2.011 Intro. to Ocean Science and Engineering

Prof. Alexandra Techet

Spring 2006

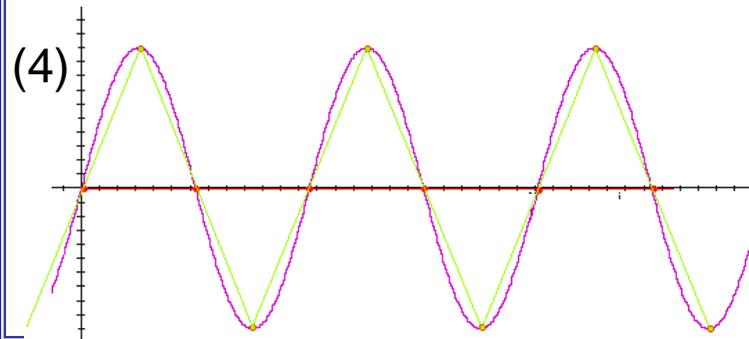Lecture 3 (14 Feb 06)

III.
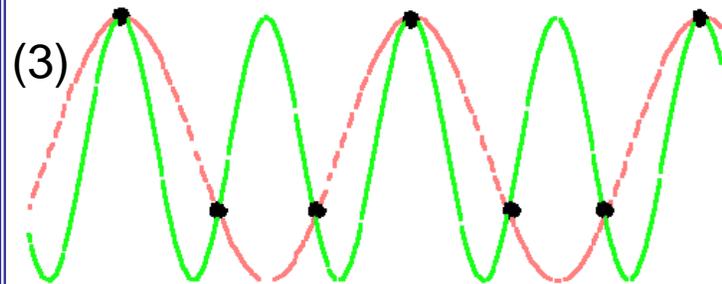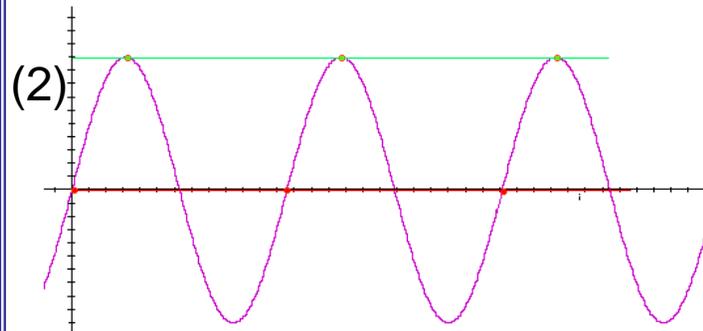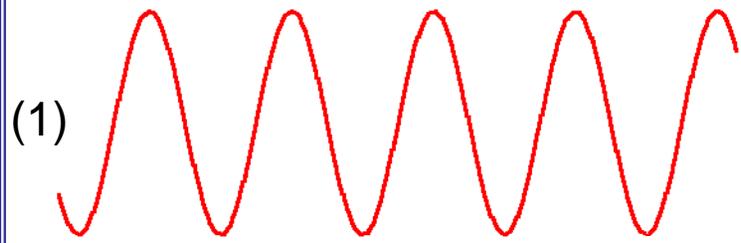# WHAT DON'T WE KNOW?

A LOT!

- To operate in the marine environment we need to understand it better through
  - Measurements (instruments, data)
  - Modeling (math, theory)
  - Simulations (numerical, computational)

- To do all this we need actual DATA about the oceans, so MEASUREMENTS are a priority!

Measurements in the Ocean

- What do we want to measure?

- What types of measurements can we make?

- How many measurements do we need?

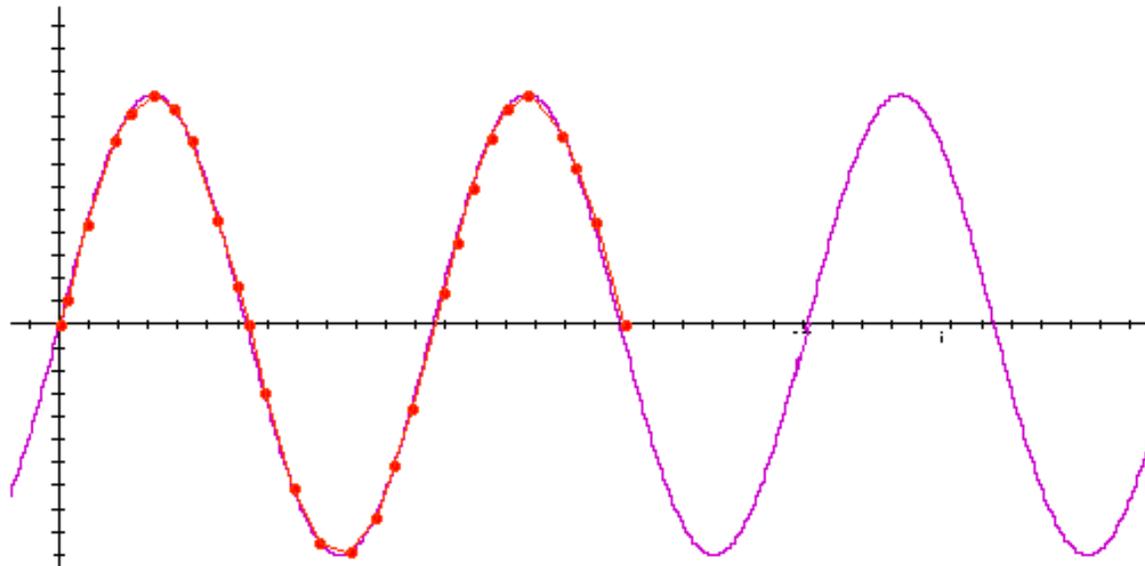- How often should we make the measurements?

Types of Measurements

- Point vs. Whole field

- Spatial vs. Temporal

- Average vs. Fluctuating

- Steady vs. Unsteady

(1)

(2)

(3)

(4)

1. Suppose we are sampling a sine wave. How often do we need to sample it to figure out its frequency?

2. If we sample at 1 time per cycle, we can think it's a constant.

3. If we sample at 1.5 times per cycle, we can think it's a lower frequency sine wave.

4. Now if we sample at twice the sample frequency, i.e Nyquist Rate, we start to make some progress. An alternative way of viewing the waveform (re)genereation is to think of straight lines joining up the peaks of the samples. In this case (at these sample points) we see we get a sawtooth wave that begins to start crudely approximating a sine wave.

Nyquist rate

- For lossless digitization, the sampling rate should be **at least twice** the maximum frequency responses. Indeed many times more the better.

Types of Measurements

- Point vs. Whole field

- Spatial vs. Temporal

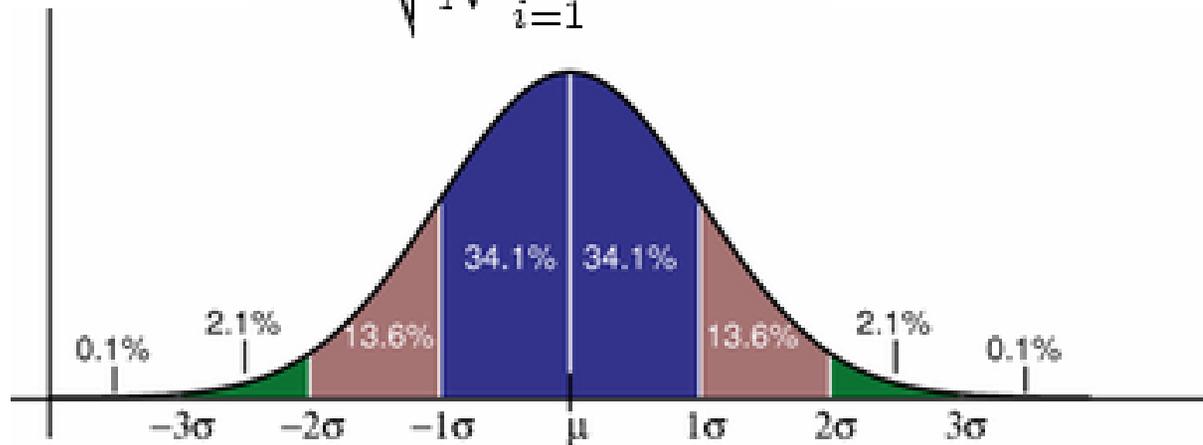- Average vs. Fluctuating

- Steady vs. Unsteady

Accuracy of Measurements

- ## Statistics
  - Mean, Standard Deviation,
  - RMS, Variance
  - Correlation

- ## Accuracy
  - Sample Error
  - Measurement/Instrument Error

- ## Excellent reference (text) on error analysis
  - Taylor, John R. <u>An Introduction to Error Analysis, The Study of Uncertainties in Physical Measurements, 2nd ed.</u>, University Science Books, 1996.

Mean & Standard Deviation

$$\bar{x} = \frac{1}{N} \sum_{i=1}^{N} x_i = \frac{x_1 + x_2 + \cdots + x_N}{N}$$

$$\sigma = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (x_i - \bar{x})^2}$$

Dark blue is less than one standard deviation from the mean. For the normal distribution, this accounts for 68.26% of the set. For the normal distribution, two standard deviations from the mean (blue and brown) account for 95.46%. For the normal distribution, three standard deviations (blue, brown and green) account for 99.73%.

Courtesy of Wikipedia.

Linearity of Measurements

- Linear Fit: $y = m*x + b$

- Signal Drift:

Existing Types of Data

- Visual (sea surface height)
- Buoys and Observatories
- Cruise
- Satellite
- Depth profiles
- Temperature
- Salinity (saltiness of the water)
- Pressure (depth)

Ship Cruises vs. Observatories

- http://www.orionprogram.org/
- The Ocean Research Interactive Observatory Networks (ORION) is a program that focuses the science, technology, education and outreach of an emerging network of science driven ocean observing systems. Building on the heritage of the ship-based expeditionary era of the last century, oceanography is commencing a new phase in which research scientists increasingly seek continuous interaction with the ocean environment to adaptively observe the earth-ocean-atmosphere system. Such approaches are crucial to resolving the full range of episodicity and temporal change central to so many ocean processes that directly impact human society, our climate and the incredible range of natural phenomena found in the largest ecosystem of the planet.

OOI Goals

- A fully operational research observatory system would he expected to meet most of the following goals:
  - continuous observations at time scales of seconds to decades
  - spatial measurements from millimeters to kilometers
  - sustained operations during storms and other severe conditions
  - real-time or near-real-time data as appropriate
  - two-way transmission of data and remote instrument control
  - power delivery to sensors between the sea surface and the seafloor
  - standard Plug-n-Play sensor interface protocol
  - autonomous underwater vehicle (AUV) dock for data download/battery recharge
  - access to deployment and maintenance vehicles that satisfy the needs of specific observatories
  - facilities for instrument maintenance and calibration
  - a data management system that makes data publicly available
  - an effective education and outreach program
-

LACK OF SUFFICIENT SAMPLES IS THE LARGEST SOURCE OF ERROR IN OUR UNDERSTANDING THE OCEAN.

IV.
The Atmosphere and The Ocean

Atmospheric Effects on the Ocean

- Weather: storms, winds, temperature
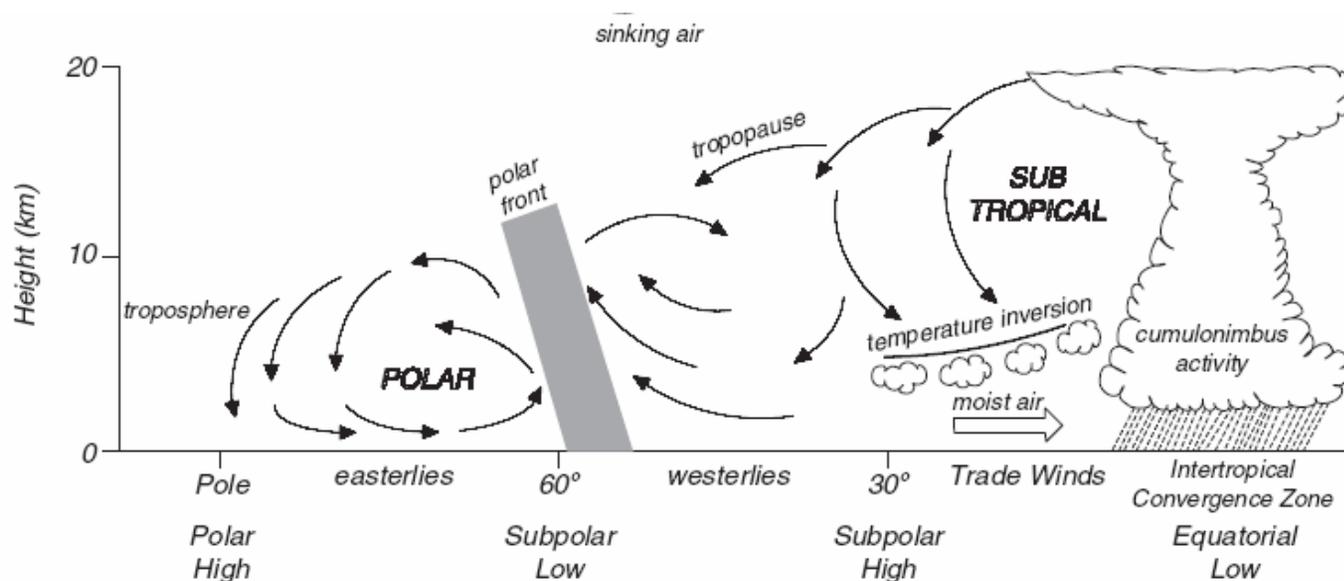- Sunlight is the main driving energy source for the ocean

Figure 4.3 Sketch of Earth's atmospheric circulation driven by solar heating in the tropics and cooling at high latitudes. **Upper:** The meridional cells in the atmosphere and the influence of Earth's rotation on the winds. **Bottom:** Cross-section through the atmosphere showing the two major cells of meridional circulation. After The Open University (1989a: 14).

Source: Introduction to Physical Oceanography, http://oceanworld.tamu.edu/home/course_book.htm

Hurricanes

Katrina (2005)

http://www1.ncdc.noaa.gov/pub/data/images/hurr-katrina-poster-8x10.jpg

Hurricane Mitch 1998

http://www.osei.noaa.gov/mitch.html
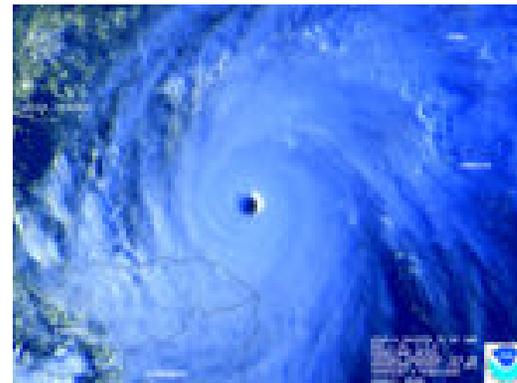
Waves

Photos removed for copyright reasons.
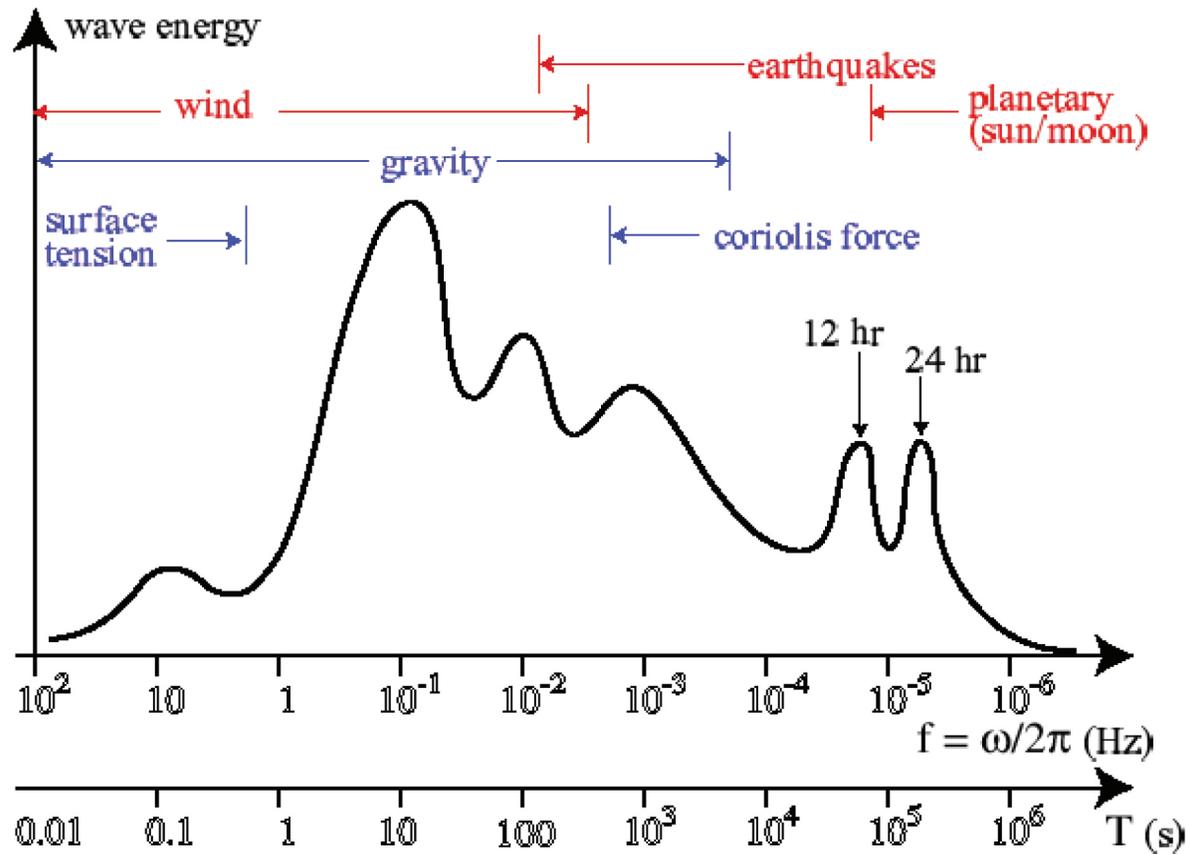
Ocean Wave Generation

Figure 1. Wave energy spectra. Red text indicates wave generation mechanisms and blue text indicates damping/ restoring forces.

Causes of Ocean Waves

- Wind blowing across the ocean surface

    - Frequency f = 10^{-2} to 10^{2} Hz

    - Period T = 1/f = 0.01 to 100 seconds

- Pull of the sun and moon

    - Frequency is on the order 10^{-4} to 10^{-6} Hz

    - Period T = 12, 24 hours (tides)

- Earthquakes – e.g. Tsunamis

    - Frequency less than 10^{-2} Hz

    - Long wave period

Wind Effects on the Ocean

- Winds cause waves by generating a *shear force* on the ocean surface

- Correlation between high wind and high waves

- The longer distance wind blows over water the larger the waves can get. This distance is called *fetch.*

- Wind also acts to exchange heat.
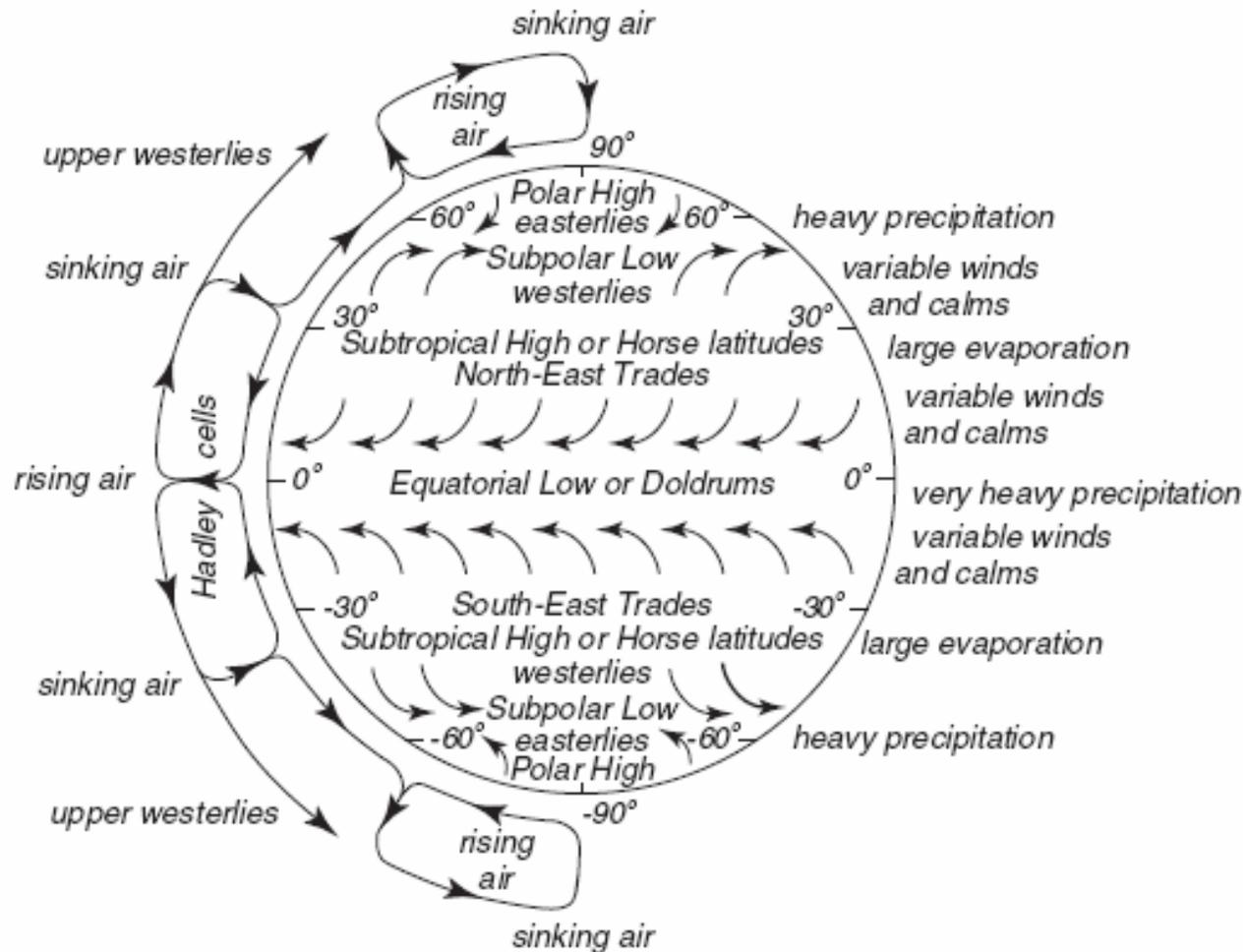
Table 4.1 Beaufort Wind Scale and State of the Sea

Beaufort Number	Descriptive term	m/s	Appearance of the Sea
0	Calm	0	Sea like a mirror.
1	Light Air	1.2	Ripples with appearance of scales; no foam crests.
2	Light Breeze	2.8	Small wavelets; crests of glassy appearance, not breaking.
3	Gentle breeze	4.9	Large wavelets; crests begin to break; scattered whitecaps.
4	Moderate breeze	7.7	Small waves, becoming longer; numerous whitecaps.
5	Fresh breeze	10.5	Moderate waves, taking longer to form; many whitecaps; some spray.
6	Strong breeze	13.1	Large waves forming; whitecaps everywhere; more spray.
7	Near gale	15.8	Sea heaps up; white foam from breaking waves begins to be blown into streaks.
8	Gale	18.8	Moderately high waves of greater length; edges of crests begin to break into spindrift; foam is blown in well-marked streaks.
9	Strong gale	22.1	High waves; sea begins to roll; dense streaks of foam; spray may reduce visibility.
10	Storm	25.9	Very high waves with overhanging crests; sea takes white appearance as foam is blown in very dense streaks; rolling is heavy and visibility reduced.
11	Violent storm	30.2	Exceptionally high waves; sea covered with white foam patches; visibility still more reduced.
12	Hurricane	35.2	Air is filled with foam; sea completely white with driving spray; visibility greatly reduced.

From Kent and Taylor (1997)

Wind Patterns

Cycle 271 22-JAN-2000 – 01-FEB-2000

Wind Speed

0.0   2.0   4.0   6.0   8.0   10.0   12.0   14.0   16.0
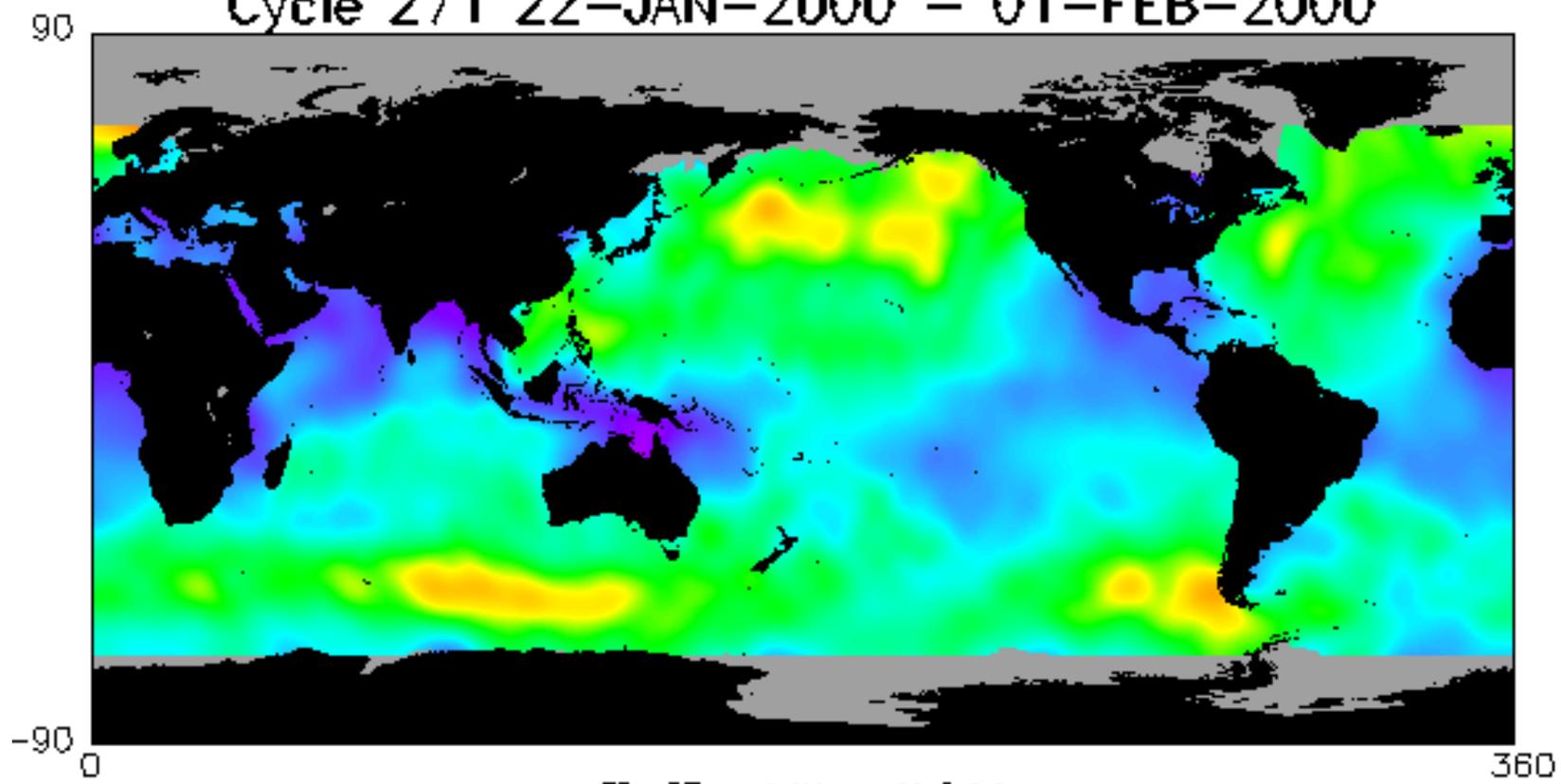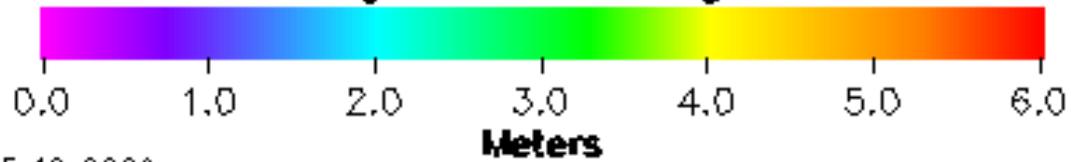Meters Per Second

JPL

Thu Mar 16 22:10:43 2000

Courtesy of JPL.

Cycle 271 22-JAN-2000 — 01-FEB-2000

Significant Wave Height

Meters

JPL

Thu Mar 16 22:05:42 2000

Courtesy of JPL.

Cycle 271 22-JAN-2000 — 01-FEB-2000

Significant Wave Height

0.0   1.0   2.0   3.0   4.0   5.0   6.0
Meters
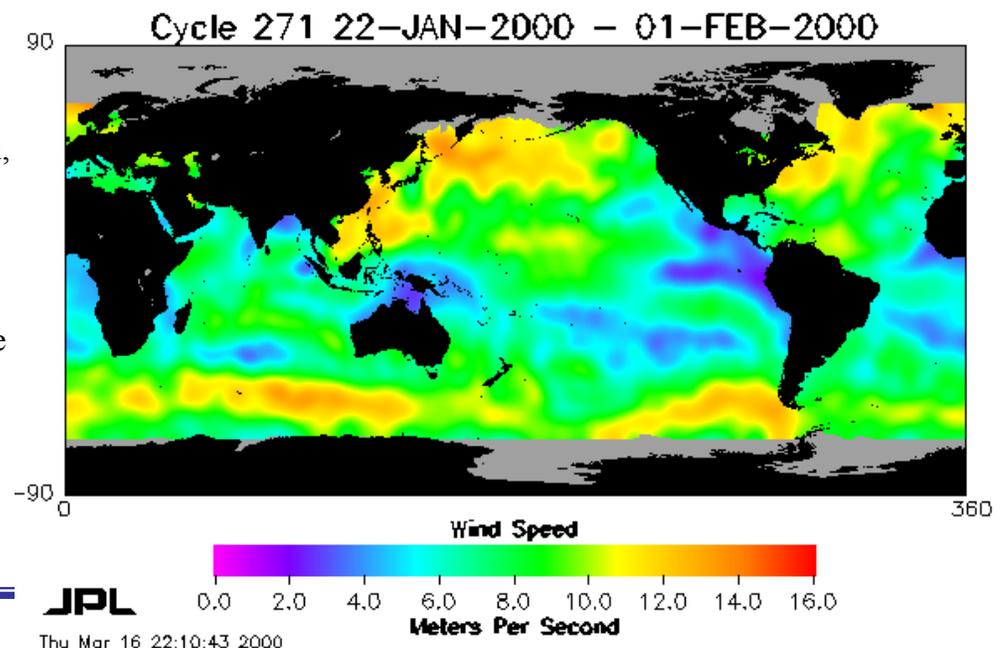
JPL
Thu Mar 16 22:05:42 2000

Courtesy of JPL.

The highest waves generally occur in the Southern Ocean, where waves over six meters in height (shown as red in images) are found. The strongest winds are also generally found in this region. The lowest waves (shown as purple in images) are found primarily in the tropical and subtropical oceans where the wind speed is also the lowest.

In general, there is a high degree of correlation between wind speed and wave height.

The highest winds generally occur in the Southern Ocean, where winds over 15 meters per second (represented by red in images) are found. The strongest waves are also generally found in this region. The lowest winds (indicated by the purple in the images) are found primarily in the tropical and subtropical oceans where the wave height is also the lowest.
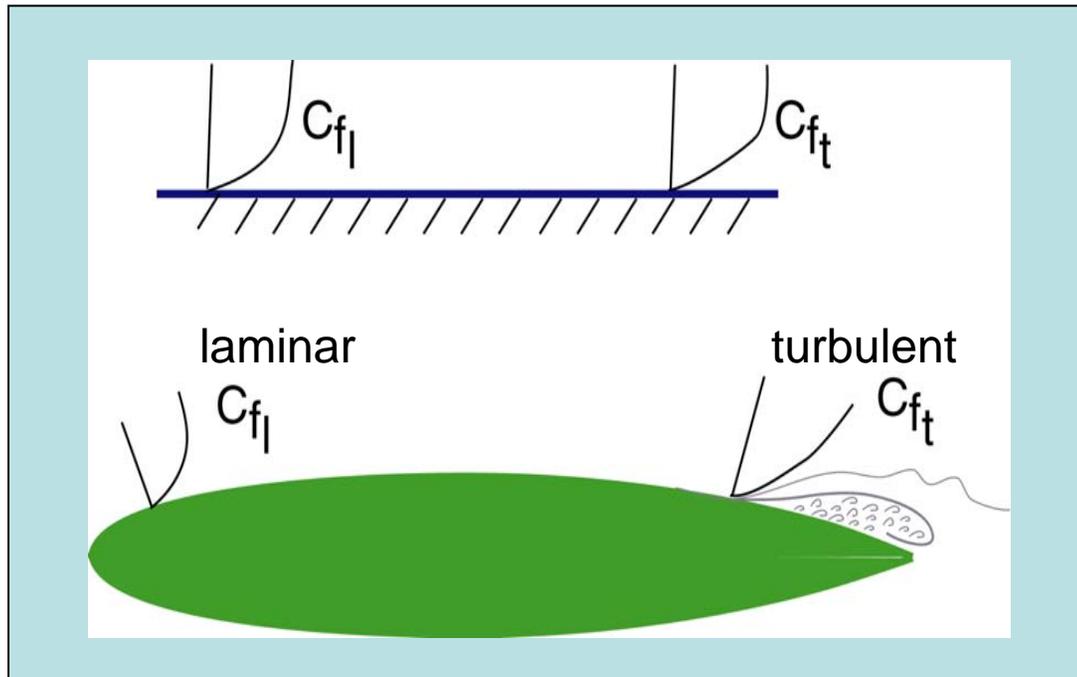

Cycle 271 22-JAN-2000 — 01-FEB-2000

Wind Speed

0.0   2.0   4.0   6.0   8.0   10.0   12.0   14.0   16.0
Meters Per Second

JPL
Thu Mar 16 22:10:43 2000

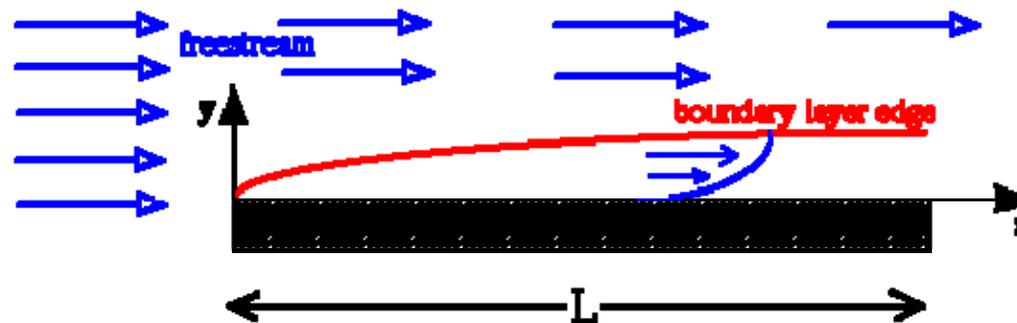Courtesy of JPL.

Types of Forces Due to Fluid Flow

Skin Friction Drag: C_f

Form Drag: C_D due to pressure (turbulence, separation)

Streamlined bodies reduce separation, thus reduce form drag. Bluff bodies have strong separation thus high form drag.

Boundary layer development

Flow over a flat surface causes a velocity gradient near the boundary due to the NO-SLIP condition.

NO SLIP CONDITION: requires that the velocity of the fluid at the wall matches the velocity of the wall, such that it does not "slip" along the boundary.
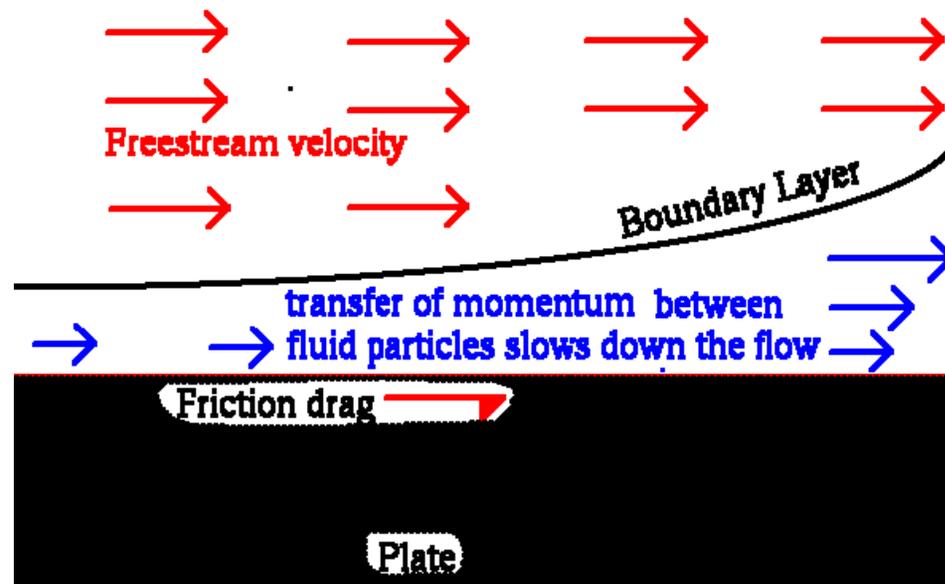
Since the velocity away from the wall is much faster a velocity gradient results in the boundary layer region since fluid is a continuous medium. In this region viscosity plays a strong role.

Wall shear stress:

$$\tau_w = \mu \frac{\partial u}{\partial y}\bigg|_{y=0}$$

Friction Drag

The transfer of momentum between the fluid particles slows the flow down causing drag on the plate. This drag is referred to as friction drag.

Freestream velocity

Boundary Layer

transfer of momentum between fluid particles slows down the flow

Friction drag

Plate

units

Friction Drag Coefficient: $\quad C_f = \dfrac{F}{\frac{1}{2}\,\rho U^2 A_w} \qquad \dfrac{\left[MLT^{-2} \right]}{\left[MLT^{-2} \right]}$
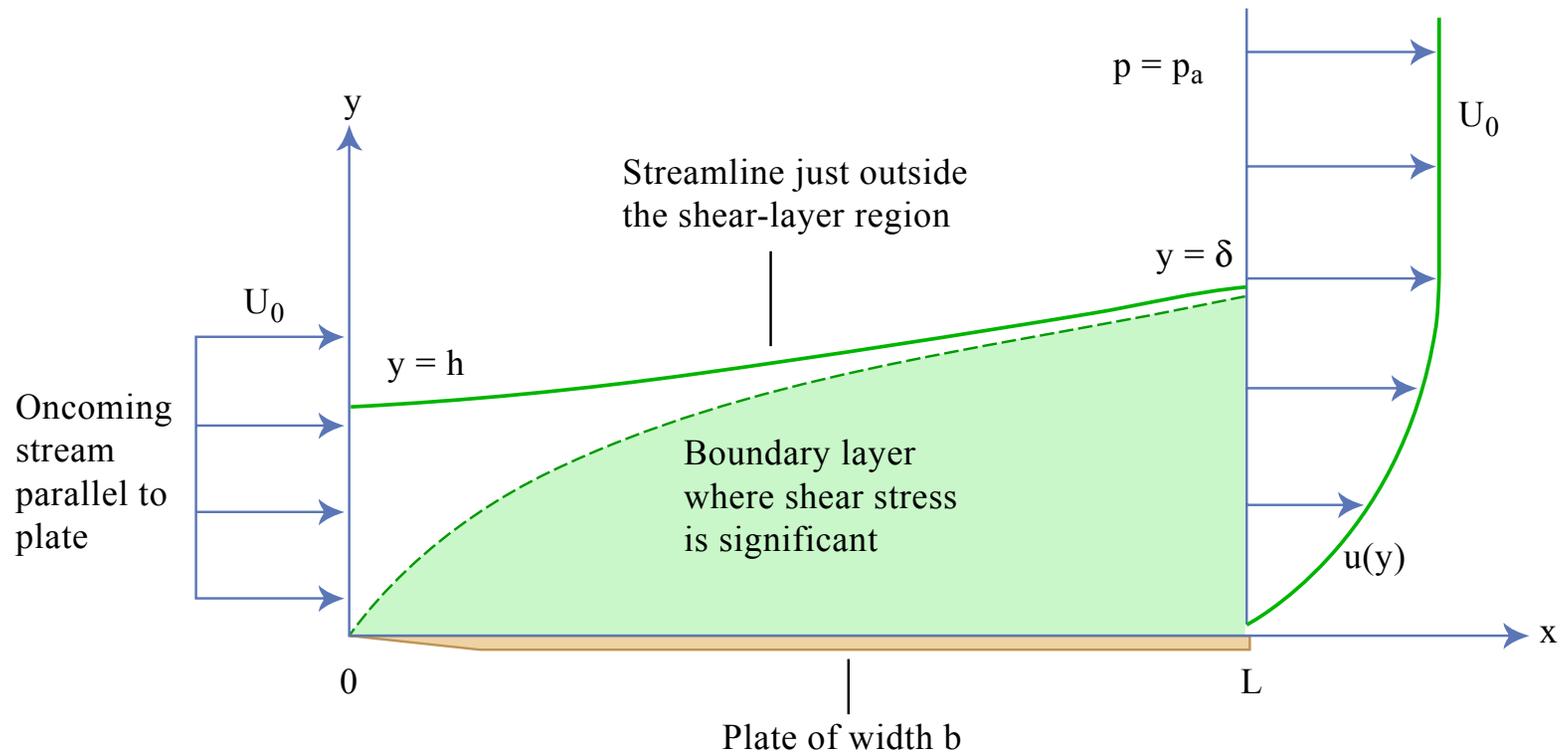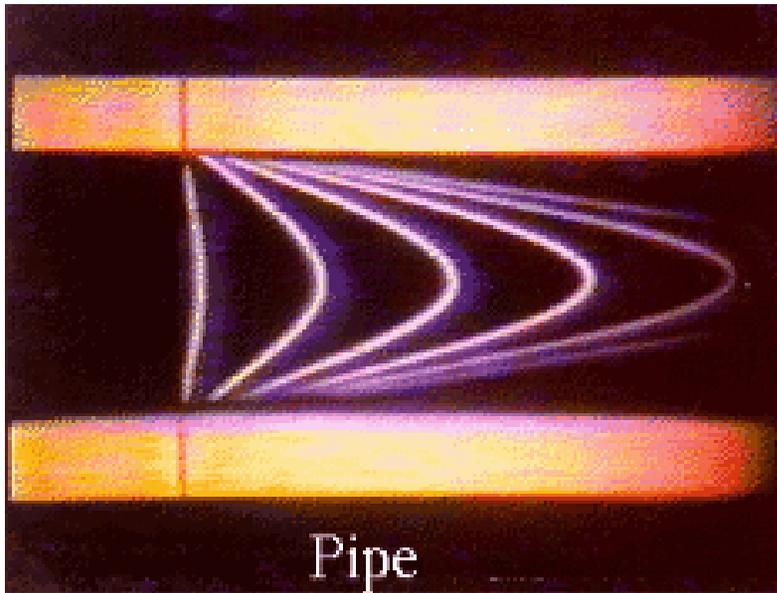
Boundary Layer

Figure by MIT OCW.

Boundary Layer Growth
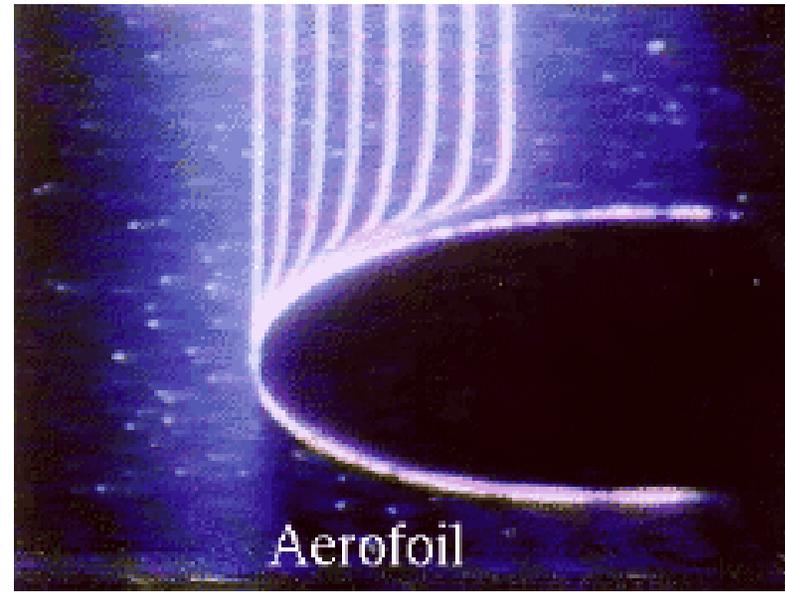
Photo removed for copyright reasons.

As a boundary layer on a plate grows its thickness increases with distance, *x.* The Reynolds number of a boundary layer is defined as

$$Re = Ux/\nu$$

Boundary layer growth

Pipe

Aerofoil

Boundary layers develop along the walls in pipe flow. A cross sectional view shows the layer at the top and the bottom creating a symmetrical profile. The flow in the middle is fastest since it has not been slowed by the momentum transfer in the boundary layers.

Boundary layers develop along the aerofoil shown above. The velocity profile changes shape over the curved leading edge. Towards the trailing edge the flow tends to separate as a result of an adverse pressure gradient.

Courtesy of IIHR - Hydroscience & Engineering, University of Iowa. Used with permission.
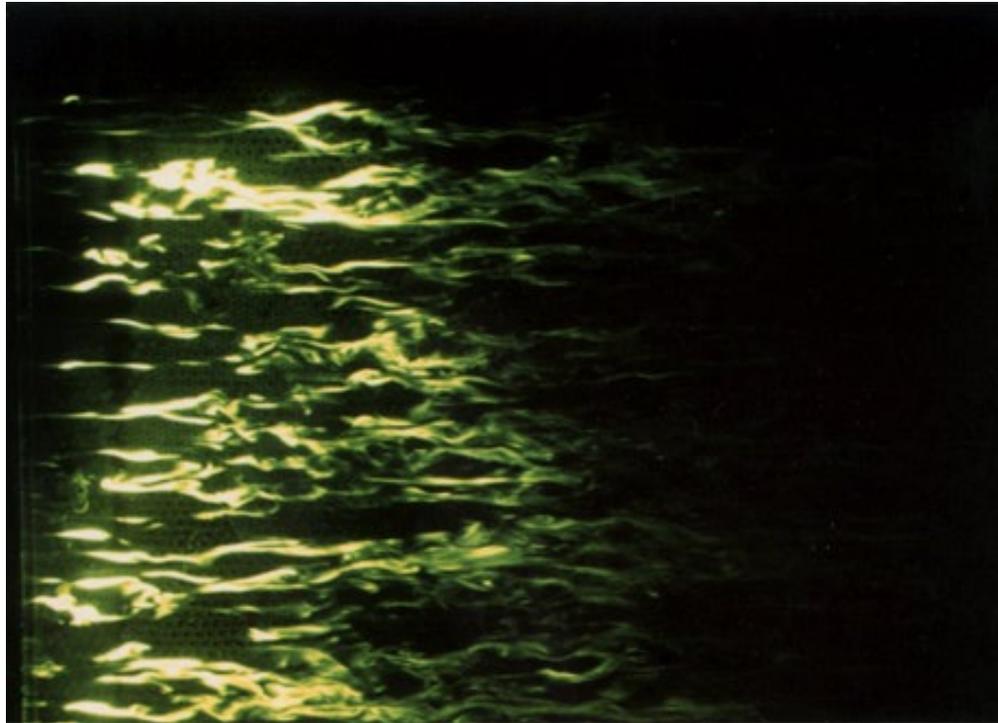
Turbulent Boundary Layers

This picture is a side view of the large eddies in a turbulent boundary layer. Laser-induced fluorescence is again used to capture the quasi-periodic coherent structures. Flow is from left to right.
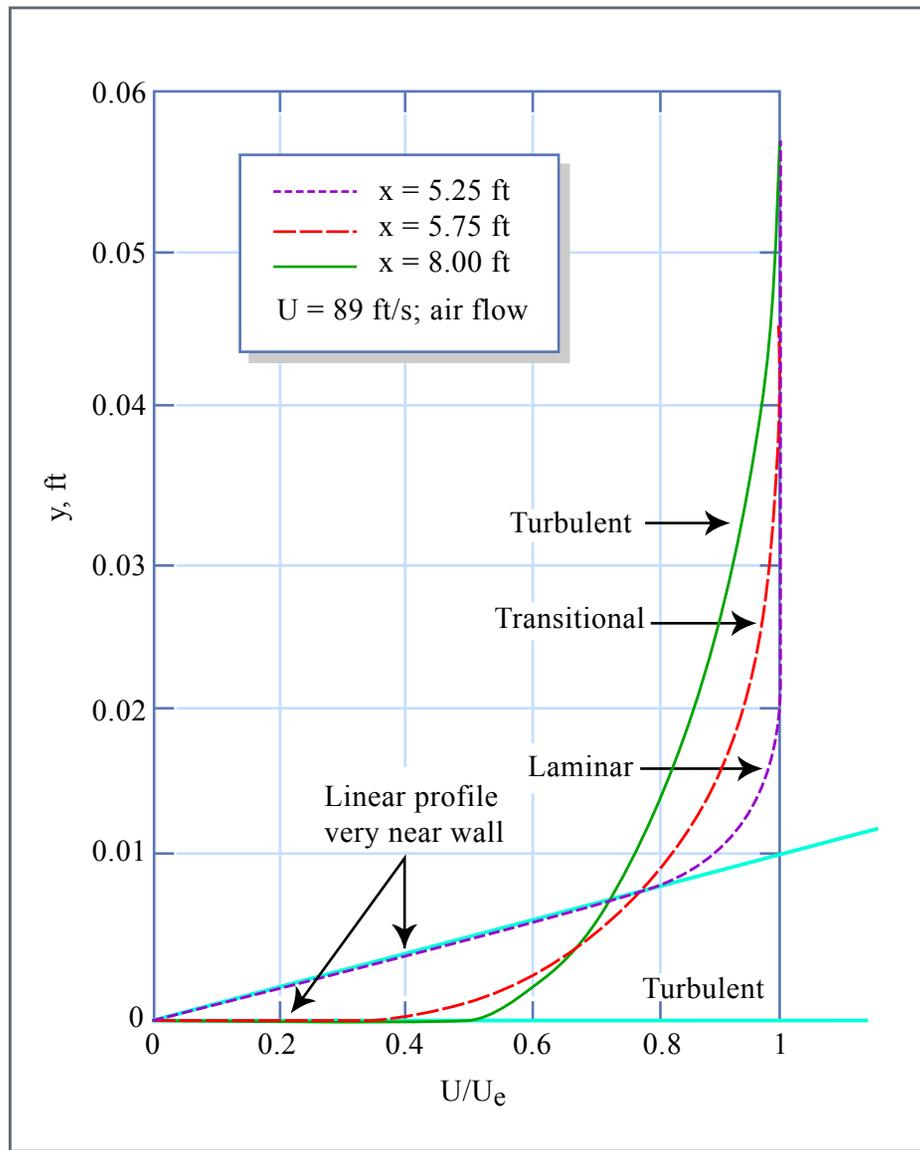
Courtesy of Prof. M. Gad-el-Hak. Used with permission.

Turbulent Wall Boundary Layer
(Top View)

This picture is a top view of the near-wall region of a turbulent boundary layer showing the ubiquitous low-speed streaks. Flow is from left to right and laser-induced fluorescence is used to visualize the streaks.

Courtesy of Prof. M. Gad-el-Hak. Used with permission.
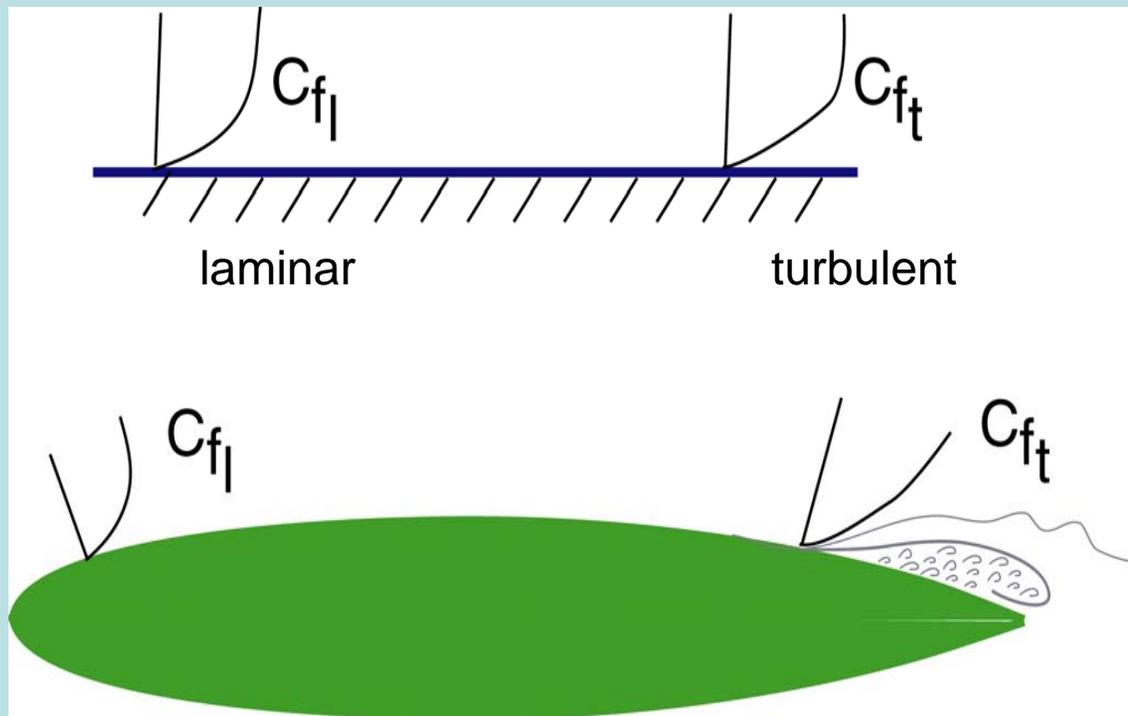
Turbulent vs. Laminar Boundary Layers:

It can be seen from these plots that the two boundary layers have quite different shapes.

Wall shear stress:

$$\tau_w = \mu \frac{\partial u}{\partial y}\bigg|_{y=0}$$

Figure by MIT OCW.

Viscous Drag

laminar   turbulent

Skin Friction Drag: C_f

Form Drag: C_D due to pressure (turbulence, separation)

Streamlined bodies reduce separation, thus reduce form drag.
Bluff bodies have strong separation thus high form drag.

Drag Coefficient

- Drag Force on the body due to viscous effects:

$$F_D = \frac{1}{2}\rho\, C_D\, A\, U^2$$

$$C_D = \frac{F_D}{\frac{1}{2}\rho U^2 A}$$

- Where C_D is often found *empirically* (through experimentation)

- C_D is dependent on Reynolds number (ie. velocity, geometry, and fluid viscosity) and is quite different in laminar vs. turbulent flows

Cylinder Drag Coefficient

Graph removed for copyright reasons.

Flat Plate Friction Coefficient

Graph removed for copyright reasons.

Sphere Drag Coefficient

Graph removed for copyright reasons.

Wind Stress on Ocean Surface

- Wind causes a *shear* stress on the surface (like friction).
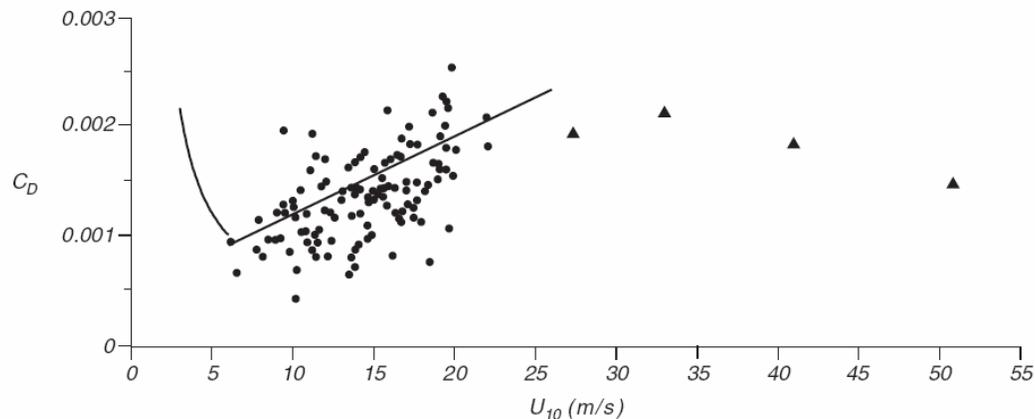- Stress is Force per Area:

$$\tau = \rho_a \, C_D \, U_{10}{}^2$$

Units $[kg/m^3 * m^2/s^2] = [kg/m/s^2] = [Force/area]$

C_D is a dimensionless parameter (no units)

- U_{10} – chosen because 10 meters is the standard height of a ships mast where wind is measured

Wind Drag Coefficient

- C_D (empirical data)

Courtesy of Prof. Robert Stewart. Used with permission.
Source: Introduction to Physical Oceanography, http://oceanworld.tamu.edu/home/course_book.htm

- C_D theoretical model

$$1000\,C_D = 0.29 + \frac{3.1}{U_{10}} + \frac{7.7}{U_{10}^2} \qquad (3 \leq U_{10} \leq 6 \text{ m/s})$$

$$1000\,C_D = 0.50 + 0.071\,U_{10} \qquad (6 \leq U_{10} \leq 26 \text{ m/s})$$

Wind Generated Waves

- Wind blows over long distance and long period time before sea state is fully developed.
- When wind speed matches wave crest phase speed the phase speed is maximized. Thus the limiting frequency is dependent on the wind speed due to the *dispersion relationship.*

$$U_{wind} \approx C_p = \omega / k = g / \omega$$

Limiting frequency: $\omega_c \approx g / U_{wind}$

Dispersion Relation: $\omega^2 = gk \tanh(kH)$
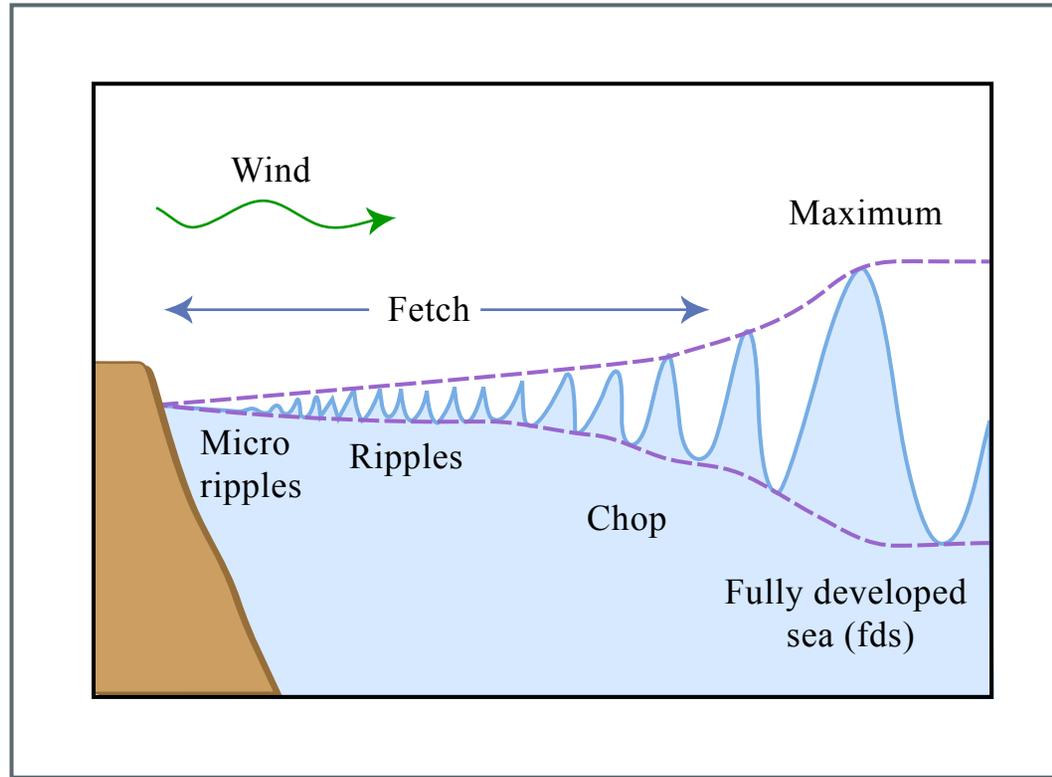
Wind Generated Waves

Figure by MIT OCW.

Energy imparted to the fluid by the wind increases proportional to the *fourth power* of the wind speed!

Depending on **duration** and **distance** (**fetch**), the waves develop into a **fully developed sea**.