Horizontal Patterns of Deep Circulation

So far, we concentrated on meridional circulation pattern. Does $v$ depend on longitude? Is there any $u$?

Note, if $LHV = 15$ Sv, $H = 4000$ m, $L = 6 \times 10^6$ m $\Rightarrow V = .06$ cm/s
Rather hard to observe.

Stommel-Arons theory provides framework for understanding horizontal deep flow.
Stommel, Arons, Faller (1958, *Tellus*)
Stommel and Arons (1960a,b, *Deep-Sea Res.*)
See Collected Works of Henry M. Stommel and
Ocean Circulation Theory

Idealize abyss as single homogeneous layer of uniform depth $H$

<table>
<thead>
<tr>
<th>thermocline</th>
<th>$z=H$</th>
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<tbody>
<tr>
<td>abyss</td>
<td>$z=0$</td>
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Geostrophy:

\[ f v = -\frac{1}{\rho_0} p_x \]

\[ f u = \frac{1}{\rho_0} p_y \]

Curl of momentum eqs:

\[ f(u_x + v_y) + \beta v = 0. \]

Continuity:

\[ \int_0^H (u_x + v_y) dz + w(H) - w(0) = 0 \]

If \( w = 0 \) at \( z = 0 \), \( w = w_T \) at \( z = H \), and \( \rho \) constant, then

\[ u_x + v_y = -w_T/H \]

Combine vorticity with continuity:

\[ \beta v = f \frac{w_T}{H} \]

Looks like Sverdrup, but now \( w_T \) is thermohaline upwelling instead of Ekman pumping. **Strongly** constrains \( v \) (and, via continuity, \( u \)).
Consequences of Upwelling

Assume downwelling localized, uniform upwelling everywhere else (just for simplicity; upwelling probably NOT uniform).

Produces STRANGE pattern
\( w_T > 0 \implies v > 0 \)
Flow is TOWARD source

How does water get away from source?
WBC

How much water flows in WBC?
Enough to satisfy mass balance.

Can reproduce these effects in laboratory with rotating tank of uniform-density water.
Beta-effect? Sloping top or bottom introduces similar behavior.
Fig. 2. Diagram of circulation induced in rotating sector by source $\oplus$ and sink $\ominus$ positioned as shown.

Fig. 3. Sketch of flow pattern expected with source $\oplus$ at apex of sector, surface of fluid rising uniformly. (Dashed arrows are sketched in to indicate portions of flow not given by elementary theory but evidently required by continuity.)

Stommel et al. (1958, *Tellus*)

Fig. 7. Photographs at 20, 80, and 220 minutes after the introduction of dye, showing the path followed by the source water ($S_0 = 50$ cc./min.) in flowing from a slot in the eastern wall near the apex to the sink ($S_1 = 5/6 S_0$) in the same wall near the rim (corresponding to Fig. 3).

Fig. 8. Photographs at 20, 60, and 80 minutes with $S_0 = 120$ cc./min. The source was at the apex and there was no external sink (corresponding to Fig. 3).
“Gyres” driven by upwelling not so strange when we consider Rotation effects

Upwelling drives convergence
Coriolis deflects converging flow
This creates cyclonic circulation
Beta-effect makes WBC flow more intense
Stommel and Arons’ model implies that WBC flows are large enough to be observable.

Swallow and Worthington (1957, *Nature*) placed a drifter into deep water off the east coast of N America and discovered the Deep Western Boundary Current (DWBC). Tracers such as CFCs also suggest DWBC.

Smethie et al. (2000, *JGR*)
Geostrophic velocity shows DWBC in N Atl (from density measurements + “Pogo” floats)

Pickart and Smethie (1993, JPO)
Flow Across the Equator

\[ \beta v = f \frac{\omega_T}{H} \]

At equator, \( f=0 \Rightarrow v_I = 0 \)
Flow across equator all in WBC

In opposite hemisphere, \( f \) is opposite sign \( \Rightarrow \) upwelling makes poleward interior flow in each hemisphere

For large enough interior flow, WBC may actually reverse sign

Fig. 13. Circulation pattern in sector bounded by meridians and latitude circles. Boundary currents will be present along north and south boundaries as well as along the western boundary. Single concentrated source.
Stommel’s Schematic of Global Deep Flow
Shows WBC’s and “Interior” Flows
Observations of DWBC and other deep flows in Atlantic (Sv)
S’ward: NADW
N’ward: AABW
Filled: current meters
Open: hydrography

Note: severe sampling problems with this data; deep floats in S Atl went in opposite directions in different years

from Hogg in Ocean Circulation and Climate
Pacific Ocean

Hydrographic estimates of deep transport:
24 N: 4.9 – 9.1 Sv
10 N: 9.6 Sv

Also some evidence of deep flow in Indian Ocean

Hogg, in *Ocean Circulation and Climate*
Some limitations of Stommel’s schematic:
• Upwelling probably isn’t uniform
• 2 layer structure is oversimplified, for instance AABW forms layer below NADW
• topographic features and thermocline shape distort beta-effect

Equal and opposite transports should occur in thermocline
Thermocline flow = combination of thermohaline + wind-driven