MAE578 Environmental Fluid Dynamics
Mon/Wed 3:30 – 4:45 pm

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Office Hours: 1:30-5:00 pm, Tuesday, or by appointment

Textbook: Atmosphere, Ocean, and Climate Dynamics,
J. Marshall & R. A. Plumb, **Required**

Textbook will cover 40-50% of the course material

Additional material: Lecture notes by instructor
Journal articles, etc.

Attendance is strongly encouraged

Prerequisites

No official prerequisites, but we will encounter some basic material from

- Thermodynamics
- Multivariate calculus, Differential equations
- Fluid mechanics (OK if you don't have it yet)

A short survey of fluid mechanics will be provided. It by no mean replaces a formal course on fluid mechanics. (You are encouraged to take one if you haven't.)

Scope:

Dynamics and thermodynamics of “large-scale” fluid flows; $L >>$ human scale

Commonly called “geophysical fluid dynamics” and “environmental fluid dynamics” (no clear distinction between the two, but EFD is usually concerned with systems of slightly smaller scales)

MAE578 is in the process of being renamed “Geophysical & Environmental Fluid Dynamic”, which will more appropriately reflect its content

Laboratory/industrial flows
→ Under “controlled” environment
→ Precise set-ups of flow parameters and
boundary conditions to serve a specific purpose
→ Closed system (to some extent)

vs.

Flows in nature (our focus)
→ Entanglement of multiple processes
→ Humans (for most of the time) are passive
observers of the system
→ Open system / complicated boundary conditions

Challenges in GEFD

- Multiple processes /scales, generally non-separable

Useful “theories” have mostly aimed at extracting a subset of the dynamics that explain a fraction of the total variance of the flow. They are each valid only within a certain range of spatial/temporal scales.

Different dynamics for different scales
→ Dominance of different groups of
terms in the Navier-Stokes equations

(No need to panic if you are not yet familiar with Navier-Stokes equations.)

Challenges in GEFD

- Incomplete observation due to the vast range of spatial/temporal scales involved
  → Envision the task of measuring the 3-D velocity and temperature field over Phoenix metro area.
  (Envision doing it globally every day, which is needed for routine weather prediction!)

- Incomplete observation due to inaccessibility to extreme flow environments
  → How do you measure the 3-D velocity field within a hurricane (which is needed to *initialize* a hurricane prediction model)?
  How about the velocity field in the deep ocean (which is relevant to Earth's long-term climate)?

Challenges in GEFD

- Difficulty in numerical simulation (or prediction) due to multiple-scale nature of the flows

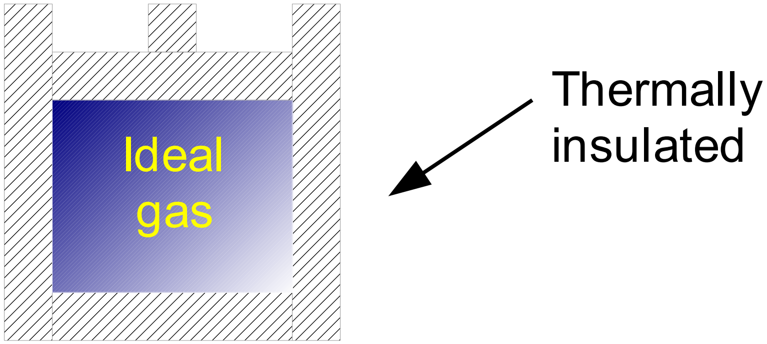
Example 1: A 3-D simulation for Phoenix metro area (100 km x 100 km x 10 km) using 100 m resolution in all 3 directions
→ 100 million grid boxes

This does not resolve street canyons; The effect of surface roughness due to urban landscape (buildings, etc.) still needs to be "parameterized"

Example 2: Global weather prediction

Dealing with an open system …

The “diabatic” terms (source and sink of energy/entropy) are important



A textbook “closed system”

Recall that for this system $dS = \frac{dQ}{T} = 0$;

Entropy S is conserved

Our “diabatic” forcing broadly refers to the dQ here

Open systems

For a large-scale environmental flow, diabatic forcing is usually important, i.e., *dQ* is large

Write the “heating rate” as $\dot{Q} \equiv dQ/dt$ where *t* is time, we have (let's ignore the complexity involving the *T* in the denominator)

$$\frac{dS}{dt} = \frac{\dot{Q}}{T}$$

An obvious source of $\dot{Q}$ is the sun.

But we are dealing with a system that flows, rather than sitting still

Take $\dfrac{dS}{dt} = \dfrac{\dot{Q}}{T}$,

the dS/dt here is the rate of change of entropy following a “control volume”. For observers fixed in space, the “local” rate of change of S is $\partial S/\partial t \equiv dS/dt$ - $\mathbf{v}\bullet\nabla S$ where $\mathbf{v}$ is the 3-D flow velocity, therefore we have

$$\frac{\partial S}{\partial t} + \boldsymbol{v}\cdot\nabla S = \frac{\dot{Q}}{T} ,$$

where the field S is a function of (x,y,z,t).

We will base many of our discussions on equations of this kind.

(This is broadly referred to as the Eulerian framework, but let's not burden ourselves with jargons.)

Not to worry if the argument in the preceding slide sounds unfamiliar to you. We will provide the detail later.

Coupling of dynamics and thermodynamics

The equation, $\frac{\partial S}{\partial t} + \boldsymbol{v} \cdot \nabla S = \frac{\dot{Q}}{T}$, is a "thermodynamic equation". We can also derive one for temperature.

We also need equations for momentum and mass.

They are all related (coupled) to each other.
A real world prediction (e.g. for air quality, weather) usually requires the use of all of them.

For a simple laboratory flow, for example a pipe flow with constant density, we would not need the thermodynamic equations at all.

Speaking of equations …

Much physical insight can be gained without invoking the full-blown partial differential equation set that govern the fluid motion. We will strive to do so.

Equations are however needed to perform quantitative calculations.

Let's be diligent about the math, but not overly relying on it for understanding the physical processes.

What phenomena are we looking at ?

(1) Large-scale atmospheric flows related to weather and climate

(2) Environmental flows that involve interactions with man-made structures (e.g. flow over urban landscape)

(3) Flows in other geophysical fluid bodies (e.g., ocean)

We will focus on (1) (~ 65%) and (2) (~ 25%). The omission of otherwise important subjects is due to time constraint. Ideally, we should have 2 semesters to cover the relevant material!

Additional recommended textbooks

For large-scale flows related to weather and climate:

(1) *Atmospheric and oceanic fluid dynamics, G. K. Vallis, Cambridge University Press*
(2) *Atmosphere-ocean dynamics, A. E. Gill, Academic Press*
(3) *Geophysical fluid dynamics, J. Pedlosky, Springer-Verlag*
(4) *An introduction to dynamic meteorology, J. R. Holton, Elsevier-Academic Press*

For environmental flows at smaller scales

(1) *An introduction to boundary layer meteorology, R. B. Stull, Springer*
(2) *Turbulence and diffusion in the atmosphere, A. K. Blackadar, Springer*

See notes in Syllabus

Visualization

With few exceptions (e.g. cumulus clouds), large-scale environmental flow phenomena are not easy to "visualize". This is sometimes a frustrating aspect of learning GEFD.

To "see" the structure of the flow, one has to assemble the observations (that are often sparse and irregularly sampled in space and time), then make plots of the flow field using a computer (or, in the old days, by hand).

We will see contour or color-shaded "maps" of large-scale flow fields in the textbook that were obtained this way. Learn to use some imagination to relate those maps to the real flow fields!

Occasionally, situations arise that allow us to “see” a certain aspect of a flow field in nature. This usually requires the presence of some kind of “tracer” (either naturally occurring or man-made) in the flow.

Example 1

Satellite image of Hurricane Ike (2008)
Photo source: NASA

Example 2

Algae in the flow (Baltic Sea)

Photo source: Swedish Coastal Guard

As interesting as those pictures are, they do not provide the 3-D velocity and temperature fields that are needed to make quantitative predictions.

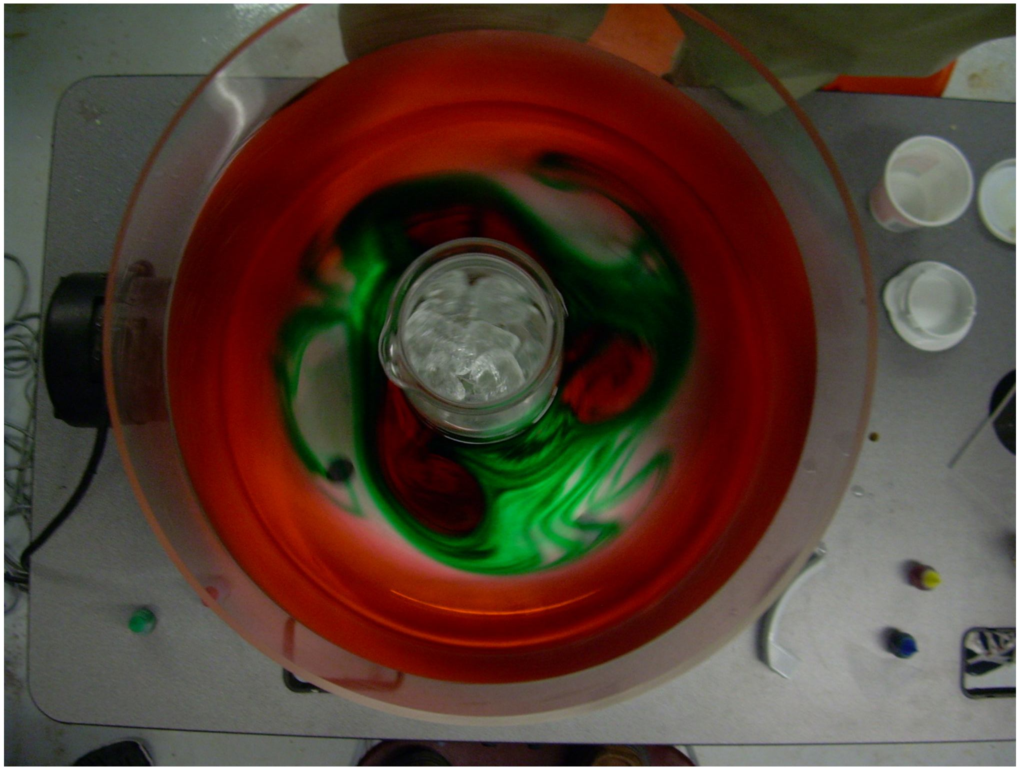
Course outline

(Expect substantial revision)

1. Overview (1 lecture)
2. Energy balance of large-scale atmospheric circulation (3 lectures)
3. Stratified flow: vertical structure, static stability, and convection (4 lectures)
4. Water vapor and precipitation (1 lecture)
5. Survey of the momentum and energy equations of fluid flows (4 lectures)
6. The effect of earth rotation (5 lectures)
7. Atmospheric boundary layer & near-surface processes (4 lectures)
8. Effect of topography and gravity waves (1 lecture)
9. Global-scale circulation of the atmosphere and oceans (4 lectures)
10. Issues with numerical simulation and prediction (1 lecture)

+ Lab sessions

Laboratory demonstrations



- Rotating tank (see pix, located at fluid lab in Psychology 103)
  -- emulates global atmosphere
- Long vertical tank for stratified fluid (under construction)

Thanks to M. Thompson, A. Sharma, N. Baker, and L. Tse for previous activities related to lab development

Lab demonstrations

- Check textbook for useful background

- Due to the large number of students and limited lab space, we will not be able to accommodate do-it-yourself sessions for students to work on the experiments. The instructor (HPH) will set up the demonstrations for participants to watch.

- 2-3 sessions planned for the semester

- We will use office hours (Tuesday 1:30-5:00) for the lab sessions. If those hours are not convenient for you, let the instructor know ASAP.

How do we use a desk-top device to emulate the fluid flow of global atmosphere?

The concept of "scaling"
-- useful for extracting the terms/processes
   that are relevant for a particular phenomenon

and "dynamical similarity"
-- allows the application of the same equation set
   to a wide range of phenomena with different
   physical scales

A by-product of these exercises is a set of non-dimensional numbers (e.g., Reynolds number) that we will occasionally use to classify the types of fluid motions
(We will not see Reynolds number often, though)

A quick aside for those who have some knowledge on fluid mechanics:

For large-scale environmental/geophysical flows, Reynolds number is always extremely large (in other words, molecular viscosity is extremely inefficient in facilitating the needed momentum transport)
→ **Flow is always turbulent**

The effect of molecular viscosity is confined to a very thin layer near the surface, although this influence does eventually propagate into the interior of the domain

For the treatment of the large-scale flow in the interior of the domain, **we usually sweep molecular viscosity (and Reynolds number) under the rug** by "parameterizing" its effect in the momentum equation

Again, do not worry if the previous 1-2 slides did not make a whole lot of sense to you. We will fill in the detail as the course progresses.

(If you already "know the stuff", all the better.)

Grade will be based on homework assignments and a term paper. (Nominally 2/3 homework, 1/3 term paper.)

Detail for term paper will be disseminated through the first half of the semester.

No exams.

Homework/project

Discussion among peers is encouraged, but please strive to form your own opinion. The final write-up of each homework/project should be your own.

Please provide proper citations if you use external sources such as journal articles and web-based resources