Lec 1  GFD 1  2015
Geophysical Fluid Dynamics-1  Winter 2015  UW  OCEAN 512/ATM S 509

Lectures: Tues/Thurs 10.30-11.50;  205 Ocean Teaching Building, with a third meeting for labs in 107 Ocean Sciences
Instructor: P.B. Rhines  rhines@uw.edu  Ocean Sciences room 319 tel 543-0593
TA: Miguel Jimenez  jimenezm@uw.edu

Web site:  www.ocean.washington.edu/courses/oc512
Prerequisite: ATM S/AMATH 505/OCEAN 511.

OUTLINE  ( an * indicates topics to be introduced only if there is time)
oceans and atmospheres: general description
   general circulation: thin layered structure of ocean and atmosphere; dominant horizontal
   velocity and weaker yet important meridional overturning circulation; stably stratified
   conservation principles
   solar radiation and the climate heat engine
   Earth's rotation

equations of motion;
   balance (relations between variables..p, u... ) and evolution of time-dependent flows
   motionless fluids: hydrostatic balance
   advection: flux of a conserved property by fluid motion
   internal (thermodynamic) and external (mechanical) energy; generalized Bernoulli equation
   equations of state
   momentum balance
   Earth's rotation: the geopotential, angular momentum, Coriolis force
   free particle on an f-plane and a sphere: inertial oscillations
   geostrophic balance, Taylor-Proudman 'stiffness', Rossby number
   hydrostatic and thermal wind balance -I

homogeneous (unstratified) fluid
   long gravity waves with rotation, Kelvin waves
   geostrophic adjustment-I
   potential vorticity (PV) and Kelvin's theorem
   Rossby deformation radius, energetics
   *spherical effects and the β-plane
   Rossby waves and *β-plumes in single layer, *effects of zonal flow
   viscous dissipation: Ekman boundary layer, Ekman number
   Ekman suction: viscous spin-up and spin-down

density-stratified fluids
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**density-stratified fluids**
- *Boussinesq and anelastic approximations
- static stability, N2, lapse rates, potential density
- geostrophic adjustment-II
- thermal wind-II revisited; Bjerknes circulation theorem and potential vorticity
- Prandtl ratio, Burger number/interal Rossby radius, available potential and kinetic energy
- meridional overturning circulations and angular momentum; *Hadley circulations

**internal gravity waves**
- dispersion relation, group velocity for non-hydrostatic internal waves
- waves propagating from a compact, oscillating source
- waves excited by flow over mountains
- *waves excited by a moving boundary

**synoptic quasi-geostrophic equations**
- rotating, stratified flow over mountains: Taylor columns and Taylor cones
- *introduction to baroclinic instability
- *potential vorticity (PV-): balance and inversion
- form stress

**GFD lab demonstrations**

We will do as many hour-long labs as possible this term; those from past years can be seen by browsing the the web pages for several different years GFD-1 course at http://www.ocean.washington.edu/research/gfd under ‘Courses using the GFD lab’. Or directly at http://www.ocean.washington.edu/research/gfd/#courses
In-class exercises, discussions
What’s New
Internal-mode tide, seen in the sea surface elevation (with horizontal energy flux) from satellite altimetry in Pacific O1 tide (25.8 hour lunar tide) excited at a seafloor ridge between Taiwan and Luzon (Zhao UW APL, JGR 2014)

note refraction due to latitude dependence of wave speed
Tides? I thought tides look like this (in sea-surface elevation): the major 12.4 lunar tide propagates as a Kelvin wave round ocean basins.
Tides? I thought tides look like this (in sea-surface elevation): no, they are internal gravity waves excited by the external tide.
- tropical Pacific warm ocean generates Rossby waves in atmosphere which are northward/eastward to cause NAO+ winters
El Niño – warm ocean interacting with tropical atmosphere, sends Rossby wave across USA.


cold tropical Pacific sends Rossby wave toward Greenland.
Also Ding, Steig, Battisti, Küttel NatureK Geosci 2011

A Rossby wave excited by warm SST in western equatorial Pacific propagates south to Antarctic Peninsula, warming it.
and...

- **global observing system for the oceans completed!** (satellite altimetry, ocean color, gravity, rainfall, winds; >3000 drifting ARGO floats, profiling T, S, O2... to 2000m; robotic Seagliders, ship-based geochemistry & biology)

- **ocean tracer observations used in conjunction with dynamics:** deconstructing the global overturning circulation (‘conveyor belt’)

- **ozone hole over Antarctica (low ozone in Austral spring):** cools stratosphere, deepening low pressure core, accelerating winds all the way to the sea surface: human induced changes in the winds.

- **annular modes of variability of westerly winds, interacting with jet streams and blocking**
Antarctic polar vortex (surf. temp, 1000mb, 300mb, 30mb dynamic height)
winter mean 500 HPa height (black) and sea-level pressure (colored, blue=low, cyclonic)

1993 JFM SLP and Z500

Coast Range Mountains of Alaska
Low SLP on Western Slope
024 Hr Fcst 1000-500 MB Thickness (dekameters)/SLP (mb) valid 12Z Tue 06 Jan 2015
(GFS initialized 12Z Mon 05 Jan 2015)
250 HPa dynamic height: winter 2005/6:

wintertime jet stream with large meanders that ‘break’, forming blocking structures that persist for days.

Matlab animation using NCEP reanalysis data and M_Map mapping tool.
University of Utah weather loops

http://weather.utah.edu/index.php?runcode=2014122818&t=gfs004&r=NH&d=DT
North Atlantic surface ocean circulation: reconstructed from satellite altimetry (showing kinetic energy of the flow)
Extremely high resolution general circulation model (~1.5 km grid cells)
Xu Xiaobiao HYCOM model FSU

Relative Vorticity at Sea Surface
2003, January 1
HYCOM 1/50
Dust! affects air quality, ocean biology (through iron fertilization)…. possibly ocean circulation (through albedo)

https://www.hcn.org/issues/46.22/the-dust-detectives
SeaWiFS ocean color satellite: estimate of chlorophyll and hence primary production of phytoplankton...hence oxygen (false color)
Thermodynamics: Gill (and Vallis) short treatment

=> a whole lot of versions of the equation of state for a gas (ideal gas usually)

moist thermodynamics

connection with energy… \( p = \rho RT \) is an energy equation once we decide on the definition of temperature, \( T \):

\[
\frac{3}{2} k T = \text{kinetic energy of a gas molecule}
\]

where \( k = \text{Boltzmann’s const.} = 1.381 \times 10^{-23} \text{ m}^2 \text{kg sec}^{-2} \text{K}^{-1} \)

Pressure \( p \) begins to look like kinetic energy because it involves flux of momentum of molecules, \( (mu \times u) \)

\[
R = \frac{R^*}{m_a} \quad R^* = 8314.36 \text{ J kmol}^{-1} \text{K}^{-1}
\]

for dry air mass \( m_a = 28.966 \) so \( R = 287.04 \)
<table>
<thead>
<tr>
<th>Name</th>
<th>Symbol</th>
<th>Formula</th>
<th>Natural variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal energy</td>
<td>$U$</td>
<td>$\int (TdS - pdV + \sum_i \mu_i dN_i)$</td>
<td>$S, V, {N_i}$</td>
</tr>
<tr>
<td>Helmholtz free energy</td>
<td>$F$</td>
<td>$U - TS$</td>
<td>$T, V, {N_i}$</td>
</tr>
<tr>
<td>Enthalpy</td>
<td>$H$</td>
<td>$U + pV$</td>
<td>$S, p, {N_i}$</td>
</tr>
<tr>
<td>Gibbs free energy</td>
<td>$G$</td>
<td>$U + pV - TS$</td>
<td>$T, p, {N_i}$</td>
</tr>
<tr>
<td>Landau Potential (Grand potential)</td>
<td>$\Omega, \Phi_G$</td>
<td>$U - TS - \sum_i \mu_i N_i$</td>
<td>$T, V, {\mu_i}$</td>
</tr>
</tbody>
</table>
thermal energy cycles of atmosphere/ocean/land system: great and small
Convection: heating from below

Scott Powell GFD lab
Convection: cold polar ocean flows equatorward beneath warm subtropical ocean

Miguel Jimenez  GFD lab
Zonally averaged meridional circulation of atmosphere (Eulerian view)
consider the differences between tropics and Arctic…(a) at 60°N latitude the sunshine incident per unit area is 50% of the full intensity with the sun overhead; (b) the albedo (whiteness) is greater.

source: IPCC-01 / TRENBERTH
255K (-18°C) - the simple radiation temp of Earth

290K = average surface temp

Figure 1.5. Vertical profile of the temperature between the surface and 100 km altitude as defined in the U.S. Standard Atmosphere (1976) and related atmosphere layers. Note that the tropopause level is represented for midlatitude conditions. Cumulonimbus clouds in the tropics extend to the tropical tropopause located near 18 km altitude.
solar radiation (kilowatt-hours per square meter, per day) varies with latitude and season (here neglecting the great effect of cloudiness)
Variation of Temperature With Latitude

- A simple radiative calculation gives an Earth with the correct average $T$, but wrongly distributed meridionally (north-south)

*slide from K. Carslaw, Univ. of Leeds*
Global meridional heat transport divides roughly equally into 3 modes:

1. atmosphere (dry static energy) \( c_p T + \Phi \)  
   \[ \text{(Bryden & Imawaki 2002)} \]

2. ocean (sensible heat)

3. joint atmosphere/ocean mode: water vapor/latent heat transport \( Lq \)

The three modes of poleward transport are comparable in amplitude, and distinct in character (sensible heat flux divergence focused in tropics, latent heat flux divergence focus in the subtropics)  
(based on Keith (Tellus 1995) climatology, similar to more modern: Trenberth et al. J.Clim 2003)

Error est.: \( \pm 9\% \) at mid-latitude; Bryden est 2.0 \( \pm 0.42 \) pW at 24N
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The northern subtropics show extremely active upward air/sea moisture flux
very similar numbers from Trenberth & Stepaniak, QJRMS 04 here, dry static energy (‘sensible heat flux’), latent heat flux, total atmospheric heat flux
consider the differences between tropics and Arctic…(a) at 60N latitude the sunshine incident per unit area is 50% of the full intensity with the sun overhead; (b) the albedo (whiteness) is greater

source: IPCC-01 / MENDERTH
Flux of fresh water by the atmosphere is concentrated in the Pacific and Atlantic storm tracks.

Globally it carries ~2 petawatts of latent heat flux … which is ~0.7 Sverdrup (0.7 megatonnes/sec) of freshwater flux.

1993 JFM 1996 JFM
1st law of thermodynamics: The increase in internal energy of a closed system is equal to the difference of the heat supplied to the system and the work done by it: \( \Delta U = Q \)

2d law:
Heat cannot spontaneously flow from a colder location to a hotter location.

Defines entropy, for thermal systems and more generally for statistical ensembles of interacting elements.

Thermodynamic potentials are different quantitative measures of the stored energy in a system.
P-V-T eqn of state

ideal gas

water
P-V-T eqn of state

ideal gas

water
condensation: latent heat => sensible heat

latent heat of vaporization/condensation
\[ L = 2.5 \times 10^6 \text{ Joules kg}^{-1} \text{ (20C)} \quad \text{Big!!} \]
\[ 2.25 \times 10^6 \text{ Joules kg}^{-1} \text{ (100C)} \]

heat of fusion (freeze/melt)
\[ 0.336 \times 10^6 \text{ Joules kg}^{-1} \]

compare with specific heat capacity of water: \[ C_p = 4000 \text{ Joules kg}^{-1} \text{ K}^{-1} \text{ at 28C} \]
….to heat water from room temperature to boiling point \( \sim 0.3 \times 10^6 \text{ Joules kg}^{-1} \)
Carnot’s original diagram for the heat-engine cycle
Heat reservoir at temperature $T_2$

$W = Q_2 - Q_1$

Heat reservoir at temperature $T_1$
Eff(%) = W / Q2 = (Q2 - Q1) / Q2
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“tephigram” T – $\phi$ .... now called T – S temp - entropy
Eff(%) = W / Q2 = (Q2 - Q1) / Q2

where is work done? d’W = \oint P \, dV

why chose isothermal expansion?

when to heat and when to cool to maximize work done?

“tephigram” T – \phi .... now called T – S temp - entropy
P-V diagram for Carnot heat engine cycle: moves along isothermal and adiabatic curves \( PV = \text{const} \) and \( PV^\gamma = \text{const} \)

\[ \gamma = \frac{C_p}{C_v} \approx 1.4 \]
Carnot Cycle, \( PV \) Diagram

- The work done by the engine is shown by the area enclosed by the curve, \( W_{\text{eng}} \)
- The net work is equal to \( |Q_h| - |Q_c| \)
- \( \Delta E_{\text{int}} = 0 \) for the entire cycle
Carnot cycle: gives the most mechanical energy you can harvest from a heat engine: view the cycle plotting temperature against entropy

\[ d'Q = TdS \]  
(heating = temperature x entropy change…at equilibrium, small amplitude)

so between 1 and 2 heat input is \( T_2 dS \)

between 3 and 4 heat output is \( T_1 dS \)

\[ \therefore d'W \text{ work done (mechanical energy produced) is } (T_2 - T_1) dS \]

and so efficiency = work done/heat input

\[ = \frac{(T_2 - T_1)}{T_2} \]
p-V diagram of the gasoline engine

Isochoric ignition and combustion

Adiabatic compression stroke

Adiabatic power stroke

Isochoric exhaust stroke

A Gasoline Engine

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Beta type Stirling engine. There is only one cylinder, hot at one end and cold at the other. A loose fitting displacer shunts the air between the hot and cold ends of the cylinder. A power piston at the end of the cylinder drives the flywheel.
p-V diagram of the steam engine

Solid line - idealized
Dotted line - actual

Heated to boiling point
Boiler pressure
Converted to steam
Super-heated steam
Adiabatic compression

Adiabatic expansion - power stroke
Cooled and condensed steam

A Steam Engine

Heat
Water tank
Cylinder
Piston
Valve
Boiler

Q₁
Q₂
The next step is to analyze the atmosphere and ocean in terms of their heat-engine activity: convection at large and small scales, which generates circulation (mechanical energy); the efficiency of this conversion of thermal energy to flow and gravitational potential energy is low, yet the GFD of the system concentrates energy in remarkable ways (atmospheric jet streams, oceanic boundary currents).