Session No. 10

Course Title: Hazard Mapping and Modeling

Session 10: Hurricane Storm Surge Modeling and Analysis

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Time: 3 hrs

Objectives:

10.1 Define the characteristics of a hurricane and the hazards associated with a hurricane storm surge.

10.2 Explain the Saffir-Simpson Hurricane Scale

10.3 Clarify the uses, capabilities, limitations and outputs of the SLOSH Storm Surge Modeling Program

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Scope:

This session provides an introduction to the characteristics of hurricanes and the hazards associated with hurricane storm surge. Modeling hurricane storm surge using the National Weather Service (NWS) SLOSH (Sea, Lake, and Overland Surges from Hurricanes) model will be examined to identify the type of information needed to characterize the nature and impacts of hurricane storm surge. The limitations of hurricane storm surge modeling will be discussed and how to read output maps and displays from the SLOSH. Finally, the session will examine the purpose and limitations for the NWS SLOSH hurricane storm surge software and how it is used for planning and emergency response operations.

Readings:

Student Reading:

FEMA (1997). Multi-Hazard Identification and Risk Assessment. Part I, Tropical Cyclones pp. 9 – 25.

Natural Disaster Survey Report Hurricane Andrew September 23 - 26, 1992 (1993). U.S. Department of Commerce, NOAA. Silver Spring, MD.

Natural Disaster Survey Report Hurricane Iniki September 6 – 13, 1992 (1993). U.S. Department of Commerce, NOAA. Silver Spring, MD.

Natural Disaster Survey Report Hurricane Hugo, September 10 – 22, 1989 (1990). U.S. Department of Commerce, NOAA. Silver Spring, MD.

Natural Disaster Survey Report Hurricane Marilyn, September 15 – 16, 1995 (1996). U.S. Department of Commerce, NOAA. Silver Spring, MD.

Service Assessment. Hurricane Bertha July 5 – 14, 1996 (1997). U.S. Department of Commerce, NOAA, Silver Spring, MD.

Service Assessment. Hurricane Fran August 28 – September 8, 1996 (1997). U.S. Department of Commerce, NOAA, Silver Spring, MD.

SLOSH Display Training (2003). “Introduction,” Pages 4 – 19 and “SLOSH Display Program pp. 29 – 43. FEMA, RUS and the U.

Instructor Reading:

FEMA (1997). Multi-Hazard Identification and Risk Assessment. Part I, Tropical Cyclones pp. 9 – 25.

Natural Disaster Survey Report Hurricane Andrew September 23 - 26, 1992 (1993). U.S. Department of Commerce, NOAA. Silver Spring, MD.

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Natural Disaster Survey Report Hurricane Hugo, September 10 – 22, 1989 (1990). U.S. Department of Commerce, NOAA. Silver Spring, MD.

Natural Disaster Survey Report Hurricane Marilyn, September 15 – 16, 1995 (1996). U.S. Department of Commerce, NOAA. Silver Spring, MD.

Service Assessment. Hurricane Bertha July 5 – 14, 1996 (1997). U.S. Department of Commerce, NOAA, Silver Spring, MD.

Service Assessment. Hurricane Fran August 28 – September 8, 1996 (1997). U.S. Department of Commerce, NOAA, Silver Spring, MD.

SLOSH Display Training (2003). “Introduction,” Pages 4 – 19 and “SLOSH Display Program pp. 29 – 43. FEMA, RUS and the U.S. Army Corps of Engineers.

Organization of American States (1991). Primer on Natural Hazard Management in Integrated Regional Development Planning. Washington, D.C. 1991

General Requirements:

Power point slides are provided for the instructor's use, if so desired.

Natural Disaster Survey Reports from several hurricane storms that impacted the United States are provided as readings as a part of this class. The reports are pincluded as a basis for student group and class discussion throughout the session. Questions within each of the following objectives provide the students a basis for examining the characteristics of hurricane hazards, how each storm is unique, and how the characteristics of the storm and geographic conditions influence hazard modeling. The session thus involves students in specific hurricane storms and provides a context for understanding how storm dynamics and varying coastal areas impact model outputs.

Objective 10.1 – Define the characteristics of a hurricane and the hazards associated with a hurricane storm surge.

Requirements:

Six hurricane Natural Disaster Survey Reports prepared by the National Oceanic and Atmospheric Administration (NOAA) are provided for students in the class. Assign all the students to read the Hurricane Andrew Report for general class discussion. Assign students to a discussion group (4 to 6 members each); assign each of the groups one of the remaining hurricane reports. Group discussion questions are provided as Appendix A of this module. Each group should read the assigned hurricane report and prepare their individual responses prior to the class. The instructor may either ask students to discuss the questions prior to class or at a time during the class as noted in the remarks below. Students should be prepared to provide a summary of their discussion during the class session.

Remarks:

I. The Hurricane Environment

A. A **hurricane** is a **tropical cyclone** which occurs in the Northern Hemisphere originating over warm tropical waters with sustained winds of at least 74 mph (64 knots) or greater for a duration of six to eight hours (PowerPoint 1 Slide 2).
B. Areas in the United States vulnerable to hurricanes include the Atlantic and Gulf coasts from Texas to Maine, the territories in the Caribbean, and tropical areas of the western Pacific, including Hawaii, Guam, American Samoa, and Saipan (PowerPoint Slide 3).

C. Tropical cyclone hazard impacts

1. Strong Winds which cause most of the structural damage
2. Heavy rainfall creates flooding
3. Storm surge causes most deaths and much salt contamination of agricultural land (PowerPoint Slide 4) (Smith 2001, p. 218).

D. Some of the most powerful storms (intense) **Category IV or V Hurricanes** include

Question: What areas of the eastern U.S. have been impacted by hurricane hazards?

1. Category V Hurricanes Hitting the US States this Century

a. Hurricane Camille 1969 - Mississippi and Louisiana

b. Hurricane Andrew, August 1992
1) Florida and Louisiana; approximately $27.0 billion damage; 58 deaths.
2) FEMA Costs from President's Disaster Relief Fund: $1.844 billion

c. Unnamed Hurricane, 1935 - Florida Keys

2. Category IV Hurricanes Have Hit US States this Century

a. Hurricane Iniki. September 1992
1) Hawaiian island of Kauai; about $1.8 billion damage; 7 deaths.
2) FEMA Costs from President's Disaster Relief Fund: $259.7 million

b. Hurricane Hugo. September 1989
1) South and North Carolina after hitting Puerto Rico and the U.S. Virgin Islands; more than $9.0 billion damage (about $7.1 billion in Carolinas); 86 deaths (57--U.S. mainland, 29--U.S. Islands).
2) FEMA Costs from President's Disaster Relief Fund: $1.334 billion

c. Hurricane Carla. 1961 - Texas

d. Hurricane Donna. 1960 - West Coast of Florida

e. Hurricane Hazel. 1954 - North Carolina/Virginia

f. Hurricane Audrey. 1957 - Louisiana

g. Unnamed Hurricanes
1) 1947 - Texas/Southwest Louisiana, • 1932 - East Texas, • 1926 - South Florida, • 1919 - Florida Keys
2) 1919- Texas, • 1915 – Texas, • 1915 - Southeast Louisiana, • 1905 - Southeast Louisiana

C. **Atlantic Hurricane Season:** The portion of the year having a relatively high incidence of hurricanes. The hurricane season in the Atlantic, Caribbean, and Gulf of Mexico runs from June 1 to November 30 (PowerPoint Slide 5).

D. The hurricane season in the Eastern Pacific basin runs from May 15 to November 30.

E. The hurricane season in the Central Pacific basin runs from June 1 to November 30.August and September are peak months during the hurricane season that lasts from June 1 through November 30.

F. Over other parts of the world, such as the western Pacific, hurricanes can occur year-round.

G. Development of a **hurricane / tropical cyclone**:

1. Tropical cyclones depend for their existence on heat and moisture and thus always form over warm oceans with sea surface temperatures of at least 26 degrees Celcia (PowerPoint 2 Slide 6). They do not form in the eastern South Pacific Ocean since the sea surface temperature is always too low. Neither do they occur in the South Atlantic because of low temperatures and unfavorable upper winds (Smith 2001, p. 214 - 216).

2. When developing, a cyclone typically consists of a **warm front** pushing northward and a **cold front** pushing southward with the center of low pressure (cyclone center) located at the junction of the two fronts.

a. A **warm front** is the leading edge of an advancing warm air mass that is replacing a retreating relatively colder air mass. Generally, with the passage of a warm front, the temperature and humidity increase, the **pressure** rises, and although the wind shifts (usually from the southwest to the northwest in the Northern Hemisphere), it is not as pronounced as with a cold frontal passage.

1) Precipitation, in the form of rain, snow, or drizzle, is generally found ahead of the surface front, as well as **convective** showers and thunderstorms. Fog is common in the cold air ahead of the front.

b) A **cold front** is the leading edge of an advancing cold air mass that is **under-running** and displacing the warmer air in its path. Generally, with the passage of a cold front, the temperature and humidity decrease, the pressure rises, and the wind shifts (usually from the southwest to the northwest in the Northern Hemisphere).

1) Precipitation is generally at and/or behind the front.

2) With a fast-moving system, a squall line may develop ahead of the front.

c) Cyclones in the Northern Hemisphere rotate counter-clockwise while Southern Hemisphere cyclones rotate clockwise.

3. Once established, cyclones have efficient thermodynamics mechanisms for maintaining themselves. A ring-like wall of towering clouds rises (from 10 to 12 km.). Most of the rising air flows outward near the top of the center of the storm. The center section of the storm acts as the main exhaust area for the storm (Smith p. 216.)

4. The release of rain and latent heat encourages even more air to rise and violent spiraling produces storm winds and heavy rain. Air sinks towards the center to be compressed and warmed in the "eye" of the storm. This warm core maintains the storm system because it exerts less surface pressure, thus maintaining the low-pressure heart of the storm.

II. Tropical cyclones are classified as follows:

A. Tropical Depression - An organized system of clouds and thunderstorms with a defined circulation and maximum sustained winds of 38 mph (33 knots) or less. In meteorology, a depression is another name for an area of low pressure, a low, or trough. It also applies to a stage of tropical cyclone development and is known as a tropical depression.

B. Tropical Storm - An organized system of strong thunderstorms with a defined circulation and maximum sustained winds of 39 to 73 mph (34-63 knots) (PowerPoint 1 Slide 7).

1. A Squall is a sudden increase of wind speed by at least 18 miles per hour (16 knots) and rising to 25 miles per hour (22 knots) or more and lasting for at least one minute.

2. Thunderstorms are local storm produced by a cumulonimbus cloud, always with lightning and thunder, and usually accompanied by strong gusts of wind, heavy rain, and sometimes hail. Thunder is the sound that follows a flash of lightning and is caused by sudden expansion of the air in the path of the electrical discharge.

C. Hurricane - An intense tropical weather system with a well-defined circulation and maximum sustained winds of 74 mph (64 knots) or higher. Hurricanes are called "typhoons" in the western Pacific, while similar storms in the Indian Ocean are called "cyclones." As a hurricane nears land, it can bring torrential rains, high winds, and storm surges.

1. Tornados may be associated with hurricanes. Tornados have a violently rotating column of air in contact with and extending between a convective cloud and the surface of the earth.

2. Tornadoes are the most destructive of all storm-scale atmospheric phenomena. They can occur anywhere in the world given the right conditions, especially after the landfall of hurricanes.

D. Natural phenomena, which affect a hurricane include (PowerPoint 1 Slide 8). :

1. temperature of the water,
2. the Gulf Stream, and

3. steering wind currents.

a. An example would include trade winds. Trade winds are the wind system, occupying most of the tropics, which are northeasterly in the Northern Hemisphere and southeasterly in the Southern Hemisphere. An **anemometer** is an instrument that measures the speed or force of the wind.

E. Hurricane **Storm Dynamics** (PowerPoint 1 Slide 9)

1. **Hurricane winds** blow in a large spiral around a relatively calm center of extremely low pressure. They form over water and draw their energy from the **warm surface water of the tropics** (usually above 27 Celsius) and latent heat of condensation, which explains why hurricanes dissipate rapidly once they move over cold water or large land-masses. The hurricane itself may be from 60 to more than 1,200 miles in diameter.

Question: Describe the characteristics of Hurricane Andrew (peak winds, path, approximate size of the storm, and approximate size of the landfall area directly impacted by the storm, and geographic area impacted. (See Rappaport, Ed (1993). *Hurricane Andrew: August 16 – 28, 1992.* Preliminary Report. National Hurricane Center and Natural Disaster Survey Report Hurricane Andrew September 23 - 26, 1992 (1993). U.S. Department of Commerce, NOAA. Silver Spring, MD.)

Question: How does Hurricane Andrew differ from Hurricanes Bertha, Fran, Hugo, Iniki, and Marilyn?

2. Hurricanes generally travel in a west-northwest direction but are known for their unpredictable patterns and numerous changes of direction. Hurricane winds in the Northern Hemisphere circulate in a counterclockwise motion around the hurricane's center or "eye," while hurricane winds in the Southern Hemisphere circulate clockwise. Hurricanes that impact the southeastern United States and the Caribbean Sea typically form over the mid-Atlantic, the southern Caribbean Sea, or the Gulf of Mexico.

3. Viewed from above, hurricanes resemble huge doughnuts, with a circle of high winds and clouds and a quiet, relatively calm cloudless center or the "**eye**". This doughnut shape can have a deceptively dangerous effect. After a hurricane roars ashore, it appears to have passed as the initial heavy winds and rain moves on and the quiet, clear eye area passes overhead. However, within an hour or so, the **eye of the hurricane** has passed and the strong winds and rains from the opposite side of the storm suddenly hit (PowerPoint 1 Slide 10).

4. Around the core of the hurricane, winds grow with great velocity, generating violent seas. Moving ashore, they sweep the ocean inward while spawning tornadoes and producing torrential rains and floods.

5. The most violent activity takes place in the area immediately around the eye, called the **eyewall**. It contains cumulonimbus clouds, severest thunderstorms, heaviest precipitation and strongest winds. Winds may gust to more than 200 miles per hour. At the top of the eyewall (about 50,000 feet), most of the air is propelled outward, increasing the air's

upward motion. Some of the air, however, moves inward and sinks into the eye, creating a cloud-free area.

F. Size, Intensity and Path of a hurricane

1. Satellite sensing now allows a tropical cyclone to be located with an average accuracy of about 100 km, although intense storms with well-developed “eyes” can often be detected to within 30-50 km. When a cyclone has moved within some 250 km of the coast, weather radar permits a more accurate fix on the position, usually to within 10 km (Crane, 1988). The National Hurricane Center in Miami maintains continuous real-time monitoring of such storms, often by flying specially equipped aircraft through the system, in order to forecast the subsequent path and ultimate landfall (PowerPoint 1 Slide 11) (Smith 2001 p 232).

2. Landfall is the term used to describe where the hurricane eye actually passes over land, usually used to describe the continental States rather than islands in the Caribbean (PowerPoint 1Slide 12).

4. Some hurricanes begin to weaken as they approach landfall, but others actually have intensified, depending on atmospheric conditions affecting the storm system. In both cases, once the hurricane passes over land it will begin to lose strength as it is separated from its energy source and friction with the passage over land drains energy from it.

5. Major hurricanes can maintain tremendous strength well inland if other atmospheric conditions remain favorable. The distance inland that a hurricane maintains major status is directly related to its forward speed; faster forward speeds increase the damage potential further inland. Forward speed is the rate of movement (propagation) of the hurricane eye in miles per hour or knots

6. A single hurricane can last for more than 2 weeks over open waters and can run a path across the entire length of the eastern seaboard.

7. Often the worst damage occurs on the coastline where the storm makes landfall. This is because the storm is still relatively strong from its energy source and especially due to the presence of storm surge.

III. Hurricane Storm Surge Hazard

A. Storm surge is an abnormal rise in sea level accompanying a hurricane or other intense storm. The storm surge height is the difference between the observed level of the sea surface and the level that would have occurred in the absence of the cyclone. It is simply water that is pushed toward the shore by the force of the hurricane winds swirling around the storm (PowerPoint 10-2 Slide1).

B. Storm surge is usually estimated by subtracting the normal or astronomic high tide from the observed storm tide. Waves on top of the storm surge will create an even greater high-water mark.

Note that the discussion of the Satir Simpson Scale in this module includes categories of storm with their surge heights for each category of storm.

C. This surge results when a hurricane moves over the continental shelf and produces a buildup of water at the coastline. This advancing surge combines with the normal tides to create the **hurricane storm tide**, which can increase the mean water level 15 feet or more (PowerPoint 10-2 Slide2).

1. This means that if the storm comes ashore during astronomical low tide, the surge will be decreased by the amount of the low tide. Likewise, if the storm makes landfall during astronomical high tide, the surge will be that much higher.

Question: What were the surge heights in Florida and Louisiana from Hurricane Andrew? (See Rappaport, Ed (1993). *Hurricane Andrew: August 16 – 28, 1992.* Preliminary Report. National Hurricane Center and Natural Disaster Survey Report Hurricane Andrew September 23 - 26, 1992 (1993). U.S. Department of Commerce, NOAA. Silver Spring, MD.) How do the surge heights compare with those in Hurricanes Bertha, Fran, Hugo, Iniki, and Marilyn?

2. Examples of **surge height** associated with powerful hurricanes

a. Hurricane Camille produced a 25-foot storm surge in Mississippi. – *Number of fatalities?? And associated number to storm surge.*

b. Hurricane Hugo in 1989 generated a 20-foot storm tide in South Carolina.

3. Example of **fatalities** from powerful hurricanes:

a. Over 6000 people were killed in the Galveston Hurricane of 1900, most by storm surge.

D. Wind driven waves superimposed on the storm tide can cause severe flooding in coastal areas, particularly when the storm tide coincides with the normal high tides. Because much of the United States' densely populated Atlantic and Gulf Coast coastlines lie less than 10 feet above mean sea level, the danger from storm tides is tremendous.

E. The surge may extend from **50 to 100 miles wide**. It sweeps across the coastline near where a hurricane makes landfall. Storm surge can range from 4 to 6 feet for a minimal hurricane to greater than 20 feet for the stronger ones. (See the size of storm surge associated with each type of hurricane later in this module in the next learning outcome).

F. The surge of high water topped by waves is devastating to the natural and built environment. The stronger the hurricane and the shallower the offshore water, the higher the surge will be. Along the immediate coast, storm surge is a great threat to life and property.

G. The maximum storm surge usually occurs **10 to 20 miles to the right of the storm track**.

However, maximum surge may occur to the left of the storm if the winds pile water up against an obstruction, such as the landside of a coastal barrier island.

H. For a hurricane, the surge typically has a duration of several hours. Storm surges can come ashore up to five hours before the storm and destroy low-elevation coastal areas. It is especially damaging when the storm surge occurs during high tide and consequently is often responsible for most hurricane-related deaths. Examples of storm damage (PowerPoint 10-2 Slide3) include:

1. Washed out bridges, roads, and buildings;
2. Destruction of wetlands, beach erosion and salt water intrusion into fresh water lakes;
3. In estuaries and bayous, intrusions of salt water endanger the public health and send animals, such as snakes, to flee from flooded areas and take refuge in urban areas.
breakup of power and phone lines.

J. Whether a hurricane is approaching or exiting land can have a significant impact on the surge characteristics of the storm (PowerPoint 10-2 Slide 4).

1. A landfalling hurricane generally will have more time and space across water to "push" a large volume of water in front of it.
2. A paralleling hurricane (one moving up or down the coast) may or may not have the general high surge levels depending on the angle of approach and the location.
3. An exiting hurricane will generally surge on its weak side and only has a relatively short distance to build up surge.
4. Of the three scenarios, the landfalling hurricane will have the greatest storm surge potential, all other factors being equal.

K. The elevation of the storm surge within a coastal basin depends upon: the meteorological parameters of the hurricane and the physical characteristics existing within the basin.

1. The meteorological parameters affecting the amount of storm surge generated include (PowerPoint 10-2 Slide5):

a. The intensity of the hurricane measured by the central barometric pressure and maximum surface winds at the center of the storm. Storm surge begins to build while the hurricane is still far out at sea over deep water. The low pressure near the center of the storm causes the water to rise. In deep water, a counter current develops well below the surface, which counters an attempt by the wind to build up surges.

b. Atmospheric Pressure is exerted by the atmosphere at a given point. Its measurement can be expressed in several ways. One is in millibars. Another is in inches or millimeters of mercury (Hg). Also known as barometric pressure.

c. Path or forward track of the storm,

d. Forward speed, and

e. Radius of maximum winds (storm size). The radius of maximum winds is measured from the center of the hurricane to the location of the highest wind speeds within the storm. This distance can vary from as little as 4 miles to as much a 50 miles. Due to the counter-clockwise rotation of the wind field, the highest surge levels are generally located at the right of the forward track of the hurricane (PowerPoint 10-2 Slide 6).

Question: What were the meteorological parameters of Hurricane Andrew as it hit south Florida and Louisiana?

2. The physical characteristics of a basin also influence potential surge heights. These factors include:

a. The level of surge in a particular area is greatly influenced by the slope of the continental shelf or the basin bathymetry. A shallow slope off the coast shown in the Figure below will allow a greater surge to inundate coastal communities.

1) Communities with a steeper continental shelf will not see as much surge inundation, although large breaking waves can still present major problems (PowerPoint 10-3 Slide1).
2) As the water depth decreases closer to the shore, the excess water that is built up by the central pressure of the storm is not able to dissipate. The increased water has no place to go except up onto the shore. The force of winds swirling around the storm pushes the water toward the shore and creates storm surge.
3)The surface current induces currents in subsurface water. This process of current creation continues to a depth that is determined by the depth of the water and by the intensity and forward motion of the hurricane. For example, a fast moving hurricane of moderate intensity may only induce currents to a depth of a hundred feet, whereas a slow moving hurricane of moderate intensity might induce currents to several hundred feet.
4) Waves are directly affected by water depth and will break and dissipate their energy in shallow water. A steep continental shelf will allow large ocean waves to approach the coastline before breaking thus increasing wave setup. This phenomenon is primarily a concern near the coastline because large wave are generally not transmitted inland.
5) Horizontal currents also are impeded by a sloping continental-shelf as the sloping continental shelf is particularly conducive to the formation of large storm surges. The amount of rise increases shoreward to a maximum level at, or some distance inland from the shoreline.
6) Waves and swells breaking at or near the coast also transport water shoreward. During storms when there is an increase in wave height and wave steepness, water cannot flow back to the sea as rapidly as it is brought shoreward. This results in a phenomenon known as "wave setup" and causes a further increase of water level along the coastline.

b. **Roughness** of the continental shelf,

c. **Configuration** of the coastline, and

d. The existence of significant **natural or man made barriers.**

e. In addition to the physical characteristics of the basin, another factor which affects the storm surge heights is the initial water level within the basin at the time of arrival of a hurricane. The water level could be either a normal high or low tide. The tide level when a hurricane

IV. Storm Surge-Structure Interaction

A. As a hurricane moves across the open ocean, the storm accumulates vast amounts of energy. As the storm makes landfall and moves inland, the **energy is dissipated as the storm interacts with the land features.**

1. The **winds** associated with a hurricane are the largest single component responsible for the buildup of storm surge within a basin. The wind blowing over the surface of the water exerts a horizontal force that induces a surface current in the general direction of the wind.

2. In general, the more intense the storm, and the closer a community is to the **right-front quadrant**, the greater the risk to the community. A larger area must be evacuated when the community lies in this high-risk area.

B. When a building becomes a barrier to the free movement of the wind or water, forces will be transmitted **from the wind or water to the building.** A building designed and constructed to be hurricane resistant must be designed to withstand these forces.

C. Water will interact with a building in three ways:

1. Storm surge will interact with a building similar to a river flood (PowerPoint 10-3 Slide2).

a. It may cause the building **to float off its foundation.** As the water strikes the building, it tends to lift the pilings or produce upward forces on the first floor of a building.

b. **Floating debris** to collide against the building.

c. If the building is left intact, **surge water** entering the building may destroy or damage the contents, walls, flooring, insulation, wiring, etc.

2. Waves and surge forces on the building are primarily the momentum of water **striking the building** and the **drag force** in the direction of the water flow.

a. Although surge typically has forward motion, the **force of the wave** is much more destructive because the velocity of the wave may be several times faster than the surge.

b. The energy from one 5½ foot wave breaking (at 10 mph) along 40 miles of beach is equivalent to the maximum power generated at Hoover Dam. Thus the amount of **kinetic energy** released by even a modest wave breaking is tremendous.

c. Because of these potential forces, most codes and standards require all **structures to be elevated** above the wave crest elevation.

d. Elevation above the wave crest eliminates all **lateral water loads** against the building itself, leaving the loads to pilings for design considerations.

e. The pilings must be **designed to resist the impact forces** of the waves and the drag forces of the water in the direction of the water's velocity.

f. Wave and current action associated with the tide also causes extensive damage. Water weighs approximately 1,700 pounds per cubic yard; extended pounding by frequent waves can demolish any structure not specifically designed to withstand such forces.

g. The currents created by the tide combine with the action of the waves to severely **erode beaches and coastal highways**. Many buildings withstand hurricane force winds until their foundations, undermined by erosion, are weakened and fail.

3. **Scour** is the erosion of sand and soils caused by wave action that may penetrate landward tens to hundreds of yards in the course of a storm (PowerPoint 10-3 Slide3).

a. Houses or buildings in the **scour zone** (typically in the first row or tier from the shoreline) often have several feet of supporting soils removed from around their pilings.

b. On low-lying, sandy coastal barriers, **scour depths** of four to six feet are common, sometimes leaving well-delineated scarps, causing sand buildups from over-wash several hundred yards landward.

c. **Grade platforms** in the scour zone typically are undercut. They then often collapse because of inadequate reinforcement and the uplift forces of the waves under them.

d. While scour generally will not erode below sea level when it confronts no steep or vertical obstructions, it may undermine protective seawalls or bulkheads, eroding well below sea level. Waves striking the Holiday Inn at Gulf Shores, Alabama during Hurricane Frederic scoured a hole about 20 feet deep on the vertical face of the inn's Gulf-front.

e. Almost all of the houses that collapsed on the Gulf shoreline on the west end of Galveston Island during Hurricane Alicia collapsed due to scour and inadequate piling penetration into supporting soils.

f. Piling penetration ranged from three feet nine inches to six feet below the pre-storm ground surface in areas that experienced six feet of scour. The buildings had to collapse, they could not resist the uplift and horizontal forces of the storm once the supporting soil was scoured away.

V. Storm Uncertainty and anticipating stronger storms

A. Hurricanes present two problems to the emergency management community. First there is always the uncertainty about how intense the storm will be when it finally makes landfall. Emergency managers and local officials balance that uncertainty with the human and economic risks to their community. This is why a rule of thumb for emergency managers is to plan for a storm one category higher than what is forecast. This is a reasonable precaution to help minimize the loss of life from hurricanes (PowerPoint 10-3 Slide 4).

B. The second uncertainty is associated with the hurricane storm tract. The path and direction of the storm can change at any point making the actual area impacted by the storm as it makes landfall difficult to predict. A review of past hurricanes illustrates the difficulty in precisely predicting the actual impact area for the landfall of the storm and its intensity.

Objective 10.2 - **Explain the Saffir-Simpson Hurricane Scale**

Requirements:

Students will be asked to apply the Saffir-Simpson Scale to Hurrican Andrew and Hurricanes Bertha, Fran, Hugo, Iniki, and Marilyn.

Remarks

I. The Saffir-Simpson Damage Potential Scale (PowerPoint 10-4 Slide1) provides a means of quantifying the potential storm surge generated by a hurricane. It was developed in the early 1970s by Herbert Saffir a consulting engineer, and Robert Simpson, then Director of the National Hurricane Center, to measure the intensity of a hurricane.

> A. It is a descriptive scale that categorizes a storm and its potential damage based on a storm's barometric pressure, wind speeds, and storm surge. The scale provides a range of wind speeds and normal surge heights associated with each of the five categories of hurricanes.
>
> B. Scale numbers are available to public safety officials when a hurricane is within 72 hours of landfall.
>
> C. Scale assessments are revised regularly as new observations are made.
>
> D. The Saffir Simpsn Hurricane Scale was intended for use as a general guide by public safety officials during hurricane emergencies. It does not reflect the effects of varying localized bathymetry, coastline configuration, barriers, or other factors that could influence the surge heights that occur at differing locations during a single hurricane event.
>
> E. Public safety organizations are kept informed of new estimates of the hurricane's disaster potential. In practice, sustained surface wind speed (1-minute average) is the parameter that determines the category since storm surge is strongly dependent on the slope of the continental shelf (National Hurricane Center).

II. Hurricane Watches and Warnings

A hurricane watch is issued when there is a threat of hurricane conditions within 24-36 hours. A hurricane warning is issued when hurricane conditions (winds of 74 miles per hour or greater, or dangerously high water and rough seas) are expected in 24 hours or less.

Question: Using the Saffir-Simpson Damage Potential Scale identify and justify the classification of Hurricane Andrew. Identify and justify the classification of the hurricane for each of the hurricanes assigned to the groups in the class.

Category	Definition	Effects
One	Winds 74-95 mph	No real damage to building structures. Damage primarily to unanchored mobile homes, shrubbery, and trees. Also, some coastal road flooding and minor pier damage – Surge 1.2 to 1.6 meters.
Two	Winds 96-110 mph	Some roofing material, door, and window damage to buildings. Considerable damage to vegetation, mobile homes, and piers. Coastal and low-lying escape routes flood 2-4 hours before arrival of center. Small craft in unprotected anchorages break moorings – Surge: 1.7 – 2.5 meters.
Three	Winds 111-130 mph	Some structural damage to small residences and utility buildings with a minor amount of curtainwall failures. Mobile homes are destroyed. Flooding near the coast destroys smaller structures with larger structures damaged by floating debris. Terrain continuously lower than 5 feet ASL may be flooded inland 8 miles or more – Surge: 2.6 – 3.8 meters.
Four	Winds 131-155 mph	More extensive curtainwall failures with some complete roof structure failure on small residences. Major erosion of beach. Major damage to lower floors of structures near the shore. Terrain continuously lower than 10 feet ASL may be flooded requiring massive evacuation of residential areas inland as far as 6 miles – surge 3.9 – 5.5 meters.
Five	Winds greater than 155 mph	Complete roof failure on many residences and industrial buildings. Some complete building failures with small utility buildings blown over or away. Major damage to lower floors of all structures located less than 15 feet ASL and within 500 yards of the shoreline. Massive evacuation of residential areas on low ground within 5 to 10 miles of the shoreline may be required – Surge: > 5.5 meters. All surge estimates are provided by Oliver 1981.

Figure #1: Saffir-Simpson Damage Potential Scale

Objective 10.3. Clarify the uses, capabilities, limitations and outputs of the SLOSH Hurricane Storm Surge Model

Requirements:

A PowerPoint presentation is provided for the discussion of the SLOSH Storm Surge Model.

A copy of the SLOSH Display Training Manual along with a program to display SLOSH Model outputs from U.S. applications of the model. The SLOSH Model display program is provided as an option for use in the class.

Remarks:

I. The **National Hurricane Center** (NHC) in Miami, Florida (National Weather Service) tracks tropical cyclones from the tropical depression stage through the hurricane stage over the North Atlantic Ocean, Caribbean Sea, Gulf of Mexico and Eastern Pacific Ocean. NHC forecasts the future position and intensity of the cyclones using mathematical computer models.

Question: What is the mission of the National Hurricane Center? How does the SLOSH Model fit within the NHC's responsibilities and organizational mission?

The NHC's mission is to save lives, mitigate property loss, and improve economic efficiency by issuing the best watches, warnings, forecasts and analyses of hazardous tropical weather, and by increasing understanding of these hazards. The TPC vision is to be America's calm, clear and trusted voice in the eye of the storm and, with its partners, enable communities to be safe from tropical weather threats. Modeling of hurricanes is critical in supporting federal, state and local efforts for the development of emergency response plans to hurricanes and in emergency operations to a specific storm.

The NHC collaborates with universities, government research laboratories, international tropical weather centers, the private sector and other National Weather Service components to maintain its leading edge in tropical meteorology through coordinated operations, research, training and forecast development techniques.

II. The **SLOSH Model** (Sea, Lake, and Overland Surges from Hurricanes) is one of the sophisticated mathematical models used by NHC to calculate potential surge heights from hurricanes for storm surge warnings and hurricane evacuation studies all over the eastern seaboard of the U.S. A major application of the SLOSH model is to support NWS hurricane warnings and regional evacuation plans. SLOSH was developed by Chester P. Jelesnianski and Jye Chen of the National Weather Service in 1978.

A. The SLOSH model is used to represent a tropical cyclone and its environment and to forecast the future motion and intensity of a cyclone. NHC forecasters interpret model results to arrive at a final track and intensity forecast, distributing it to the public in the form of advisories (PowerPoint 10-4-Slide2).

1. The SLOSH model **simulates inland flooding** from storm surge and permits the overtopping of barriers and flow through barrier gaps. The results from a SLOSH flooding and hazards analysis can help estimate the extent and timing of an evacuation (PowerPoint 10-4-Slide3) (Allenstein 1985).

2. SLOSH analysis can help the decision-maker in a crisis situation answer the following questions (PowerPoint 10-4-Slide 4) (Allenstein 1985):

a. What is the nature of the approaching natural threat?

b. Who is at risk and to what extent?

c. Where should these people go for safety?

d. How much time is there to evacuate?

B. The model output contains information concerning the range of expected peak surge heights within the hurricane warning area and this surge information is based on SLOSH calculations when available (Jarvinen 1985; Mercado 1994).

C. SLOSH is not a prediction model in the strict sense that prediction models step forward in time from a set of initial conditions (Allenstein 1985). Rather, SLOSH requires that the time varying hurricane forces be externally provided to the model as boundary conditions (PowerPoint 10-4-Slide2).

1. These boundary conditions are provided through a separate atmospheric model which transforms input data concerning (PowerPoint 10-4-Slide 5)

a. hurricane track,

b. central sea level pressure, and

c. radius of maximum wind into a distribution of sea surface wind stress and pressure forces.

2. These factors are converted into a time dependent, horizontal distribution of wind stress and pressure forces. When combined with other input data, these forces generate the abnormal storm surge water levels.

D. The mathematical models used at NHC are of three basic types: Statistical, Dynamical or Combination (Statistical and Dynamical together) (PowerPoint 10-4-Slide 6).

1. Statistical models forecast the future by using current information about the hurricane and comparing it to historical knowledge about the behavior of similar tropical cyclones. The historical record for storms over the north Atlantic begins in 1871, while the record for storms for the east Pacific extends back to 1945. Statistical models rely on what has happened such as the climatology of past storms.

2. Dynamical models work differently. They are designed to use the results of global atmospheric model forecasts in different ways to forecast tropical cyclone motion and intensity. Global models take current wind, temperature, pressure and humidity observations and make forecasts of the actual atmosphere in which the cyclone exists. Dynamical models can be classified as either barotropic or baroclinic.

3. Statistical-dynamical models are an intermediate class that incorporate numerically forecast data into a statistical prediction framework, similar to the Model Output Statistics

used to provide guidance for specific parameters such as temperature and probability of precipitation. Because of their mathematical simplicity, dynamical models ignore the behavior of historical storms. **Combination models** using both dynamical and statistical approaches are used to capitalize on the strengths of each. Because of their simplicity, statistical models were designed first for tropical cyclone forecasting in the late 1960's. In the early seventies, combination models were developed as global models began making forecasts in tropical regions. As computers became more powerful, global models improved and pure dynamic models are beginning to dominate the accuracy race.

IV. Uses of SLOSH

A. SLOSH (is a two dimensional model that) was developed for **real time forecasting** of surges from actual hurricanes within selected Gulf and Atlantic coastal basins and for evacuation planning (PowerPoint 10-4-Slide 7).

1. It furnishes **surge heights for open coast**, and has the added capability to compute the **routing of storm surge into bays, estuaries, or coastal river basins** as well as calculating surge heights for over land locations.

2. Significant natural and man-made barriers are represented in the model and their effects simulated in the calculations of surge heights within a basin.

B. SLOSH is used to define flood-prone areas for **evacuation planning.** It is a tool in preparing an evacuation plan for coastal communities to the threat of a hurricane landfall. Regional evacuation studies utilize SLOSH.

1. The flood areas are determined by compositing peak model surge values using input parameters from 200 to 300 hypothetical hurricanes. Separate composite flood maps are produced for up to five levels of hurricane intensity.

2. SLOSH is able to estimate the overland tidal surge heights and winds that result from **hypothetical hurricanes** with selected storm characteristics including pressure, size, forward speed, track and winds. The resultant **tidal surge** is then applied to a **specific locale's shoreline**, incorporating the unique bay and river configurations, water depths, bridges, roads and other physical features (Jelesnianski and Taylor 1973).

C. SLOHS model is also designed for use in an **operational mode**; that is, for forecast / hind-cast runs without controlled, local calibration, or observed winds. The rationale for this design is to avoid having the forecaster predict unavailable input data. The SLOSH model contains a storm model into which simple, time-dependent meteorological data are input and from which the driving forces of a simulated storm are calculated.

D. If a local jurisdiction has a Hurricane Evacuation Study (which combines SLOSH model results with traffic flow information), the jurisdiction does not need information about storm surge heights in a real hurricane situation. Local officials only need to know the forecast of the storm's intensity at landfall and the tide at that time to be able to make an appropriate evacuation decision (PowerPoint 10-4-Slide 8).

V. **Data requirements** for SLOSH include (PowerPoint 10-4-Slide 9).

A. **Storm positions** (Latitude and Longitude) at six-hour intervals for a 72-hour track.

B. The lowest atmospheric sea level **pressure** in the eye of the hurricane at six-hour intervals.

C. The **storm size** measured from the center to the region of maximum winds; commonly referred to as the "radius of maximum winds". Wind speed is not an input parameter since the model calculates a wind-field for the modeled storm by balancing forces according to meterological input parameters.

D. The **initial height of the water surface** well before the storm directly affects the area of interest. This initial height is the observed still water level occurring about two days before storm arrival and includes an existing anomalous rise in the water surface. Water surface elevations are referenced to the vertical datum used to specify land elevations and water depths within the model. All water surface elevations, land elevations, and water depths were referenced to NGVD.

1. **Tidal fluctuations** immediately prior to landfall have not been accounted for because a small error in predicting the phasing of storm track and astronomical tide would likely invalidate the model results. The possible effects of landfall occurring at a particular phase of the tide, such as at the time of high or low tide, are evaluated as an increment to the surge values predicted by the SLOSH model.

E. The **characteristics of a particular basin** including:

1. The **topography** of inland areas;

2. **River basins and waterways**;

3. **Bathymetry** of near shore areas, bays and large inland water bodies;

4. Significant natural and man-made **barriers** such as barrier islands, dunes, roadbeds, floodwalls, levees, etc.; and

5. A segment of the continental shelf.

VI. SLOSH Model Outputs

A. SLOSH produces a **Grid** representing a natural basin or large geographical area. The smallest grids usually represent an area of about 0.01 square miles (PowerPoint 10-5 Slide 1). This permits inclusion of topographic details such as highway and railroad embankments, causeways, levees, etc.

B. The SLOSH model provides four major types of information on the effects of the simulated hurricanes.

1. Surface envelope of the highest surges above mean sea level. The surge elevation is determined for each grid cell. The surge height is compared to the ground surface elevation which is the average of the ground surface elevations found in that grid (PowerPoint 10-5 Slide 2).
2. Time histories of surges at selected grid points (PowerPoint 10-5 Slide 3);
3. Computed wind speeds at selected grid points;
4. Computed wind directions at selected grid points.

C. In addition to the graphic display of model results, SLOSH model output for a modeled storm consists of a tabulated storm history containing hourly values of storm position, speed, direction of motion, pressure, and radius of maximum winds; a surface envelope of highest surges; and for pre-selected grid points, time-history tabulations of values for surge heights, wind speeds, and wind directions. If desired, the model can also furnish two-dimensional snapshot displays of surges at specified times during a simulation (PowerPoint 10-5 Slide 4).

D. The major output of the model is a vulnerability analysis to identify the areas, populations, and facilities which are potentially vulnerable to flooding associated with hurricanes (PowerPoint 10-5 Slide 5). The storm surge data provided by SLOSH is used:

1. To develop inundation maps;
2. To determine evacuation zones and evacuation scenarios for local areas;
3. To quantify the population at risk under a range of hurricane intensities; and
4. To identify major medical institutional and other facilities that are potentially vulnerable to storm surge.

E. Graphical output from the SLOSH model displays color-coded storm surge heights for a particular area in feet (PowerPoint 10-5 Slide 6). The SLOSH model's reference level is the National Geodetic Vertical Datum (NGVD), which is the elevation reference for most maps.

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F. The storm surge height calculations are applied to a specific locale's shoreline, incorporating the unique bay and river configurations, water depths, bridges, roads and other physical features. If the model is being used to estimate storm surge for an actual hurricane (as opposed to a hypothetical one), forecast data is put in the model every 6 hours and updated as new forecasts become available.

G. The time-history data of surge heights, wind speeds, and wind directions are tabulated for each pre-selected grid point in the model. These data are listed for each grid point at ten-minute intervals for a 72-hour segment of a simulated storm track, starting 48 hours prior to landfall and continuing for 24 hours after landfall or closest approach.

VI. Potential peak surges for a regional hurricane study

A. The objective of a hazards analysis provided by the SLOSH Model is to determine potential peak surges in a coastal area. These peak surges or the highest surge reached at all locations within an area are included in the model application. The highest surge is called the maximum envelope of water (MEOW) (PowerPoint 10-5 Slide 7).

B. The Maximum Envelopes of Water (MEOWs) are developed from many peak surges calculated for individual hurricanes that differ only in the point of landfall. Multiple storms are modeled for a study area because it is not possible to precisely forecast the ultimate landfall location, forward speed, approach direction, and other characteristics of a threatening hurricane (PowerPoint 10-5 Slide 7).

C. The displays from the MEOW's in a hurricane study do not predict the limits of inundation from a single storm, but rather delineate the areas that are threatened by storm surge from all hurricane scenarios modeled in the study.

D. The maximum surge calculations (MEOW) determined in a hurricane study along a coastline do not necessarily occur at the same time (PowerPoint 10-5 Slide 8). The time of the maximum surge for one location may differ by several hours from the maximum surge that occurs at another location. A plot of the maximum water surface elevation attained at each grid cell over the duration of the simulated storm does not represent a "snapshot" of the storm surge at a given instant of time. Instead, it represents the highest water level at each grid cell during a hurricane irrespective of the actual time of occurrence (PowerPoint 10-5 Slide 9).

E. Each MEOW represents the highest maximum surge in a study area (peak surge). The location of the peak surge depends on:

1. Where the eye of a hurricane crosses the coastline,
2. Hurricane intensity,
3. The bathymetry of the basin,
4. Configuration of the line,
5. The approach direction of the storm, and
6. The radius of maximum winds.

H. There are only 5 MOMs per basin, one per storm category.

An Example of the Application of SLOSH: In the Southeast Louisiana Hurricane Preparedness Study (Corps 1994), a total of 1,640 simulated hurricanes (164 storm tracks) were modeled using the SLOSH model. The characteristics of the simulated hurricanes were determined from an analysis of historical hurricanes which occurred within the study area. These tracks had combinations of parameters representing five categories of hurricane intensity, as described by the Saffir-Simpson Hurricane Scale; nine approaches directions for landfall (west, west-northwest, northwest, north northwest, north, north northeast, northeast, east northeast, and east), two forward speeds of 5 and 15 miles per hour; and numerous landfall or closest approach locations separated by 20 miles or less along the coastline. For the Southeast Louisiana Hurricane Evacuation study prepared by the Corps of Engineers (1994), the SLOSH Model formed the basis of the study.

VII. SLOSH Model Accuracy (PowerPoint 10-5 Slide 10)

A. The SLOSH model is generally accurate within plus or minus 20 percent. For example, if the model calculates a peak 10 foot storm surge for the event, you can expect the observed peak to range from 8 to 12 feet.

1. An analysis of hurricane forecasts made by the National Hurricane Center indicates the magnitude of error that can be expected in forecasting the track of approaching hurricanes. The average error in the official hurricane track forecast between 1970 and 1079 was 51 miles for the 12-hour forecast, 109 miles for the 24-hour forecast, 247 miles for the 48-hour forecast, and 377 miles for the 72-hour forecast (Jarvinen 1985).

2. The error range from a study reported in 1985 notes that the error range is from –2.16 meters to + 2.68 meters. The mean absolute error is 0.43 meters with a standard deviation of 0.61 meters. Seventy-nine percent of the errors are within one standard deviation of the mean error; 97 percent are within two standard deviations; and 99 percent are within three standard deviations (Jarvinen 1985).

3. Thus if a storm were forecast to make landfall due south of New Orleans in 24 hours, and if, in fact, it made landfall anywhere between Dauphin Island, Alabama and Marsh Island, Louisiana, the error in the forecast landfall position would be no worse than average.

4. There has been a small, but statistical significant, longer downward trend in the forecast errors in the Atlantic basin over the period 1970-1991. The downward trend is found not only in the 24-hour forecast, but also in the 48- and 72- hour forecasts.

B. Errors also occur in forecasting the maximum sustained wind-speed of an approaching hurricane. During the period 1970-1979, the average error in the official 24-hour wind speed forecast was 15 miles per hour (mph), and the average error in the official 24-hour wind speed forecast was 15 mph, and the average in the 12 hour forecast was 10 mph.

C. Hurricane evacuation decision makers should note that an increase in wind speed of 10 to 15 mph can easily raise the intensity category of the approaching hurricane on category on the Saffir/Simpson Hurricane Scale.

D. To account for inaccuracies in forecasting the behavior of approaching hurricanes, the National Hurricane Center recommends that public officials faced with an eminent evacuation prepare for the evacuation as if the approaching hurricane will intensify one category above the strength forecast for landfall (Mercado 1994).

E. The model accounts for astronomical tides (which can add significantly to the water height) by specifying an initial tide level, but does not include rainfall amounts, river-flow, or wind-driven waves. This information is however, combined with the model results in the final analysis of at-risk-areas (PowerPoint 10-5 Slide 11).

F. The point of a hurricane's landfall is crucial to determining which areas will be inundated by the storm surge. Where the hurricane forecast track is inaccurate, SLOSH model results will be inaccurate. The SLOSH model, therefore, is best used for defining the potential maximum surge for a location.

G. The SLOSH Model has been **calibrated and verified.**

1. After a SLOHS model has been constructed for a coastal basin, **verification experiments** are conducted (PowerPoint 10-6 Slide1). The verification experiments are performed in a “hind-cast” mode, using the real-time operational model code and storm parameters and an initial observed sea surface height occurring approximately 48 hours before the storm landfalls or affects the basin.

2. The computed surge heights are compared with those measured from historical storms and, if necessary, adjustments are made to the input or basin data. In

3. In instances where the model has given realistic results in one area of a basin, but not in another, closer examination has often revealed inaccuracies in the representation of barrier heights or missing values in bathymetric or topographic data.

4. Ideally there would be a large number of actual storm events with well documented meteorology and storm surge histories which could be compared to the storm surge histories hind-cast by the SLOSH model for the same storms (PowerPoint 10-6 Slide2).

5. In reality, hurricanes are rare for any given region, and it is even rarer to find adequate, reliable measurement of storm surge elevations over a representative number of sites within a region due to the difficulty in making such measurement during hurricane conditions.

6. The computed surge heights are compared with those measured from historic storms and, if necessary, adjustments are made to the SLOSH input or basin data (PowerPoint 10-6 Slide3).

7. Adjustments are not made to force agreement between computed and measured surge heights from historical storms but to more accurately represent the basin characteristics or historic storm parameters.

8. In the case of historic storms, most of the data has been coarse; with parameters prescribed invariant with time and with an unrealistically smooth storm track.

9. When necessary, further analysis and subjective decisions are employed to amend the track or other parameters of the historic storms used in the verification process.

10. PowerPoint 10-6 Slide 4 shows a satellite image of Hurricane Lili (2002) in the Gulf of Mexico. Brian Jarvinen from the National Weather Service conducted a verification of the SLOSH Model with data collected during Hurricane Lili.

13. PowerPoint 10-6 Slide 5 shows the actual path of the storm. PowerPoint 10-6 Slide 6 shows a diagram of the extent of maximum and secondary winds for Hurricane Lili.

14. PowerPoint 10-6 Slide 7 shows the SLOSH model output as run by the National Weather Service. PowerPoint 10-6 Slide 8 shows a comparison of the observed and SLOSH calculated hydrographs for three locations along the Louisiana Coast.

15. PowerPoint 10-6 Slide 8 shows the storm's path, maximum and secondary wind bands as well as the observed tide gage, high water marks, and SLOSH model outputs along the coast. The slide also provides a comparison of the observed and SLOSH model outputs for Hurricane Lili.

Question: A review of the recorded observations and SLOSH model outputs from the National Weather Service shows that in some locations there is from 1 to 4.5 feet difference in the height of the water. Do you consider this to be a significant difference? Why? Should we be concerned about the validity of the SLOSH model as run for Hurricane Lili?

The SLOSH Model was designed to provide information to help public officials, private businesses and citizens make emergency planning and response decisions for hurricane wind and storm surge threats. For both emergency planning and response considerations, the SLOSH Model provided highly accurate estimates of the hurricane wind and storm surge hazards. Public officials could examine the threats associated with a hurricane and provide citizens with an assessment of the dangers posed by the storm. Accurate warning of the storm was possible with the model outputs; public officials could issue geographic specific evacuation orders well in advance of the storm.

For Hurricane Lili, the greatest difference between the observed and modeled outputs occurred well outside the danger area for the storm. The error observed in Grand Isle, LA is significantly different from any other observation point in the study area and likely explained by the data inputs rather than the performance of the SLOSH model. NWS staff use the data recorded at Grand Isle to determine why the model outputs did not more closely describe the actual storm. For all other data points in the study, the results provided an accurate basis for emergency planning and response decisions. Decision makers are concerned about the validity of a model to accurately characterize the nature and extent of a hazard. The assessment of Hurricane Lili shows that the SLOSH Model provides extremely accurate model results for hurricane planning and response decisions.

16. The values or functions for the coefficients within the SLOSH model are generalized to serve for modeling all storms within all basins and are set empirically through comparisons of computed and observed meteorological and surge height data from numerous historical hurricanes (PowerPoint 10-6 Slide 9).

H. Possible sources of error for SLOSH include (PowerPoint 10-5 Slide 10) (Mercado 1994):

1. Noise in surge observations often exceeding = or – 20%.

2. The bathymetry given to SLOSH is not accurate.

3. The topography given to SLOSH is not accurate.

4. Errors in the initial water height.

5. Wind wave effects, astronomical tidal effects, storm rainfall, and riverine flooding. These effects are often included in observed high water mark data used for verification.

6. Noise in observed meteorological parameters. Sometimes it is the storm track which is a source of error.

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This book describes a hurricane that hit Galveston, TX. on September 8-9, 1900. "The best estimate and the one accepted by most people is that 6000 lost their lives in Galveston and possibly as many as 2000 died in other coastal areas that night."

Appendis A

Questions for Group Discussion

Natural Disaster Survey Reports

1. Describe Hurricane Andrew (peak winds, path, approximate size of the storm, approximate size of the landfall area directly impacted by the storm, and geographic area impacted.

(See Rappaport, Ed (1993). *Hurricane Andrew: August 16 – 28, 1992.* Preliminary Report. National Hurricane Center and Natural Disaster Survey Report Hurricane Andrew September 23 - 26, 1992 (1993). U.S. Department of Commerce, NOAA. Silver Spring, MD.)

2. How does Hurricane Andrew differ from Hurricanes Bertha, Fran, Hugo, Iniki, and Marilyn?

3. What were the surge heights in Florida and Louisiana from Hurricane Andrew? (See Rappaport, Ed (1993). *Hurricane Andrew: August 16 – 28, 1992.* Preliminary Report. National Hurricane Center and Natural Disaster Survey Report Hurricane Andrew September 23 - 26, 1992 (1993). U.S. Department of Commerce, NOAA. Silver Spring, MD.)

4. How do the surge heights compare with those in Hurricanes Bertha, Fran, Hugo, Iniki, and Marilyn?

5. What were the meteorological parameters (intensity of the storm, atmospheric pressure, track of the storm, forward speed and radius of maximum winds) of Hurricane Andrew as it hit south Florida and Louisiana?

6. Using the Saffir-Simpson Damage Potential Scale identify and justify the classification of Hurricane Andrew. Identify and justify the classification of the hurricane in the group assignment.

Appendix B

Hurrevac

HURREVAC uses NWS forecast storm data and displays the track of a storm. Using Hurricane Evacuation Study (HES) data, it derives the potential for storm surge and calculates evacuation times based on storm speed and intensity. It can also be used as a "what-if" tool to help emergency managers determine courses of action for different storm characteristics.

HURREVAC tracks hurricanes on computer plot maps using information from the National Hurricane Center (National Weather Service, NOAA). Marine advisories on tropical storms are normally issued by the National Hurricane Center every six hours: 0500EDT, 1100EDT, 1700EDT, and 2300EDT. At times, intermediate advisories are also issued. These advisories contain information on present and forecast position, intensity, size, and movement that is displayed by HURREVAC. HURREVAC estimates when various evacuation decisions should be made, using data from the federal hurricane evacuation study for the areas. The process is as follows:

1. The arrival of tropical storm (34 knots or 39 mph) winds in your area is computed using the NHC projects with adjustment for a direct-hit or worst-case approach to your community.
2. Clearance times are computed using Saffir-Simpson scale category of storm, response of the public, and occupancy readings for the area. The basic data for the clearance times is produced by a local Hurricane Evacuation Study, usually performed by the Corps of Engineers, National Weather Service and FEMA.. The clearance time is subtracted from the arrival of tropical storm force winds to reach a suggested evacuation decision time. This approach is based on the need to have the at-risk population out of vulnerable areas before tropical storms force winds reach the coast.

The HURRicane EVACuation program (HURREVAC) was developed by Sea Island Software, Inc. was developed in response to a need for data to prepare hurricane evacuation decisions.

These studies were produced for regions of the United States to assist government emergency managers in making decisions for their states/communities when under a hurricane threat.

First major use of the program came with Hurricane Hugo (1989) in South Carolina and Georgia. Subsequently, the program was developed for 13 states, the US Virgin Islands and Puerto Rico.

HURREVAC tracks hurricanes using information from the National Hurricane Center (National Weather Service, NOAA) and provides estimates of when various evacuation decisions should be made, using data from the federal hurricane evacuation study for the area.

It is a tool that you may be used to help in the hurricane decision-making process.

Hurrevac outputs may be exported in several GIS formats.

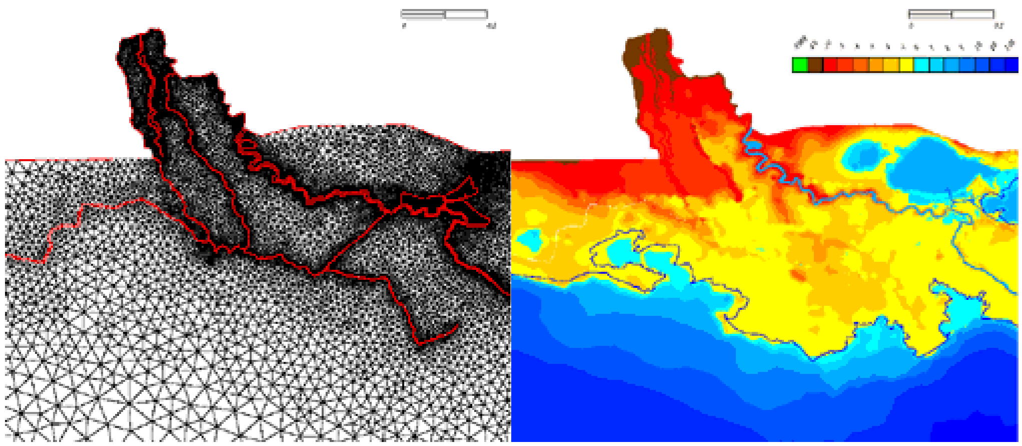
1. A storm track *as points and lines* – Separate files are created for the two shape types and are differentiated by "_p" and "_l" tacked on to the end of the filenames. An exported storm track may

include either the forecasted track from the current advisory, the past (actual) track derived from old advisories, or both the past and forecasted track. Nodes (in the line file) and points (in the points file) represent the initial positions of each advisory for the past track and the 0,12, 24, 36, 48, 72, 96, and 120-hour forecasted positions for the current advisory. The past and forecasted tracks are exported as 2 separate lines and attributed with "0" and "120" to represent their respective values. Points are attributed with a date/time field and a maximum wind speed field.

2. Wind ranges from any forecast hour (0-72) *as polygons* – Up to three rings with values of 39, 58, and 74 mph may be output.
3. Wind swath through hour 72 of current advisory *as polygons* – Up to three polygons with values of 39, 58, and 74 mph may be output.
4. Error swath or error swath plus winds *as polygons* -- Up to three polygons with a single attribute field indicating 72-hour average error (72), extended forecast average error (120), and average error plus winds (0).
5. Error ellipse (with or without winds) from any forecast hour (0-120) *as polygons* – One polygon (attribute value of 72 or 120) for the error ellipse and a larger wind ellipse (attribute value of 0).
6. MEOW (Max Envelope of Wind) for specified region and storm conditions *as polygons* – Polygons are attributed with 39, 58, 74, 92, 109, and 127 mph to indicate the maximum wind possible for the region.
7. HPC rainfall isopleths for specified day (1-3) *as polygons* – Polygons have attribute values to indicate a region's expected rainfall in 100th of inches.
8. NWS river flood outlook *as polygons* – Polygons have attribute values to indicate whether the likelihood of flooding in a region is possible (1), likely (2), or imminent or occurring (3).

Appendis C

Advanced Circulation Model for Coastal Ocean Hydrodynamics



ADCIRC is a natural hazard numerical model developed for the specific purpose of generating long time periods of hurricane storms along shelves, coasts, and within estuaries. The intent of the model is to produce long numerical simulations for very large computational domains in a unified and systematic manner.

Computational models of flow and transport in continental margin waters are used to predict free surface elevation and currents for applications ranging from evaluating coastal inundation, defining navigable depths and currents in near shore regions, to assessing pollutant and/or sediment movement on the continental shelf.

The ability of these computer models to accurately represent the actual waterbody physics depends on the flow processes and phenomena considered in the calculation, the validity of the governing equations, the body and boundary forcing functions, the scope of the computational domain, the accuracy and robustness of the numerical algorithms, and finally the temporal and spatial discretization applied in the calculation.

It is certain that high spatial and temporal grid resolution is one of the key factors in improving the accuracy of flow calculations in the coastal ocean.

ADCIRC has been extensively applied by both the U.S. Army and Navy for tidal and hurricane storm surge predictions in regions including the western North Atlantic, Gulf of Mexico and Caribbean Sea, the Eastern Pacific Ocean, the North Sea, the Mediterranean Sea, the Persian Gulf and the South China Sea. Other users of ADCIRC include governmental agencies, consulting firms and university researchers for applications ranging from real time hurricane storm surge predictions to impact studies of sewage outfall placement.

ADCIRC can be run either as a two-dimensional depth integrated (2DDI) model or as a three-dimensional (3D) model. In either case, elevation and velocity of the storm is calculated.

Appendix D

Measurement Units

NAUTICAL MILE: A unit of length used in marine navigation that is equal to a minute of arc of a great circle on a sphere. One international nautical mile is equivalent to 1,852 meters or 1.151 statue miles. Refer to a sea mile.

MILLIBAR (MB): A metric measurement of atmospheric pressure used by the National Weather Service.. Standard surface pressure is 1,013.2 millibars.

STANDARD SURFACE PRESSURE: The measurement of one atmosphere of pressure under standard conditions. It is equivalent to 1,013.25 millibars, 29.92 inches of mercury, 760 millimeters of mercury, 14.7 pounds per square inch, or 1.033 grams per square centimeter.

KNOT: A unit for the measurement of speed in the nautical system. It is the nautical miles per hour.

STATUTE MILE: Commonly known as a ground mile.

PRESSURE: The force per unit area exerted by the weight of the atmosphere above a point on or above the earth's surface. Also known as atmospheric pressure or barometric pressure.

RAIN: Precipitation in the form of liquid water droplets greater than 0.5 mm. If widely scattered, the drop size may be smaller. It is reported as "R" in an observation and on the METAR. The intensity of rain is based on rate of fall. "Very light" (R--) means that the scattered drops do not completely wet a surface. "Light" (R-) means it is greater than a trace and up to 0.10 inch an hour. "Moderate" (R) means the rate of fall is between 0.11 to 0.30 inch per hour. "Heavy" (R+) means over 0.30 inch per hour.

MEAN SEA LEVEL: The heights of the sea surface midway between its average high and low water positions.

HURRICANE PATH OR TRACK: Line of movement (propagation) of the eye through an area.

STORM TRACKS: The path or tracks generally followed by a cyclonic disturbance.

SWATH: The width of the path of the hurricane. Usually this path area is about 125 miles wide with 75 miles to the right of the eye and 50 miles to the left of the eye.

FEEDER BANDS: In tropical parlance, the lines or bands of thunderstorms that spiral into and around the center of a tropical system. Also known as outer convective bands, a typical hurricane may have three or more of these bands. They occur in advance of the main rain shield and are usually 40 to 80 miles apart. In thunderstorm development, they are the lines or bands of low-level clouds that move or feed into the updraft region of a thunderstorm.