**Hurricanes: Observations and Dynamics**

Houze Chapter 10.
Holton Section 9.7.
http://ww2010.atmos.uiuc.edu/(Gh)/guides/mtr/hurr/home.rxml

**Definition:**

Hurricanes are intense vortical (rotational) storms that develop over the tropical oceans in regions of very warm surface water.

Hurricanes are called **typhoons** when they occur over the western Pacific.

Before they reach the hurricane/typhoon strength (when winds near the center of vortex is > 32 m/s), they are called **tropical cyclones**.

**Horizontal scale** ~ 500 km, vertical depth ~ 10 – 15 km

Although hurricanes have radial scales of several hundred kilometers, but the horizontal scale of the region of intense convection and strong winds in a hurricane is typically only about 100 km in radius. Thus, it is reasonable to classify **hurricanes as mesoscale systems**.
**Regions of formation:**

- Between 5° and 20° latitude, but not at the equator (need Coriolis force)
- Sea surface temperature > 26.5°
- Moderately conditionally unstable atmosphere
- Weak vertical shear

**Locations of formation over a 20-year period:**

*Figure 10.1* Locations of tropical cyclone formation over a 20-year period. (From Gray, 1979. Reprinted with permission from the Royal Meteorological Society.)
Tracks of tropical cyclones and sea-surface temperature

Figure 10.2 Tracks of tropical cyclones in relation to mean sea-surface temperature (°C). September temperatures are taken for the Northern Hemisphere. March temperatures are taken for the Southern Hemisphere. (From Bergeron, 1954. Reprinted with permission from the Royal Meteorological Society.)
General Patterns of Cloud and Precipitation in Hurricanes

Figure 1.28  Visible wavelength satellite view of Hurricane Allen (1980). (Photo courtesy of Frank D. Marks, Jr.)
Figure 10.4  Radar echo pattern seen in Hurricane Alicia (1983) labeled according to the schematic of Fig. 10.3. Contours are for 25 and 40 dBZ. (From Marks and Houze, 1987. Reproduced with permission from the American Meteorological Society.)
Figure 10.3 Schematic representation of the typical echo pattern seen by airborne radar in flights through hurricanes in relation to the low-level wind pattern. (From Willoughby et al., 1984b. Reprinted with permission from the American Meteorological Society.)
Major Features:

- Cyclonic spiral convergent bands at the low-levels and anticyclonic outward spiral cirriform clouds at the upper levels

- Hurricane eye – a typically a cloud free center of 10-50 km in diameter

- Eye wall – deep convection surrounding the eye. Slopes outward with height. Two eye-wall structures had been observed.

- Rainbands – typically spiral bands of clouds outside the eye wall. Often propagate outwards from eye.

- Reflectivity – even in eye wall, $R_{\text{max}} \sim 45 – 50 \text{ dBz}$. 30-35 typical. In thunderstorms, $R \sim 55 – 70 \text{ dBz}$. 
The winds - In the horizontal cross-section

Figure 10.5 Low-level (900 mb) wind field associated with Hurricane Gloria (1985). (a) Large-scale flow analysis. Tick marks indicate boundaries of three nested rectangular domains defined for the analysis; in the inner domain, wavelengths less than about 150 km have been filtered out. In the intermediate and outer domains, wavelengths less than about 275 and 440 km have been removed. (b) High-resolution wind analysis, in which wavelengths less than about 16, 28, and 44 km have been filtered out in the three successively larger domains, whose boundaries are indicated by tick marks. Solid lines with arrows are streamlines. Dashed lines are isotachs labeled in m s$^{-1}$. (Courtesy of James Franklin, Hurricane Research Division, U.S. National Oceanic and Atmospheric Administration.)
Figure 10.8 Upper-level (200 mb) wind fields associated with Hurricane Gloria (1985).
**Horizontal Distribution of winds**

~ symmetric in terms of system relative winds

Asymmetric in total winds due to the hurricane motion – stronger on the "forward" side.

Vorticity \( \frac{V}{R} + \frac{\partial V}{\partial r} \) in cylindrical coordinates.

Typical value ~ \( \frac{50m/s}{50km} = 1 \times 10^{-3} s^{-1} \).
The winds - In the vertical cross-section

Figure 10.6 Vertical cross section of the mean radial wind (u) in western Atlantic hurricanes. Analysis is a composite of data collected in many storms. (From Gray, 1979. Reprinted with permission from the Royal Meteorological Society.)

Figure 10.7 Vertical cross section of the mean tangential component of the wind (v) in Pacific typhoons. Analysis is a composite of data collected in many storms. (From Frank, 1977. Reprinted with permission from the American Meteorological Society.)
- Maximum tangential wind at the edge of eye wall
- Max speed ~ 0.5 – 1.5 km above sfc
- Vertical shear < 0.0 since the thermal wind opposes the observed wind throughout the troposphere. Why – because hurricanes have warm core (see next figure)
- The vertical shear is relatively weak, though, due to vertical momentum mixing by Cb clouds
Thermodynamic Structure

Figure 10.11 Radial cross section through an idealized, axially symmetric hurricane. On left: radial and vertical mass fluxes are indicated by arrows, equivalent potential temperature (K) by dashed lines. On right: tangential velocity in m s$^{-1}$ is indicated by solid lines and temperature in °C by the dashed lines. (From Wallace and Hobbs, 1977, as adapted from Palmén and Newton, 1969.)
Temperature departure from the mean

- ~ 10° - 15° warmer inside eye due to subsidence
- Warm core causes surface low-pressure (hydrostatic balance)
- $\theta_e$ in hurricane more potentially stable than outside (since instability has been realized)
- $\theta_e$ in eye much higher (15° - 30° more)

Note:

(a) If one starts with $\theta_e = 350$K and go up along moist adiabat and $p_{sfc} = 1000$mb (typical for most tropical disturbances), we can show

$$\Delta p_{sfc} = -2.5 \Delta \theta_e.$$ 

(b) Air from outside hurricane (where $p \sim 1000$mb) going towards the center (where $p \sim 950$ mb) should normally cool adiabatically – but observed temperature stays the same or increases slight. This is due to sensible heat flux from the sea surface $\Rightarrow \theta_e$ increases substantially.

The air-sea interaction theory further points out that the latent-heat flux from the sea surface as the air flow towards the center at large wind speed is another major energy source.

Presence of warm-cored eye a key feature of hurricanes $\Rightarrow$ pressure drop at the center.
Landfall

- greater frictional convergence
- convection may actually intensify (but less high $\theta_e$ air from the surface cause pressure to rise)
- wind damage $\leftarrow$ large scale $V_0$ but also from convective downdrafts
- weak to moderate tornadoes are common after landfall
- sfc winds now $\sim 50\%$ of 1 km winds (vs 70\% over ocean) so vertical shear increases significantly
- CAPE in hurricanes relatively small

Damages:

- Strong winds, convective gusts
- Sea level rise by 1-2 m due to low pressure
- Storm surge $\sim 2 – 10$ m, strongest in the right front quadrant
- Waves
- Tornadoes
- Flooding from rains
Hurricane Dynamics

Hurricane vortex cannot be understood without including the rotation of the earth in the vorticity balance.

The rapid rotation is produced by concentration of the vertical component of absolute vorticity by vortex stretching.

Maximum tangential wind speeds range typically from 50 to 100 m s\(^{-1}\).

Centrifugal force cannot be neglected compared to the Coriolis force.

Thus, to a first approximation, the azimuthal (tangential) velocity in a steady-state hurricane is in gradient wind balance with the radial pressure gradient force.

Hydrostatic balance also holds on the hurricane scale, which implies that the vertical shear of the azimuthal (tangential) velocity is a function of the radial temperature gradient (thermal wind balance).

The kinetic energy of hurricanes is maintained in the presence of boundary layer dissipation by conversion of latent heat energy acquired from the underlying ocean.

This potential energy conversion is carried out by a transverse secondary circulation associated with the hurricane, as shown below:
The energetics of the steady-state hurricane can be viewed as an example of a Carnot cycle heat engine in which heat is absorbed (in the form of water vapor) from the ocean at temperature $T_s$ and expelled by radiative cooling to space at temperature $T_o$ at the top of the storm. Since $T_s \sim 300$ K and $T_o \sim 200$ K, the efficiency of the heat engine, given by

$$\varepsilon = \frac{T_s - T_o}{T_s}$$

can be as high as 30%. This mechanism for hurricane formation and maintenance is referred to as the air-sea interaction theory. More details later.
Hurricane Formation Theories

**CISK (Conditional Instability of the Second Kind) Theory** (1960's – 1970's)

Represents a cooperation between convection and large-scale convergence:

- Weak disturbances containing vorticity
- Ekman layer (BL) convergence through Ekman pumping
- Increased convection
- Latent heat release
- Temperature increase
- Sfc pressure falls
- Increased vorticity
- Increased convergence
- A feedback loop - stability

Linear analysis to capture the above instability process has not been very successful, however, since there is little evidence that such interaction leads to a growth rate maximum on the observed scale of hurricanes.
**Air-sea interaction theory**

A dramatically different view has been proposed, mainly by Emanuel since late 80's which is referred to as the air-sea interaction theory.

It is based on the fact that the potential energy for hurricanes arises from the **thermodynamic disequilibrium between the atmosphere and the underlying ocean.**

Since the subcloud boundary layer is unsaturated, the BL air has a potential for significant increase in q⁰ (also T) therefore $\theta_e$ (or moist entropy), therefore the real energy source is believed to be the warm surface of the topical oceans.

References:
