4. Hurricane [continues]

1) Tropical cyclone (TC) climatology
   [What does that tell us about necessary ingredients for these storms?]
   a) TC occurs over the very warm water (SST > 26.7°C or 80°F)
      Storms occur in all tropical ocean basins except the SE Pacific and SE Atlantic
      e.g. most intense in the W Pacific (warmest SST)
      e.g. almost none in SE Pacific & SE Atlantic (too cold)
   b) No TC at the equator (very weak Coriolis force)
   c) Not many tropical cyclones in Western South Atlantic (too much vertical wind shear and too few triggers)
   d) Tropical Cyclone Seasons
      N Atlantic: June-Nov
      W Pacific: April-Jan.
   e) Decadal Variations in Atlantic hurricane activity
      - Before 1960s, fewer tropical cyclones
        [maybe some TCs were undetected before satellite era]
      - 1970-1994 [low activity] vs 1995-2013[more active]. Potential causes:
        Sea surface temperatures: Atlantic Multi-Decadal Oscillation
        Vertical shear: El Niño
2) TC Lifecycle
   a) Life stage
      - Tropical disturbance (cluster of thunderstorms with weak winds)
      - Tropical depression (Cyclonic circulation evident; winds up to 38 mph)
      - Tropical storm (Storm gets a name; winds between 39~73 mph)
      - Hurricane (winds > 74mph; about 6 per season in Atlantic)

      Note: Evolution from a tropical disturbance to a hurricane is <u>not inevitable</u>.
   b) Necessary condition for hurricane development
      For a tropical disturbance to develop into a hurricane, it needs:
      - Very warm water (SST > 26.7°C or 80°F)
      - Weak vertical shear
        [Vertical wind shear inhabits the formation of hurricanes
        … but helps the formation of strong tornados]
      - Some Coriolis force (needs to be at least 5° away from the equator)
   c) TC weaken over land (cut off from warm surface waters, their source of energy)
   d) TC death and (maybe) Rebirth as mid-latitude low

      Typically, TC die when they move over land or cold water or into a region of strong vertical shear. But TC that recurve over the ocean can change into an extra-tropical cyclone

      e.g. Hurricane John, Hurricane Freda
3) Motion
   a) Hurricanes tend to move with the flow in their surrounding environment:
      - Easterlies (winds from the east) in the deep tropics
      - Westerlies (winds from the west) in mid-latitudes

      Nevertheless, hurricanes also influence their own track: when moving from the east in the deep tropics they tend to angle to the north due to the northward increase in the Coriolis force
   b) Recurving

- Once westward moving storms in the deep tropics drift far enough north, they recurve back to toward the east as they feel the westerly (eastward) winds in mid-latitudes.
- While getting far enough north, storms may transit to mid-latitude storms

4) Storm surge
   a) Where are the stronger winds and waves?
      - In NH, Right-hand side of TC gets higher winds
        net wind = environmental wind + storm generated wind]
        [Left-hand side: net wind = environmental wind - storm generated wind]
      - In NH, Higher waves in the right-front quadrant. Why?

      Waves are generated by wind blowing across the sea surface.
      1. The stronger the winds, the bigger the waves.
      2. The more time the waves are exposed to the wind, the larger they get.
      Waves generated at right-front quadrant of storm continues to be exposed to strong wind when account for hurricane motion as well a wave propagation.
      - In SH, the most dangerous quadrant is the left front.
   b) Most hurricane-caused fatalities are due to water (flooding & storm surge)
   c) Record High storm surge: 43-48'Bathurst Bay Cyclone (Australia) [1899]
   d) Causes of the storm surge:
      Primary: the storm's winds pushing water towards the coast
      Secondary: local drop in pressure near the eye (typically contributes just 5%)
   e) Storm surge influenced by
      - Wind speed (major factor)
      - Drop in atmospheric pressure (minor factor)
      - Shape of the sea floor slope (shallow slope is more favorable for storm surge, since it prevents cold water from mixing upward to the surface while the hurricane is approaching)
      - Path of the storm relative to the coast (Is the storm approaching head-on or almost parallel to the coast)
   f) Is it possible to get negative storm surge in some places?
      Yes. Example: Irma storm surge. Causes: wind push water away from shore.
   g) Factors Determining the Storm Tide
      - Astronomical tide (2 high tides, 2 low tides per day)
      - Storm surge (generated by the hurricane)
        Higher wave when it is high tides (storm tide + normal high tide)
   h) Example:
      Galveston, TX, 1900
      - Shallow bottom slope
      - Taken by surprise (Warnings from Cuban forecasters ignored)
      - 15'storm surge (Galveston Island was only 8'above sea level)
      - 6,000-12,000 dead (worst US disaster)
      - Galveston was finished as "The New York of the Gulf
      - high sea wall was built and the city was raised

      Ike (2008): 40% of Galveston residents did not evacuate in response to the mandatory order …
5) Hurricane impacts and adaptation
   a) High winds
      e.g. Hurricane Andrew exposed weaknesses in home construction

Building codes upgraded

b) storm surge (coastal)
c) Flooding with heavy rainfall (inland, typically most severe when the storm encounters mountains)

6) Tropical cyclone forecast
   - Improvements:
     Over the past 30 years in the north Atlantic, hurricane intensity forecasting has improved little while hurricane track forecasting has improved significantly
   - Forecasting challenges
     - Knowing the current state of the atmosphere
     - Modeling how the atmosphere will evolve from its current state
     - Improvements in track forecasts have come from improvements in both determining the current state and improving models.
     - Lack of improvement in 24-hour intensity forecasts may be limited by sensitivity of hurricane development of small, hard to observe properties of the current state
   - Seasonal Forecast
     Outlook: number of named storms, hurricanes and major hurricanes
     Forecast for 2019: near normal
     Hurricane Seasonal Forecast are largely based on forecast of:
     - Sea surface temperatures (SST) in the tropical north Atlantic
       [Local effect of SST beneath the hurricanes]
     - Presence of El Niño or La Niña
       [Remote influence of SST in the equatorial Pacific Ocean]
7) Impacts of EI Niño on hurricanes
   - EI Niño is a phenomenon that happens over tropical Pacific and shows warm anomaly (warmer than the average condition) over eastern equatorial Pacific.
   - EI Niño is associated with a shift of thunderstorm activity eastward along the equator
     [EI Niño tends to make the winters warmer and drier in the Pacific Northwest]
   - EI Niño affects hurricanes via changes in vertical wind shear
     Increases the vertical wind shear in tropical Atlantic →less hurricanes
     Decreases the vertical wind shear in Eastern Pacific → more hurricanes
8) Climate Change
   a) Global warming: Greenhouse gas effect
   b) What is expected to happen:
      - sea-level rise (may make stronger storm surge)
      - More floods/heavy rainfall (warmer air holds more moisture)
      - More drought (since the air can hold more moisture, surface evaporation will increase)
   c) Impact to hurricane
      - Warmer temperatures means: Warmer ocean & More water vapor in the air
      - But also need to think about wind shears.
        Prediction of increased shear over the Gulf of Mexico could act to weaken hurricanes
      - Recent model results are suggesting fewer but more intense storms
9) Some historical tropical cyclones (more details in the slides):
   a) Galveston & Ike

b) Katrina [2005]
   - Before the landfall, the track forecast was better than the intensity forecast
   - Many New Orleans neighborhoods being located several feet below sea level
   - Evacuation orders were issued
   - Superdome was a shelter for residents who was not able to evacuate
   - Levees breaches occurred a few hours after Katrina made landfall was attributed to design flaws

c) Superstorm Sandy [2012]
   - Hit as an extratropical storm (with cold fronts and asymmetric structure)
   - Took an unusual path
   - Hit at high tide
   - Forecast was good (European center is better than NWS)
   - Did significant damage to New York City

d) Harvey, Irma, Maria [2017]
   Hurricane Harvey: TX, Heavy rainfall and flooding
   Hurricane Irma: FL, Strongest storm ever in the open Atlantic Ocean
   Hurricane Mari: Puerto Rico; biggest black-out in US history, Slow deliveries & installations of blue roofs …

e) Cyclone Nargis [2008]: Myanmar; the deadliest storm after 2000

Miscellaneous

Satellite Imagery

Visible images	IR images
The visible images display the earth very similar to how humans see it with their eyes or how typical cameras view it.	Infrared satellites are measuring the temperature of the clouds. The higher the cloud tops are, the colder they will be. They can display multi-colors to highlight temperatures.
Not useful at night Cannot loop images for long periods.	Images available night and day.
On visible satellites, clouds are thicker when they looks brighter. In a visible image, you may see cloud texture, Space is black in visible image	Low clouds (warmer) are darker, high clouds (colder) are brighter. IR image has lower resolution than visible image. Space is white (cold) in IR .