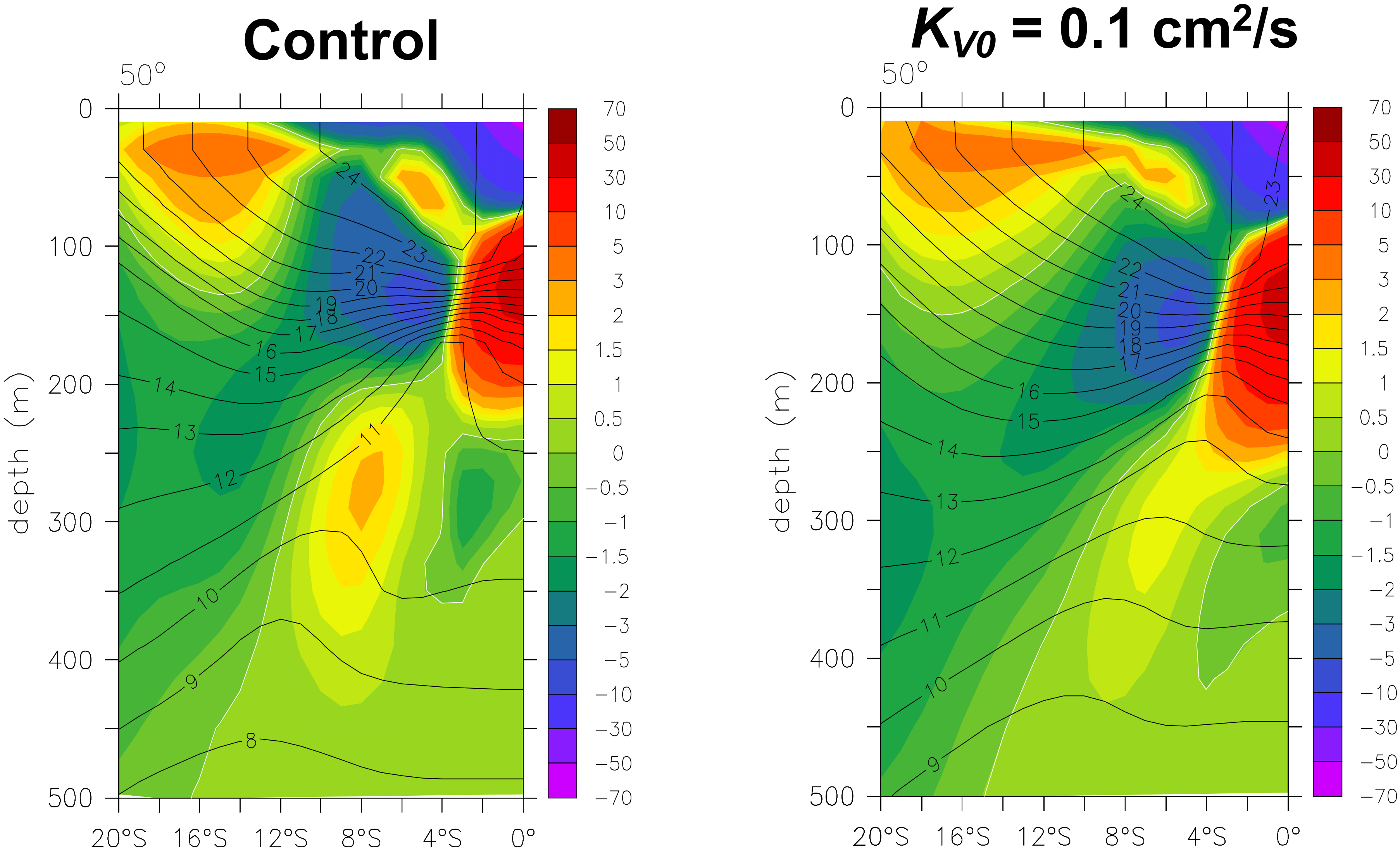
5) Subtropical Cells and deeper overturning cells

6) Importance of mixing

Eastern boundary



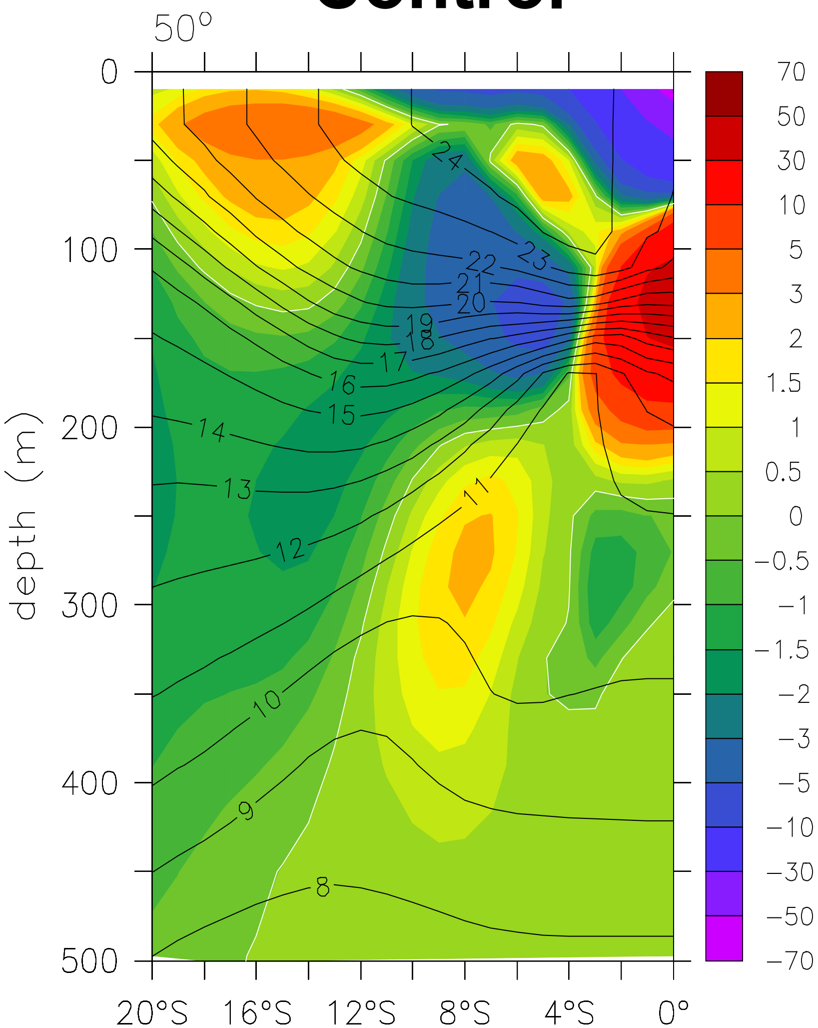
Sensitivity to vertical diffusivity



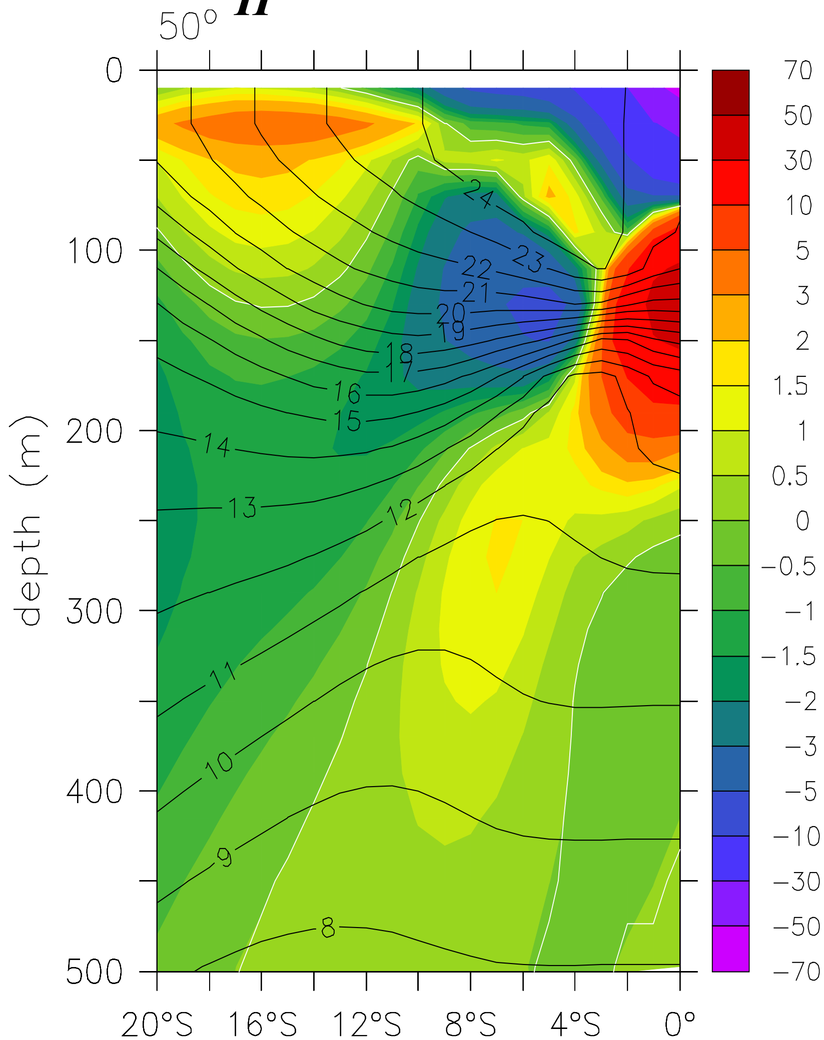
The **TJ weakens**, and **half the upwelling shifts to equator**

Sensitivity to K_H

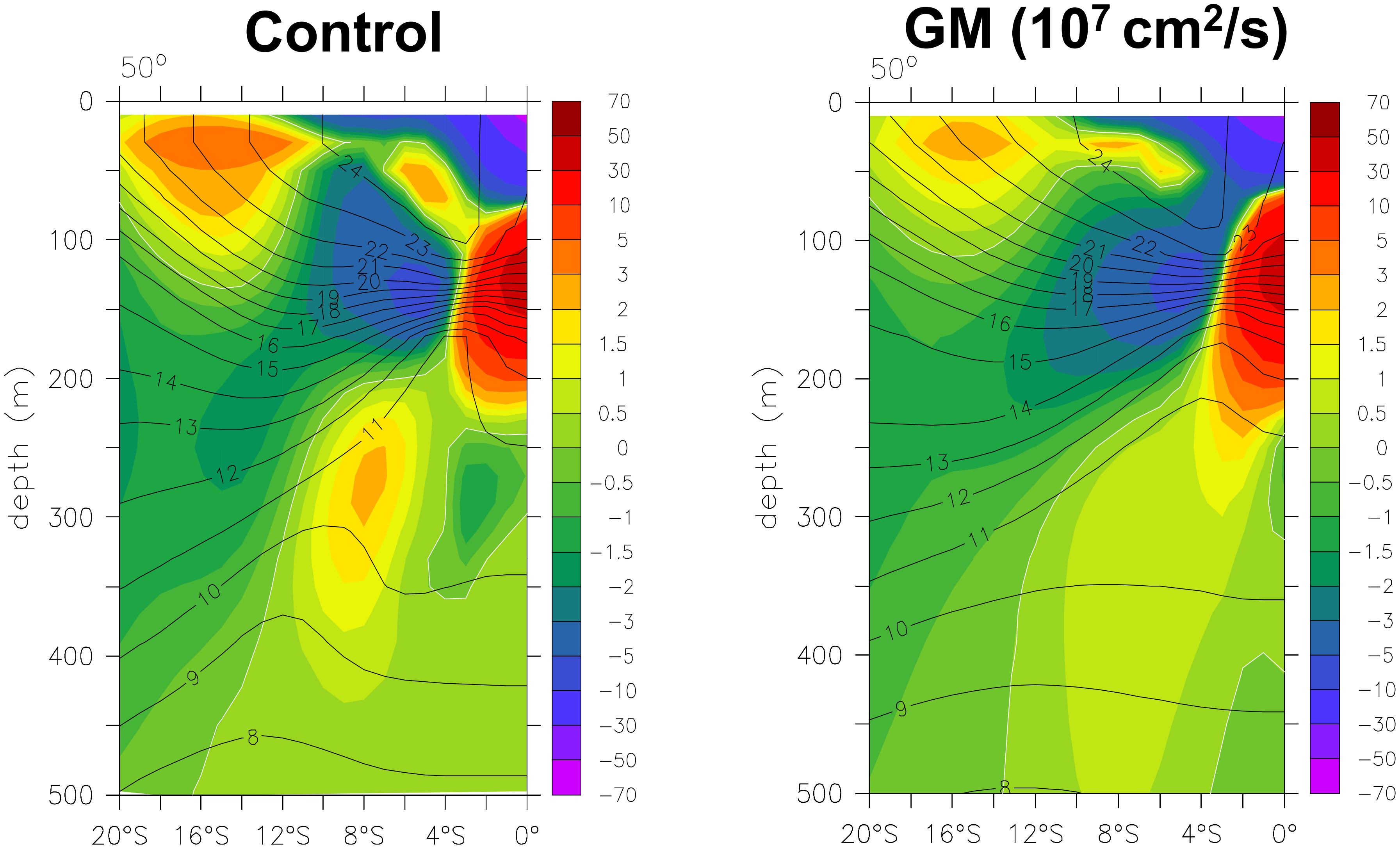
Control



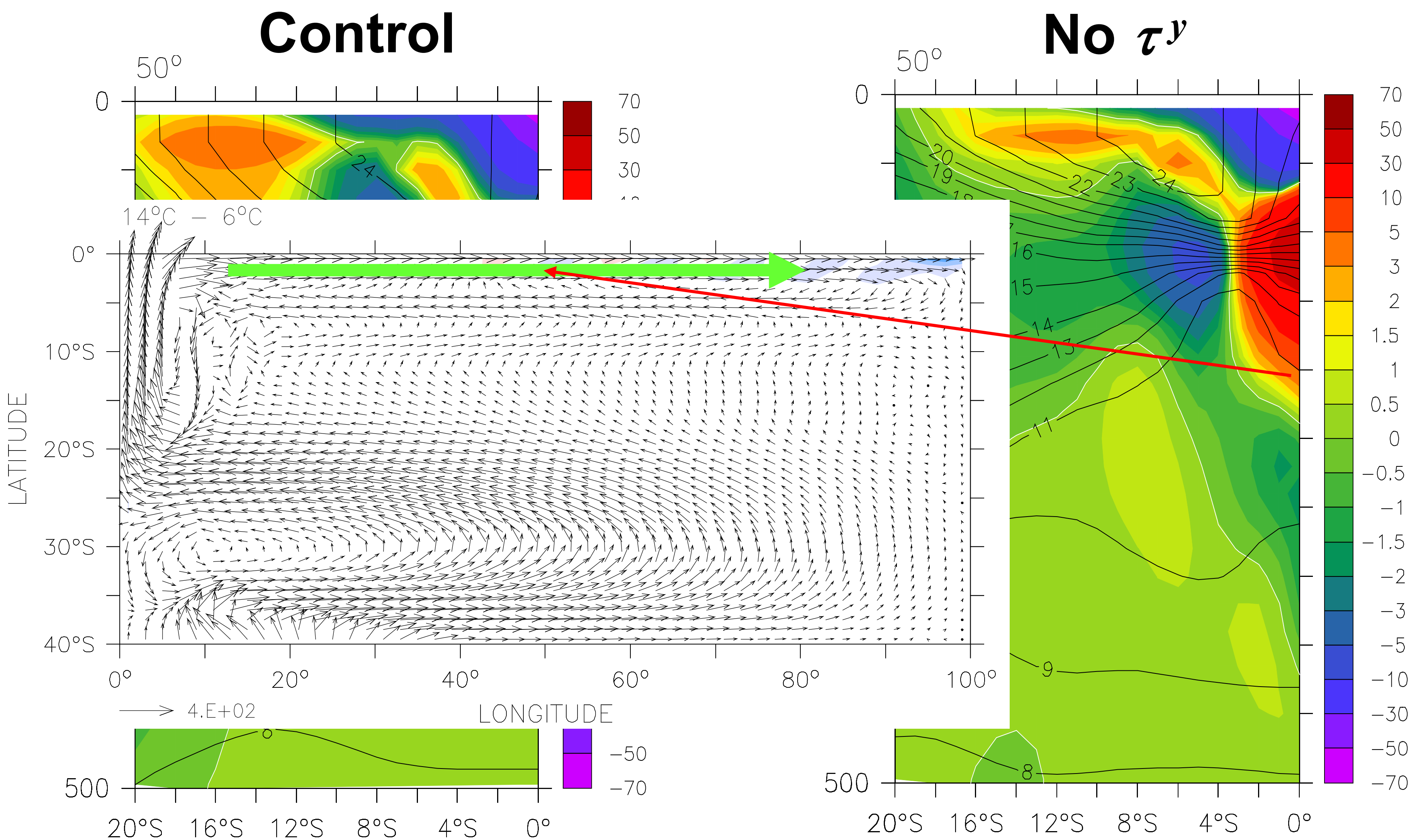
$K_H = 10^6$ cm²/s



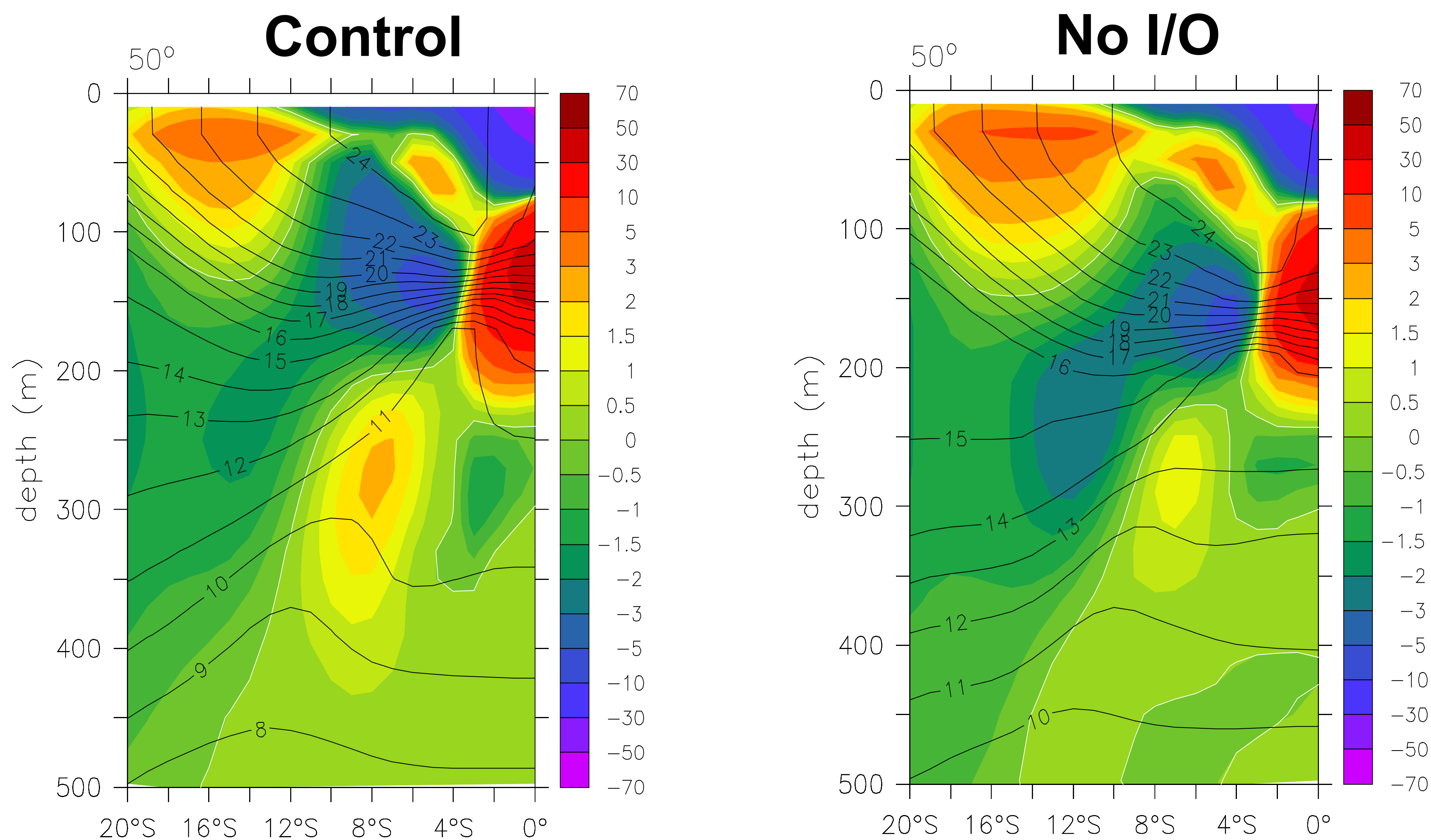
Sensitivity to GM diffusion



No τ^y



No inflow/outflow



The **TJ weakens**, and its core temperature rises by 2.5° C