Demonstration Experiments

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Some easy-to-assemble demonstration experiments illustrate the basic nature of large-scale flows in rotating systems such as in weather and climate studies.

I. **Rotating flows**

1. Taylor columns in homogeneous fluids.
2. Cones and lenses in stratified fluids.

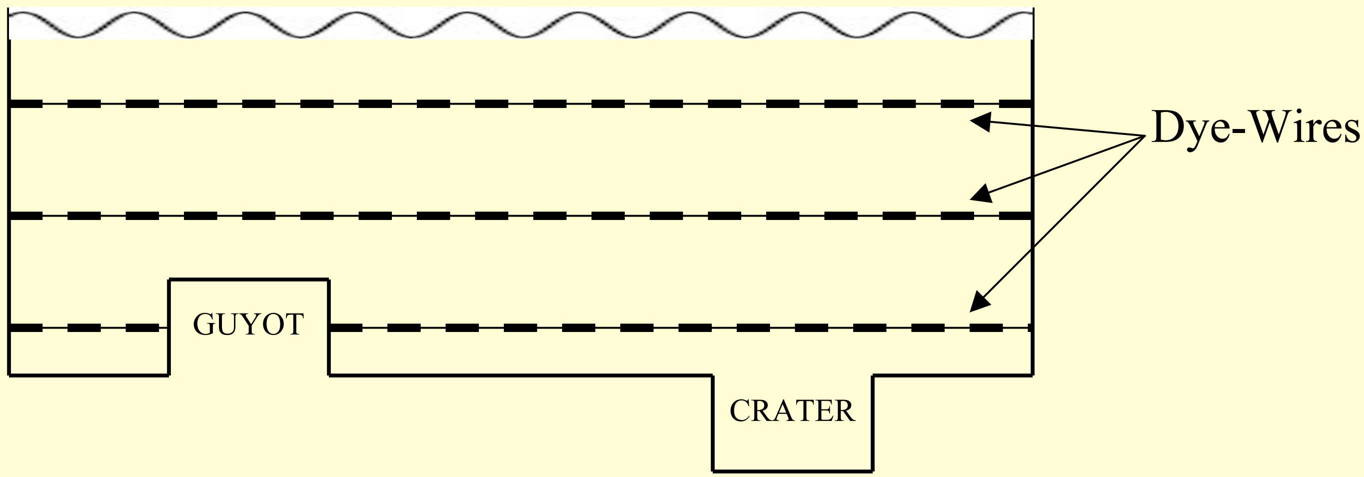
II. **Buoyancy-driven flows**

1. Rayleigh-Benard convection
   - a) Plan view
   - b) Elevation
2. Hadley/Horizontal convection
   - a) Non-uniform heating
   - b) Non-uniform heating and salting
3. Double-diffusion
   - a) Salt fingers
   - b) Diffusive convection
   - c) Lateral interleaving.

I. **Rotating flows**

1. Taylor columns in homogeneous fluids

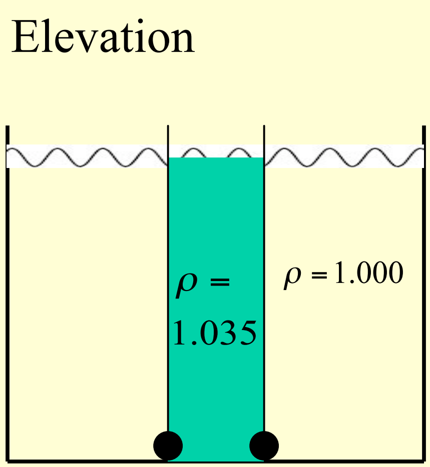
- The Taylor-Proudman theorem states that for steady, slow, inviscid motion of a rotating incompressible fluid, u, v, w may not vary with z (in the direction parallel to the rotation vector).
- Visualization here is via flows that follow depth contours i.e., at low Rossby number f/h is the potential vorticity conserved following the motion.

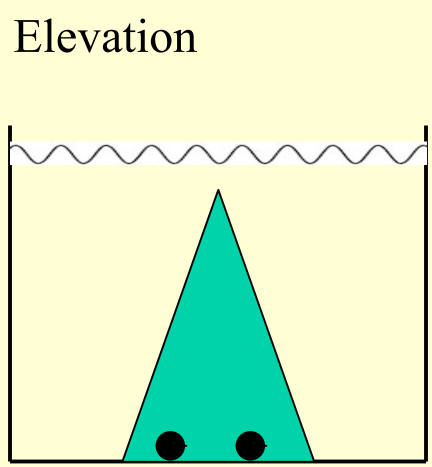


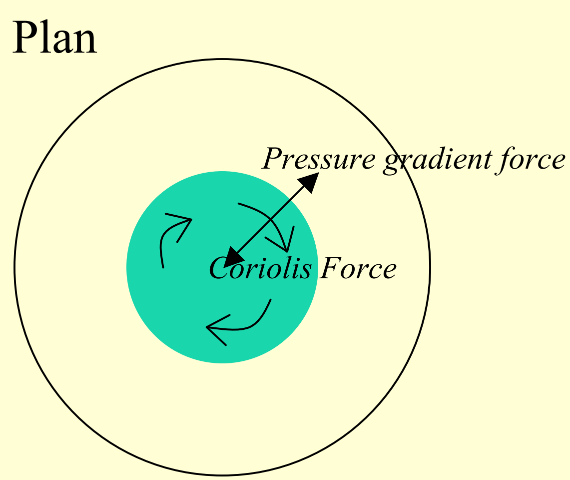
Rotating tank of water containing pH indicator thymol blue.

I. **Rotating flows**

2. Cones and lenses in stratified fluids.





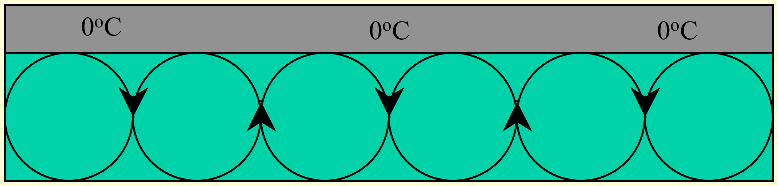


Flow in geostrophic balance

II. **Buoyancy-driven flows**

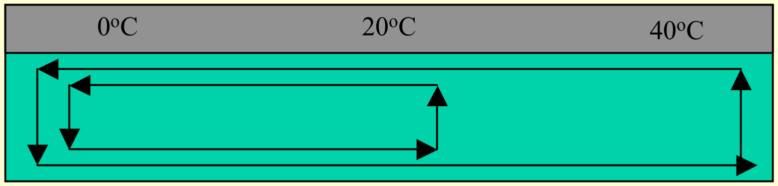
1. Rayleigh-Benard convection
    a) Plan view
    b) Elevation
2. Hadley/Horizontal convection
    a) Non-uniform heating
    b) Non-uniform heating and salting
3. Double-diffusion
    a) Salt fingers
    b) Diffusive convection
    c) Lateral interleaving

Uniform heating below and/or uniform cooling above

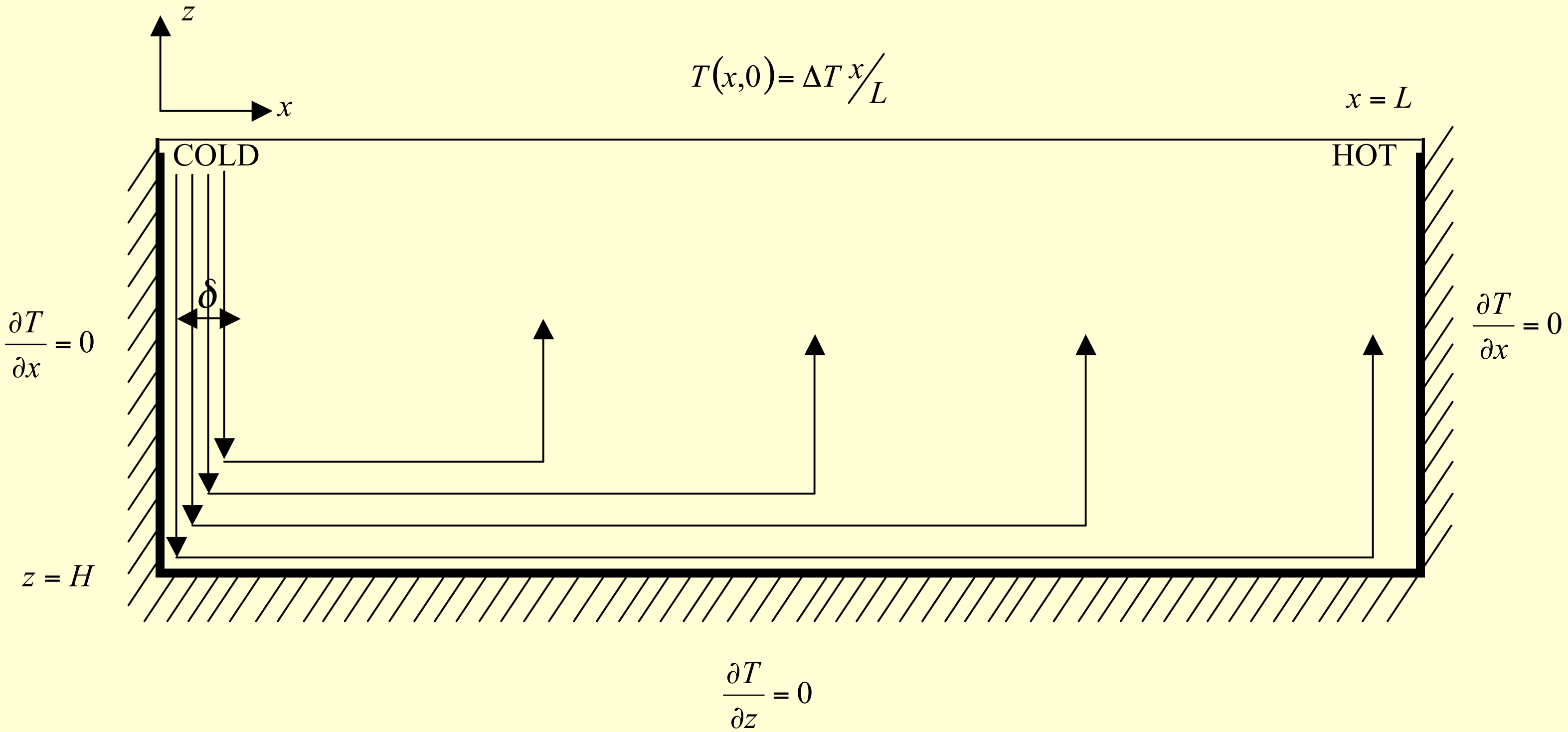


Multi-cellular flow, cell width equal to depth

Non-uniform heating below and/or non-uniform cooling above

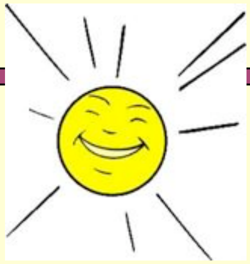


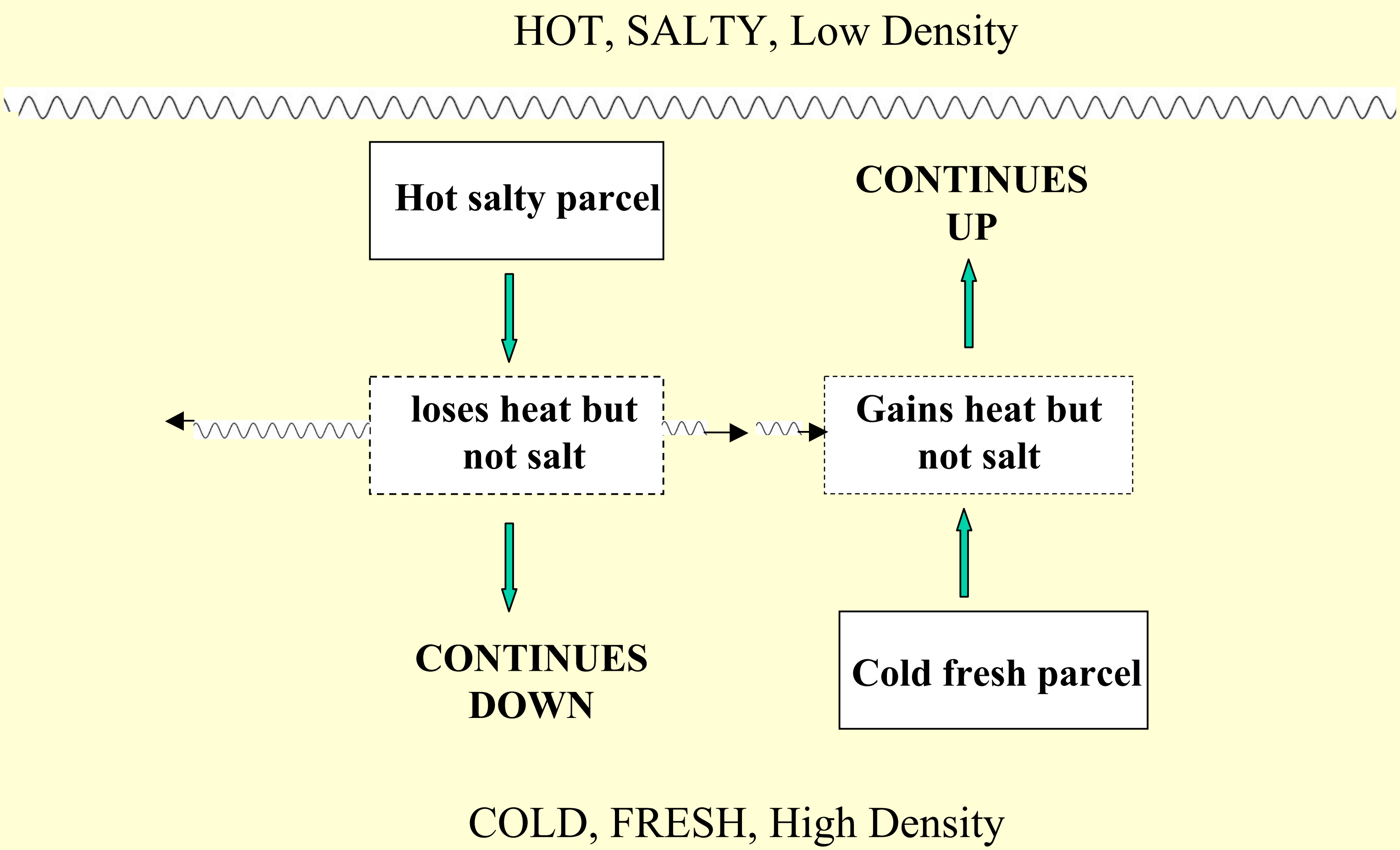
Uni-cellular flow.



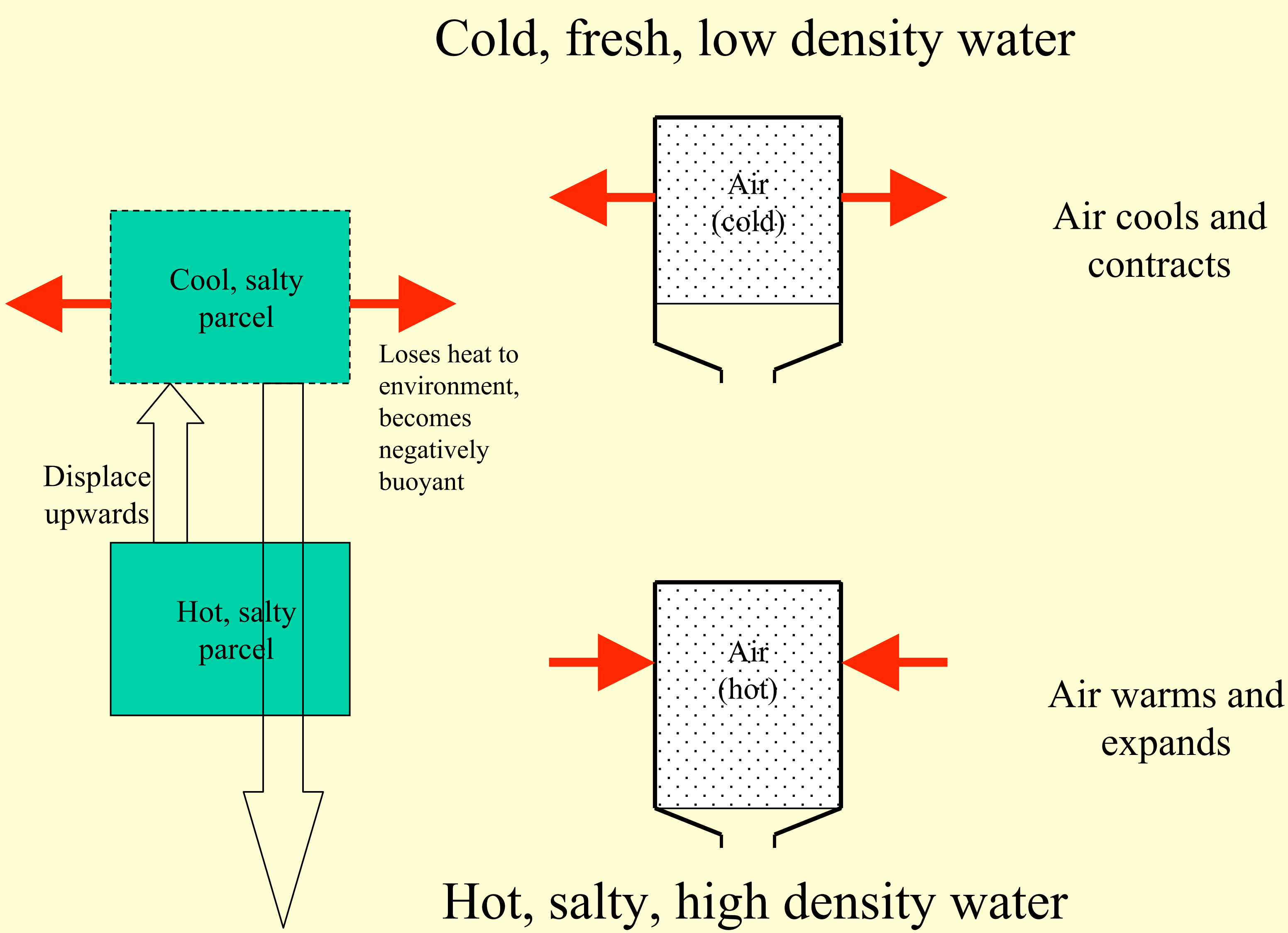
To maintain this flow, cold water must be converted into hot water near $x = L$.

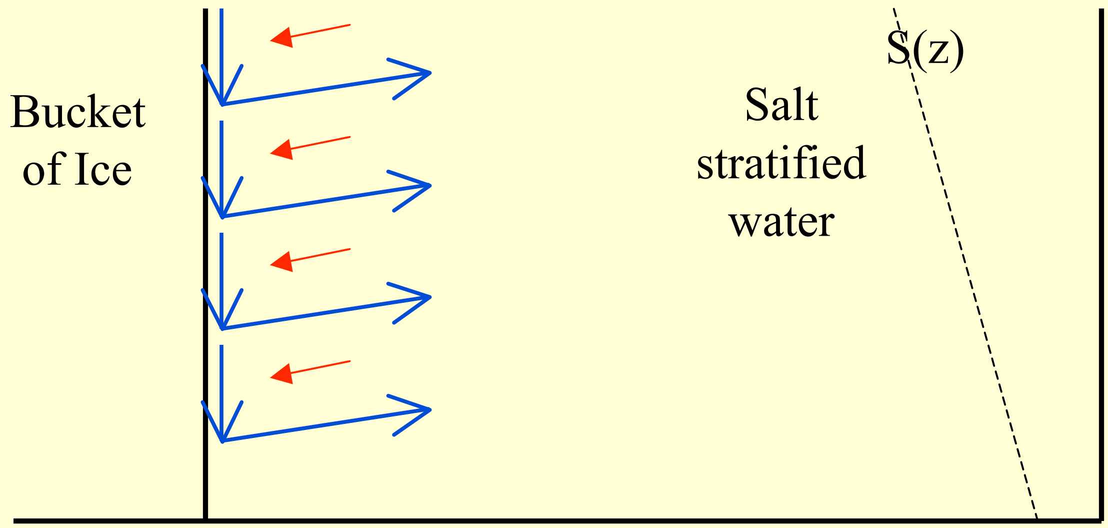
Salt finger instability





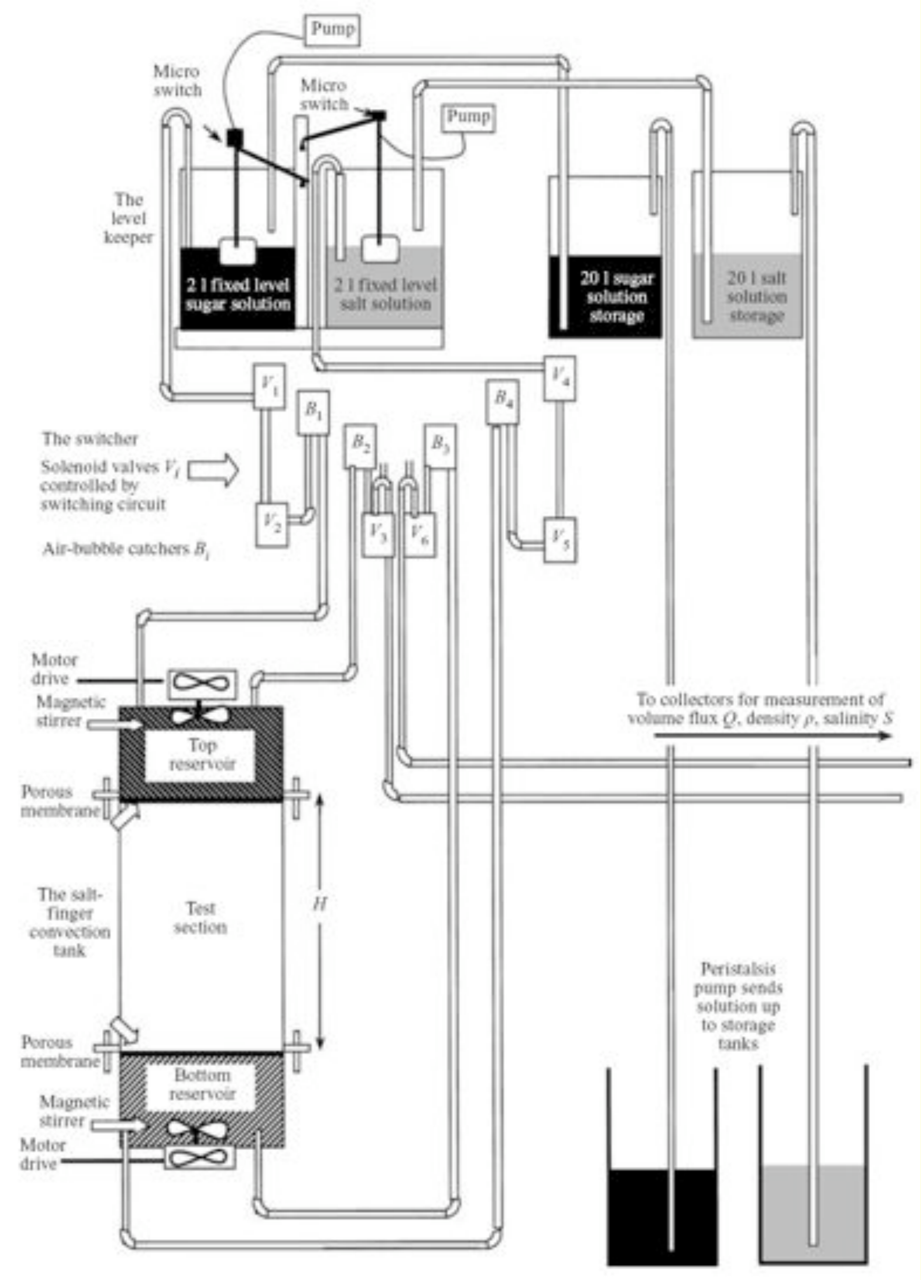
Bouncing Bottles



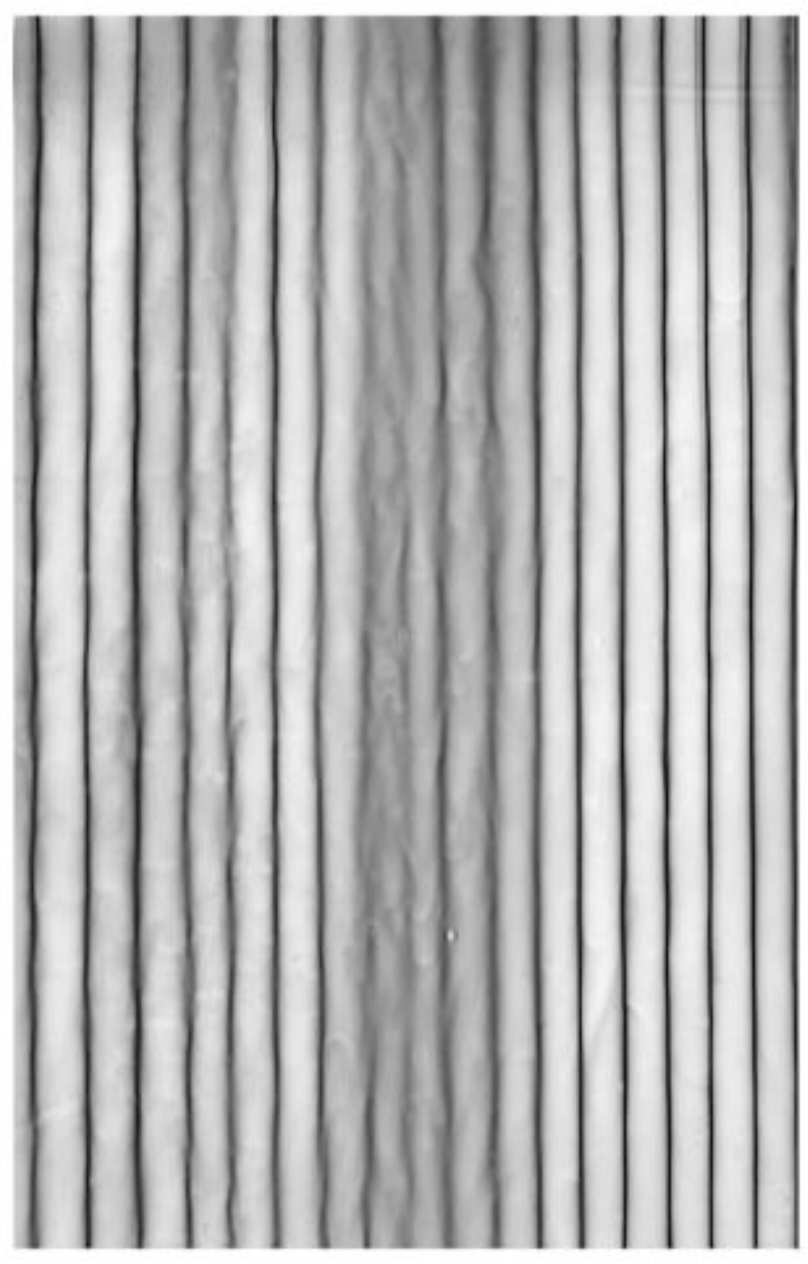


Layer formation and lateral intrusions

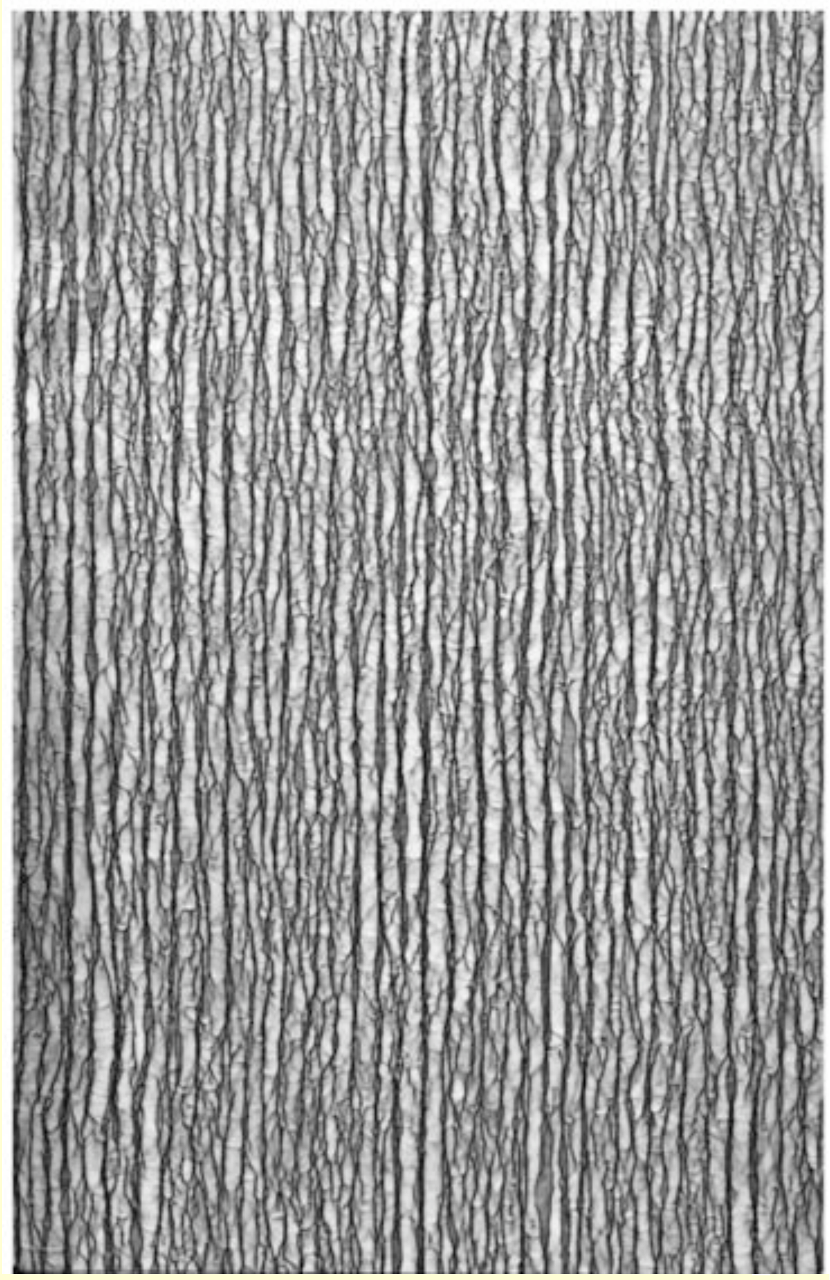
Schematic diagram of the apparatus.



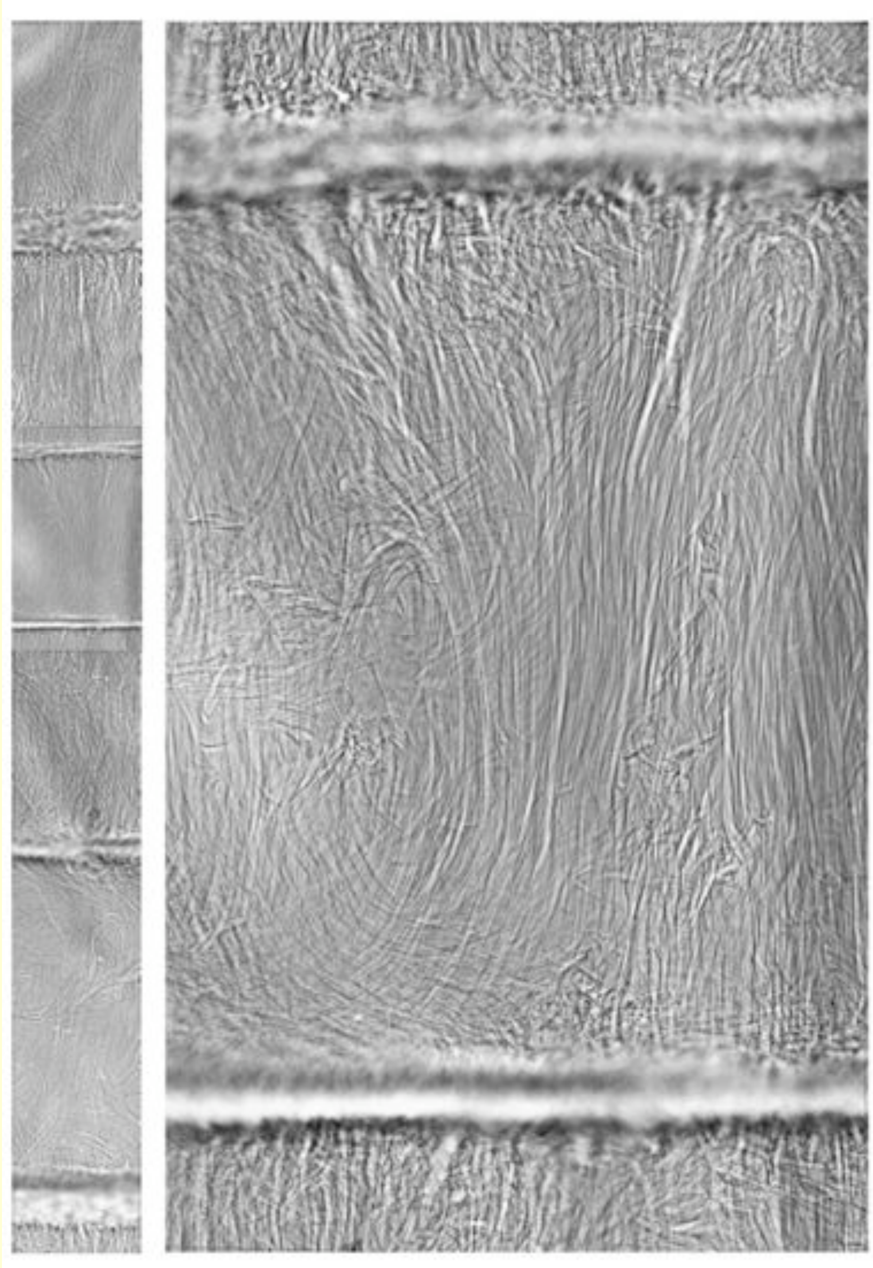
Shadowgraph of straight salt fingers. The part shown here is an excerpt from a 2m tall shadowgraph of straight fingers. The width of the image corresponds to 6.0cm at the tank. Exposure time was 6s. $|R_s| = 7.12 \times 10^{15}$, $R_p = 1.25$, Stern number A = 0.20.

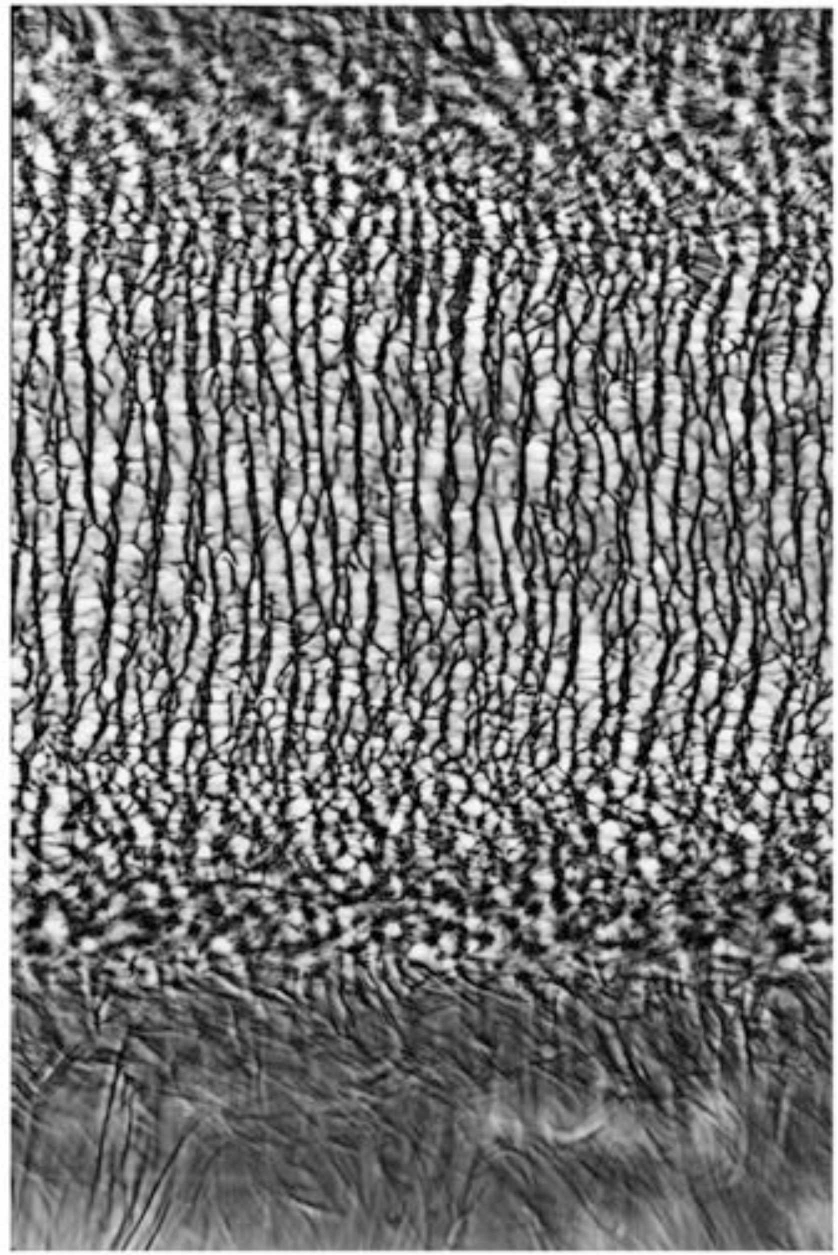


Shadowgraph of lumpy salt fingers. The part shown here is an excerpt from a 2m tall shadowgraph of lumpy fingers. The width of the image corresponds to 8.5cm at the tank. Exposure time was 10s. $|R_s| = 7.60 \times 10^{15}$, $R_p = 1.25$, Stern number $A = 0.39$.



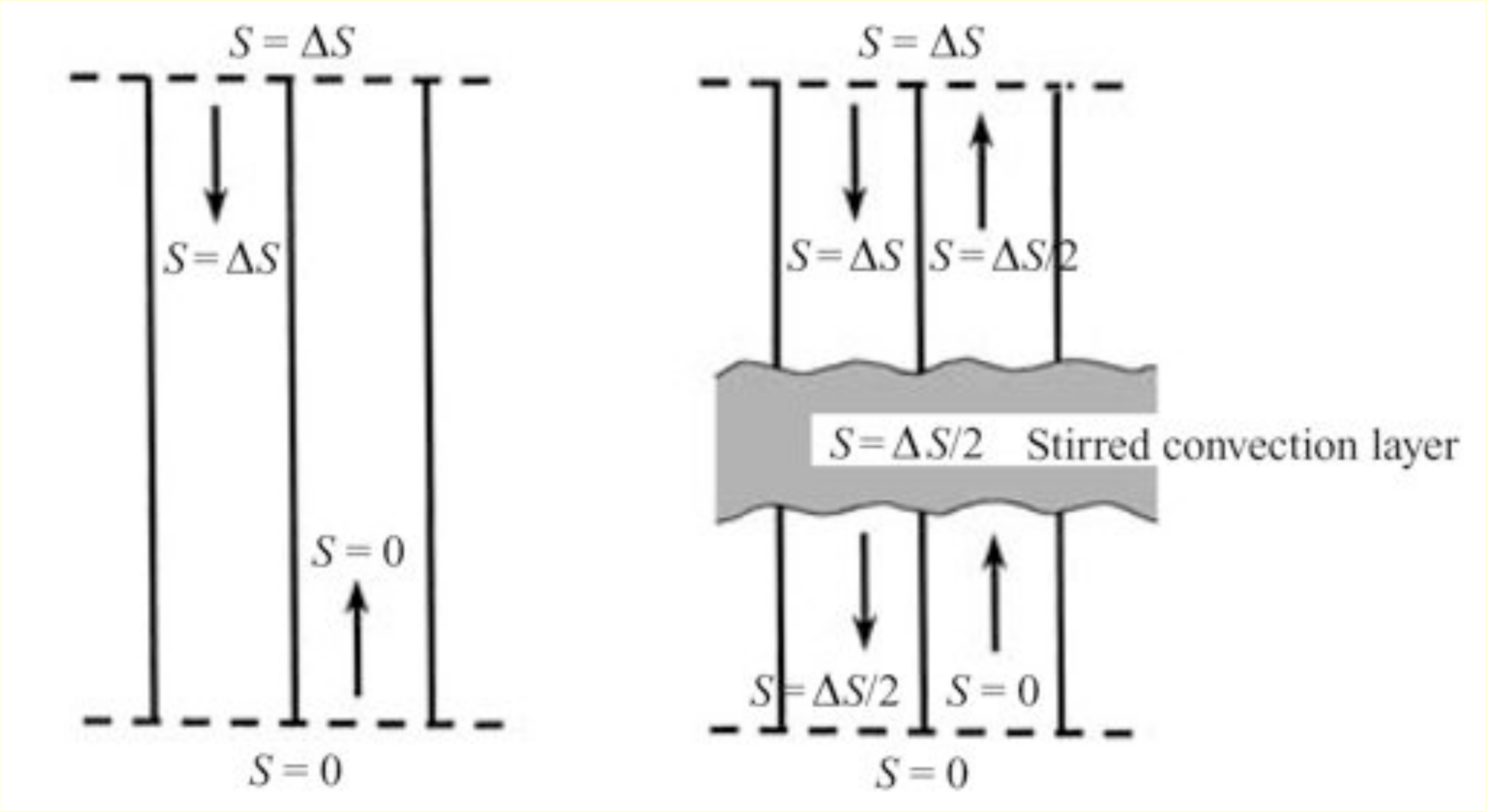
Shadowgraph of a portion of a thermohaline staircase. This excerpt is from a 2m tall shadowgraph which had ten finger zones and nine convection zones in alternation. The narrow strip at the left corresponds to 101 cm out of the total 183 cm depth of the tank and shows six finger zones and five convection zones. Due to limitations of the scanner, the third full convection zone bounded by two (blurred) finger zones. The blurring is from rapid fluctuations at the junction between the finger and convection zones. The height of the image to the right corresponds to 16 cm at the tank. Exposure time was 10 s. $|R_s| = 1.00 \times 10^{15}$, $R_p = 1.25$.



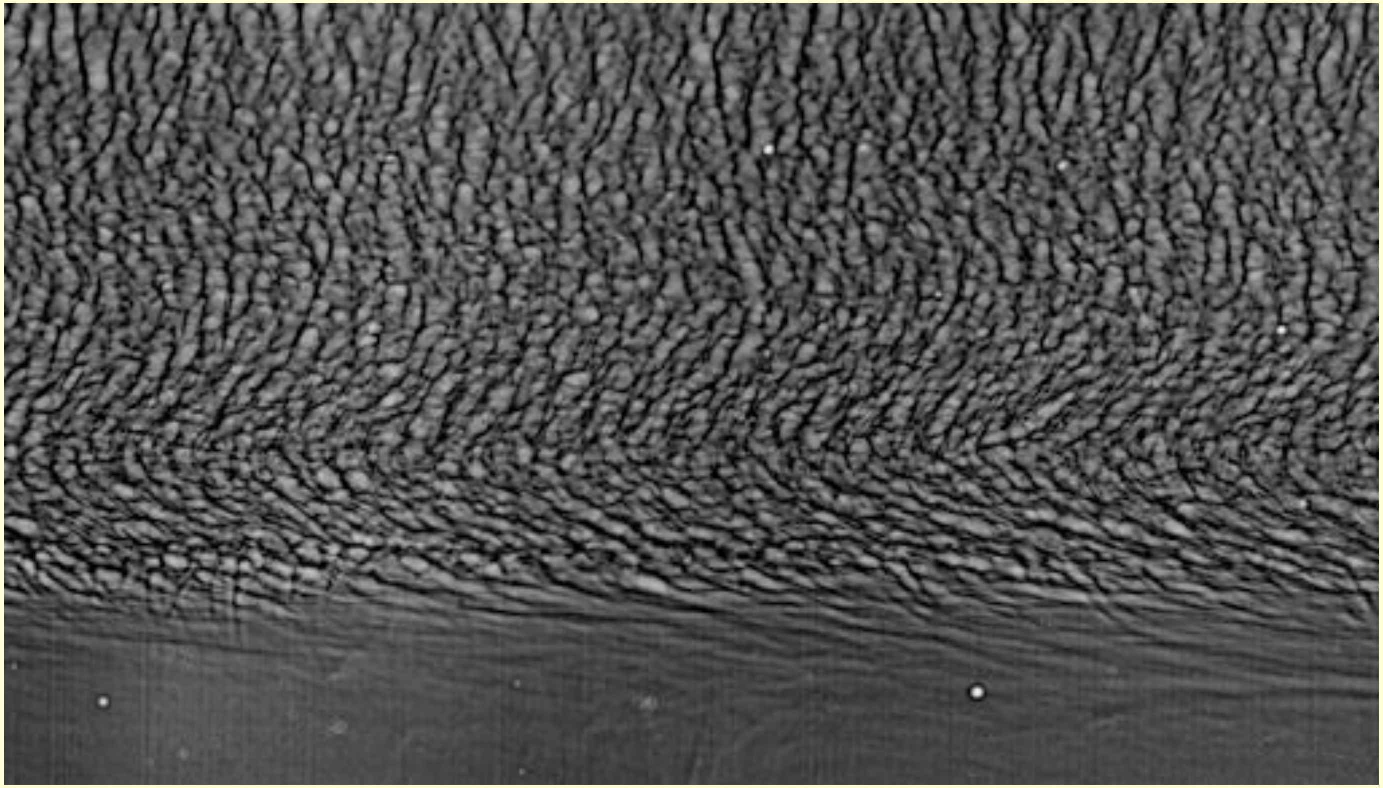


Shadowgraph of a portion of a thermohaline staircase showing a magnified view of a finger zone. The width of this image corresponds to 13.6 cm at the tank. Exposure time was 10 s.

$|R_s| = 9.42 \times 10^{15}$, $R_p = 1.25$.

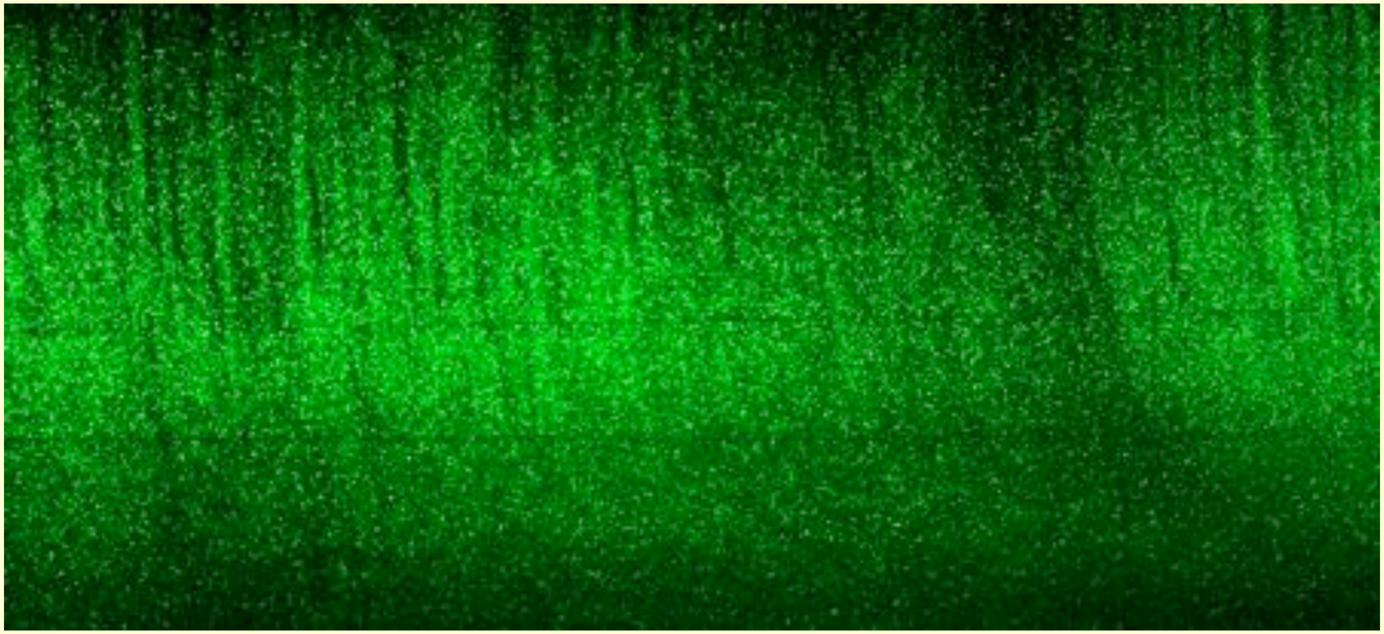


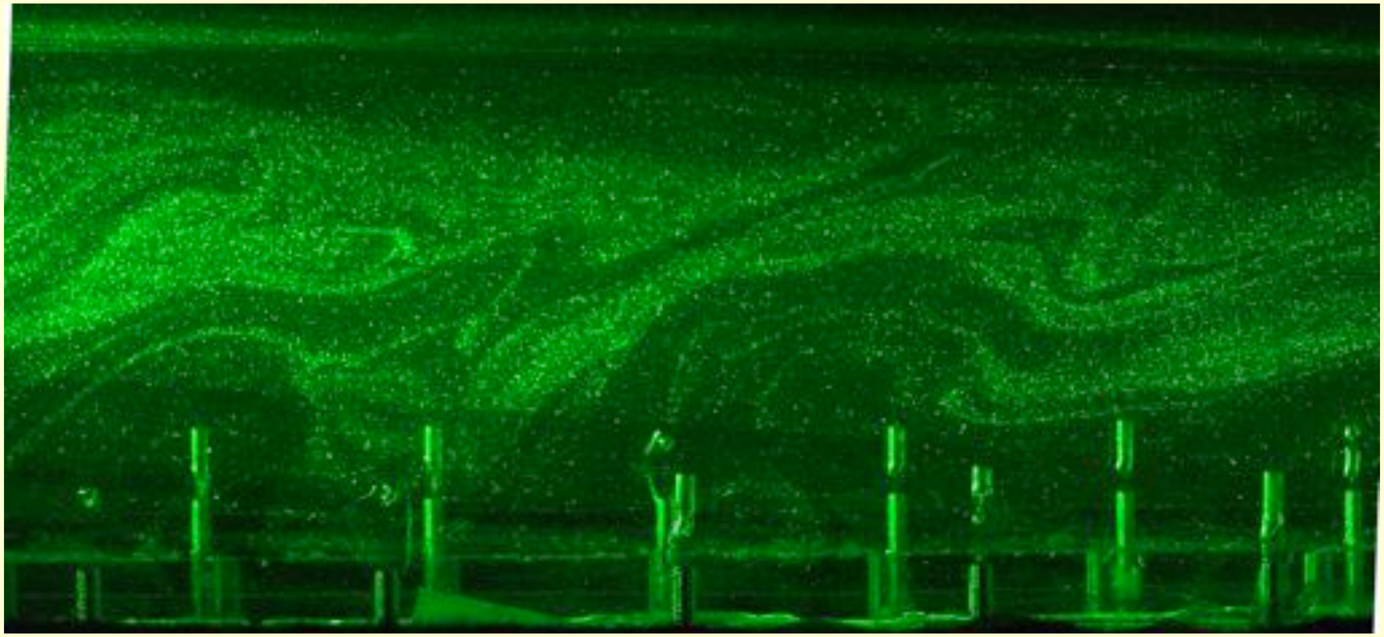
A schematic model of the drop in S-flux when coherent fingers are stirred by convection layers

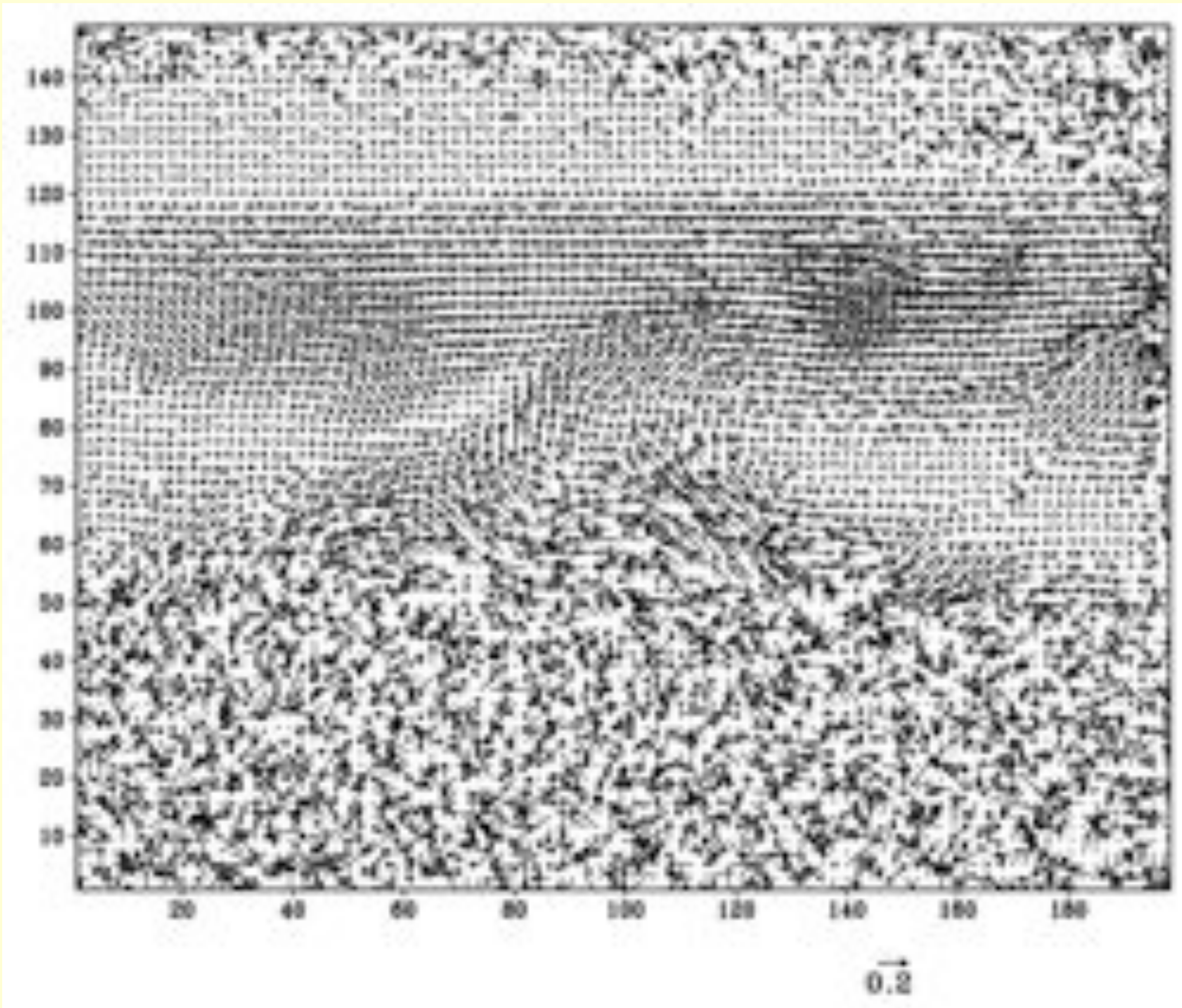


Shadowgraph of salt fingers above a convecting layer, with large-scale flow from left to right directly under the fingers. The image represents 9.2 cm in the *x* direction, 5.2 cm in the *z* direction, excerpted from a photograph 150 cm wide by 30 cm tall, which was uniformly of this character at all *x.* The fingers occupied 20 cm, the convection occupied 10 cm in depth. Note the tilt of the fingers that end in the convecting flow.

Tracer Particles in a vertical sheet (*x, z*) at mid-depth in *y*, showing fingers in the upper part of the tank (top) and tilted plumes in a large-scale shearing convection in the lower part of the tank (bottom) . The tracers were introduced from the upper left, 5 hours prior to this imaging. They traveled downwards in the down-going fingers and entered the convecting fluid. Meanwhile fluid free of tracers came from the far right along the lower part of the convecting layer, leading to this visualization.







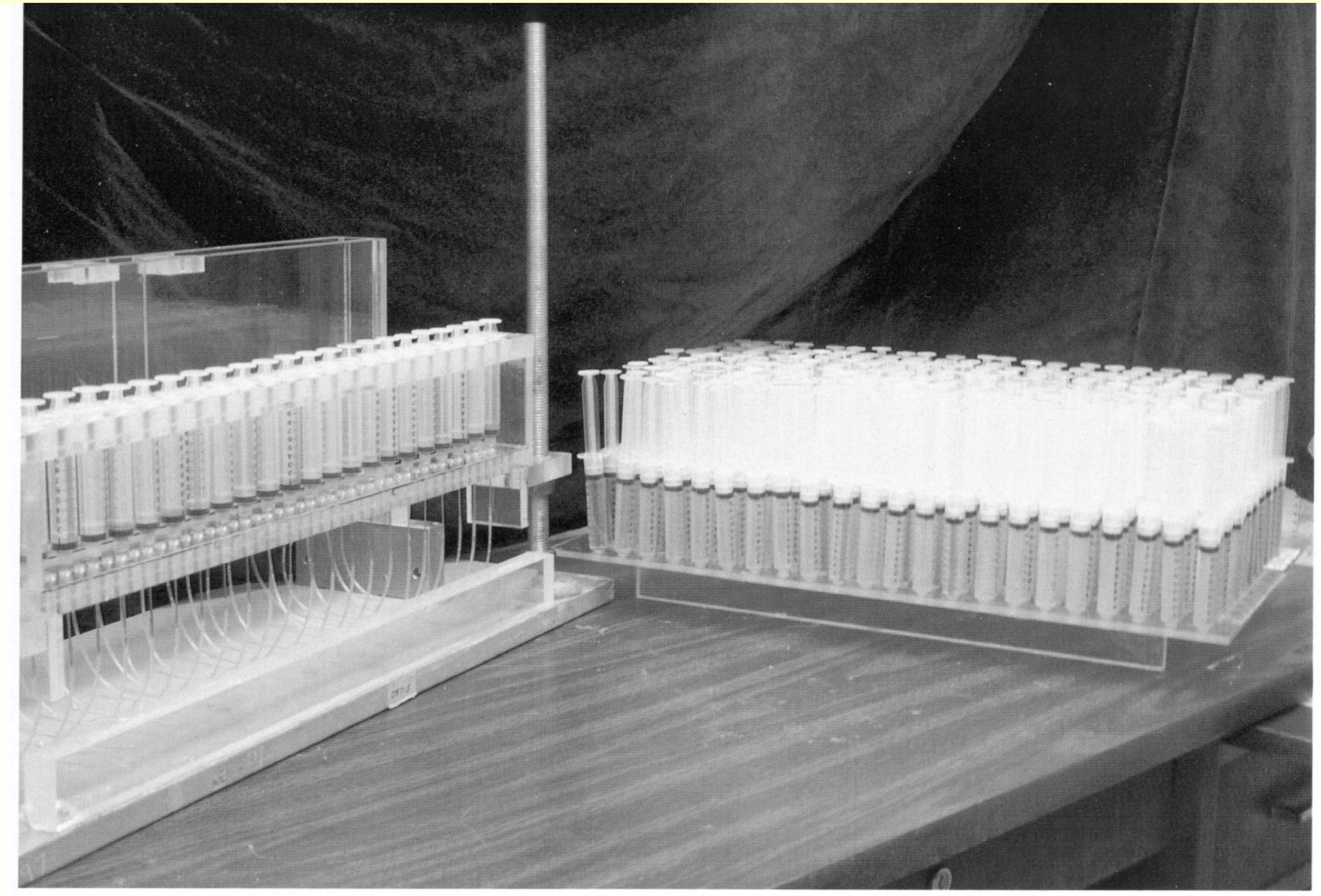
Showing a portion of the PIV-derived flow vectors on the vertical (*x, z*) sheet.

$$\rho(x,z) = \rho_0\left[1 - \alpha T(x,z) + \beta S(x,z)\right]$$

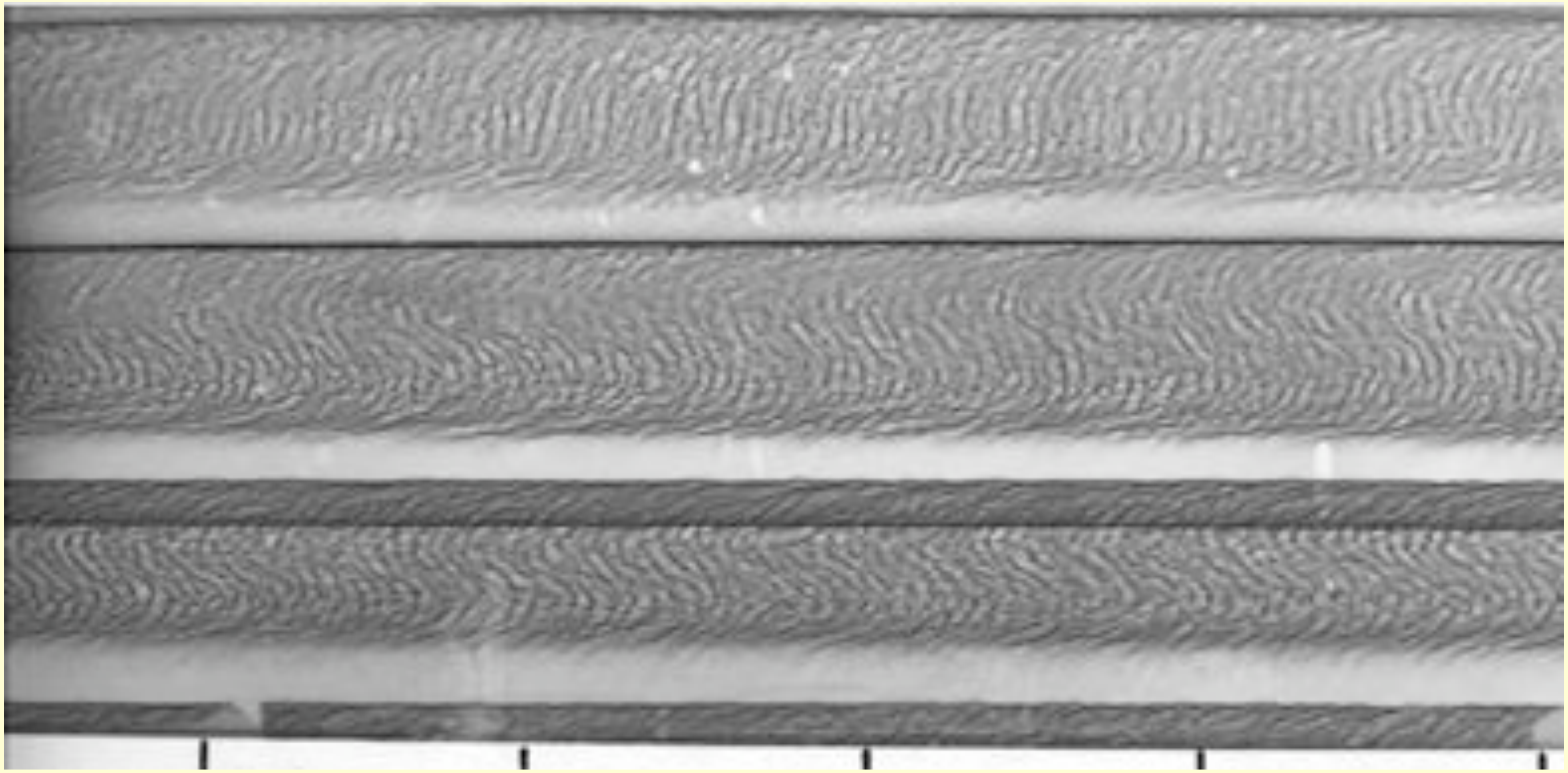
$$\text{with } \alpha T(x,z) = ax + bz$$

$$\beta S(x,z) = ax + cz$$

Since then, $\alpha \dfrac{\partial T}{\partial x} = \beta \dfrac{\partial S}{\partial x}$

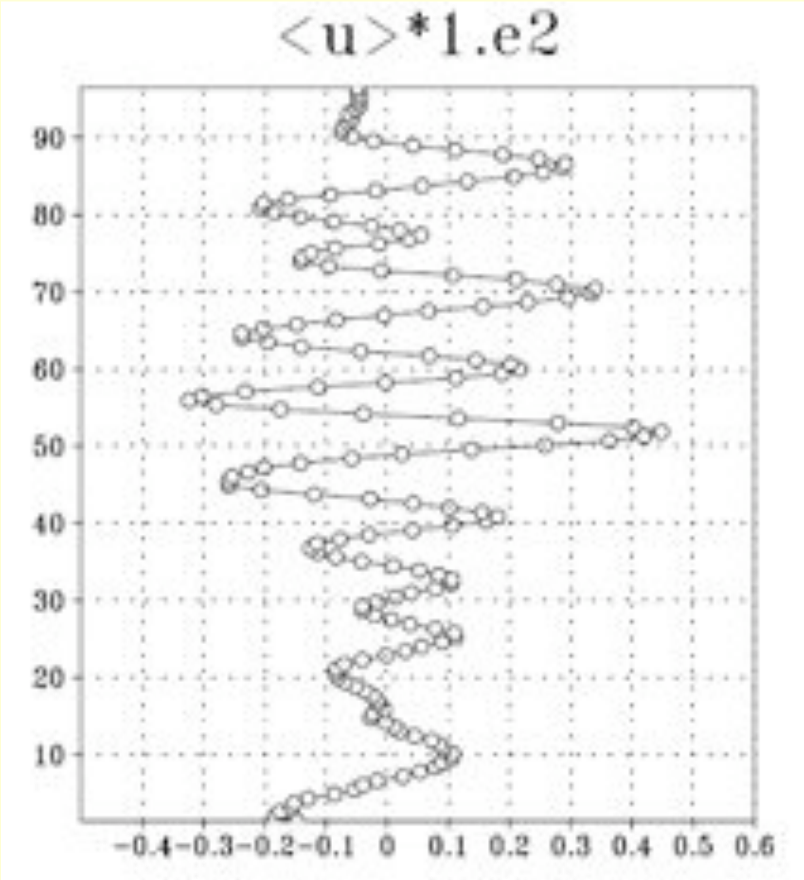


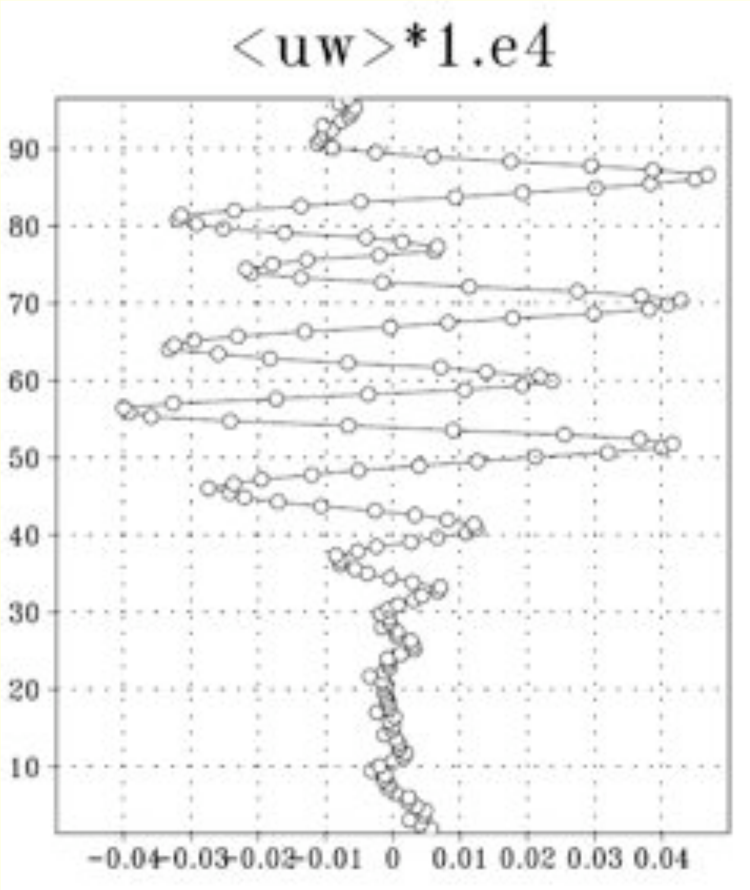
Apparatus to make continuous horizontal property gradients for interleaving experiment.



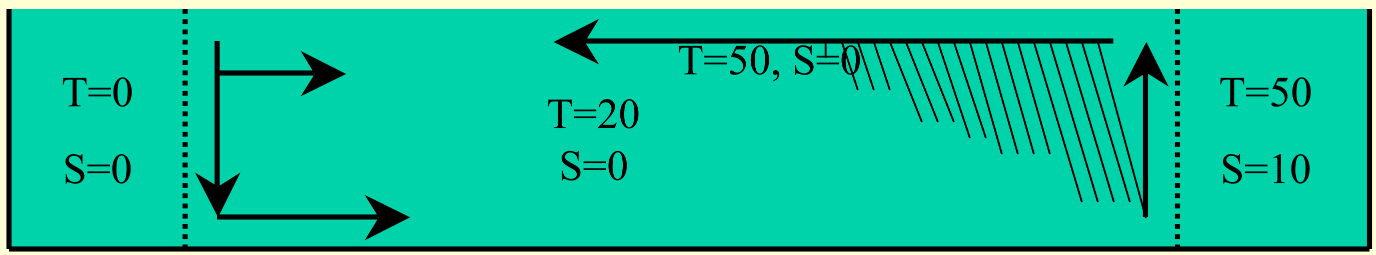
Shadowgraphs showing salt-finger favorable interleaving. The long edge of the photograph is in the direction of the horizontal x-axis. The tick marks along the horizontal are 2.54 cm apart. $R_\rho^\nu = 4$.

Shadowgraph showing interleaving on a continuous gradient, intruding into regions of no horizontal gradient. The distance between lines on the scale is 2.54 cm. The heavy black line along the bottom indicates the “middle one third” where continuous property gradients were initially imposed.





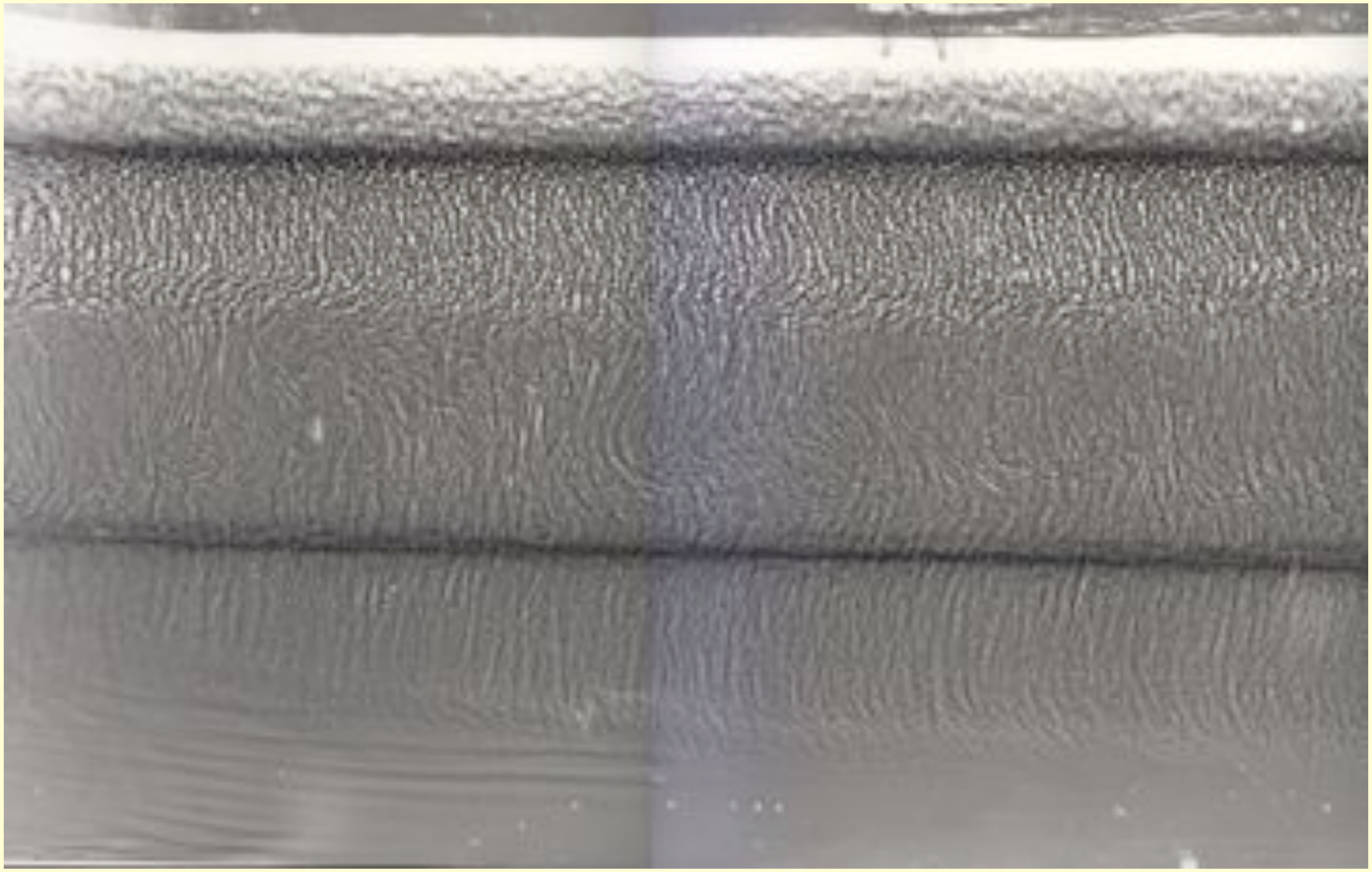
Horizontal averages over the domain (10 cm in x) of the horizontal velocity $\overline{u}$ and of the Reynolds stress as they vary with vertical coordinate z. Doubly stable.



Non-uniform heating and salting

Horizontal convection: Non-uniform heating and salting

Cold,
Fresh



Hot,
Salty

Conclusions

- Demonstrations experiments can be easy. They allow one to show that “if you do this to a fluid it responds thusly”.
- Visualization is important to show this response.
- Visualization is also important in early stages of measurement programs – it may help decide what quantities need to be measured.