Westward Intensification of the Mean Circulation on the Bering Sea Shelf

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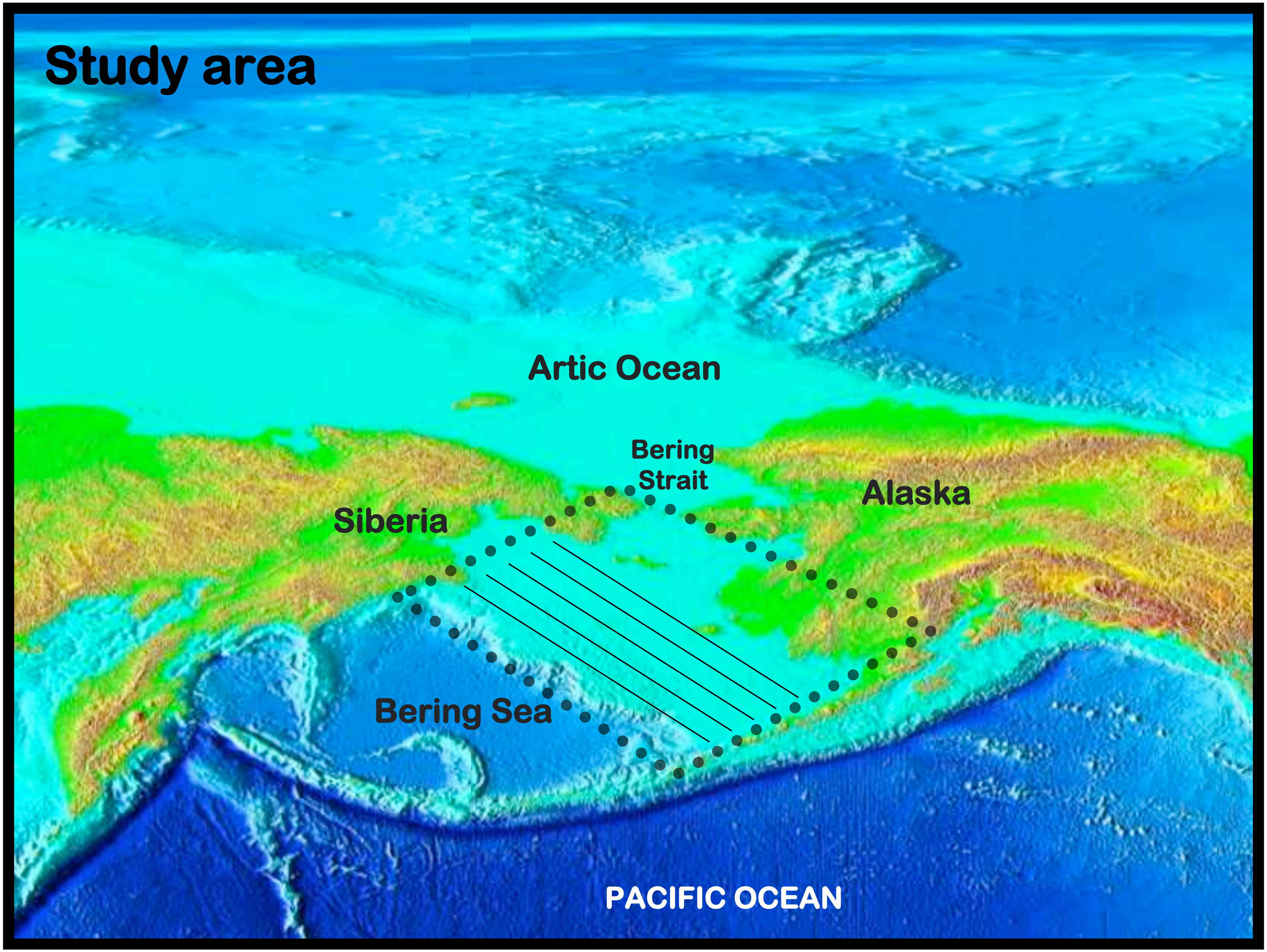
Outline

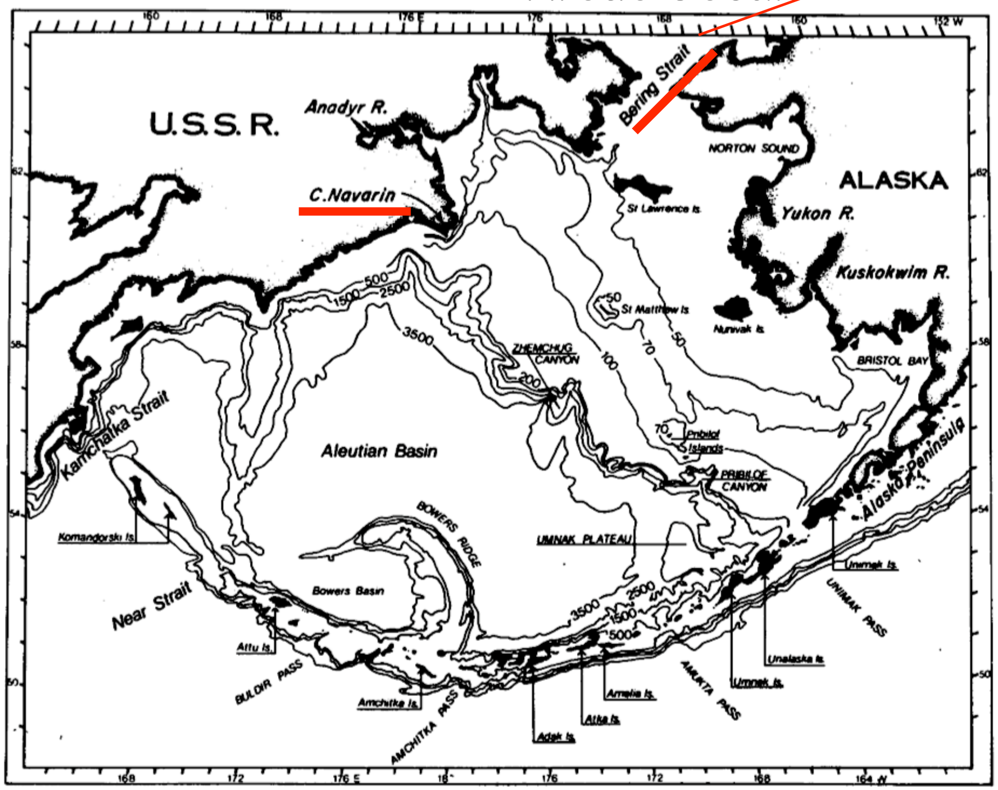
1. Introduction
2. Oceanographic Background of Bering Strait Outflow
3. Laboratory Model
4. Numerical Model
5. Conclusions
5. Study guide questions

1. Introduction


Study area
Artic Ocean
Bering
Strait
Siberia
Alaska
Bering Sea
PACIFIC OCEAN

Mean: 0.5 - 1.0 Sv
northward

Arctic Ocean



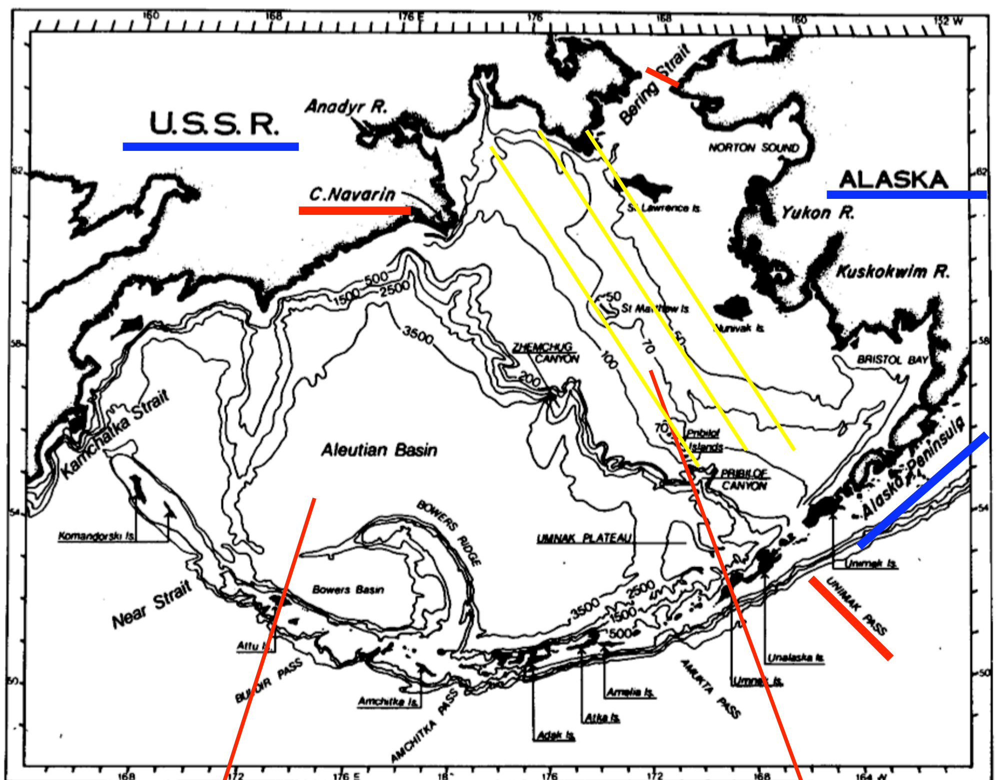
The Bering Sea (depth in meters)

Thesis:

Bulk of the transport supplying the Bering Strait outflow occurs in the west, crossing the shelfbreak near Cape Navarin and flowing northward along the Siberian coast.

Consequence: significant mean cross-isobath flow must exist from the shelfbreak (~170m depth) to the Strait (~50m depth).
Dynamical implications: draw Bering Strait outflow across a shoaling bottom on the rotating earth.
This can explain the apparent **Westward Intensification**.

Arctic Ocean



Bounded by land on three sides

Isobaths

Bering Strait: narrow (85km), shallow (50m)

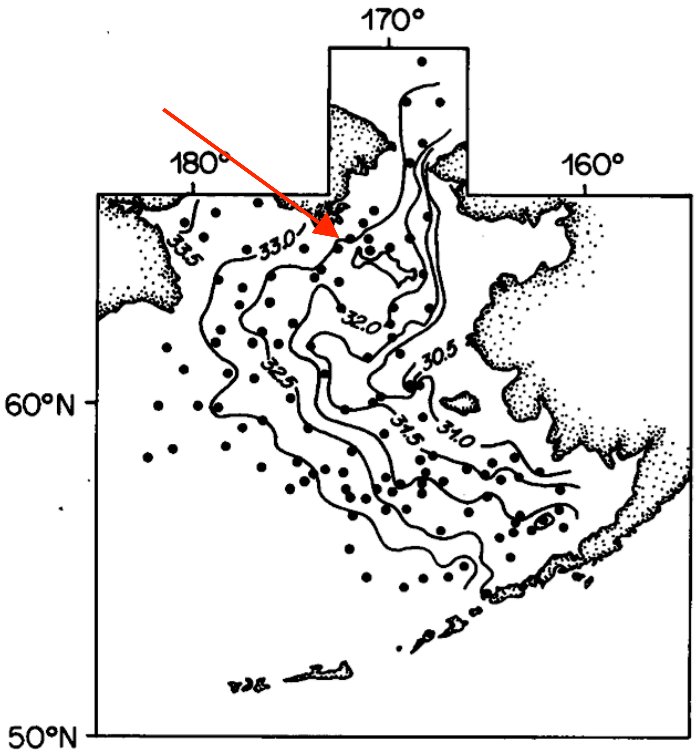
River runoff onto the shelf

40% abyssal plain (>3500m)

40% continental shelf (<200m)

2. Oceanographic Background of Bering Strait Outflow

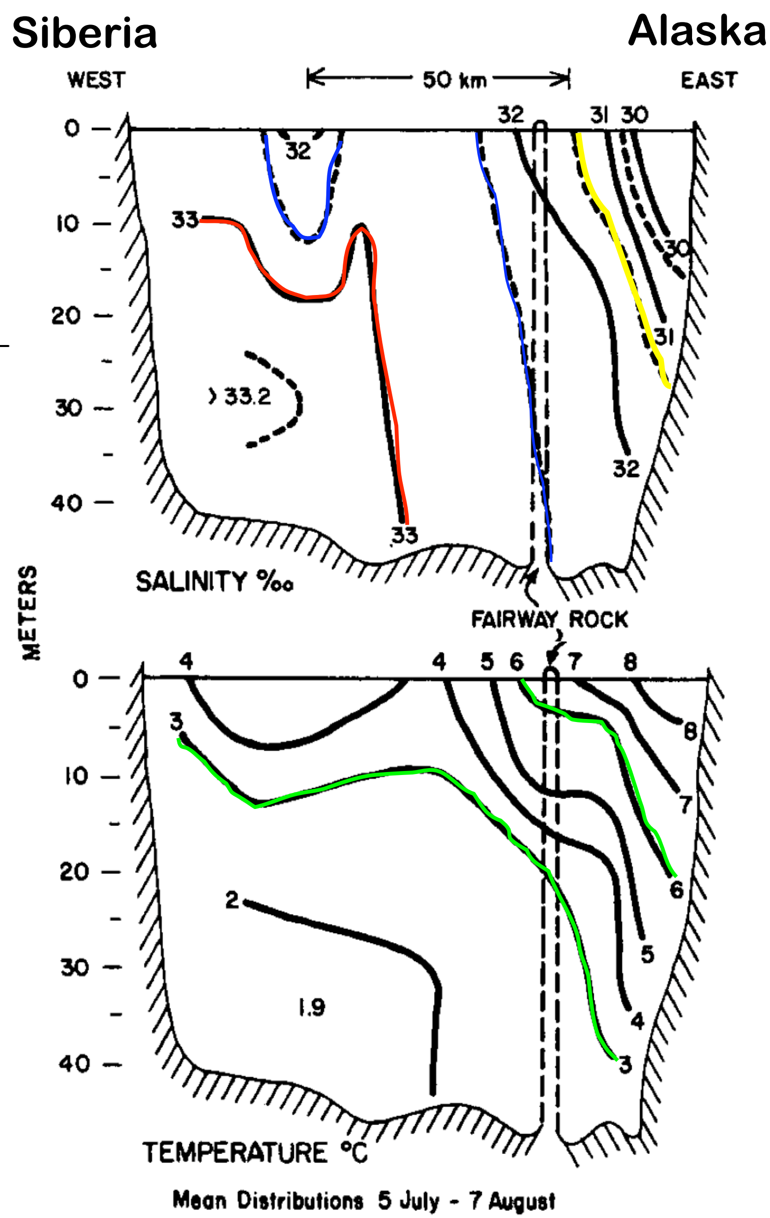
• Classify waters on the shelf by <u>salinity</u>



Salinity distribution at the bottom of the shelf in summer 1962-64

Significant feature:
High S tongue, extending from the deep basin near Cape Navarin through the Gulf of Anadyr to Bering Strait

Implication:
There is a considerable flow of water across the shelfbreak toward the Strait.



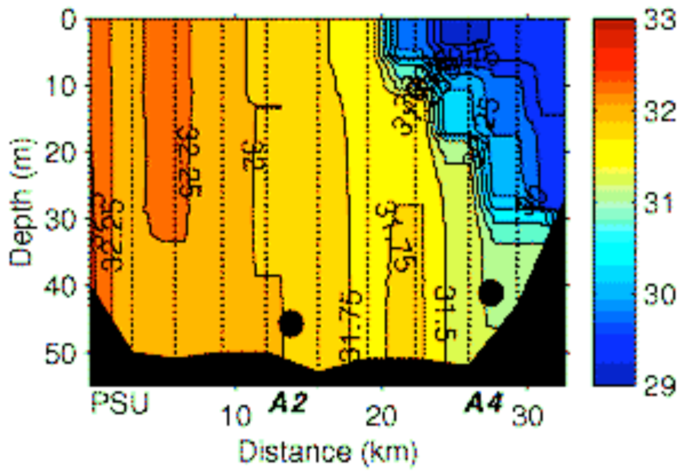
Mean S and T distribution for Bering Strait for early summer

- Higher S ("Anadyr water") on the Siberian side, lower S on Alaskan side
- Cooler water on Siberian side, warmer water on Alaskan side

- Coachman et al. (1975): three water masses based on S
  - Median S of 33 for Anadyr water
  - 32.5 for "Bering Shelf" water
  - 31.5 for "Alaskan coastal" water

Eastern Bering Strait section

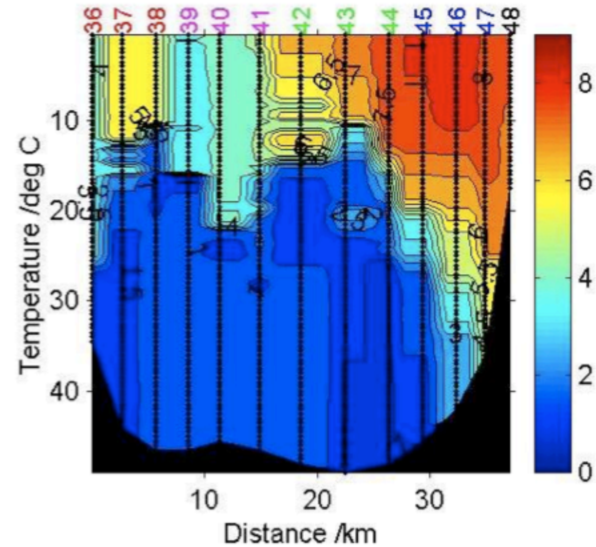
Diomede Island S Alaska



July 2003 CTD salinity section across the eastern channel of Bering Strait from Diomede islands (left) to Alaska (right). Note the fresh (warm) ACC on the Alaskan coast.

["Revising the Bering Strait Freshwater Flux into the Arctic Ocean", R. A. Woodgate and K. Aagaard, accepted for publ. in Geophysical Research Letters, Dec 2004]

Diomede Island T Alaska



Preliminary CTD Sections, Bering Strait

[Woodgate, 2005, Laurier Mooring report]

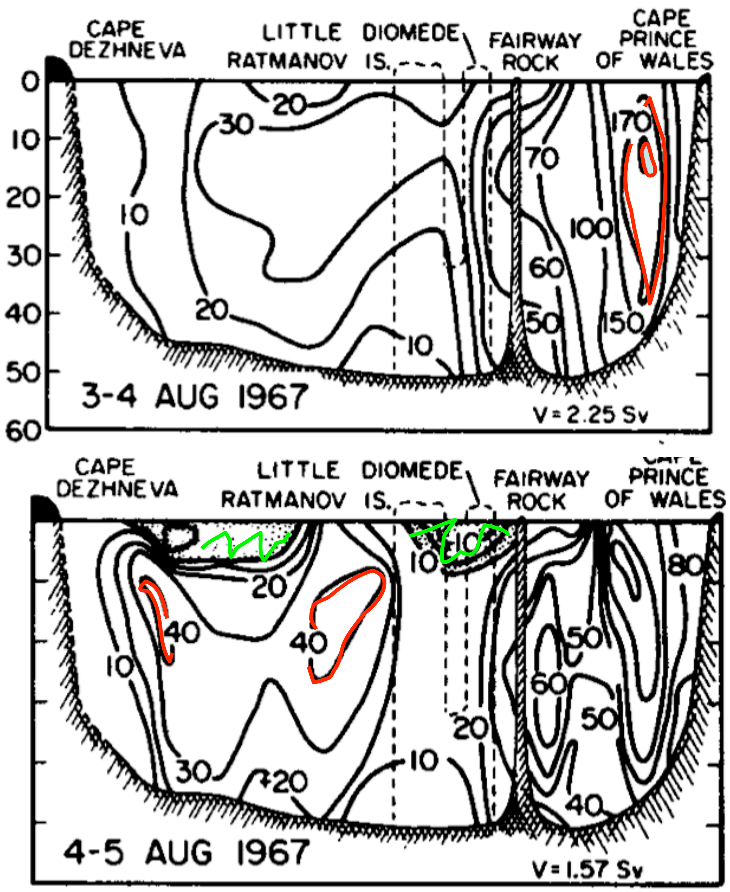
- **Available direct current measurements (in 1986!):**

  inadequate to estimate transports and to infer locations of currents across the shelf

- **Use of estimates of river runoff and S as a water mass tracer**

  → synthesis of the shelf water balance can be constructed

- **Bering Strait mean flow: driven by sea level difference between Pacific and Atlantic.**



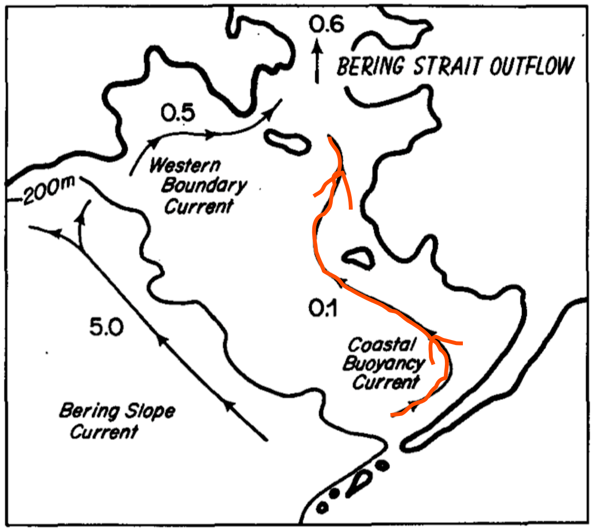
Velocity (cm/s) obtained by lowering a current meter from an anchored ship during Aug 1967.
Shaded areas: southward flow

Estimated transports: 2.2 and 1.6 Sv northward.

Hypothesized western boundary current probably supplies the northward flow of higher S water in the western 2/3 of the Strait.

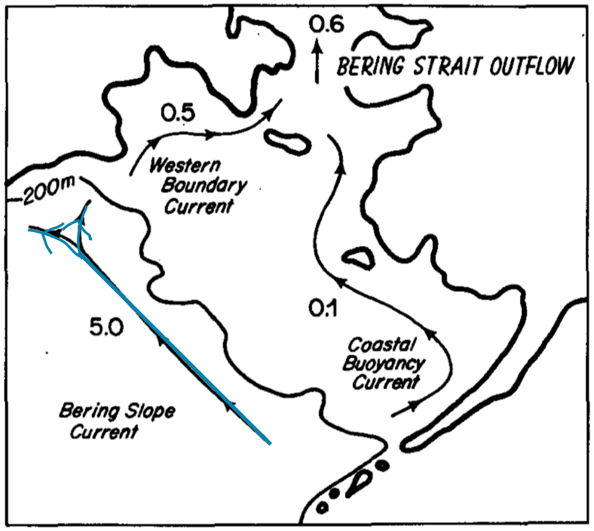
- **High speed jet (low S coastal water) on the Alaskan side**
- **Northward flow (higher S Anadyr water) on the Siberian side.**
- **Bering Strait flow: annual cycle with mean: ~0.6Sv**

- Two paths to the Strait:
- Eastern current appears to be weak in the south but persistent throughout the year.
- River runoff only accounts for a small fraction of the Bering Strait outflow.
- This coastal flow plus river runoff accounts for only 15% of the Bering Strait outflow.
- Roughly corresponds to the low S Alaskan coastal water found on the Alaskan side of the Strait.



Schematic of currents that supply the Bering Strait outflow. Numbers are transports in Sv, and are intended to suggest relative sizes of the flows only.

- Northwestward flowing Bering Slope Current: 5 Sv, but parallel to the slope until Cape Navarin
- Strong S signal close to Siberian coast, but no measurements.
- Most likely location of remaining 85% of the overflow supply: along the Siberian coast, in a western boundary current (coincident with S tongue).
- High S Anadyr water does not contribute 85% to the overflow transport in the Strait.
- Some of the water has to undergo significant modifications before it reaches the Strait.



Schematic of currents that supply the Bering Strait outflow. Numbers are transports in Sv, and are intended to suggest relative sizes of the flows only.

- The western boundary current contribution corresponds to the Anadyr and Bering Shelf waters.

3. Laboratory model

- **Concept of western-intensified source-sink flow was applied to Bering Strait Shelf:**
  - **Placement of a local sink near the center of a coast.**
  - **In the (topographic) β-plane analogy, the sink is in the center of the zonal northern coast.**
  - **Bottom with a slope of 1:5 was placed in 2m-turntable.**
  - **Rotation period of 15s (fluid experienced topographic β-effect).**

- Walls corresponds to eastern, southern, western walls of topographic β-plane.
- Tank covered with transparent plastic (little or no wind stress).
- Moveable sink placed at northern shoreline.
- Run commenced after fluid spin up, pump (sink) was started, evolution of the dye recorded by camera above the tank

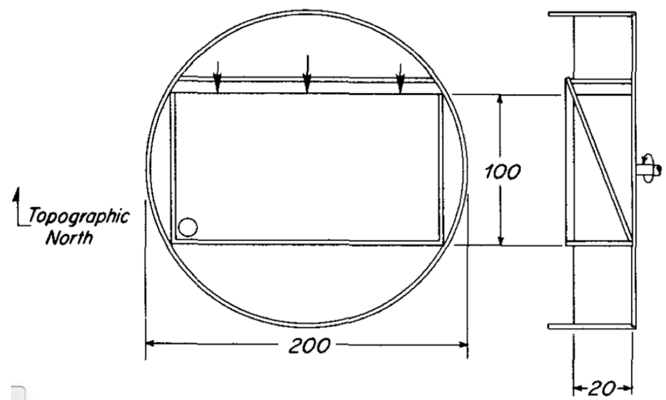
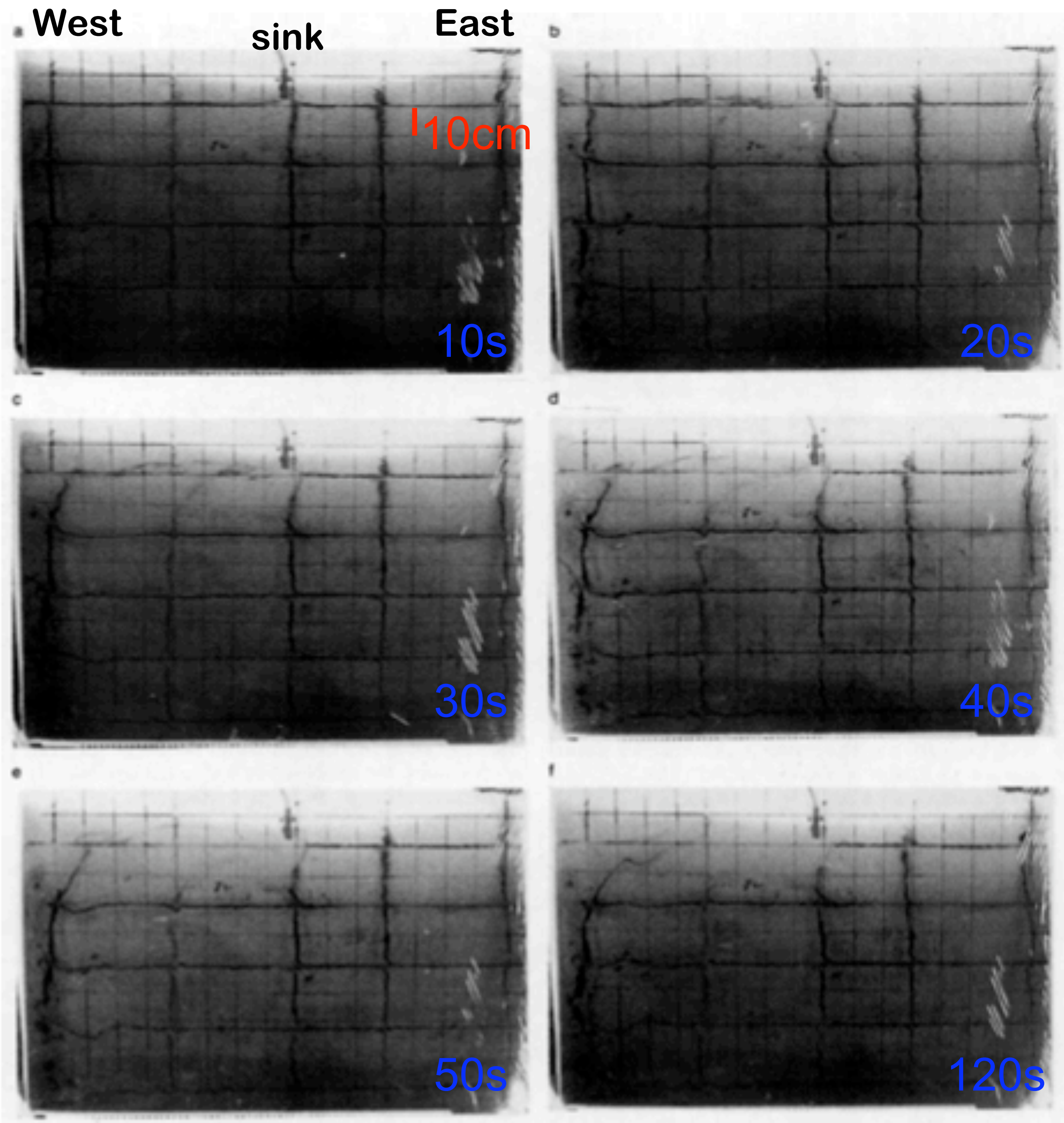
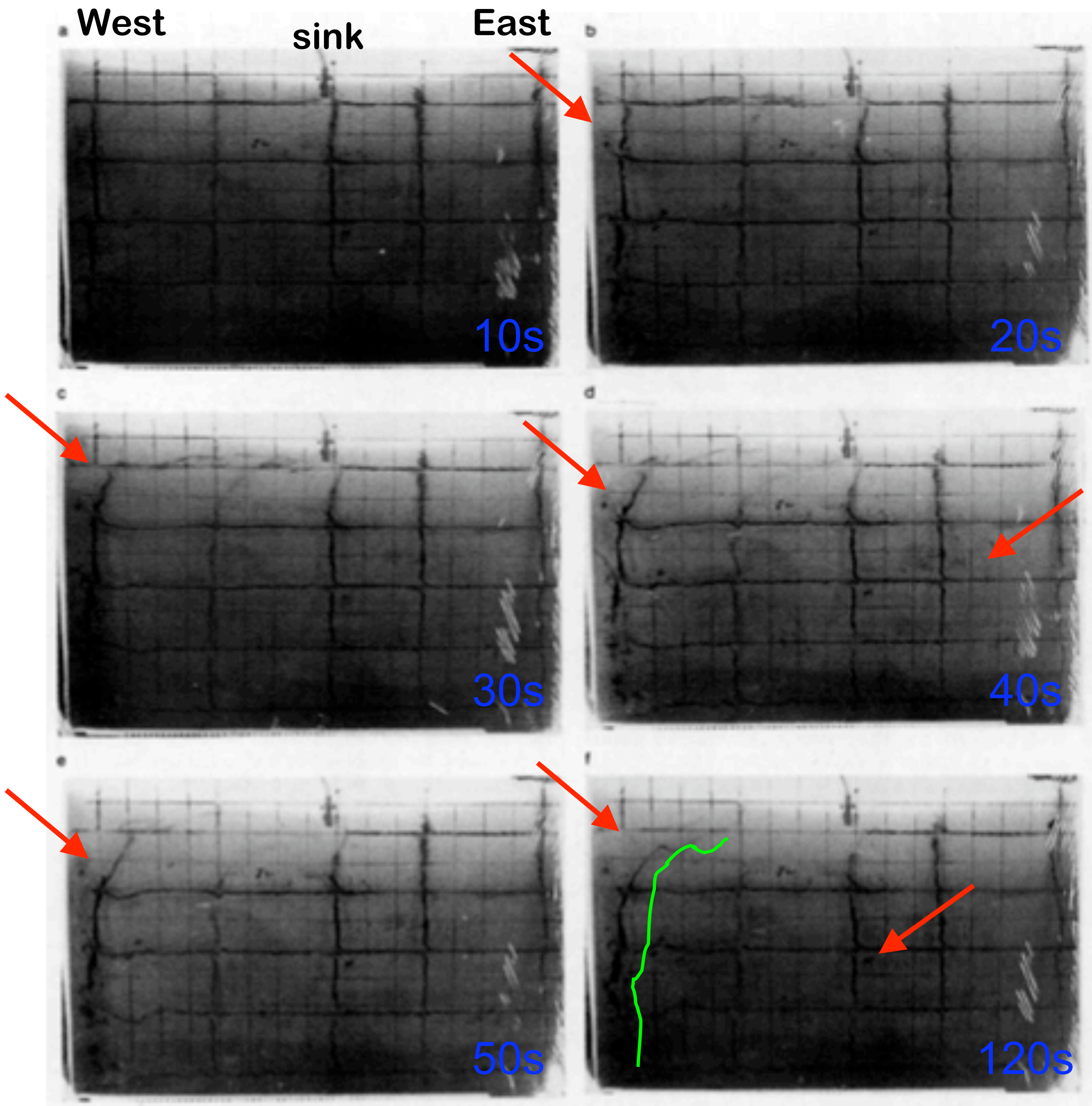


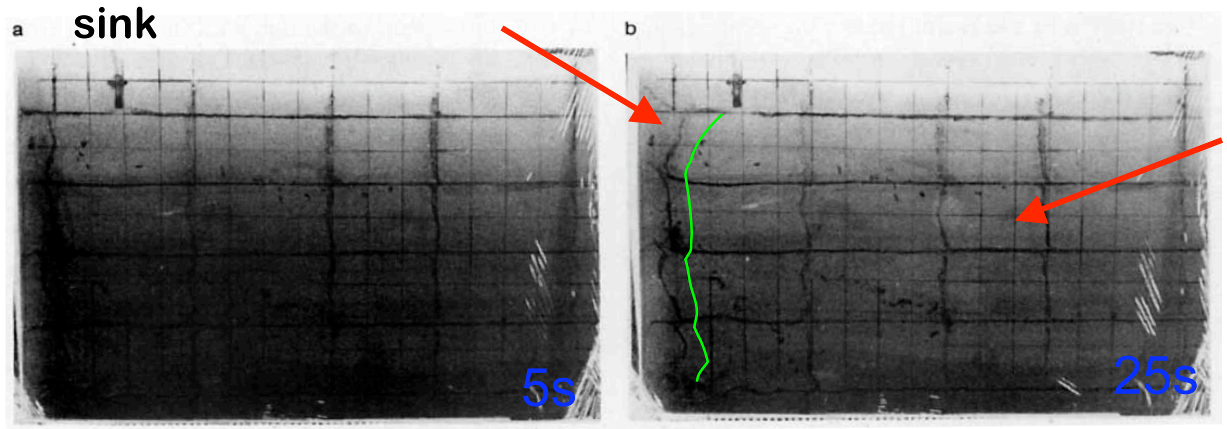
Diagram of laboratory apparatus. Left: top view, right: side view (with the vertical exaggerated by 2). Arrows show individual locations of the sink, circle in the lower left corner is the gravity return flow through a hole in the false bottom.



Top view of the evolution of a rectangular grid of dye in a rotating fluid with a sloping bottom. Dye has been in place for at least 60s before the first photograph was taken. Times after start of the sink are indicated in figure. Period of rotation: 15.05s. Volume flux of the sink: $24 cm^3 s^{-1}$

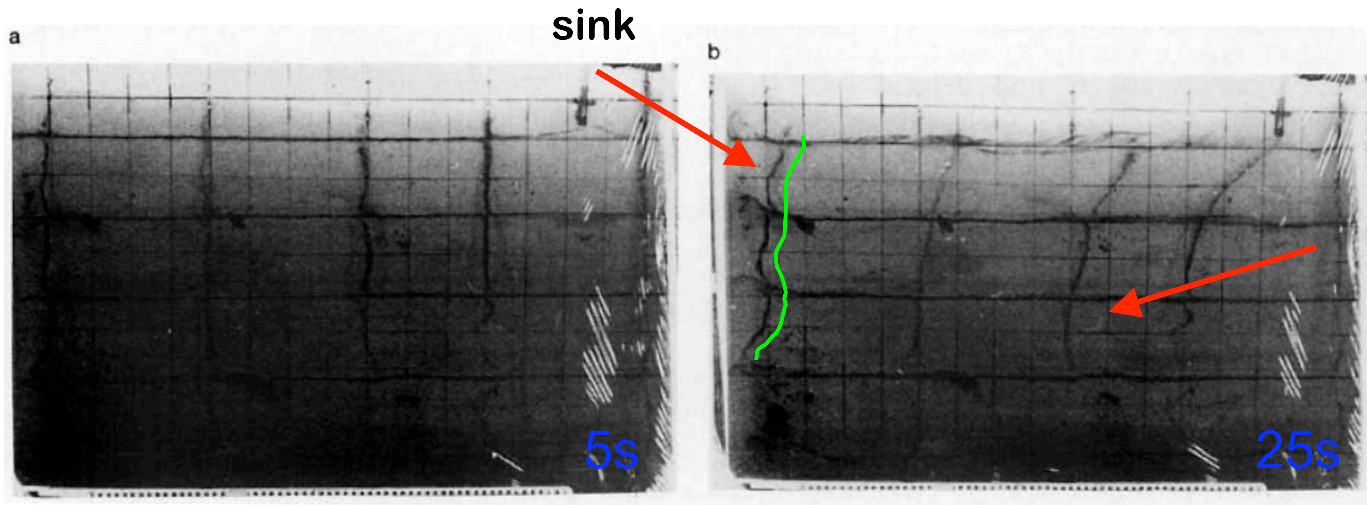


Current flowed up the western wall, along the shallow part of the shelf to the sink. Little or no current elsewhere, neither to the right (east) nor in the interior of the fluid.



Same type of experiment as in previous figure except sink is near the west coast. Period of rotation: 15.5s, volume flux: $16 cm^3 s^{-1}$.

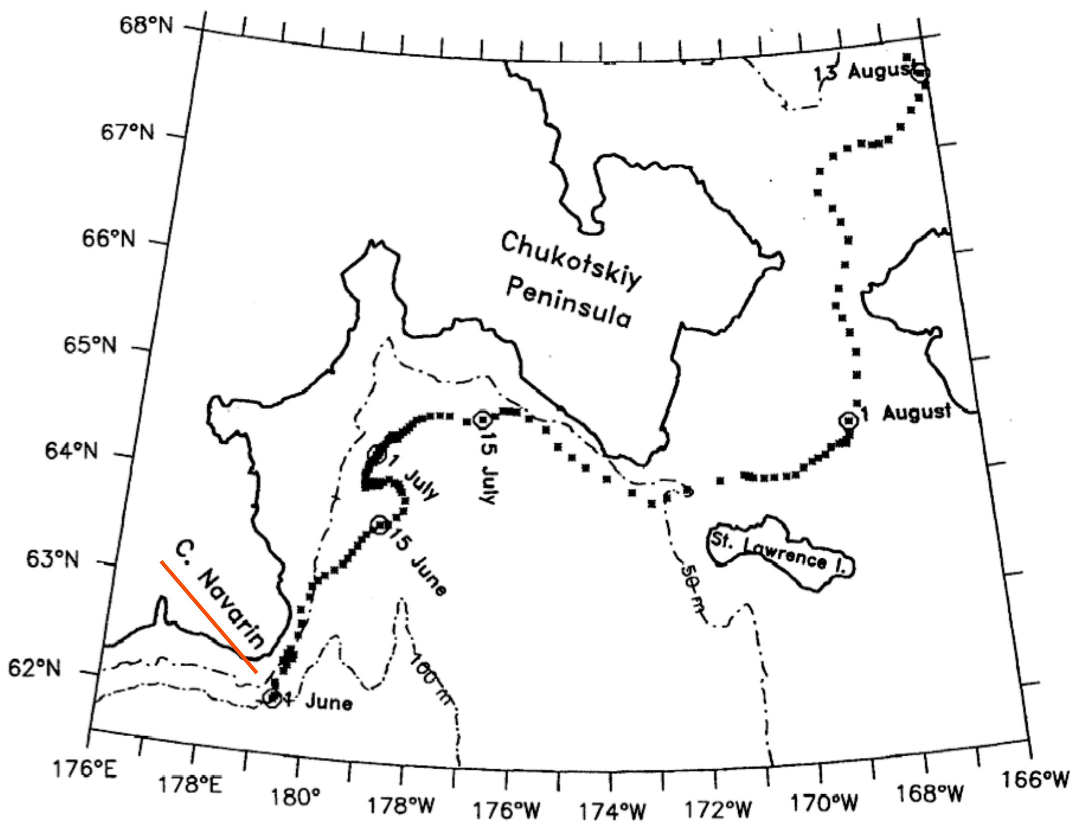
- Same experiment, except sink in the West.
- Same result as in last experiment.
- Most of the water moving up the shelf did so in the western boundary current.
- Lack of currents elsewhere.



Same type of experiment as in previous figure except sink is near the east coast. Period of rotation: 15.4s, volume flux: 53cm^{3}s^{-1}.

- Same experiment, except sink in the East.
- Same result as in last experiments.
- Most of the water moving up the shelf did so in the western boundary current.
- Lack of currents elsewhere.

J.E.Overland et al., Direct evidence of northward flow on the northwestern Bering Sea shelf. *J. Geophys. Res.,* 101, 8971-8976, 1996.



Positions of buoy 7210 from June 1 to August 13, 1994

- **Two classical length scales for width of western boundary current (linear flow):**
  - **Stommel scale (due to bottom friction):**

$$W_s = \left(\nu / 2 f \tan^2 \alpha\right)^{1/2}$$

  - **Munk scale (due to lateral friction of interior flow):**

$$W_m = 2\pi\left(\nu / \beta\right)^{1/3} 3^{-1/2} = 2\pi\left(\nu d / f \tan\alpha\right)^{1/3} 3^{-1/2}$$

    - **f: Coriolis parameter**
    - ν**: kinematic viscosity of the fluid**
    - **tan**α**: bottom slope with** β_0 **= f*tan** α**/d**
    - **d: depth of fluid**

- **Plugging in values:**
  - $d=10cm$, $f=4\pi/15s^{-1}$, $\tan\alpha=0.2\nu=0.01cm^2s^{-1}$
  - $W_s = 0.4cm$
  - $W_m = 3.1cm$

- **Observed width of western boundary current:**
  - At d=10cm: ~10 cm in exp.1
  - ~7-8 cm in exp. 2
  - ~15 cm in exp. 3

- **Munk scale closer to observations, but still too small.**

- Third possible length scale:
  - Inertial boundary layer, nonlinear advection dominates
  - Degree of non-linearity: compare bottom friction time scale to advective time scale
  - ratio: ~0.77 → advective effects are of same order as bottom friction effects
  - → inertial boundary layer appears possible!
- Steady-state width of inertial boundary current:

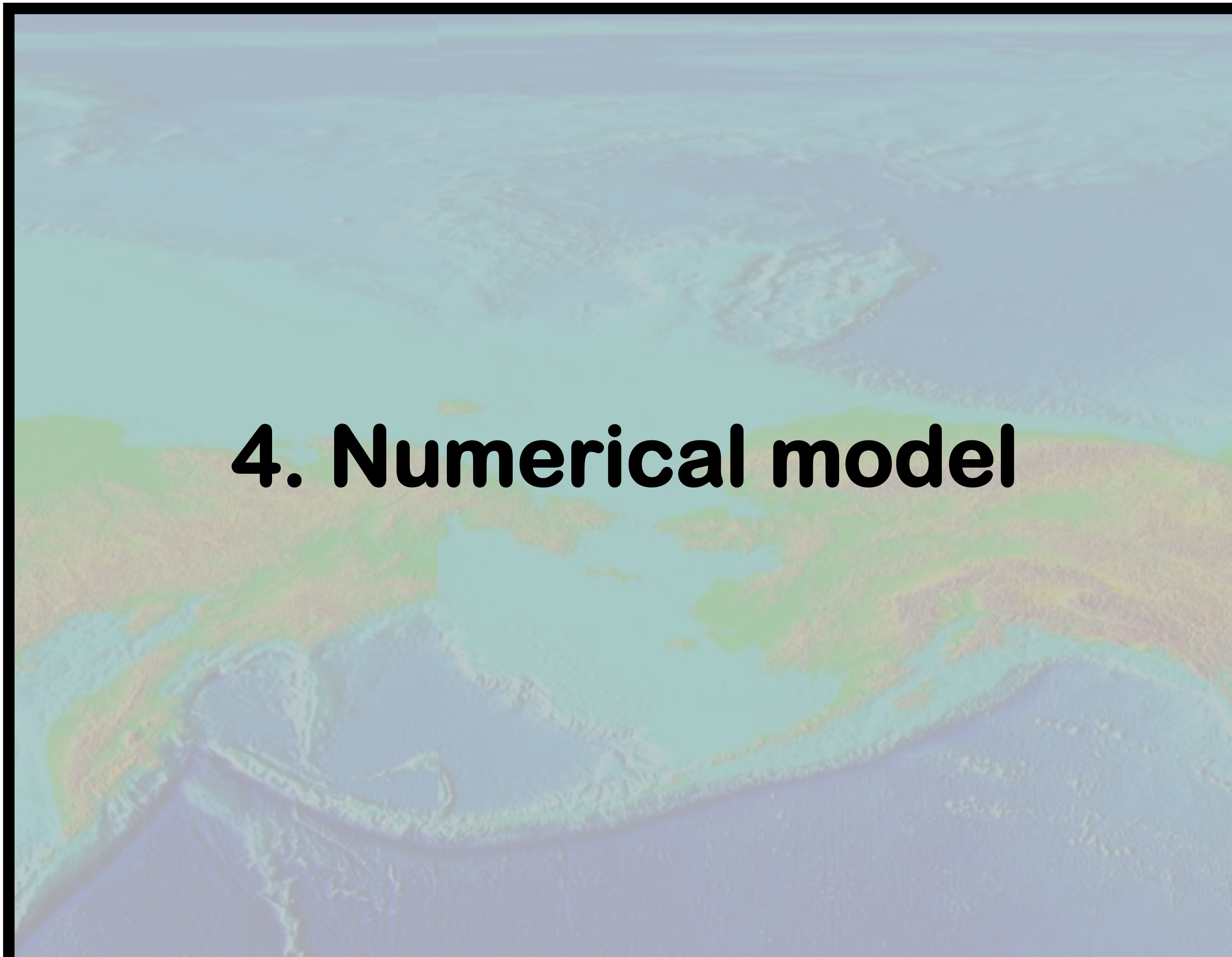
$$W_I = \left(V_I d / f \tan\alpha\right)^{1/2}$$

  - V_I: interior velocity normal to boundary layer

- For inertial boundary layer of width W_I=10cm, an interior velocity of V_I=-1.7cms^{-1} is required.
- Large westward displacements of north-south dye lines were not observed in experiments.
- → Internal scale does not apply here, or steady state was not reached in experiment.
- Calculated volume flux of western boundary current, compare to that of the pump: western boundary current contains the volume flux of the pump, current carries all the water on the shelf that goes into the sink.

- **Conclusion of lab experiments:**
  - **Laboratory experiment shows a western boundary current with a width somewhat greater than that expected by frictional theory.**
  - **Boundary current may be inertial, then it must still evolve in time.**
  - **All of the flow into the sink comes via the western boundary current, and from nowhere else.**

4. Numerical model

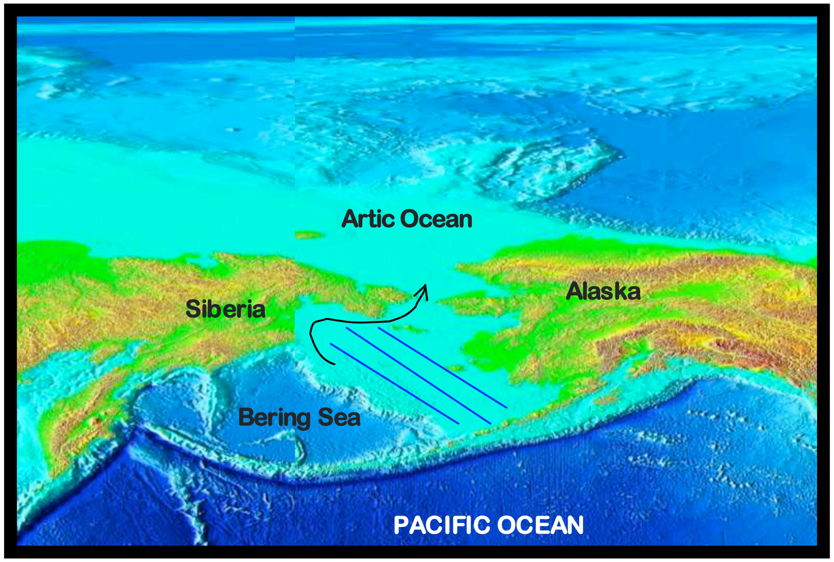


4. Numerical model

Goal: Investigation of the dynamics of the circulation of the Bering Sea and of the laboratory experimental results

Neither friction nor nonlinear effects seemed to account for the western current width.

Simple linear numerical model to illustrate the existence of the Western Boundary Current (WBC):



$$-fv = -g\frac{\partial \eta}{\partial x} - \frac{ru}{h}$$

$$fu = -g\frac{\partial \eta}{\partial y} - \frac{rv}{h}$$

$$\frac{\partial (uh)}{\partial x} + \frac{\partial (vh)}{\partial x} = 0$$

$$uh = -\frac{\partial \psi}{\partial y} \quad vh = \frac{\partial \psi}{\partial x}$$

transp. stream-function

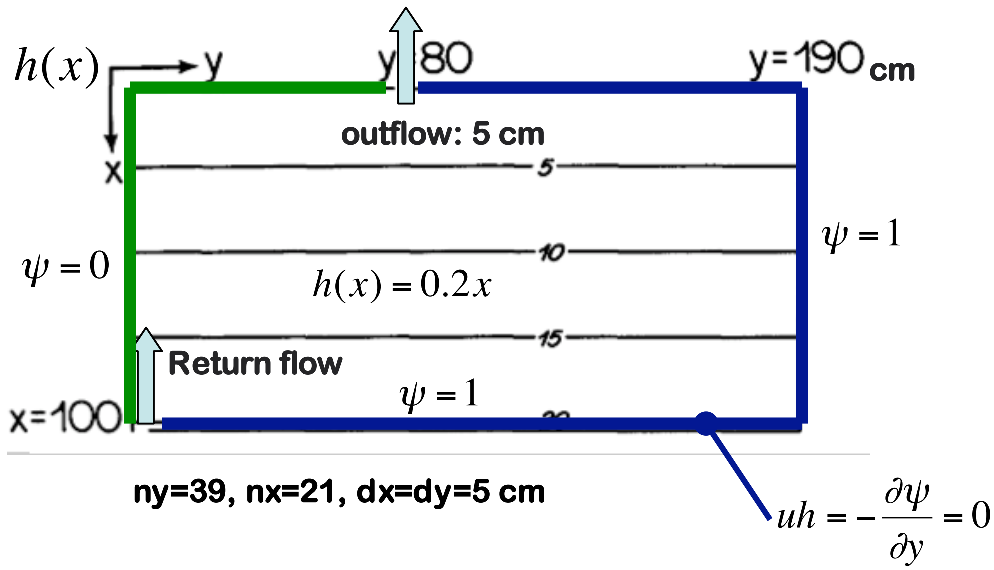
Governing equation (~advection - diffusion)

$$\nabla^2 \psi + \left(\frac{f\, dh/dx}{r}\right)\frac{\partial \psi}{\partial y} - \left(\frac{2\, dh/dx}{h}\right)\frac{\partial \psi}{\partial x} = 0$$

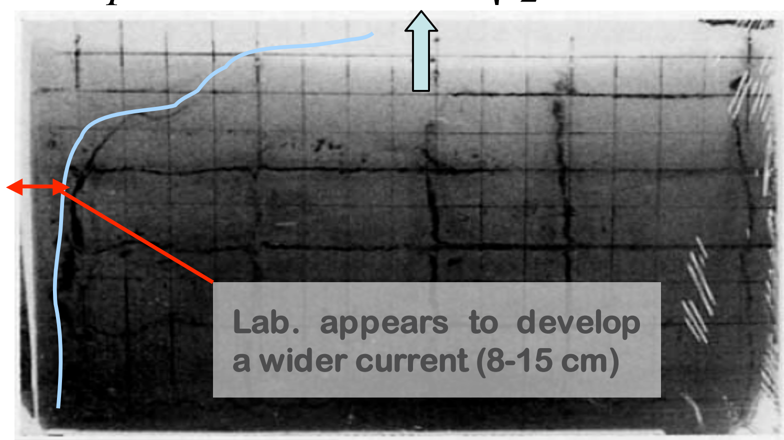
Solved with an upwind differencing method of Fiadeiro and Veronis (1977)

4a. Simulation of Lab. Experiment

Model characteristics and parameters

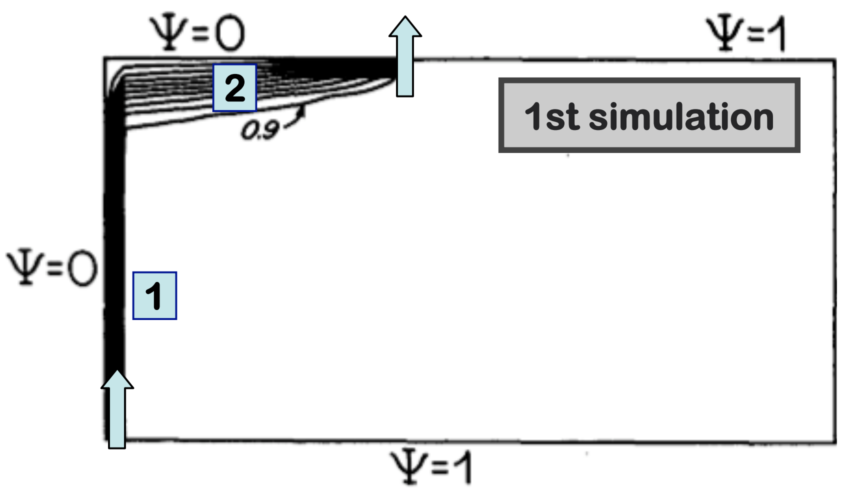


$$f = \frac{4\pi}{T} = 0.8378 s^{-1} \qquad r = \sqrt{\frac{\nu f}{2}} = 0.065 cm.s^{-1}$$



Scale given by: r/fh_x ~ 0.39 cm, model does not resolved details of it

Results

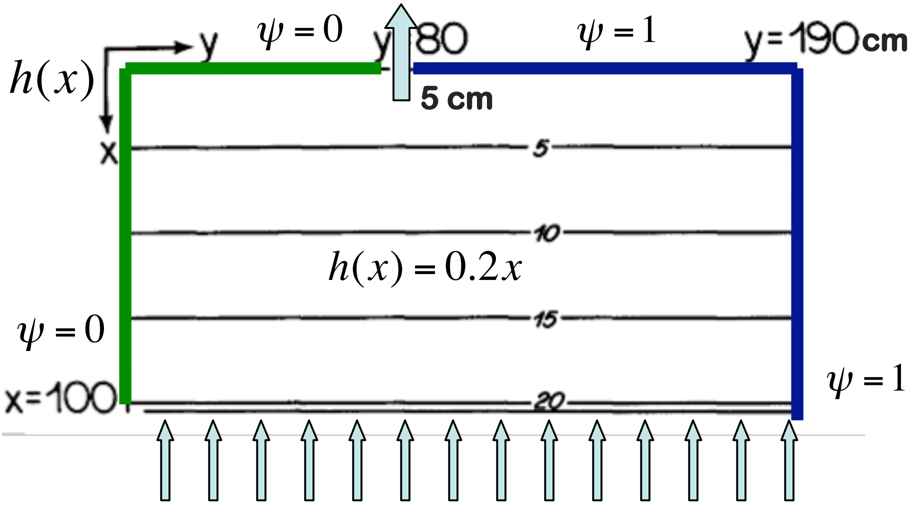


1 **Cross isobath flow analogous to WBC described by Stommel (1948)**

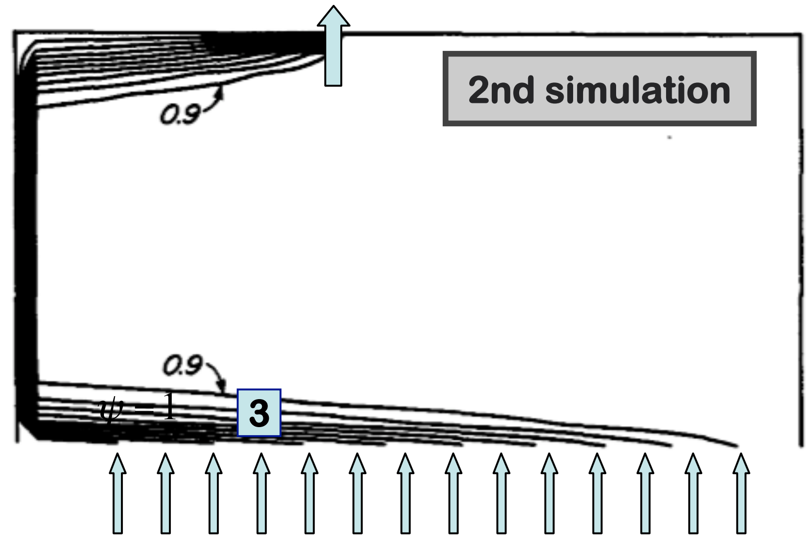
2 **Northern coast: current turns and spreads into an alongshelf boundary layer, analogous to ATW solution (Csanady, 1978)**

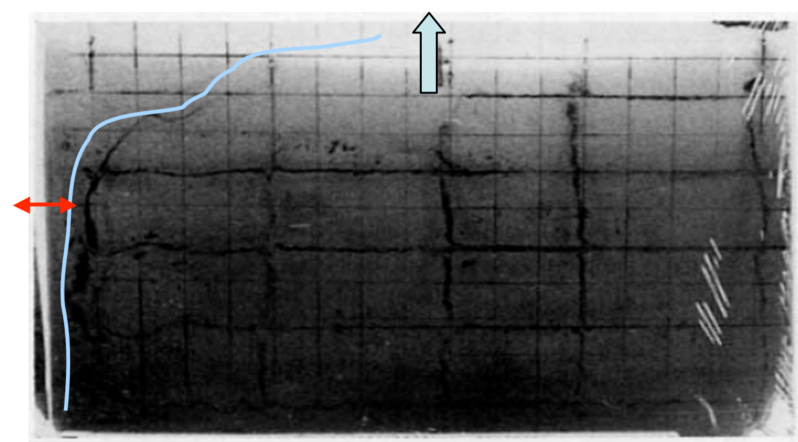
4a. Simulation of Lab. Experiment

Bathymetric domain



flat bottom $\frac{\partial^2 \psi}{\partial x^2} = \frac{\partial}{\partial x}\frac{\partial (vh)}{\partial x} = 0$



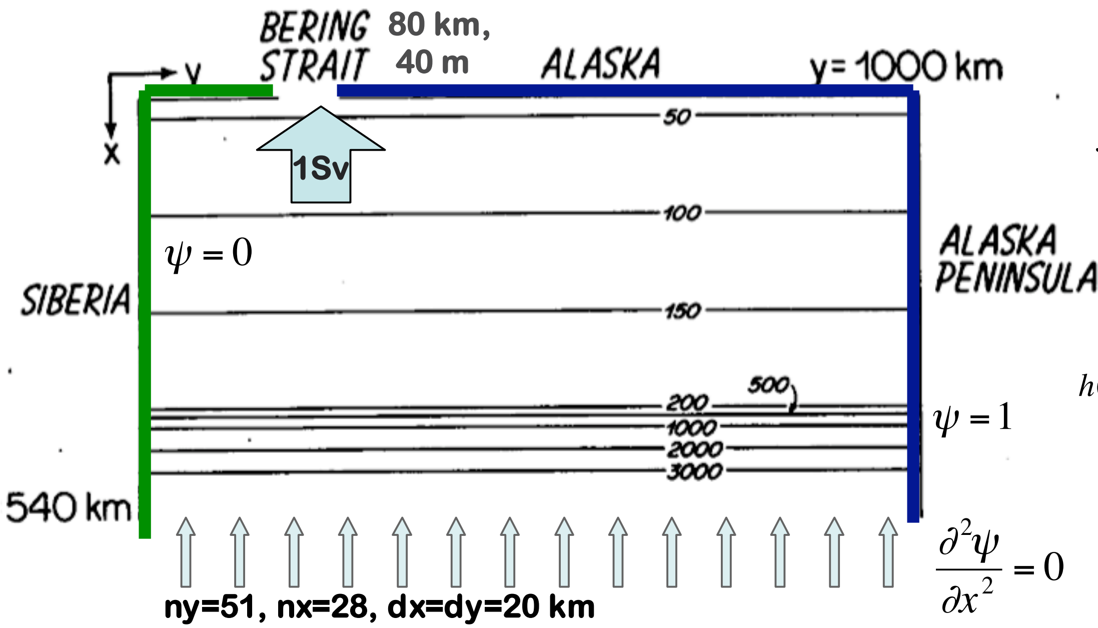


Could the location of the gap in the offshelf wall be responsible for the cross isobath flow?

3 **Inflow spread over the entire offshelf boundary, turning sharply toward west**

Has little effect on the interior flow!

4b. Mean Circulation of Bering Sea



topographic effects are larger

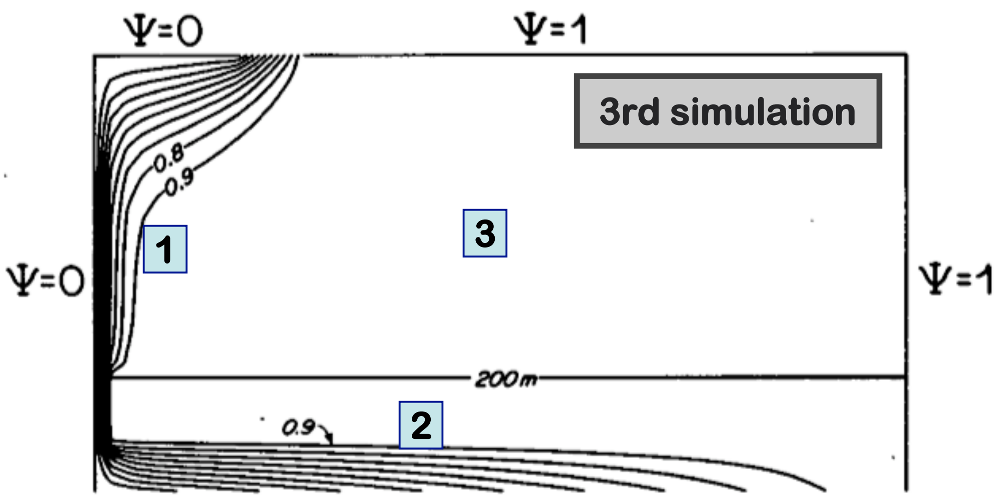
$$f = 1.27 \times 10^{-4} \qquad r = 0.1 cm.s^{-1}$$

$$\beta \approx 1 \times 10^{-13} cm^{-1} s^{-1}$$

$$\beta_T \approx \frac{f\, dh/dx}{h} \approx 5 \times 10^{-12} cm^{-1} s^{-1}$$

$$h(x) = \begin{cases} 40 + 4 \times 10^{-4} x & x < 400km \\ 200 + 0.035(x - 4 \times 10^{5}), & 400km < x < 480km \\ 3000 & x > 480km \end{cases}$$

slope



1 Predicts strong WBC as in lab. experiment

2 Inflow over entire deep basin, turns to Siberian Coast

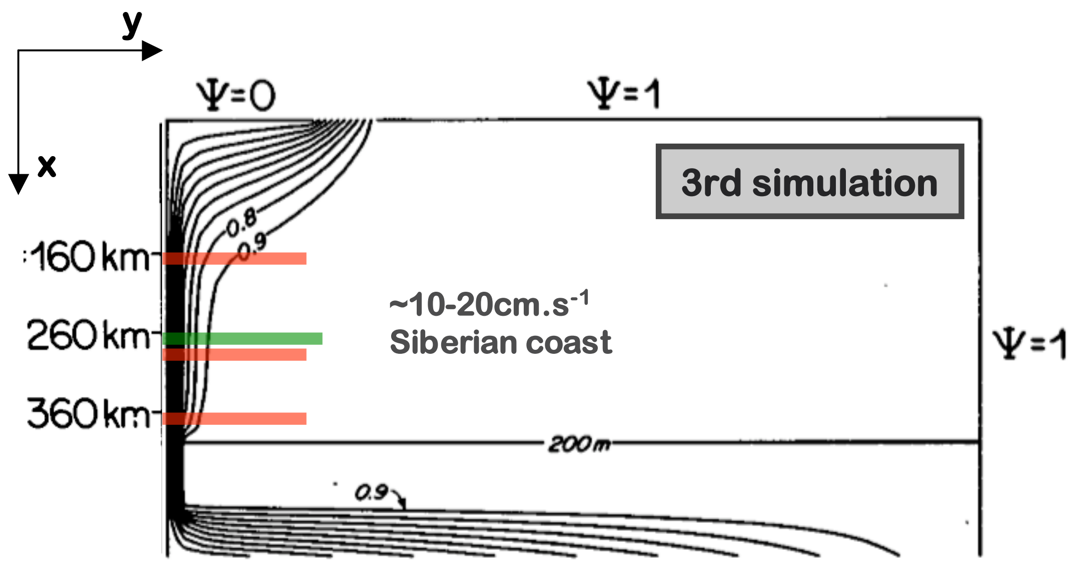
Stommel scale of bc:

$$r/f\; dh/dx = 20km \qquad (shelf)$$

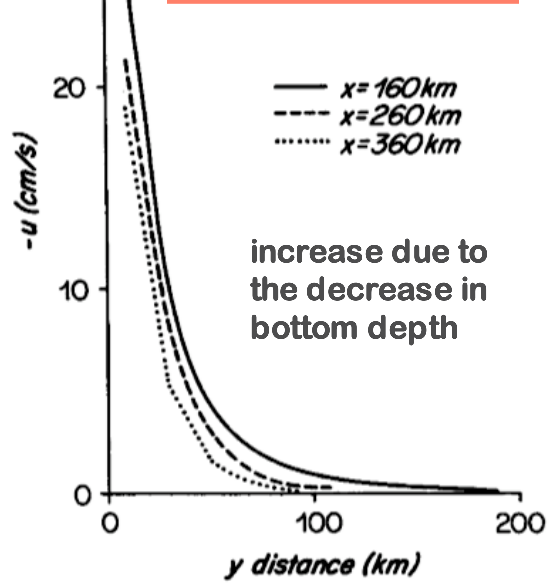
$$r/f\; dh/dx = 0.22km \qquad (slope)$$

3 Very little transport occurs outside the boundary current

4b. Mean Circulation of Bering Sea

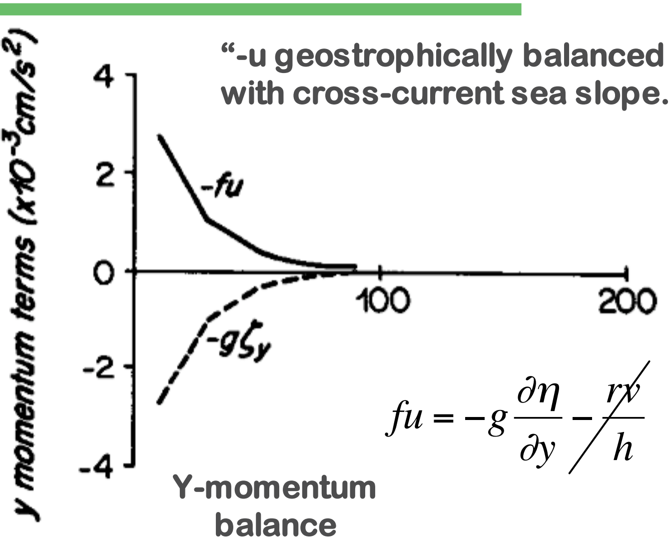


Velocity structure

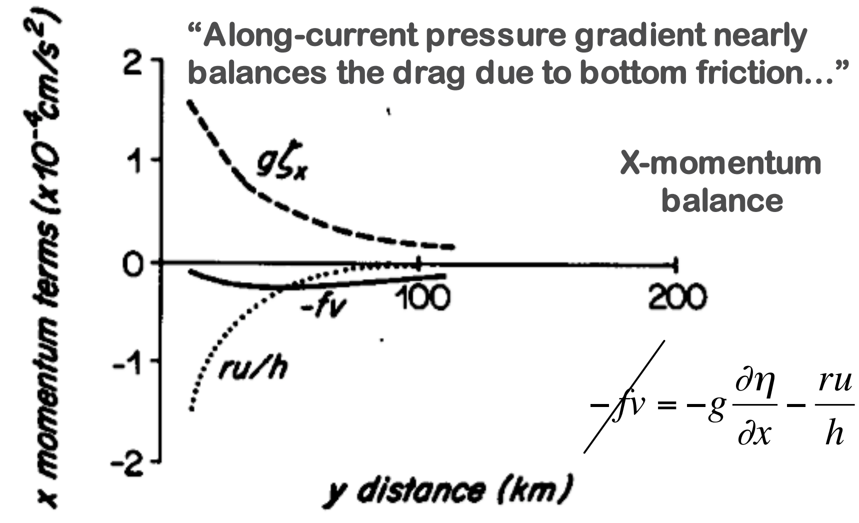


Momentum balance (x=260 km)

$$p \approx \rho f \psi \approx \rho g \eta$$

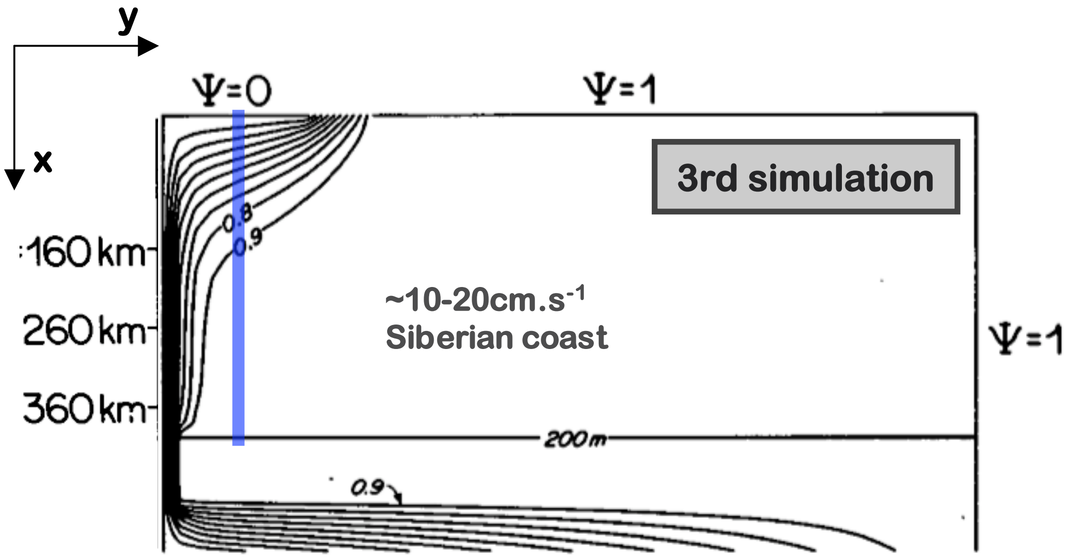


$$fu = -g\frac{\partial \eta}{\partial y} - \frac{rv}{h}$$



$$-fv = -g\frac{\partial \eta}{\partial x} - \frac{ru}{h}$$

4b. Mean Circulation of Bering Sea

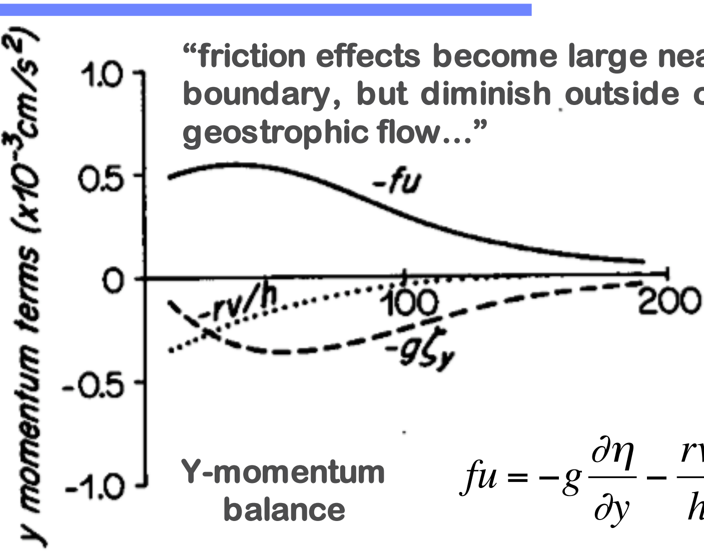


$$p \approx \rho f \psi \approx \rho g \eta$$

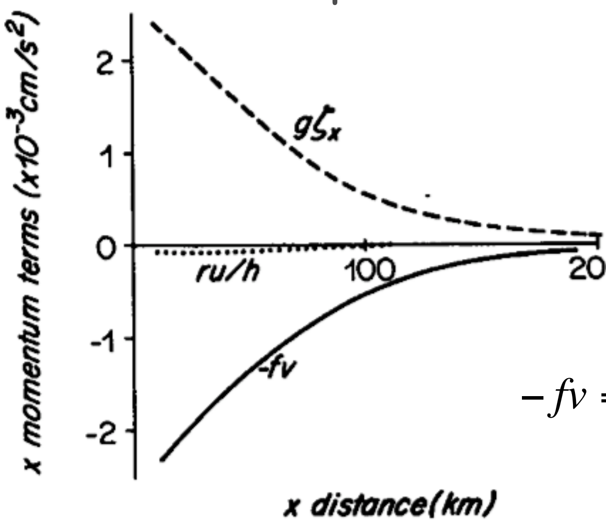
"approaching the northern boundary the along-shelf current v is nearly in geostrophic balance with the offshore sea slope ..."

Momentum balance (y=100 km)

"friction effects become large near the boundary, but diminish outside of the geostrophic flow..."



$$fu = -g\frac{\partial \eta}{\partial y} - \frac{rv}{h}$$



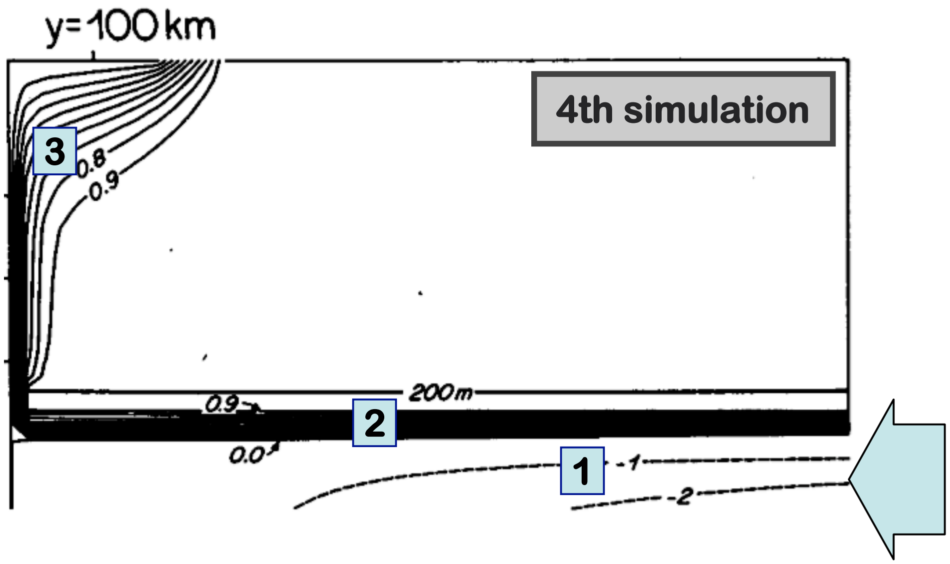
X-momentum balance

$$-fv = -g\frac{\partial \eta}{\partial x} - \frac{ru}{h}$$

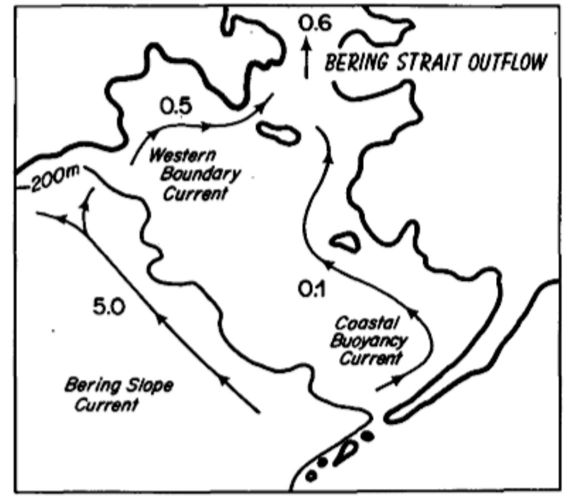
5b. Mean Circulation of Bering Sea

Observations suggest that there may be a substantial flow in the deep part of the Bering Sea (4-5 Sv) (Kinder, 1975)

The effect can be qualitatively modeled by an imposing transport trough Alaska Peninsula



uniformly Imposed Seaward of 1000 m



"Suggest that Bering Strait outflow may draw most of its water from the entire slope and little from deep basin…"

1 Deep inflow fills deep basin and supplies the transport for the Bering Strait outflow

2 Current parallel to the shelf break is generated and held there by deep flow

3 Shelf flow is virtually unaltered by deep mean flow

5. Conclusions

5. Conclusions

Based on observations, major part of supply to the mean Bering Strait outflow occurs as a Western Boundary Current (WBC)

The existence of that WBC could not be confirmed by direct measurements, but were explained in dynamical terms

Analogy to Stommel's (1948) explanation for WBC: meridional gradient of Coriolis parameter is replaced by the gradient of depth

Laboratory and numerical experiments demonstrated the topographic β effect:

Critical shelf features were included:

-shoaling bottom, earth rotation, friction and forced outflow

"envisaged mechanism is physically real for a sink at the coast and the numerical model showed it can be applicable to the Bering Sea"

Aspects that were excluded from the modeling work:

***-density variations*:**

Shelf is strongly stratified, this could partially mitigate the effect of the varying bottom

Anadyr could modify pressure gradients on Siberia coast

-wind stress and atm. pressure:

relatively high values and large fluctuations (days to years). It can dominate the variability near the Strait.

-tides:

kinectic energy dominate on south but is less important over northern shelf (r can be improved)

-topography: **Gulf of Anadyr: induce curvature**
St. Lawrance Island: split flow
Siberian coast: not a vertical wall: could move current away off coast

Other oceanographic situations: Western Mediterranean: flow forced across shoaling topography of Strait of Gibraltar forms a narrow boundary against African slope

6. Study guide questions

Study guide questions

1) What drives the mean circulation in both laboratory and numerical model, i.e. , does a western boundary current always require a wind stress?

1a)The source/sink system drives the mean circulation

1b) No. In the large scale case, winds play the role of the source/sink. But essentially, the existence of the WBC requires the presence of *bottom friction* in the large scale models.

In Bering Sea, the intensification can be seen as follows:

Scale of u width:

assume $$vh = \frac{\partial \psi}{\partial x} \approx 0$$

$$\frac{\partial}{\partial y}\left(\frac{\partial \psi}{\partial y}\right) + \left(\frac{fh_x}{r}\right)\frac{\partial \psi}{\partial y} = 0$$

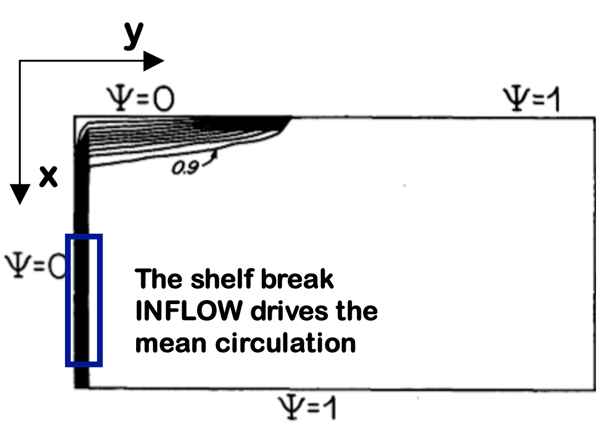
$$-\frac{\partial}{\partial y}(uh) + \left(\frac{fh_x}{r}\right)(-uh) = 0$$

$$h\frac{\partial u}{\partial y} + \left(\frac{fh_x}{r}\right)uh = 0$$

$$u' + (fh_x/r)u = 0$$

$$u(y) \approx U_o e^{-(fh_x/r)y}$$

$$\boxed{\nabla^2\psi + \left(\frac{fh_x}{r}\right)\psi_y - \left(\frac{2h_x}{h}\right)\psi_x = 0}$$



Cross-shore intensification:

$$\nabla^2\psi + \left(\frac{fh_x}{r}\right)\psi_y - \left(\frac{2h_x}{h}\right)\psi_x$$

assume $$vh = \frac{\partial \psi}{\partial x} \approx 0$$

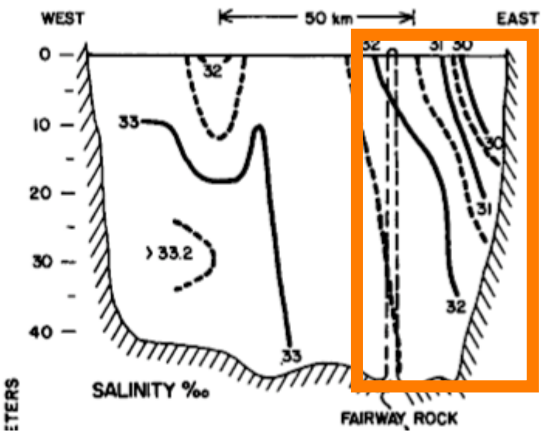
$$\psi_{yy} + \left(\frac{fh_x}{r}\right)(-uh) = 0$$

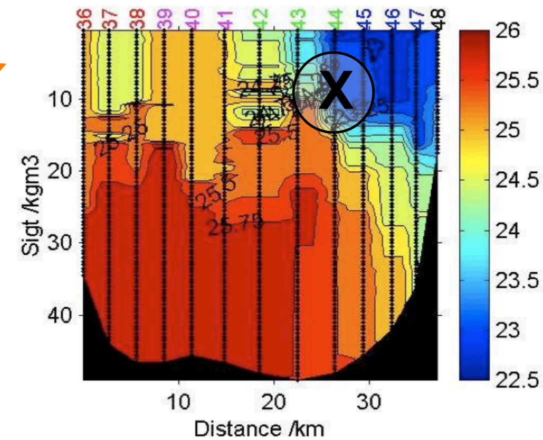
$$u\uparrow \approx \underbrace{\left(\frac{r}{fh_x}\right)}_{cte}\underbrace{\psi_{yy}}_{cte}\left(\frac{1}{h(x)\downarrow}\right)$$

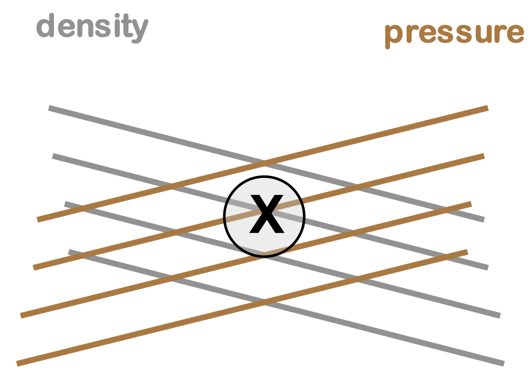
hand waving...

Study guide questions

2) What baroclinic current speeds and directions would expect from the section shown across the Bering Strait?



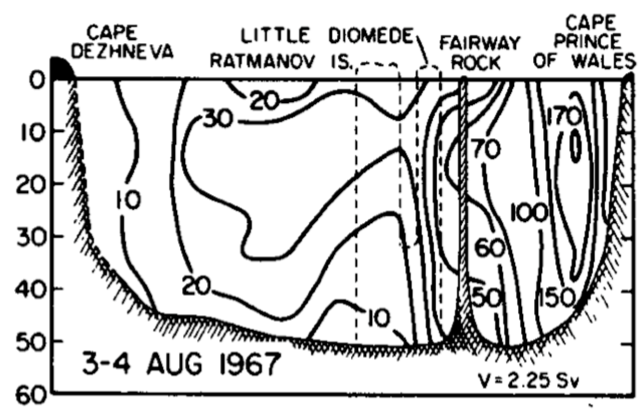




[Woodgate, 2005, Laurier Mooring report]

$$\frac{\Delta V}{\Delta z} = \frac{-g}{\rho_o f}\left(\frac{\Delta\rho}{\Delta x}\right) \approx \frac{-9.8}{(1025)(1.3\times10^{-4})} \approx -\left(\frac{22.5-25}{30000}\right)$$

$$\Delta V = \left(\frac{22.5-25}{30000}\right)40 \approx 0.24 m.s^{-1}$$



Study guide questions

3) What physical process are considered in the laboratory and numerical models and how do they relate to non-dimensional parameters we derived in class?

Laboratory:

-barotropical model, no wind stress at surface nor density gradients
-shoaling bottom,
-tank rotation,
-bottom friction
-forced inflow/outflow
-note: non-linearity is present and experiments evolve in time

Numerical Model

We have "stronger control" so we can set:

$R_o << 1$

$R_{oT} << 1$ $\quad \partial / \partial t = 0$ steady state solution

simple formulation of friction

4) What is the governing equation that forms the essence of the model applied to the Bering Sea and how does it relate to what we discussed in class?

The essence of the physics is given by a vorticity equation in terms of the transport stream-function:

$$\nabla^2 \psi + \left(\frac{f h_x}{r} \right) \psi_y - \left(\frac{2 h_x}{h} \right) \psi_x = 0$$

Any ideas on how to relate it to the potential vorticity conservation?

Study guide questions

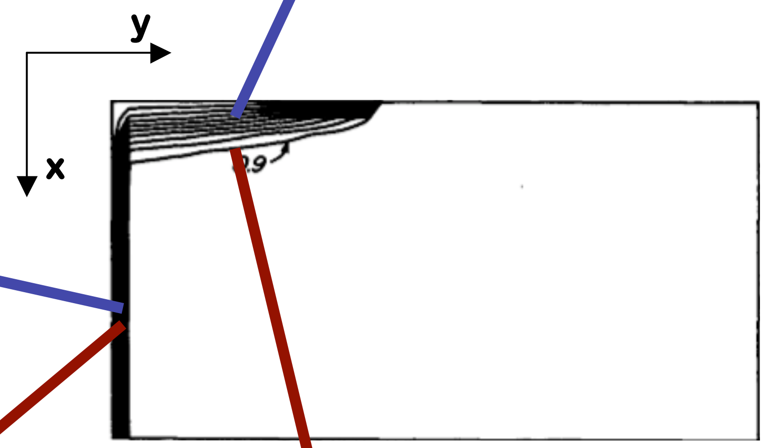
5) What are the dominant force and vorticity balances in different part of the domain

$$-fv = -g\frac{\partial \eta}{\partial x}$$

$$fu \approx -g\frac{\partial \eta}{\partial y} - \frac{rv}{h}$$

$$fu \approx -g\frac{\partial \eta}{\partial y}$$

$$\frac{ru}{h} = -g\frac{\partial \eta}{\partial x}$$



$$\nabla^2\psi + \left(\frac{fh_x}{r}\right)\psi_y - \left(\frac{2h_x}{h}\right)\psi_x = 0$$

$$\psi_y \approx 0 \qquad \psi_{xx} - \left(\frac{2h_x}{h}\right)\psi_x = 0$$

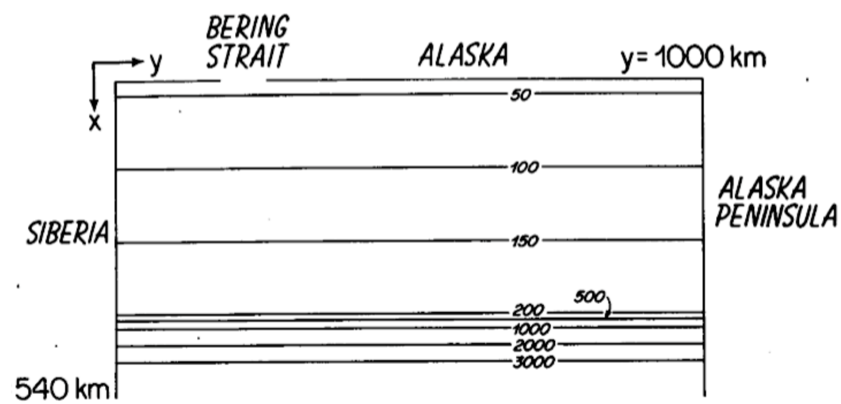
$$\psi_x \approx 0 \qquad \psi_{yy} + \left(\frac{fh_x}{r}\right)\psi_y = 0$$

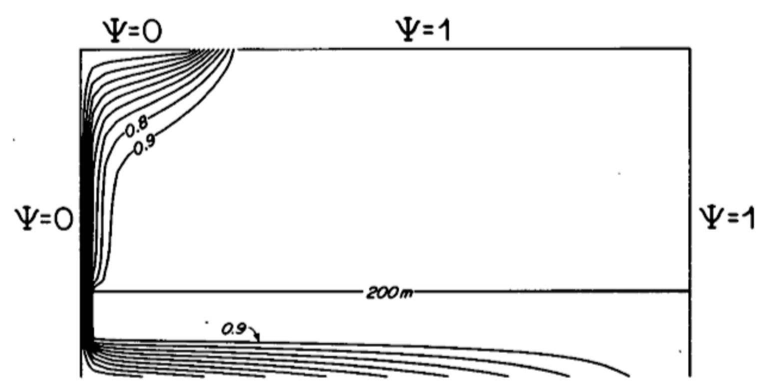
Study guide questions

6) Does the basic geostrophic flow follow the bottom contours?

Not in the entire domain. Near the shelf break and on the north coast the flow follows the isobaths.

The western boundary current on the other hand, even demonstrating a near-geostrophic nature, explicitly flows against the slope





Study guide questions

7) Which physical process breaks the geostrophic constraint, that is, what is the origin of the relative vorticity term in the main governing equation?

$$-fv = -g\frac{\partial \eta}{\partial x} - \frac{ru}{h}$$

$$fu = -g\frac{\partial \eta}{\partial y} - \frac{rv}{h}$$

$$uh = -\frac{\partial \psi}{\partial y} \qquad vh = \frac{\partial \psi}{\partial x}$$

$$\frac{\partial (uh)}{\partial x} + \frac{\partial (vh)}{\partial x} = 0 \quad \Rightarrow \quad \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial x}\right) = \frac{-u}{h}\frac{dh}{dx}$$

$$\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \Rightarrow \frac{\partial v}{\partial x} = \left(\frac{1}{h}\frac{\partial (vh)}{\partial x} - \frac{v}{h}\frac{dh}{dx}\right)$$

$$f\frac{\partial v}{\partial y} = g\frac{\partial^2 \eta}{\partial x \partial y} + \frac{r}{h}\frac{\partial u}{\partial y}$$

$$f\frac{\partial u}{\partial x} = -g\frac{\partial^2 \eta}{\partial x \partial y} - r\left(\frac{1}{h}\frac{\partial v}{\partial x} + v\frac{\partial (1/h)}{\partial x}\right)$$

$$f\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right) = 0 + \frac{r}{h}\frac{\partial u}{\partial y} - r\left(\frac{1}{h}\frac{\partial v}{\partial x} - \frac{v}{h^2}\frac{dh}{dx}\right)$$

$$-f\left(\frac{u}{h}\frac{dh}{dx}\right) = -\frac{r}{h}\left(\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}\right) + \left(\frac{rv}{h^2}\frac{dh}{dx}\right)$$

$$\frac{r}{h}\left(\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}\right) = \frac{dh}{dx}\left(\frac{fu}{h} + \frac{rv}{h^2}\right)$$

$$\frac{1}{h}\left(\frac{\partial vh}{\partial x} - \frac{\partial uh}{\partial y}\right) = \left(\frac{fu}{r}h_x + 2\frac{v}{h}h_x\right)$$

$$\frac{1}{h}\left(\frac{\partial}{\partial x}\frac{\partial \psi}{\partial x} - \frac{\partial}{\partial y}\left(-\frac{\partial \psi}{\partial y}\right)\right) = \left(\frac{fu}{r}h_x + 2\frac{v}{h}h_x\right)$$

$$\boxed{\left(\frac{\partial^2 \psi}{\partial x^2} + \frac{\partial^2 \psi}{\partial y^2}\right)} + \left(\frac{fh_x}{r}\psi_y - 2\frac{h_x}{h}\psi_x\right) = 0$$

Study guide questions

8) Why does the Rossby radius of deformation not enter the dynamics that are certainly dominated by rotation and ambient vorticity gradients?

Specifically for the WBC, as seen its width it's given by the Stommel scale of the boundary current

$$u(y) \approx U_o e^{-(fh_x/r)y}$$

For a decay of 1/e: $$y = \frac{r}{fh_x}$$

Specifically for the WBC, as seen its width it's given by the Stommel scale of the boundary current


End