MET 200 Lecture 15  Hurricanes
Structure and Climatology

- What is the structure or anatomy of a hurricane?
- How to build a hurricane? - hurricane energy
- Hurricane climatology - when and where

Hurricane Katrina

Last Lecture: Atmospheric Optics
The amazing variety of optical phenomena observed in the atmosphere can be explained by four physical mechanisms.

- Scattering • Reflection • Refraction • Diffraction

Colorado Flood Damage

Hurricanes: Useful Websites
http://www.wunderground.com/hurricane/
http://tropic.ssec.wisc.edu
http://www.nhc.noaa.gov

Hurricane Alberto
Hurricanes are much broader than they are tall.
Typhoon Francisco

Typhoon Lekima
Hurricanes are Tropical Cyclones

Hurricanes are a member of a family of cyclones called Tropical Cyclones. West of the dateline these storms are called Typhoons. In India and Australia they are called simply Cyclones.
Hurricane Isaac: August 2012

Characteristics of Tropical Cyclones

- Low pressure systems that don’t have fronts
- Cyclonic winds (counter clockwise in Northern Hemisphere)
- Anticyclonic outflow (clockwise in NH) at upper levels
- Warm at their center or core
- Wind speeds decrease with height
- Symmetric structure about clear "eye"
- Latent heat from condensation in clouds primary energy source
- Form over warm tropical and subtropical oceans

Differences between hurricanes and midlatitude storms:
- Winter storms have cold and warm fronts (asymmetric).
- Occur in the middle and high latitudes (30˚- 60˚ latitude).
- Winter storms are generally larger than tropical cyclones.

- Energy source (latent heat vs temperature gradients)
- Vertical structure (warm vs. cold core lows; hurricanes decay with height: no jet stream aloft over hurricanes).
- Horizontal structure (fronts vs. no fronts; horizontal scale)
A Question of Size

1980 Winter Storm vs. Hurricane Iniki, 2 PM HST on September 12, 1992

Anatomy or Structure

Basic structure includes spiral rainbands and a concentric eye wall that surrounds a clear eye.

Tropical Cyclone Life Cycle

Stages of storm development
1. Tropical Depression: surface wind < 39 mph (33 kt)
2. Tropical Storm: 39 ≤ surface wind ≤ 74 mph (64 kt)
3. Hurricane: surface winds > 74 mph (65 kt)

Hurricane Structure

Hurricanes are much broader than they are tall.
Satellite Derived Cloud Height

Infrared temperature of clouds used to estimate their height.

Structure in Hurricane Katrina

Inside the Eye Wall

Hurricane Structure

Hurricane Floyd in 3-D

Structure in Hurricane Katrina

Inside the Eye Wall

Hurricane Structure

Hurricane Inez

Note the stadium structure of the eye.
Radar Observations
- Spiral rainbands
- Symmetric eye wall
- Clear eye

Hurricane Hugo
What's wrong with this photo?

Radar Observations of Andrew

Hurricanes weaken with height
Structure in the rainfall seen in radar data.
Katrina at Landfall

Lightning Strikes in Katrina

Shedding Light on Storms

Wind Observations

Wind distributions in Andrew (at single time) and Katrina (wind history - winds weaken inland)
Hurricane Anatomy/Structure

• Hurricanes are “Warm-Core Lows”
Note where rising and sinking motion occurs.

Hurricane Energy Source

Latent Heat released when Water Vapor condenses in clouds is the Key

• Hurricanes (a.k.a. Typhoons, Tropical cyclones) are giant engines that convert heat into wind energy.
• Consider a rain rate of 2 inches per day over an area of 300 mi radius (typical for tropical depression, tropical storm, and hurricane)
• Over a 7 day lifecycle, the energy released is equal to 50,000 1 MT nuclear explosions!
• This is equivalent to the total explosive yield of the nuclear arsenals of the US and USSR at the height of the Cold War!

Model of Hurricane

Purple = heavy rains
Red = high winds

100 km
To Build a Hurricane

Since pressure is the weight of the air, the atmosphere must concentrate warm, moist air over one place to create very low pressure at sea level.

Warm air molecules move faster and take up more space resulting in lower sea-level pressure.

How to Build a Hurricane: Five Requirements

1. Warm ocean water with a temperature > 80° F.
2. An area of low pressure.
3. Thunderstorms – deep moist unstable air.
4. Little wind shear (change in the wind speed or direction with height).
5. Genesis must occur ≥3° from Equator.

Hurricane Energetics

- Tropical cyclones are rare
- Roughly 80 per year worldwide
- Assume a one week life span
- Result – 1-2 storms any day in an area half the surface area of the planet
- Reason – you need to bring 5 prerequisites together to produce a storm

Saturation Vapor Pressure

Due to the nonlinearity of the Clausius Clapeyron equation, \( \frac{d(w)}{dT} \) increases with T. Only for temperatures above a threshold value of ~26.5°C is the rate of increase strong enough to support the development of tropical cyclones.
Prerequisites for Hurricane Formation

1. Warm ocean water with a temperature > 80°F (26°C) to a depth of ~50 m, so that cooler water cannot easily be mixed to the surface by winds. (Deep thermocline)

2. A pre-existing disturbance with cyclonic circulation (large low-level vorticity) persisting >24 hrs. As the air in the disturbance converges, angular momentum is conserved and the wind speed increases.

3. Small wind shear or little change in the wind speed or direction with height in the vicinity of the developing storm. (dv/dz<10 m/s from 850-200 mb)

4. Unstable troposphere characterized by enhanced thunderstorm activity. CAPE>1000 (Final CAPE in eyewall rather modest.)

5. Large relative humidity in the middle troposphere (no strong downdrafts). Moist air weighs less than dry air, contributing to lower surface pressures.

Convective Instability of the Second Kind (CISK)

- Convective available potential energy (CAPE) leads to rising motion / increase in moisture content. Rising air condenses, releases lots of latent heat.
- Latent heating aloft leads to high pressure and divergence aloft (organizes the large scale circulation)
- Divergence aloft leads to lower surface pressure.
- Lower surface pressure increases surface convergence.
- Moisture flux leads to larger CAPE.
- Rotation serves to organize flow.
- CISK assumes significant CAPE exists in hurricanes. Analysis of sounding data show this is not the case.

Air-sea Interaction Instability

- Surface convergence leads to rising motion / increase in moisture content.
- Rising air condenses, releases lots of latent heat.
- Latent heating aloft leads to high pressure and divergence aloft (organizes the large scale circulation)
- Divergence aloft leads to lower surface pressure.
- Lower surface pressure increases surface convergence.
- Stronger surface winds increase ocean-air moisture flux.
- Rotation serves to organize flow.
- This theory relies on a non-linear increase of surface fluxes associated with increasing surface wind speeds.

Diagram from Bergeron, QJRMS, 1954
Estimation of Momentum Flux

Mean values of the neutral drag coefficient as a function of windspeed at a 10-m height. The dashed line refers to Charnock’s relation with \( n = 0.014 \). After Garratt (1977).

\[ U^2 = \text{Stress} = C_D U^2 \]
\[ U^2 \approx 5 \text{ at } 40 \text{ m/s} \]

Elegant Example of Carnot Heat Engine

Total entropy per unit mass of air

1. \[ s = C_p \ln T + \frac{L_w W}{T} - R \ln p \]
   - \( C_p \): heat capacity
   - \( L_w \): latent heat of vaporization of water
   - \( R \): gas const.
   - \( W \): mixing ratio = mass of vapor/mass of dry air
   - \( T+P \): temp+press.
   - \( S \): is conserved except by sfc Fluxes + radiation

In hurricanes entropy gain occurs at relatively high temp (26-30 C), loss occurs at much lower T (-60- -80 C). Carnot theorem- the thermodynamic efficiency of the heat engine is:

2. \[ \varepsilon = \frac{T_s - T_0}{T_s} \]
   - \( T_s \): temp at which heat is added (SST)
   - \( T_0 \): temp. of loss (Tstrat)

Total mechanical energy available is

3. \[ E = \varepsilon T_s (S_c - S_a) \]
   - \( S_c \): entropy at center
   - \( S_a \): entropy of far environment

By requiring the surface air at the eye to achieve saturation wrt water, a lower bound on \( P_c \) can be determined from (5).

Hurricane Energy Source

Maximum available energy may be used to calculate the central pressure of the nature of the storm

4. \[ -S^c \alpha dp = \varepsilon T_s (S_c - S_a) \quad \text{using } \alpha = \frac{RT}{p} \]

5. \[ RT_s \ln \frac{P}{P_a} = -\varepsilon T_s (S_c - S_a) \]

Relationship between sea surface temperature, temperature at hurricane anvil outflow and maximum wind speed.
Prerequisites for Hurricane Formation

Prerequisites for Hurricane Formation

Easterly waves off coast of Africa provide convergence and rotation of the winds.

Easterly Waves trigger cyclogenesis over the Atlantic.

Observed sea surface temperature and predicted and observed minimum central pressure at sea level in tropical cyclones.

Hurricane Energy Source

Low Sea-level Pressure – Strong Winds

Relationship between surface pressure and wind speed for a number of tropical cyclones. Tropical cyclones are classified as hurricanes when their pressure is 980 millibars or lower, and sustained wind speeds are greater than 74 mph.

Hurricane development initiated by the passage of a wave disturbance in the subtropics (e.g., easterly waves).
Where and when do these conditions exist in the world?

1. Warm Water SST > 26 °C (80°F)
2. A surface low with unstable air and deep moisture.
3. Low wind shear
The strength of the storms is color coded along the tracks, with light blue for weak tropical storms and orange and red for strong storms (cat 3-5).

Hurricanes travel the warm Gulf Stream.
Atlantic Hurricane Climatology

Number of hurricanes per month in the Atlantic Basin.

US Hurricane Climatology

- Category of US hurricanes at the time of landfall.

Likely Tracks

Questions?