

Lecture summary - Waves and Instabilities

Shallow water equations

Knudsen number: $K_n = \frac{\text{mean free path}}{\text{smallest length scale}}$

Shallow water equations: Assumption $H \ll L$ and homogeneous ($\rho = \text{const}$)

- 1) Use scaling to obtain hydrostatic equilibrium and incompressibility
- 2) Obtain $\nabla_H p = \rho g \nabla_H \eta$
- 3) Use continuity and BC to obtain $\frac{Dh}{Dt} + h \nabla_H \cdot \vec{u} = 0$

Two layer model: Assumption same as before, note $\nabla_H p_0 = 0$.

- 1) Write NS equations with new continuity.
- 2) First layer same as before
- 3) The second layer uses continuous pressure. $p_2(z) = p_0 + p_1 g(\eta_0 - \eta_1) + p_2 g(\eta_1 - z)$
- 4) Obtain reduced gravity $g' = g \frac{\rho_2 - \rho_1}{\rho_1}$

Reduced gravity model: (aka 1.5) Assume $H_2 \gg H_1$.

- 1) Notice that shallow part is much faster, $\vec{u}_2 \approx 0$
- 2) Obtain relation $\nabla_H \eta_0 \approx -\frac{g'}{g} \nabla_H \eta_1$
- 3) Set $h_1 = \eta_1 - \eta_0$ which gives g' and h_1 for upper layer.

Potential vorticity: Material invariance, assume shallow. Use $\zeta = \left(\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \right)$.

- 1) Start by $\frac{\partial (eq2)}{\partial x} - \frac{\partial (eq1)}{\partial y}$
- 2) Solve for ζ and $\frac{D}{Dt} \zeta$
- 3) Use continuity

Note: All functions of Q are material invariants.

Wave theory

Linear wave solution: Assume SWE, $f = f_0$ and $\vec{u} = \epsilon \tilde{\vec{u}}$, $\vec{v} = \epsilon \tilde{\vec{v}}$, $\eta = H + \epsilon \tilde{\eta}$.

- 1) Neglect all ϵ^2 terms.
- 2) Apply Fourier ansatz
- 3) Solve for $\omega(f_0, k, l)$
- 4) Two solutions:
 - i. $\omega = 0 \rightarrow$ Geostrophic
 - ii. $\omega \neq 0 \rightarrow$ Pointcarré waves: Generally dispersive, but not in
- 5) Use $c = \sqrt{gH}$ and Rossby radius of deformation $L_D = \frac{c}{f_0} = \frac{\sqrt{gH}}{f_0}$.
 - i. If SW: $\omega \gg f_0 \rightarrow \omega^2 = c^2(k^2 + l^2)$
 - ii. if LW: $\omega \approx f_0$ "Internal oscillations"

Geostrophic adjustment: Assume linearized waves

- 1) Use equations to derive expression for $\zeta(Q)$
- 2) Begin by doing $\frac{\partial (eq1)}{\partial x} + \frac{\partial (eq2)}{\partial y} = -g \nabla H^2 \eta$
 - i. Insert ζ when possible
 - ii. Use continuity as $\frac{\partial^2 \eta}{\partial t^2} = -H \frac{\partial \eta}{\partial t} \left[\frac{\partial u}{\partial x} + \frac{\partial v}{\partial x} \right]$
- 3) Split solution into homogeneous and particular as $\eta = \eta_w(t) + \eta_p$
- 4) Use the starting scenario to determine Q , use relation from before.
- 5) Use particular solution to derive η_p and determine geostrophic wind.

Quasi-geostrophic: Linearize PV-equation and get $\frac{\partial}{\partial t} \left(\nabla^2 \psi - \frac{\psi}{L_D^2} \right) + J(\psi, \nabla^2 \psi) + \beta \frac{\partial \psi}{\partial x} = 0$

- 1) Assumptions:
 - $\text{Ro} \ll 1$
 - $\beta y/f \ll 1$
 - $\eta/H \ll 1$
- 2) Go from PV-equation and extract f_0/H
- 3) Taylor expand and neglect order ϵ^2
- 4) Introduce stream-function

Rossby waves with no flow: Start from quasi-geostrophic.

- 1) Reference state $\psi = \epsilon \psi'$ and $-\partial_x \psi = u$ and neglect ϵ^2
- 2) Fourier ansatz
- 3) Obtain dispersion relation $\omega = \frac{-\beta k}{k^2 + l^2 + 1/L_D^2}$
 - SW: stationary
 - LW: Non-dispersive, westward

Rossby waves with background flow: Assume $\vec{u} = (u_0, 0)$

- 1) Reference state $\psi = \epsilon \psi'$, $u = u_0 + \epsilon u'$ and $v = \epsilon v'$ and neglect ϵ^2
- 2) Fourier ansatz
- 3) Obtain dispersion relation $\omega = u_{0k} - k \frac{\beta + u_0/L_D}{k^2 + l^2 + 1/L_D^2}$
 - SW: background flow
 - LW: Non-dispersive, westward

Kelvin waves: Wave propagation along a fix surface (like coast)

- 1) Assume $\text{Ro} \ll 1$ and $\vec{u} = (u, 0)$
- 2) Take x-derivative to write 1 equation
- 3) Fourier ansatz: $\eta = \hat{\eta}(y) e^{ikx - \omega t}$ and solve for dispersion
- 4) Take time-derivative of eq 1 and 3 to obtain amplitude.

Instabilitets

Barotropic instability:

2 layer model: Assume rigid lid but surface pressure

- 1) Determine the pressure from continuity and 2 layer SWE
- 2) Introduce stream-function form geostrophic flow
- 3) Expand PV-conservation by approximations
- 4) For solutions define
 - Barotropic mode: $\bar{\psi} = \frac{F_1 \psi_2 + F_2 \psi_1}{F_1 F_2}$
 - Baroclinic mode: $\tau = \frac{1}{2} [\psi_2 - \psi_1]$

Criterion for barotropic instability:

- Rayleigh-Kuo: For instability $\frac{\partial q}{\partial y}$ must change sign in the domain.
- Fjörtoft: For instability $\frac{u_s - u_0}{dq_0/dy} > 0$

Phillips model: Assume the three standard assumptions and $H_1 = H_2$ and $u_1 = -u_2 = u$

- 1) Start from PV-equation for two layers $\frac{D}{Dt} [q_i] = 0$
- 2) Use reference state $\bar{u}_i = u_i + \epsilon u' = \frac{d\psi_i}{dy} + \epsilon \frac{d\psi'_i}{dy}$ and $\bar{v}_i = \epsilon v' = \epsilon \frac{d\psi_i}{dx}$ and $\bar{\psi}_i = \psi_i(y) + \epsilon \psi'(x, y, t)$
- 3) Use Fourier ansatz $\psi'_{1,2} = \hat{\psi}_{1,2} e^{ikx + iky - ik\zeta t} = \hat{\psi}_{1,2} e^{ikx + iky + \sigma t}$
- 4) Use math to solve for ζ
- 5) Obtain three cases:
 - i. $U=0$ and $\beta \neq 0 \rightarrow$ Rossby waves (Two roots give baroclinic vs barotropic)
 - ii. $U \neq 0$ and $\beta = 0 \rightarrow$ High value cut-off Unstable if $\frac{\lambda}{2\pi} < \frac{L_D}{\sqrt{8}}$. No low value cut-off
 - iii. $U \neq 0$ and $\beta \neq 0 \rightarrow$ Cut-off $\frac{\beta}{\sqrt{2} U_0} < k < k_d$

Baroclinic instability:

- Thermal wind $\frac{\partial \vec{u}}{\partial z} = \frac{1}{f_0} \hat{z} \times \nabla b$
- Potential energy decreases when lapse rate is not constant

• Slanted convection: From $\Delta PE = g \Delta \rho \Delta z$ and Taylor \rightarrow displacement if $\phi > \alpha > 0$

◦ Slope of displacement: $\alpha = \Delta z / \Delta x, y$

◦ Slope of isopycnals: $\alpha = -\frac{\partial \rho}{\partial y} / \frac{\partial \rho}{\partial z}$

$$\begin{aligned} \text{Equatorial dynamics} \\ \text{Equation 1: } \frac{\partial \vec{u}}{\partial z} = \frac{1}{f_0} \hat{z} \times \nabla b \\ \text{Equation 2: } \frac{\partial \rho}{\partial z} = -\frac{\partial \rho}{\partial y} \frac{\partial y}{\partial z} \\ \text{Equation 3: } \frac{\partial \rho}{\partial y} = -\frac{\partial \rho}{\partial x} \frac{\partial x}{\partial y} \\ \text{Equation 4: } \frac{\partial x}{\partial z} = \frac{\partial x}{\partial y} \frac{\partial y}{\partial z} \\ \text{Equation 5: } \frac{\partial y}{\partial z} = \frac{\partial y}{\partial x} \frac{\partial x}{\partial z} \\ \text{Equation 6: } \frac{\partial x}{\partial y} = \frac{\partial x}{\partial z} \frac{\partial z}{\partial y} \\ \text{Equation 7: } \frac{\partial z}{\partial y} = \frac{\partial z}{\partial x} \frac{\partial x}{\partial y} \\ \text{Equation 8: } \frac{\partial x}{\partial z} = \frac{\partial x}{\partial y} \frac{\partial y}{\partial z} \\ \text{Equation 9: } \frac{\partial 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