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Water movements: Waves and Currents

BGY C56H3 Lecture 3 - September 25, 2000

HYDRODYNAMICS

- Wind, solar radiation, gravity, and earth's rotation (Coriolis force) are important forces causing water movements in lakes.
- Within a lake morphometry of the basin, stratification structure (density gradient), and exposure to wind (fetch) are important considerations.
- Knowing water movements is important because currents and waves influence the distribution of dissolved substances (e.g., gases), nutrients and food, and the distribution of microorganisms and plankton.
- Surface currents - nonperiodic, net unidirectional water flows. Normally exhibit sheared flow, which means velocity decreases with depth due to drag imparted by viscosity.
- Waves - periodic or rhythmic water flows.

Water Flow

- Water flows can either be laminar or turbulent. Laminar flow occurs at slow speeds and is characterized by smooth, unidirectional movement (i.e., ordered) with a uniform velocity profile. Turbulent flow occurs at higher speeds and is disordered, chaotic, and multidirectional with sheared flow profiles (reduction in flow with depth resulting from drag imparted by viscosity), that ultimately results in eddy formation.
- Shift from laminar to turbulent flow in a fluid in a smooth tube is related to the viscosity and density of the fluid, its velocity, and the size of the channel or tube through which the fluid flows.
- Reynolds Number, R_e, is used to determine if flow is laminar or turbulent in a tube.

$$R_e = (pDv)/\mu,$$

p is density, D is the diameter of the channel or tube, v is velocity, and μ is viscosity.

- $R_e < 1{,}000$ flow is laminar
- $R_e > 1{,}000$ flow is turbulent.
- Using depth for D in lakes, velocities of only a few mm/s will induce turbulent flow, with $R_e \sim 10^6$. LAMINAR FLOW IS ALMOST NEVER OBSERVED IN THE EPILIMNION OF STRATIFIED LAKES or in UNSTRATIFIED WATER.
- At epilimnion-metalimnion and metalimnion-hypolimnion interfaces, there is usually laminar flow. Water in each layer flows in opposite directions.
- In stratified lakes two important, but opposing forces are working:
  1. the vertical velocity gradient (called vertical shear) which forces mixing, and
  2. the vertical density gradient which prevents mixing of adjacent layers.
- Whether or not mixing occurs between these miscible layers, i.e., the stability of stratification, can be predicted using the Richardson number, R_i. The Richardson number is the ratio b/a:

$$R_i = [g(dp/dz)]/[p(dv/dz)^2]$$

g is acceleration due to gravity (9.8 m/s^2), is density, v is velocity, and z is depth.

- $R_i < 0.25$ in stratified fluid subjected to shearing flow, increases in friction and in mixing perpendicular to current direction occur, i.e., stratification is not stable.
- $R_i > 0.25$, flow remains stable and stratification is stable. There is no mixing of adjacent layers as they flow by one another because friction is low.
- When $R_i < 0.25$, the critical velocity difference along a the density interface (where two layers of different densities are in contact with each other) is exceeded, so disturbances grow in amplitude and vortices form.
- Vortices increase mixing since they form a transitional layer in which there is both shear (velocity gradient) and a density gradient.
- If vortex formation and mixing occurs, the transitional layer will occur in the epilimnion since there is usually no density gradient. The metalimnion is generally stable since there is rarely substantial water flow, except when internal seiches occur.

EDDIES

- Eddies are parcels of water with circular motion (swirls). Technical definition - an assemblage of shear waves of a spectrum of many lengths or "eddy diameters". Eddies have both vertical and horizontal motion and increase the diffusion of heat and dissolved substances (turbulent diffusion).
- Turbulence consists of a series of nested eddies of varying sizes in which energy is transferred from largest to progressively smaller eddies until viscosity prevents further eddy formation.
- The rate of turbulent diffusion is a function of the eddy diffusion coefficient (K_z), which is a measure of the rate of exchange or intensity of mixing across a plane. K_z varies with average density, velocity of vertical motion, and mixing length.
- K_z varies inversely with stability. Thus K_z decreases from turbulent epilimnion into more stable metalimnion and hypolimnion.

WAVES

Surface Waves

- Wind Drift - surface motion produced by friction of wind blowing over water surface.
- Traveling Surface Waves (Progressive waves) - occur when wind sets surface into oscillation. These are generally of short wavelength and confined to surface layers. Limnological significance is minimal except in shore areas. Causes surface water particles to move in a circular orbit called cycloid. Vertical motion of cycloids decreases with increasing depth, cycloid diameter halved for every depth increase of wavelength/9.
- Wavelengths of short surface waves are less than water depth (except in shore areas) so they travel at speeds proportional to wavelength$^{1/2}$. These waves are also called deepwater waves and are said to be dispersive.
- In moderate to large lakes maximum height of short waves (H) is related to fetch (X)

$$\mathbf{H\ (cm) = 0.105 * sqrt\ (X,\ cm)}$$

  e.g., based on a fetch of 482 km for Lake Superior, the predicted wave height is 7.3 m, which is consistent with the maximum observed height of 6.9 m.
- Shallow water or long waves have wavelengths > 20 X water depth and speed is proportion to depth$^{1/2}$. Because speed is not related to wavelength, these waves are not dispersive. Cycloid motion of water is transformed into back and forth movements which extend to the bottom of the water column.
- As shallow water waves enter shallow areas, height increases until it collapses over the front as a breaker.

SURFACE CURRENTS

- Generated by wind, changes in atmospheric pressure, horizontal density gradients, and influx of water into a lake.
- Moderate to large lakes, path of current is influence by Coriolis force due to rotation of the earth. This deflects surface currents to the right of wind direction in the Northern Hemisphere and to the left in the Southern Hemisphere.
- In the open waters of large lakes wind drift will be deflected at 45° angle to prevailing winds. Currents below surface move at progressively greater angles to wind as distance to surface increases. Deepest currents flow in opposite direction to wind. This spiral staircase flow is called an EKMAN SPIRAL. The angle of deflection relative to the wind decreases as depth decreases and is insignificant in lakes < 20 m deep.
- Velocity of wind driven currents about 2% of wind velocity and is independent of height of surface waves.

- **GYRE** - another type of whole-lake surface drift in the direction of prevailing winds and subject to geostrophic effects of Coriolis force. Slow counterclockwise flow (in northern hemisphere) around perimeter of lake with relatively stagnant centre. Importance is that they transport organisms with little energy expenditure. Also distribute nutrients and toxics. Found in large lakes such as the Great Lakes, e.g., in Lake Ontario patterns of sediment contamination (metals, organics) are consistent with counterclockwise gyre.

- **LANGMUIR SPIRALS** - windrows (lines of foam) oriented in same direction as wind on windy day and at right angles to waves are boundaries of pairs of Langmuir spirals.

- Spirals are a series of vertical helical clockwise and counterclockwise rotating cells of water. Produce alternate areas of upwelling and downwelling. Foam accumulates above downwelling zone. Spirals have approximate diameter equal to depth of thermocline in stratified lakes (i.e., epilimnion thickness) or lake bottom if lake is shallow and not stratified. One of the main ways through which turbulence is transported downward and the upper layers of water are mixed.
- Langmuir spirals seem to occur as a result of interactions between surface waves and wind-driven currents and occur in most lakes at wind speeds > 2-3 m/s. Streaks aren't seen at speeds > 7 m/s even though Langmuir spirals are occurring because surface turbulence disrupts foam aggregation.
- Downwelling flows tend to be faster than swimming abilities of most zooplankton or algae. Spirals may mix plankton, heat, or dissolved gases in epilimnion. Windrows or slicks contain algae, zooplankton and oily substances or natural foaming agents from death and decay of plankton and shoreline vegetation.
- Inhibition of algal P/S may occur because spirals expose them to surface-light intensities. Zooplankton such as *Daphnia* tend to concentrate in slicks. This influences predator distribution. Result: patchy horizontal distribution of predators and prey.

WHOLE LAKE MOVEMENTS

- Generally waves with wavelengths similar to basin dimensions and can be either oscillations of the water surface or isotherm depth (thermocline).
- Long waves are reflected by the basin boundaries and produce standing waves characterized by nodes about which substantial horizontal motion occurs while vertical motion is nil.
- These standing waves are **SEICHES**, from French meaning to dry, referring to periodic drying exposures of shallow littoral zones.
- Seiches are most often caused by wind induced tilting of the water surface and thermocline. When wind stops lake flows back towards equilibrium but overshoots. These oscillations continue but are dampened each time by friction and gravity.

Surface Seiches

- Occurs in unstratified lakes. Maximum amplitude occurs on the surface but it involves the entire water column.
- Surface seiches are generated when winds blow fairly constantly in one direction, driving surface water downwind. Water piles up on lee shore and wind holds it there until it drops, at which time driving force is released and accumulated water mass flows back under gravity. Produces standing wave that rocks back and forth with decreasing motion which is damped by friction and gravity.
- Surface seiches are apparent on lakes as small up and down motions.
- Period of oscillation at the node, t is

t = (2l)/(sqrt(g*zbar))

where t is the period (sec), l is length of basin at surface (cm), g is acceleration due to gravity (9.8 m/s^2), and zbar is mean depth.
- Unimodal surface seiches are common. Multimodal seiches can be generated by periodic exertion and release of pressure on the surface in the centre of a basin.
- Amplitude is usually small compared to internal seiches and impacts are variable. Generally not important to chemistry or biology of lake as energy is low.
For example, in Lake Erie surface seiches can exceed 2 m (t=14 hr) and can have positive and negative effects, flushing of river deltas and harbour areas, shoreline property damage and erosion.
- Surface seiches can occur under ice cover as well. They are common in Lake St. Clair during spring ice breakup.

Internal Seiches

- Occur when lake is stratified and involve different density layers oscillating in a standing wave relative to one another. Most frequently occur at the thermocline and are usually detected by the rise and fall of the thermocline. Occur only under stratified conditions and aren't apparent from surface. Usually much larger than surface seiches and may be as high as 10 m and period is often much longer. Small lakes usually not affect by internal seiches.
- Results from large scale horizontal water movements due to wind. Resulting currents flow rhythmically back and forth in opposite directions and constitute major deepwater movement in lakes.
- Internal seiches are important because transport heat and dissolved substances large distances both vertically and horizontally and they may significantly alter the distribution and productivity of

phytoplankton (algae) and zooplankton, directly or indirectly through changes in thermal and chemical stratification.

- Motion of seiches is not simply back and forth movement since they are subject to Coriolis force. This results in a circular track called an inertial circle with flow deflected onto the right shore in the Northern Hemisphere.

Coastal Jets

- Occur in conjunction with thermal bar formation in large lakes.
- Density differences at vertical bar (which is 4 C) drive downward flowing currents along the bar into the lower portions of the inshore and offshore waters. Coriolis force combined with density gradient induces a counterclockwise coastal current inside the thermal bar.

River Currents

- River water entering a lake will flow into water of similar density. Inflow movements related to temperature, dissolved substances, and suspended particles.
- 3 types of inflow movement:
    1. Overflow - river water is less dense than lake water and so stays at the surface,
    2. Underflow - river water density is greater than lake water and so flows along the bottom, e.g., spring melt runoff.
    3. Interflow - river water density is greater than epilimnion but less than meta- or hypolimnion. Flow enters as a plume at intermediate depth.
- Extent of plume is a function of discharge volume in relation to lake volume

Currents Under Ice

- Lakes are usually not stagnant under ice cover. Slow currents occur due to release of heat from sediments (convective currents). Most of this heat was accumulated during the previous summer.
- Horizontal velocities are usually greater than vertical velocities.