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 10:00 and end at 10:50 AM. Bring pencils and a scientific calculator.

ASSIGNMENT for Friday: Formation, Emanuel pp. 93-101

1. **Lecture 1, Introduction:** Hurricanes are beautiful, but...they destroy property and kill people.
   1. 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<sup>th</sup> voyage), or maybe 1495 (2<sup>nd</sup>)]
   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 N₂ & O₂, with some H₂O, CO₂, and noble gasses.
   2. Atmosphere is very shallow (100 km) compared to its horizontal extent
   3. Troposphere:
      i. Temperature decreases with height
      ii. Where nearly all weather happens
   4. Stratosphere
      i. Above the Tropopause (15 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°) 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 (RR Paradigm)
   2. Warm core $\rightarrow$ 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 IR---Greenhouse effect
   7. Incoming and outgoing radiation balance worldwide, 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. EM radiation
   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
      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°
      iv. Friction speed up (makes more westerly)
      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°
   4. Westerlies are unsteady because shifting north south wind carries heat to the poles

9. **Lecture 9, Heat Engines:**
   1. TC low central 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
1. CATS 1-5, from barely a hurricane to worst imaginable
   i. CATS 3-5: Major hurricanes, V > 100 kt, cause 80% of damage
   ii. 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)
      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 12)
   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°C
ii. Moister than 80% RH
iii. Conditional Instability
iv. Pre-existing disturbance
v. Low Shear, and
vi. More than 5° from Equator (SLIDE 19)

4. Easterly (African) Waves are the pre-existing disturbances in the Atlantic
5. Monsoon depressions 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. Termination (LEC 13)
   1. Impacts at landfall (SLIDE 20)
   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 the “Perfect storm”
   5. Extratropical transition (SLIDE 21)
      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

14. Motion (LEC 14)
   1. Track Characteristics
      i. East to West motion equatorward of 30° latitude
      ii. West to East poleward of 30°
      iii. Recurvature at about 30°
      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 22)
4. Bermuda and Azores Highs separated by a trough. Some storms recurve around west end of Bermuda High; others recurve in mid-Atlantic between the Bermuda & Azores Highs (SLIDE 23)