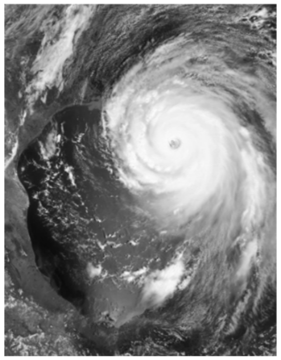
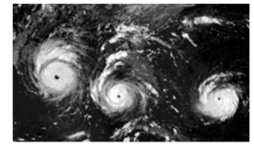
Chapter 24: Tropical Cyclones

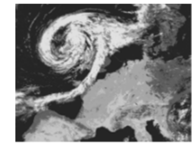


- Hurricane Naming, Track, Structure
- Tropical Cyclone Development

ESS124
Prof. Jin-Yi Yu

Tropical Cyclones vs. Mid-latitude Storms





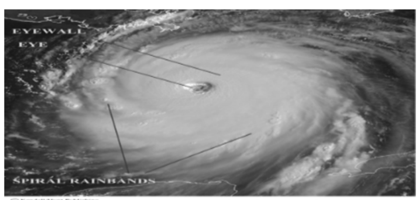
Tropical cyclones

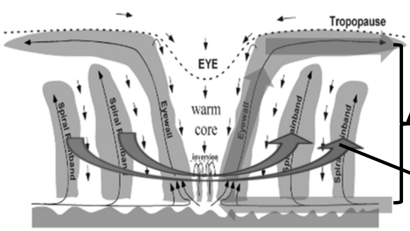
- ❑ The tropical cyclone is a low-pressure system which derives its energy primarily from evaporation from the sea in the presence of high winds and lowered surface pressure.
- ❑ It has associated condensation in convective clouds concentrated near its center.

Mid-latitude storms

- ❑ Mid-latitude storms are low pressure systems associated cold fronts, warm fronts, and occluded fronts.
- ❑ They primarily get their energy from the horizontal temperature gradients that exist in the atmosphere.

An Overview of Tropical Cyclone





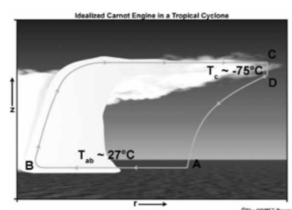
Secondary Circulation
- **Boundary layer inflow**
- **Eyewall ascending**
- **Upper tropospheric outflow**

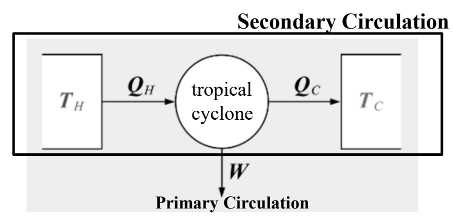
converting thermal energy from ocean to kinetic energy

Primary Circulation
- **Axis-symmetric circulation**
- **Conserving angular momentum**
- **Balanced flow**

Driven by the Secondary Circulation

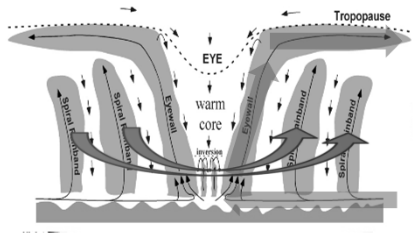
Secondary Circulation: A Carnot Cycle (Carnot Heat Engine) (Kerry Emanuel 1988)





- ❑ A heat engine acts by transferring energy from a warm region to a cool region of space and, in the process, converting some of that energy to mechanical work.
- ❑ The Carnot cycle is a theoretical thermodynamic cycle and can be shown to be the most efficient cycle for converting a given amount of thermal energy into work, or conversely, creating a temperature difference (e.g. refrigeration) by doing a given amount of work.

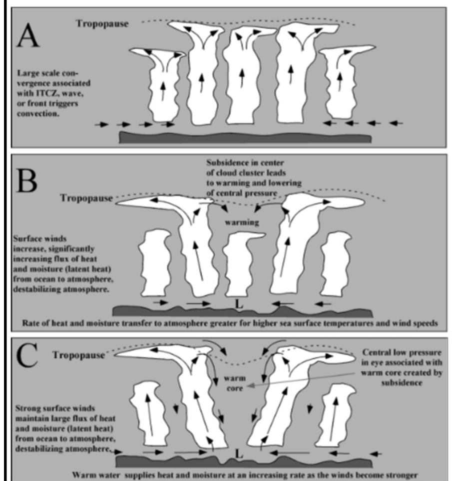
Two Circulation Components of Tropical Cyclone



Secondary Circulation

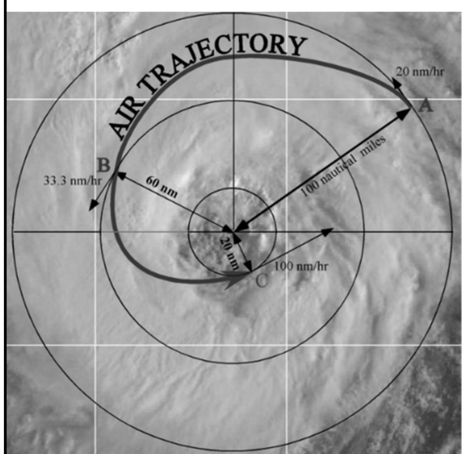
➔ Centrifugal and Coriolis Forces are not in perfect equilibrium with the pressure gradient.
➔ Air is forced to center and then rises
➔ Conservation of Angular Momentum
➔ As air enters to a small radius, its speed has to become faster
➔ Increases the rotational speed of the tropical cyclone.
➔ **Primary Circulation**

WISHE (Wind Induced Surface Heat Exchange) Mechanism



Low pressure at the center
➔Enhance surface winds
➔ increase surface heat fluxes
➔ some airs sink to the center
➔adiabatic warming at the center
➔Lower pressure at the center
➔Stronger winds
➔Stronger heat exchanges
➔Stronger descending
➔Even warmer at the center
➔Even stronger low
➔…….

The Source of Strong Rotating Winds

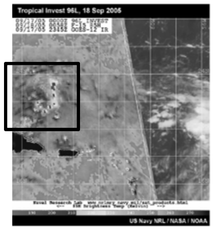


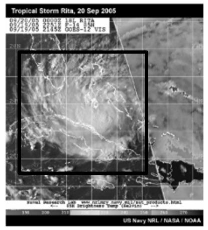
- The strong rotating winds in the core of a hurricane is a result of the conservation of angular momentum.

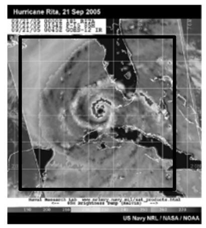
Hurricane Formation

- ***Tropical Disturbance***: Clusters of small thunderstorms.
- ***Tropical Depression***: When at least one closed isobar is present, the disturbance is classified as a ***tropical depression.***
- ***Tropical Storm:*** Further intensification, to wind speeds of 60 km/hr (37 mph), place the storm in the category of ***tropical storm.***
- ***Hurricane***: Hurricane status is gained when winds reach or exceed 120 km/hr (74 mph).

Stages of a Tropical Cyclone Lifecycle







Tropical Disturbance | Tropical Storm | Tropical Cyclone

Cyclogenesis

A process transits the asymmetric disturbance into a self-sustaining symmetric storm

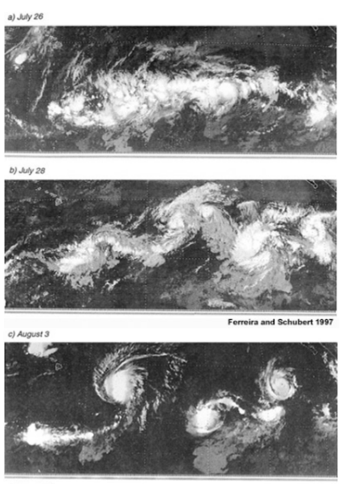
Intensification

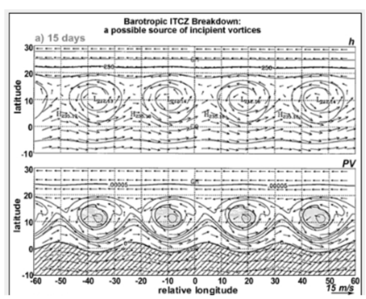
Further development of a tropical storm to a cyclone with a axis-symmetric structure and a clear eye.

Sources of Incipient Disturbances

- ❑ ITCZ breakdown
- ❑ Easterly waves
- ❑ Subtropical storms
- ❑ Monsoon trough
- ❑ Equatorial waves (Rossby, mixed Rossby-gravity)
- ❑ Mesoscale convective complexes

Genesis in the Monsoon Trough





❑ A potential vorticity model provides evidence that the continuous PV source associated with convection in the ITCZ will act to destabilize and break down the ITCZ periodically through combined barotropic-baroclinic instability.

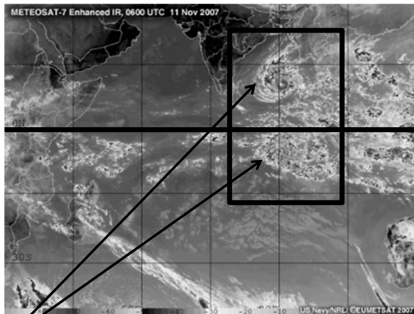
Tropical Disturbances and Easterly Waves

Courtesy of NOAA

- Some tropical disturbances form in association with mid-latitude troughs migrating toward lower latitudes, some form from ITCZ-related convection, but most develop from easterly waves.
- ***Easterly waves***, or undulations in the trade wind pattern, spawn hurricanes in the Atlantic (typically 2–3000 km).
- Only about 10% tropical disturbances intensify into more organized, rotating storms.

ESS124
Prof. Jin-Yi Yu

Genesis from Equatorial Waves



- Twin tropical cyclones that straddle the equator at formation have a flow structure suggestive of equatorial Rossby waves.
- Equatorial Rossby waves may initiate genesis, others argue that the shorter wavelength mixed Rossby-gravity waves are also important.

Development of Hurricane

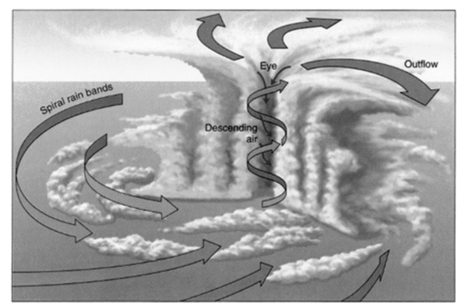
HURRICANE FORMATION

Trigger Mechanisms for initial Thunderstorms	Environment required for Hurricane formation	Spin up of thunderstorm clusters into Hurricane
1. Intertropical convergence zone 2. Easterly waves in trade wind flow 3. Cold fronts extending into tropics	1. Sea surface temp > 80°F 2. Deep layer of warm water 3. Weak wind shear 4. At least 5° from equator	1. Wind induced transfer of heat from the ocean to the atmosphere 2. Conservation of angular momentum

Hurricane Dissipation

- After making landfall, a tropical storm may die out completely within a few days.
- Even as the storm weakens, it can still bring in huge amount of water vapor and rainfall hundreds of kilometers inland.

Hurricane Structure

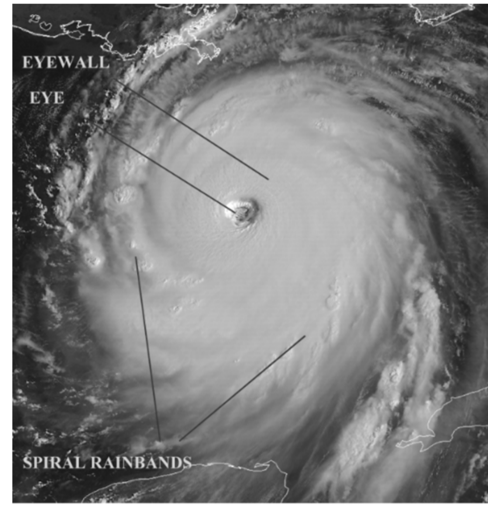


- A ***central eye*** surrounded by large cumulonimbus thunderstorms occupying the adjacent ***eye wall***.
- Weak uplift and low precipitation regions separate individual ***cloud bands***.

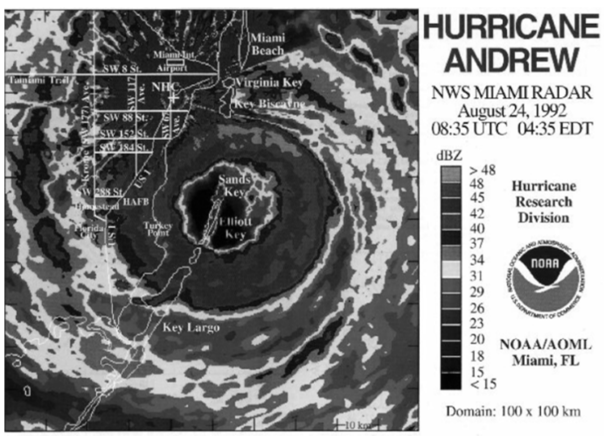
Hurricane Characteristics

- Definition: Hurricanes have sustained winds of 120 km/hr (74 mph) or greater.
- Size: Average diameters are approximately 600 km (350 mi). (one third the size of mid-latitude cyclone)
- Duration: days to a week or more.
- Strength: Central pressure averages about 950 mb but may be as low as 870 mb.
- Power: The energy released by a single hurricane can exceed the annual electricity consumption of the US and Canada.

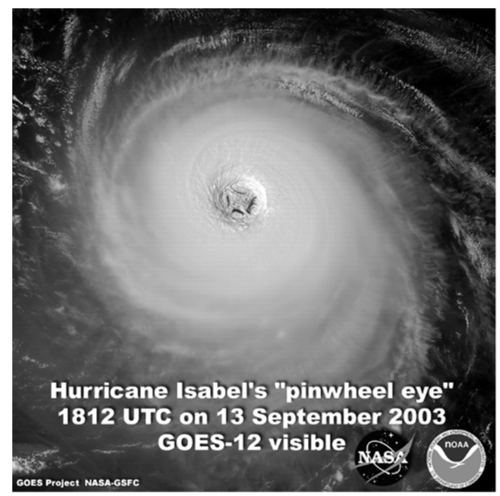
Typical Hurricane Eye (Hurricane Katrina, 2005)



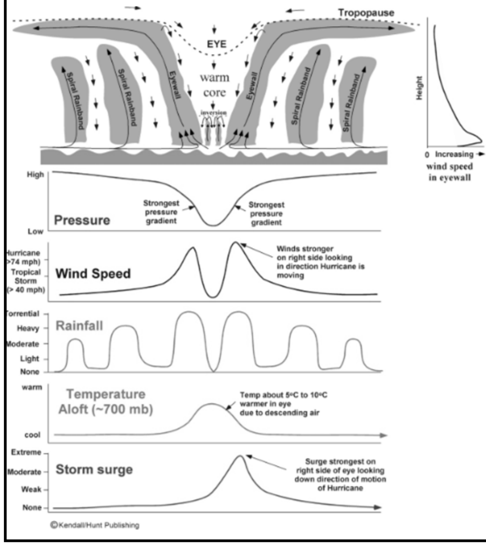
Radar Image of Hurricane Andrew



Courtesy NOAA/National Climate Data Center

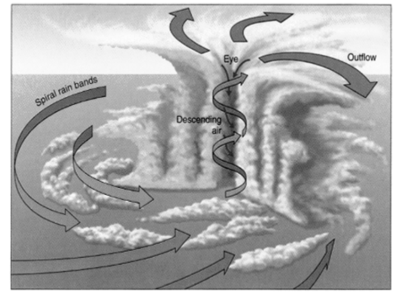


Vertical Cross Section of Hurricane



- ❑ Most of the air in the eye descends very slowly, taking days to traverse the eye's depth.
- ❑ Air sinks in the eye warms adiabatically and make the eye much warmer than other regions of the hurricane.
- ❑ In the eye wall air ascends from the surface to the tropopause.
- ❑ Pressure gradient is the strongest near the eye wall, where the most violent winds are produced.
- ❑ Strongest rainfall is also produced near the eye wall.
- ❑ Strongest storm surge occurs to the right of the hurricane.

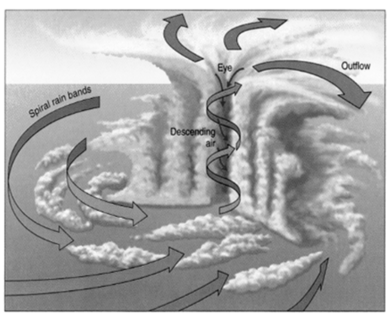
Hurricane Eye and Eye Wall



❑ The eye moves at a speed of 20 km/hr ➔ The calm weather associated with the eye will last less than an hour.

- The eye is an area of descending air, relatively clear sky, and light winds which is about 25 km (15 mi) in diameter on average.
- A shrinking eye indicates storm intensification.
- The eye wall is comprised of the strongest winds, the largest clouds, and the heaviest precipitation with rainfall rates as high as 2500 mm/day (100 in.).

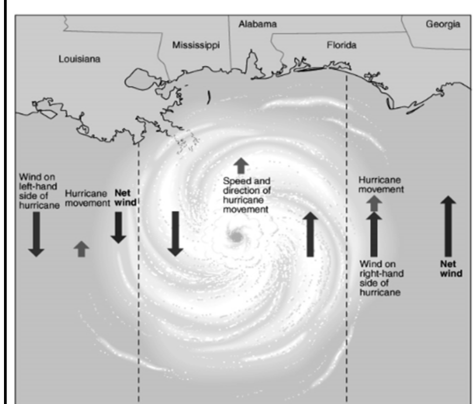
Pressure Structure



❑ The upper portions of the storm are blanketed by a cirrus cloud cap due to overall low temperatures.

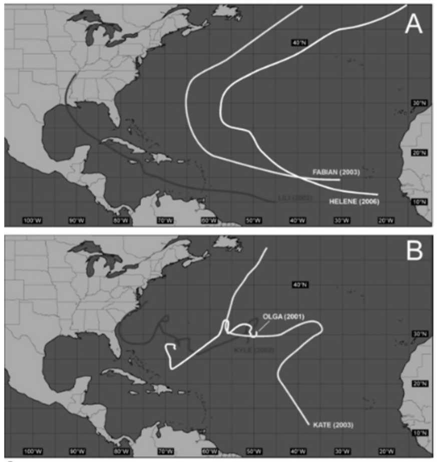
- The horizontal pressure gradient with altitude decreases slowly.
- At about 400 mb, pressures within the storm are approximate to that outside.
- Surface-400mb: Cyclonic circulation.
- 400mb-tropopause: anticyclonic circulation.

Hurricane Wind Structure



- Winds and surge are typically most intense in the ***right front quadrant*** of the storm where wind speeds combine with the speed of the storm's movement to create the area of highest potential impact.

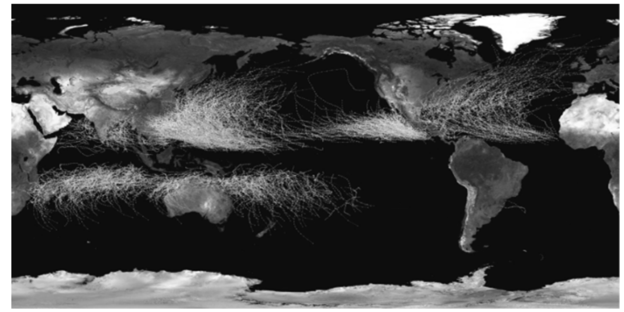
Hurricane track



- ❑ Hurricane tracks are affected by (1) subtropical high, (2) trade wind, and (3) Coriolis force.
- ❑ Hurricanes typically form within the trade wind belt and normally moves westward with the winds.
- ❑ Due to the subtropical high and the Coriolis force, hurricanes tend to move poleward.
- ❑ Eventually hurricanes cross from the trade wind belt into the mid-latitude westerly belt, and begin to move eastward.

ESS124
Prof. Jin-Yi Yu

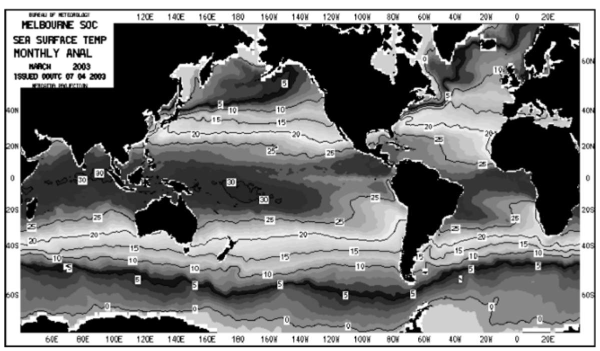
Naming Convention



- ❑ ***Hurricanes:*** extreme tropical storms over Atlantic and eastern Pacific Oceans.
- ❑ ***Typhoons:*** extreme tropical storms over western Pacific Ocean.
- ❑ ***Cyclones:*** extreme tropical storms over Indian Ocean and Australia.

ESS124
Prof. Jin-Yi Yu

Ocean Temperature And Hurricane



- ❑ Hurricanes depend on a large pool of warm water.

ESS124
Prof. Jin-Yi Yu

Annual Hurricane Frequency

Table 12–1 Maximum, Minimum, and Average Number of Hurricanes (and Their Counterparts) per Year over Various Parts of the World's Oceans, 1968 to 1989 (1968 to 1990 for the Southern Hemisphere)

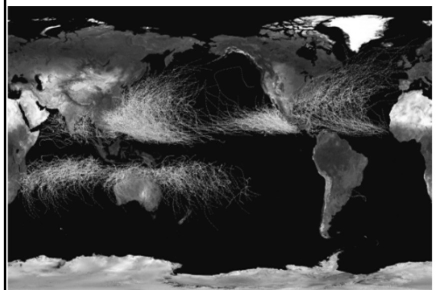
Basin	Maximum	Minimum	Average
Atlantic	12	2	5.4
Eastern Pacific	14	4	8.9
Western Pacific	24	11	16.0
Northern Indian Ocean	6	0	2.5
Southwestern Indian Ocean	10	0	4.4
Southeastern Indian Ocean/Australia	7	0	3.4
Australia/Southwestern Pacific	11	2	4.3
Global	65	34	44.9

Source: Colorado State University

- ❑ **No hurricane in the Southern Atlantic Ocean.**
- ❑ **Western Pacific hurricanes are the strongest.**

ESS124
Prof. Jin-Yi Yu

Conditions Necessary for Hurricane Formation



- ❑ Hurricanes form only over deep (several tens of meters) water layers with surface temperatures in excess of ***27 ºC.***
- ❑ Poleward of about 25º, water temperatures are usually below this threshold.
- ❑ Hurricanes are most frequent in late summer and early autumn during high SST times.
- ❑ ***Coriolis force*** is an important contributor, and as such, hurricanes do not form equatorward of 5º.
- ❑ Need an unstable atmosphere: available in the western tropical ocean bur not in the eastern parts of the ocean.
- ❑ Strong vertical shear must be absent for hurricane formation.

ESS124
Prof. Jin-Yi Yu

Hurricane Seasons

- Hurricanes obtain their energy from latent heat release in the cloud formation process.
- Hurricanes occur where a deep layer of warm waters exists and during the times of highest SSTs.
- For the N.H., August and September are the most active months.
- For the S.H., the hurricane season is January-March.

ESS124
Prof. Jin-Yi Yu

Naming of Hurricanes

TABLE 24.2 Atlantic Hurricane Name List

2008	2009	2010	2011	2012	2013*
Arthur	Ana	Alex	Arlene	Alberto	Andrea
Bertha	Bill	Bonnie	Bret	Beryl	Barry
Cristobal	Claudette	Colin	Cindy	Chris	Chantal
Dolly	Danny	Danielle	Don	Debby	Dean
Edouard	Erika	Earl	Emily	Ernesto	Erin
Fay	Fred	Fiona	Franklin	Florence	Felix
Gustav	Grace	Gaston	Gert	Gordon	Gabrielle
Hanna	Henri	Hermine	Harvey	Helene	Humberto
Ike	Ida	Igor	Irene	Isaac	Ingrid
Josephine	Jaoquin	Julia	Jose	Joyce	Jerry
Kyle	Kate	Karl	Katia	Kirk	Karen
Laura	Larry	Lisa	Lee	Leslie	Lorenzo
Marco	Mindy	Matthew	Maria	Michael	Melissa
Nana	Nicholas	Nicole	Nate	Nadine	Noel
Omar	Odette	Otto	Ophelia	Oscar	Olga
Paloma	Peter	Paula	Philippe	Patty	Pablo
Rene	Rose	Richard	Rina	Rafael	Rebekah
Sally	Sam	Shary	Sean	Sandy	Sebastien
Teddy	Teresa	Tomas	Tammy	Tony	Tanya
Vicky	Victor	Virginie	Vince	Valerie	Van
Wilfred	Wanda	Walter	Whitney	William	Wendy

*Hurricane names retired in 2007 will be replaced on the 2013 list.

- When a tropical disturbance reaches the stage of tropical storm, it will be given a name.
- The name come from an A-W list created by World Meteorological Organization (WMO).
- Six lists are created for the Atlantic Ocean, each list is used for one hurricane season.
- The names of the hurricanes that cause devastating damages are removed from the list forever.

ESS124
Prof. Jin-Yi Yu

Hurricane Intensity Scale

Table 12–2 The Saffir-Simpson Scale

Category	Pressure mb	Wind Speed km/hr	Wind Speed mph	Storm Surge m	Storm Surge ft	Damage
1	≥ 980	119–154	74–95	1–2	4–5	Minimal
2	965–979	155–178	96–110	2–3	6–8	Moderate
3	945–964	179–210	111–130	3–4	9–12	Extensive
4	920–944	211–250	131–155	4–6	13–18	Extreme
5	< 920	> 250	> 155	> 6	> 18	Catastrophic

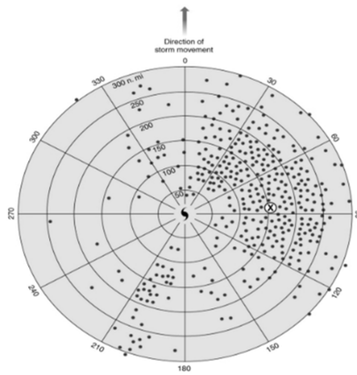
- The Saffir-Simpson scale.
- Five categories: larger numbers indicate lower central pressure, greater winds, and stronger storm surges.

ESS124
Prof. Jin-Yi Yu

Hurricane Damages

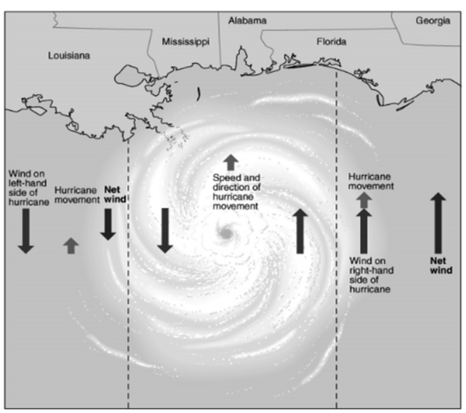
- Heavy rainfalls
- Strong winds
- Tornadoes
- Storm Surges: A rise in water level induced by the hurricane.

Hurricane Induced Tornadoes



- Most hurricanes also contain clusters of tornadoes.
- Most of these tornadoes occur in the right front quarter of the hurricane movement.
- It appears the slowing of the wind by friction at landfall contribute to the formation of tornadoes.

Hurricane Wind Structure



- Winds and surge are typically most intense in the ***right front quadrant*** of the storm where wind speeds combine with the speed of the storm's movement to create the area of highest potential impact.

Storm Surges

- Process 1: Hurricane winds drag surface waters forward and pileup the waters near coasts.
- Process 2: Lower atmospheric pressure raises sea level (for every 1 mb pressure decrease, sea level raises 1 cm).
- Storm surges raise costal sea level by a meter or two for most hurricanes, but can be as much as 7 meters.

Hurricane Watches and Warnings

- ***Hurricane watch***: if an approaching hurricane is predicted to reach land in more than 24 hours.
- *Hurricane Warning*: if the time frame is less, a ***warning*** is given.