Exam composition: 50-60% short answer, multiple guess or matching; 50-40% short explanation, draw and explain or problems. You will have whole 50 minutes. We will begin promptly at 11:00 and end at 11:50 AM. Bring pencils and a scientific calculator

ASSIGNMENT for Wednesday and Friday: Waves: *Emanuel* pp. 147-152; and Storm Surge: Emanuel 165-171.

1. **Lecture 1, Introduction:** Hurricanes are beautiful, but…they destroy property and kill people.
    1. They are circular vortices smaller, but more intense, than middle-latitude frontal cyclones
    2. *Kamikaze* frustrates Kublai Khan's invasions of Japan in 1274 & 1281
    3. Names: Hurricane (W. Hemisphere), Typhoon (Pacific west of dateline), Tropical Cyclone (Worldwide)

2. **Lecture 2, Early History:**
    1. Columbus: First European encounter a hurricane [1502 (4^{th} voyage), or maybe 1495 (2^{nd})].
    2. *La Floride*: Hurricane in 1565 (and old-fashion massacre) left Florida in Spanish hands until 1813.
    3. 1780: Deadliest hurricane season on record. Three October hurricanes killed 27,000 during American Revolution.
    4. Redfield-Ried Paradigm: "The storm was in the form of a great whirlwind"…1831 (**SLIDE 3**)

3. **Lecture 3,Introduction to the Atmosphere:**
    1. Earth's atmosphere is mostly N_2 & O_2, with some H_2O, CO_2, and noble gasses.
    2. Atmosphere is very shallow compared to its horizontal extent. The boundary of space is officially at 100km, but in the tropics the troposphere is 15-18 km deep.
    3. Troposphere:
        i. Temperature decreases with height
        ii. Where nearly all weather happens
    4. Stratosphere
        i. Above the Tropopause (15-18 km in topics):
        ii. Temperature nearly constant with height
    5. Sun heats the Earth mainly in the topics.
    6. Atmosphere & Ocean move heat poleward
    7. Infrared radiation to space in all latitudes cools the Earth
    8. Frontal (Middle latitude, poleward of 30^o) Cyclones
        i. Cold wind from pole on the W side; warm wind from tropics on the east side
        ii. Move heat poleward almost horizontally
        iii. Larger than tropical cyclones

        iv. Tropical cyclone move heat vertically from the warm ocean to the cold tropopause, as do convective clouds generally
    9. Big Picture With the Atmosphere
        i. Middle latitudes: Wind from the W, horizontal heat transport
        ii. Tropics: Wind from the east, vertical heat transport
    10. Bermuda, the Sea Venture and Shakespeare's Tempest

4. Lectures 4, Structure:
1. Hurricanes are circular, long-lived vortices that move more slowly than its circulating wind (Redfield Reid Paradigm)
2. Warm core → low-hydrostatic pressure in the center (**SLIDE 4**)
3. Circulating wind in gradient balance with pressure distribution
4. Wind increases from calm at the center to a maximum at the edge of the clear eye, and then decreases with distance from the center outside the eye
5. Secondary circulation (**SLIDES 5 & 6**)
    i. Frictional inflow
    ii. Buoyant, outward sloping eyewall updraft
    iii. Precipitation-driven convective downdrafts
    iv. Upper tropospheric outflow
    v. Outer anticyclone
    vi. Clear eye, filled with subsiding air.

5. Lecture 5, 19th Century:
1. Espy-Redfield conflict, radial inflow or circulation. Role of latent heat release
2. Telegraph led to founding of organized observing and forecasting 1860-1870
3. Fr. Viñes as a hurricane scientist and forecaster
4. Herndon and the loss of the Central America with all that gold (1857)
5. European powers humbled in Samoa 1889
6. Hog Island (1893), 6 US landfalls that year…

6. Lecture 6, Sun and Sea:
1. Tropical weather
    i. Temperatures don't change much
    ii. Steady winds, mostly from east
    iii. Frequent showers
2. The tropics are mostly covered by oceans with the sun nearly overhead, year-around.
3. Solar heating (**SLIDES 7 & 8**): Maximum = 1000 W m^{-2}; average = 240 W m^{-2}.
4. Incoming solar radiation: Visible wavelength , 0.4 to 0.7 µm
5. Outgoing solar radiation: Infrared ~10 µm
6. Atmosphere traps Infra-Red (IR) radiation---Greenhouse effect
7. Incoming and outgoing radiation balance wordwide, but there is an excess of heating in the tropics

7. **Lecture 7, Convection:**
    1. In the Tropics:
        i. Convection transports heat upward
        ii. More important than IR radiation
    2. Kinds of heat
        i. Electromagnetic radiation (UV, Vis and IR)
        ii. Sensible: Temperature change
        iii. Latent: Stored when water evaporates or in other phase changes
    3. Air-mass cumulus life cycle-stages (**SLIDE 9**)
        i. Cumulus
        ii. Mature
        iii. Dissipating
    4. Tropical squall lines (**SLIDE 10**)
        i. Replace warm moist surface air with cold wake, or cold pool
        ii. Suppress convection for 2-4 days afterward.

8. **Lecture 8, Trade Winds:**
    1. Convection moves heat upward
    2. Hadley Cell (**SLIDE 11**)
        i. Converges moisture toward the equator at low levels
        ii. Rising warm air in the Intertropical Convergence Zone (ITC or ITCZ)
        iii. Pushes warm air northward at 15-18 km altitude
    3. Trade winds (**SLIDE 12**)
        i. Steady—hence the name
        ii. Blow from east
        iii. Rotate more slowly than the surface of the planet equatorward of 30^{o}
        iv. Friction speed up (makes more westerly) the motion
        v. Exported air keeps its angular momentum so the wind in middle latitudes becomes westerly
        vi. Westerlies move faster than surface so friction slows the wind poleward of 30^{o}
    4. Westerlies are unsteady because north-south shifting of the wind carries heat toward the poles

9. **Lecture 9, Heat Engines:**
    1. TC have low central hydrostatic pressure due to warm vortex-core
    2. The Swirling wind is in gradient balance with low pressure
    3. Energy drawn from sea (mostly through evaporation) is balanced by:
        i. Loss to frictional work
        ii. Heat carried away by upper-tropospheric exhaust (**SLIDE 13**)
    4. Energy is released through moist adiabatic expansion that changes stored latent heat into sensible heat in the eyewall
    5. Analysis like the Carnot Cycle in steam engines
        i. Defines Maximum Potential Intensity (MPI)

ii. Reasonable agreement between theory and observations

10. Lecture 10, Intensity:

1. Saffir-Simpson Scale
   i. CATS 1-5, from barely a hurricane to worst imaginable
   ii. CATS 3-5: Major hurricanes, V > 100 kt, cause 80% of damage
   iii. Key values: **CAT 1**, barely a hurricane, 75 mph**; CAT 3**, 111 mph; **CAT 5** > 155 mph.
2. Rapid deepening: CAT 1 or 2 to CAT 4 or 5 in less than a day
3. Most hurricanes are weaker than MPI because of
   i. Shear---vertical change of surrounding wind---brings cooler, drier air into the storm and causes asymmetric convection (**SLIDE 14**)
   ii. Storm-induced cooling of the sea by upwelling and mixing (**SLIDE 15**)
   iii. Concentric-eyewall replacements: New eye forms around old and strangles it (**SLIDE 16**)
   iv. Life cycle duration: Not enough time or warm, open ocean to reach MPI

11. Lecture 11, Galveston 1900 and Early 20th Century:

1. Summer of 1900, US experienced a heat wave, implying a strong Bermuda High
2. Weather Bureau threatened by superior Cuban TC forecasts
3. Cape Verde Hurricane
   i. Passed along S coast of Cuba over the island and into the Gulf by way of the Dry Tortugas
   ii. Intensified rapidly in Gulf and maybe again at landfall
   iii. Struck Galveston as CAT 4, night of 8-9 SEP 1900
4. Weather Bureau in DC completely lost the picture, expected recurvature to threaten NJ
5. Isaac Cline may or may not have warned city
6. 8000 Texans (including Cora Cline) died---worst US natural disaster (**SLIDE 17**)
7. Cline recovered from trauma and wrote Tropical Cyclones
8. First Radio ship reports in 1910 (*SS Cartago*)
9. Damaging Hurricanes of 1915, 1916 & 1919
   i. Affected the Gulf Coast, Galveston, New Orleans, and Corpus Christi
10. Suppressed 1911 and 1914 seasons due to El Niño
11. Fate of ordinary mariners and landsmen from the past remains obscure
12. Modern accounts capture the total human impacts
13. No routinely effective warnings before 1940s
14. Huge economic and human disasters at intervals of decades (on average)
15. But hurricane are like bananas; they come in bunches
16. Advent of radio reports, movement of TC forecast center from DC, and (later) routine upper-air observations set the stage for modern practice

12. TC Formation (LEC 13. Lecture 12 got omitted in post-Irma confusion**)**

1. 6 TC “Basins” in order of activity: NW Pacific, S Indian, NE Pacific, SW Pacific, N Atlantic, N Indian Oceans **(SLIDE 18)**
2. Atlantic Activity: 11 Named Storms 6 Hurricanes, 2 Major Hurricane (REMEMBER NUMBERS)
3. Conditions for Hurricane Formation:
   i. Sea Warmer than 26^{o}C
   ii. Moister than 80% RH
   iii. Conditional Instability
   iv. Pre-existing disturbance
   v. Low Shear, and
   vi. More than 5^{o} from Equator **(SLIDE 19)**
4. Easterly (African) Waves are the pre-existing disturbances in the Atlantic
5. Monsoon depressions provide the pre-existing disturbances elsewhere
6. Hurricanes grow through Enhanced evaporation due to high winds (WISHE, Wind Induced Surface Energy Exchange), unlike squall lines which live off of the (much lower amount of) energy stored in the air above the sea instead of the energy stored in the sea itself.
7. Names:
   i. Wind less than 35 kt, no closed circulation **Tropical Disturbance**
   ii. Wind less than 35 kt (40 mph), closed circulation, **Tropical Depression**
   iii. Winds more than 35 kt, but less than 65 kt, **Tropical Storm**
   iv. Winds more than 65 kt (75 mph), **Hurricane** (W Hemisphere) or **Typhoon** (NE Pacific)
   v. Elsewhere variation on **Tropical Cyclone** are used

13. Motion (LEC 14)

1. Track Characteristics
   i. East to West motion equatorward of 30^{o} latitude
   ii. West to East poleward of 30^{o}
   iii. Recurvature at about 30^{o}
   iv. Most move northward at US landfall
2. Poleward & westward motion due to Earth’s rotation, Beta Gyres
3. Apart from this “beta drift” TCs move with steering flow—the prevailing wind around the storm **(SLIDE 20)**
4. Bermuda and Azores Highs are often separated by a trough. Some storms recurve around west end of Bermuda High; others recurve in mid-Atlantic between the Bermuda & Azores Highs **(SLIDE 21)**

14. Termination (LEC 15)

1. Impacts at landfall **(SLIDE 22)**
2. Hurricane weakens exponentially after landfall with a 7-h halving time
3. Fujiwhara dance: TC rotate around a common center of mass
4. Vortex filamentation & merger: One for the price of two, the“Perfect storm”
5. Extratropical transition **(SLIDE 23)**

        i. Hurricane merges with front, which wraps into the storm circulation
        ii. Or, hurricane triggers frontal instability, causing formation of a middle-latitude cyclone which filaments the hurricane
        iii. Often major rain event, as in Hazel of 1955
    6. Rainfall patterns shift from left of shear in TCs to poleward (ahead) in frontal cyclone
    7. Topographic enhancement can be very heavy
    8. TC rain is a major hazard to life

Florida Hurricanes of 1926 & 1928 (LEC 16, Slide 24)

1. Miami land boom of the 1920s
2. Bubble burst by several factors, including the 1926 Hurricane
    a. Cape Verde Storm; CAT 4 at landfall
    b. Big Storm that passed over port, downtown, present site of FIU
    c. Merrick and the UofM devastated
3. 1928 Hurricane
    a. Also a Cape Verde Storm
    b. In Puerto Rico it was the first official CAT 5
    c. Killed > 4000 total, 2500 in US
    d. Struck Palm Beach Co; most of the US dead were African American or Bahamian farm workers South of Lake Okeechobee
    e. Deaths undercounted at the time
4. These hurricanes led to adoption of first US municipal building code in (Miami) Dade County.
5. South Florida was economically dead until 1940

Labor-Day Storm of 1935 & New England Hurricane of 1938 (LEC 17)

1. Florida East Coast Railway Key West Extension
    a. Built 1905-1912 by Flagler, Merideth & Krome
    b. Menaced by 5 hurricanes during construction
    c. Engineering Marvel
    d. Operated at a loss for 23 years
    e. Wiped out by 1935 Labor-Day Storm
2. Labor Day Storm was the first recorded US landfall by a CAT 5 hurricane
    a. 892 mb pressure record stood until 1988
3. Killed > 423, mostly Veterans working on Overseas Highway
4. 1938 New England Hurricane
    a. Recurving, fast moving (50 kt motion) Cape Verde storm
    b. Struck Long Island with little warning
    c. CAT 2-3 winds widespread
    d. Heavy rains after a wet summer caused widespread flooding
    e. Claimed nearly 400 lives; did $300M in damage = $4B today
    f. Prototypical New England Hurricane: “Long Island Express”