Official's Guide for Hurricane Evacuation Decision Making

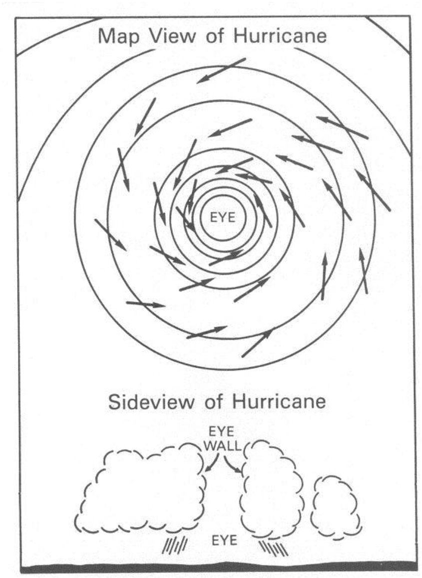
HURRICANE FORMATION AND BEHAVIOR

A hurricane is an intense *tropical cyclone*, which is a low-pressure system that develops a rotating surface wind circulation over tropical waters. Hurricanes occur when sea water becomes warm and evaporates at a high rate. This usually takes place from June through November but extended into December during the 2005 hurricane season. Rising water vapor lowers the atmospheric pressure at the sea surface, which causes wind to flow in to replace the rising air. When the warm moist air reaches a high altitude, it cools and releases its latent heat of evaporation, causing thunderstorms. As the earth rotates, it imparts a corresponding rotation to the tropical system's wind—counterclockwise in the Northern Hemisphere. Most hurricanes striking Texas originate in the Atlantic Ocean, but others are born in the Caribbean and some even begin in the Gulf of Mexico.

Hurricane Structure

The main components of a hurricane are the eye, the eye wall, and the rain bands that spiral inward toward the eye wall (see Figure 1). The *hurricane eye* is a relatively calm, clear area usually 20-40 miles across. It is surrounded by a dense wall of thunderstorms—the *eye wall*—that has the strongest winds within the storm. The storm's outer *rain bands* range in width from a few miles to tens of miles and are 50–300 miles long. These rain bands have high wind speeds and can extend out hundreds of miles from the hurricane eye.

Figure 1. Typical hurricane structure



HURRICANE DAMAGE MECHANISMS

The destructive force of hurricanes comes from high wind, tornadoes, coastal flooding from storm surge, and inland flooding from heavy rain.

High Wind

High wind is probably the most obvious hurricane threat, and wind speed defines a hurricane's classification category into one of the five categories of the Saffir-Simpson scale (see Table 1). In general, wind effects depend upon an object's size, shape, material strength, and anchoring but even *Tropical Storm* force (39 mph) wind can overturn high profile vehicles, such as recreational vehicles and buses. Thus, emergency managers prefer to complete evacuations before the arrival of Tropical Storm wind so they can avoid having such vehicles block evacuation routes.

The wind speed experienced at a given location depends upon the intensity of the hurricane and that location's distance and direction from the hurricane eye. For a large storm, hurricane-force wind extends out 150 miles from the eye and Tropical Storm force wind extends out 300 miles. However, hurricanes do not have symmetric wind patterns. Wind speed tends to be higher in a hurricane's right forward quadrant (the location to the right of the track and forward of the hurricane eye as one looks from the sea toward the land) because the forward movement speed of the hurricane is added to the speed of the wind rotating around the eye. Conversely, wind speed tends to be lower in the left forward quadrant because the forward movement speed of the hurricane is subtracted from the speed of the wind rotating around the eye. Wind gusts can exceed the maximum sustained wind speed by 25% or more.

Table 1: Saffir-Simpson Hurricane Scale

Saffir/ Simpson Category	Wind speed (mph)	Expected Surge (ft)	Expected Damage
Tropical Storm	39-73	<4	• Damage most likely to be caused by inland flooding.
One	74–95	4–5	• Vegetation: some damage to foliage. • Street signs: minimal damage. • Mobile homes: some damage to unanchored structures. • Other buildings: little or no damage.
Two	96–110	6–8	• Vegetation: much damage to foliage; some trees blown down. • Street signs: extensive damage to poorly constructed signs. • Mobile homes: major damage to unanchored structures. • Other buildings: some damage to roof materials, doors, and windows.
Three	111–130	9–12	• Vegetation: major damage to foliage; large trees blown down. • Street signs: almost all poorly constructed signs blown away. • Mobile homes: destroyed. • Other buildings: some structural damage to small buildings.
Four	131–155	13–18	• Vegetation: major damage to foliage; large trees blown down. • Street signs: all down. • Mobile homes: destroyed. • Other buildings: extensive damage to roof materials, doors, and windows; many residential roof failures.
Five	>155	>18	• Vegetation: major damage to foliage; large trees blown down. • Street signs: all down. • Mobile homes: destroyed. • Other buildings: some complete building failures.

Moreover, wind speed is lower the farther away along the coastline a location is from the point at which the eye makes landfall. This is a very important point to bear in mind because few people who have "survived" a Category Four hurricane have actually borne the impact of wind exceeding 130 mph. This is a reason why many people overestimate their homes' ability to withstand the impact of a major storm. Finally, wind speed decreases as a hurricane moves inland because the storm is cut off from its source of energy (warm water) and because of surface friction from rough terrain. There is an almost immediate 10% decrease in wind speed at landfall and a 50% decrease within the first ten hours.

Tornadoes

Hurricanes can produce tornadoes, usually in the rain bands that spiral out from the eye. These tornadoes generally occur some distance from the center of the storm. Tornadoes are much more compact and, therefore affect a much smaller area, than the hurricane that spawned them. However, tornado wind speed can be even greater—up to 400 mph or more. There were 23 tornadoes associated with Hurricane Alicia that struck Galveston in 1983. However, most of the tornadoes were weak, with wind speeds between 40–72 mph. The strongest tornado, which struck near Tyler, had a wind speed of 113–157 mph.

Storm Surge

A storm surge is a large dome of water, often 50–100 miles wide, that sweeps across the coastline to the right (looking from the sea toward the land) of the hurricane's point of landfall. Storm surge is only one factor affecting the depth of the water over the land. A normal high tide must be added to that of the storm surge (or a low tide subtracted from it), although this usually only accounts for two feet or less along the Texas coast. More significant is the effect of wind-generated waves, which can be more than 50% higher than the still-water surge depth (the surge depth as measured by the "average" between the wave peak and trough). Breaking waves crash into buildings with tremendous force—smashing windows and doors, collapsing walls, and sweeping even the strongest swimmers to their deaths. These waves reach their greatest height on the open coast but are generally much smaller in protected bays and bayous.

Inland Flooding

Hurricanes can generate widespread torrential rainfall that results in deadly and destructive floods. These floods can threaten areas well inland from the effects of hurricane wind and storm surge. Rainfall rates during hurricanes can range up to two inches per hour. Because slow moving hurricanes take many more hours to pass through an area, they generally deposit greater amounts of rainfall—some hurricane impact areas have experienced up to 30 inches of rainfall over a period of several days

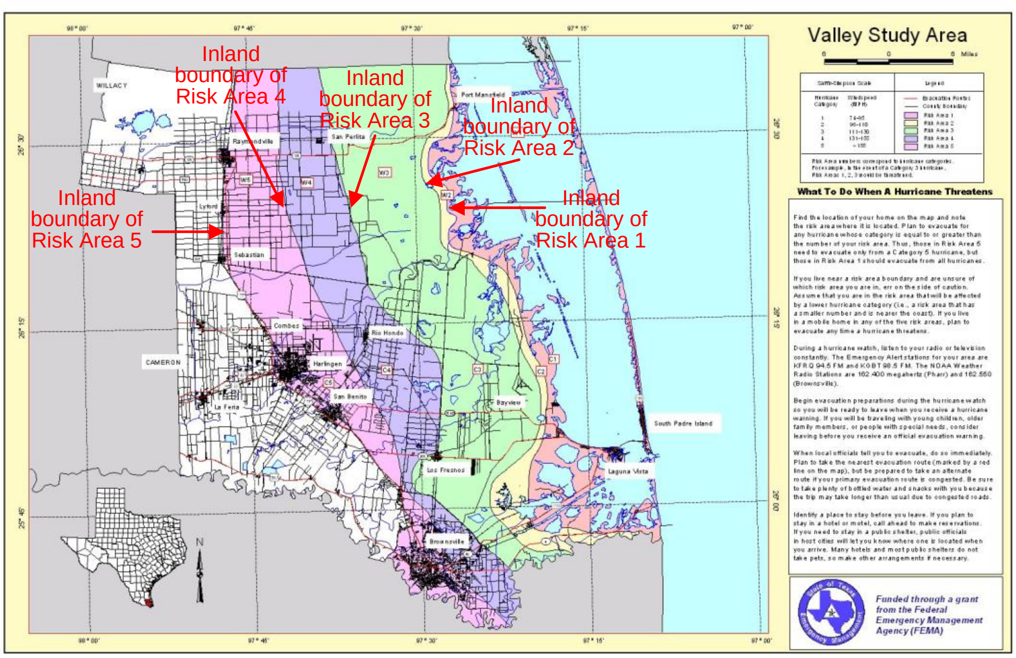
HURRICANE HAZARD ANALYSIS

Hazard Analysis

Hurricane surge hazard is assessed using a computer model that generally is accurate within plus or minus 20%. For example, if the model predicts a 10 foot storm surge, the observed peak will be between 8-12 feet. The surge model does not include breaking waves or inland flooding caused by rainfall.

Analysts use the data on surge depth and wind speed to define the boundaries of *Risk Areas*. On most of the Texas coast, each Risk Area comprises the portion of a county that is expected to be affected by the corresponding hurricane category (see Figure 2). That is, Risk Area 1 is the area expected to be affected by hurricane Category 1 (74–95 miles per hour winds), Risk Area 2 is the area expected to be affected by hurricane Category 2 (96–110 miles per hour winds), and so on. Risk Area boundaries generally run parallel to the coast, but can be very irregular where there are rivers or bays. Risk Area boundaries are far apart when the terrain is flat and close together when the terrain is steeply sloped.

Figure 2. Typical hurricane risk areas



Evacuation Analysis

In the first phase of an evacuation analysis, transportation planners identify each county's evacuation route system—the roads people can use to move inland from the coast. The planners then use traffic engineering data to estimate the capacity of the evacuation route system, which is the number of vehicles per hour that can pass through the evacuation route system. Some jurisdictions have large traffic capacities because they have many freeway lanes that move vehicles rapidly away from the coast. Other jurisdictions have lower traffic capacities because they have fewer lanes or because the highways have traffic signals that stop evacuating vehicles to allow cross traffic to move through intersections.

In the first phase of the evacuation analysis, transportation planners use census data to assess the number of households in each risk area. They also use data from a *behavioral expectations survey* of coastal residents to assess what people expect to do when a storm threatens. This survey is mailed to randomly selected residents living in each risk area within each study area. The survey asks questions designed to reveal what proportion of the residents are likely to evacuate from each risk area at each storm category, how long it will take them to prepare, where they intend to go, how many vehicles they will take, what roads they expect to use, and where they expect to stay while they are gone from their homes.

This evacuation analysis produces a table of *evacuation time estimates* (ETEs) that indicate the amount of time required to evacuate a specific set of risk areas. The ETEs are important to local authorities because they determine how close a hurricane can get before they should begin an evacuation. Although the specific calculations are rather complex, the basic idea is that the ETE = Demand/Capacity. This is, the ETE for a given set of risk areas is determined by dividing the traffic demand (in vehicles) by the evacuation route capacity (in vehicles per hour) to produce the number of hours needed to compete the evacuation. This leads to two general principles.

- For a given population size, the larger the evacuation route system capacity, the smaller the ETE.
- For a given evacuation route system capacity, the larger the population size, the larger the ETE.

ETEs are calculated from a number of variables whose values are uncertain. For example, surveys have shown the average number of evacuating vehicles per household is 1.3 but this has varied unpredictably from 1.1 to 2.2. Thus, as Table 2 indicates, ETEs for a given set of risk areas to be evacuated are defined by their

- minimum probable ETE,
- most probable ETE, and
- maximum probable ETE.

Table 2: ETE table

Risk Areas to be Evacuated	Minimum Probable ETE	Most Probable ETE	Maximum Probable ETE
Risk Area 1 only	6	8	10
Risk Areas 1 and 2	8	10	12
Risk Areas 1 to 3	13	16	20
Risk Areas 1 to 4	18	22	27
Risk Areas 1 to 5	25	30	36

HURRICANE TRACKING

The National Hurricane Center (NHC) monitors the progress of hurricanes and provides critical information about the approaching storm. Each forecast/advisory provides *current* data on the hurricane eye's latitude/longitude coordinates and the storm's intensity. The forecast/advisory also contains *forecasts* of the eye location, hurricane intensity, and hurricane size for 12, 24, 36, 48, and 72 hours from the current time. The NHC issues a new forecast/advisory every six hours. The first one is normally issued when meteorological data indicate a cyclone has formed and subsequent advisories are issued at 4:00 AM, 10:00 AM, 4:00 PM, and 10:00 PM Central Daylight Time.

Hurricane Location

A hurricane's location is defined by the position of its eye in degrees (and tenths of a degree) of latitude or longitude. One degree of latitude equals 60 nautical miles (each nautical mile equals 1.15 statute miles), but degrees of longitude vary in length because longitudinal meridians are most widely spaced at the equator and converge at the poles. Sometimes the rain bands, and even the eye itself, are obscured by higher level clouds, making it difficult to locate the storm's position precisely by satellites. In such cases, the eye can be located only within about 18-30 miles, whereas a well-defined eye can be located within 6-12 miles.

Hurricane Track

As a hurricane's wind moves around the eye in a circular motion, the eye itself moves over the surface of the earth. The location of the hurricane eye over time, the *hurricane track*, is important to local authorities because it determines whether or not the hurricane will landfall in their jurisdiction. Most Atlantic hurricanes begin their lives by tracking due west across the Atlantic Ocean but gradually curve toward the north. However, hurricanes have followed many other tracks (see Figure 3).

- Some of them continue on a straight track until they make landfall.
- Others have made sharp changes in direction,
- Occasionally, hurricanes even make circular loops.

Figure 3. Types of hurricane tracks

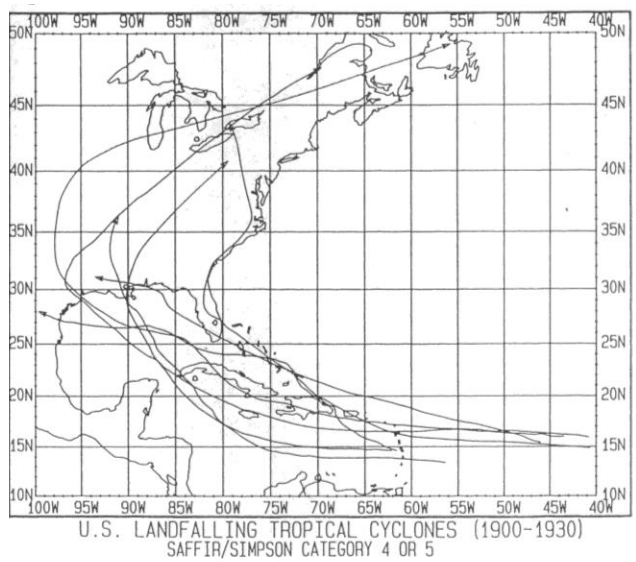
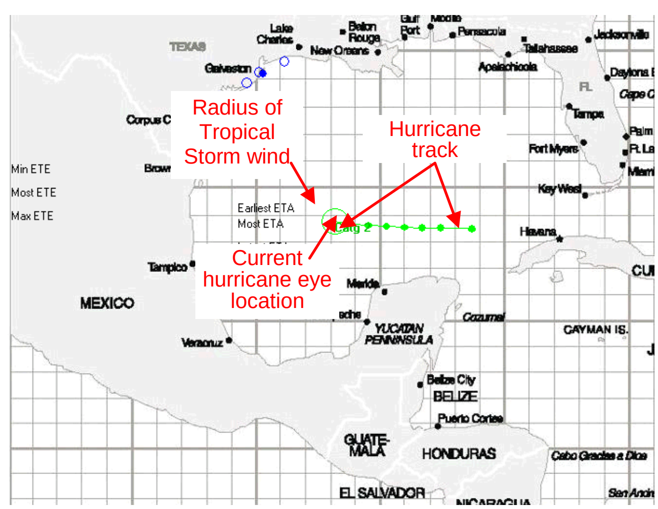


Figure 4 shows a hurricane tracking map in which the positions of the hurricane eye, as reported by the NHC in forecast advisories, are represented by a succession of dots moving from right to left. The dot on the farthest right side of the track is the location at which the storm became classified as a hurricane. The dot on the farthest left side of the track is the hurricane's current location.

Figure 4. Hurricane tracking map



It is even more difficult to forecast a storm's future location than to identify its current location because there is uncertainty about how the hurricane track will be affected by other weather systems. In general, the longer the time interval until landfall, the greater is the uncertainty about the hurricane track (see Table 3). In turn, this uncertainty about the hurricane's track makes it difficult for local authorities to decide whether or not to evacuate their jurisdictions. The track forecast accuracy at 36 hours (100 mi) is especially important because this is the ETE for most urbanized areas of the Texas Gulf coast. *This is the average error, not the maximum error.* Consequently, the error could be larger than 100 miles, even though very large errors are unlikely.

Table 3: Track Forecast Accuracy

Forecast period (hours)	Average Absolute Error (nautical miles)
72	180
48	125
36	100
24	75

Hurricane Forward Movement Speed

A hurricane's forward movement speed is defined by the rate at which the hurricane eye moves along its track. Hurricane forward movement speed is important to local authorities because it determines how soon the hurricane will make landfall in their jurisdiction. The faster is a hurricane's forward movement speed, the sooner it will arrive and, therefore, the sooner an evacuation must be initiated.

A storm's forward movement speed averages about 10 mph, but can range from 0–30 mph and can vary over time. However, hurricanes can speed up, maintain a constant speed, slow down, or stall (stop all forward motion). In general, the longer the time interval until landfall, the greater is the uncertainty about the hurricane's forward movement speed. Consequently, uncertainty about hurricane forward movement speed makes it difficult to decide how soon to begin evacuations.

Hurricane Strike Probabilities

The NHC issues strike probability forecasts, which predict the likelihood of a hurricane striking within 65 miles of specific locations on coast. On the Texas Gulf coast, these locations are Brownsville, Corpus Christi, Port O'Connor, Freeport, Galveston, and Sabine Pass. Probabilities are given for the time periods 0-24, 24-36, 36-48, and 48-72 hours. As Table 4 indicates, prediction accuracy decreases as the forecast period increases.

Note that the maximum probability at 36 hours before landfall is only 25 percent. This means that there is, *at most*, a 25 percent chance the storm will strike within 65 miles of the point of landfall projected from the storm's track. Consequently, densely populated areas with long ETEs might need to initiate evacuations even though it is most likely that the hurricane will strike somewhere else.

Table 4: Maximum Strike Probabilities

Forecast period	Maximum probability	Miss/Hit Ratio
72	10%	9 to 1
48	13-18%	7 to 1
36	20-25%	4 to 1
24	35-50%	2 to 1

Hurricane Intensity

A hurricane's intensity (defined by its Saffir-Simpson category) can increase, remain the same, or decrease over time. Hurricane intensity is important to local authorities because it determines how far inland (i.e., how many risk areas) authorities must evacuate their residents. In general, the longer the time interval until landfall, the greater is the uncertainty about hurricane intensity. Consequently, uncertainty about hurricane intensity makes it difficult to decide how far inland to evacuate.

As is the case with forecasts of hurricane location, forecasts of wind speed decrease in accuracy as the length of the forecast period increases. As Table 5 indicates, the average forecast error at 36 hours—a time when some jurisdictions must make a final decision whether or not to evacuate—is approximately 15 mph. A difference of this size is frequently large enough to change a hurricane by one category on the Saffir-Simpson scale. *This is the average error, not the maximum error.* Consequently, the error could be larger than 15 mph, even though very large errors are unlikely.

Table 5: Wind Speed Forecast Accuracy

Forecast period (hours)	Average error (mph)
72	23
48	18
36	15
24	12
12	9

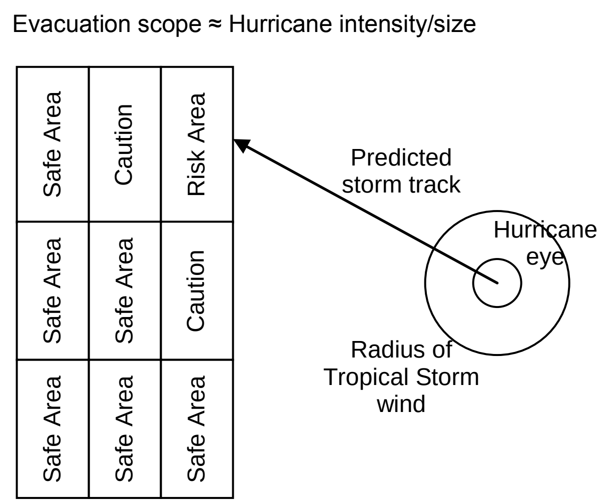
EVACUATION DECISION MAKING

As a hurricane approaches, an emergency manager must decide:

- Whether or not to evacuate the jurisdiction,
- When to begin evacuating the jurisdiction, and
- How far inland the evacuation should extend.

The way to make these decisions can be understood by examining Figure 5, which shows a hurricane approaching a coastal jurisdiction. In the right-hand side of the figure, there is a small circle indicting the hurricane eye surrounded by a lager circle showing the radius of Tropical Storm force wind. The hurricane itself is moving along a track toward a coastal location labeled the *Risk Area*, which includes the hurricane eye's most probable point of landfall, the distance on either side of the eye's landfall that there will be damaging wind and surge, and the distance inland from the coast that the damaging wind and surge will extend. There is a *Caution Area* next to the Risk Area along the coast because of the uncertainty about the storm track and another Caution Area inland from the Risk Area because of the uncertainty about the storm intensity. Finally, there are *Safe Areas* farther along the coast and also farther inland that are expected to escape damaging wind and surge. Of course, these areas are not completely safe because a very large change in track or intensity could cause them to be affected.

Figure 5. Hurricane evacuation decision parameters



Because hurricanes are expensive and disruptive, emergency managers usually want to wait as long as possible to begin an evacuation. The *evacuation decision deadline* is the time beyond which it is no longer safe to delay an evacuation. If an emergency manager starts an evacuation after the *evacuation decision deadline*, the last evacuees will still be in the Risk Area when Tropical Storm force wind arrives. Remember, this is the wind speed at which an evacuation could be stalled if high profile vehicles such as buses and recreational vehicles are overturned by high wind striking them from the side.

In order to finish an evacuation before Tropical Storm force wind arrives, emergency managers must start the evacuation ETE hours beforehand, where ETE is the evacuation time estimate. In turn, the ETE depends on the size of the evacuation zone. Thus, if the ETE for Category 5 hurricane is 30 hours, the evacuation decision deadline is 30 hours before the arrival of Tropical Storm force wind.

This amount of time can be expressed as an *evacuation decision arc*, which converts a measure of time (the ETE) into a measure of distance (that can be seen on a hurricane tracking map). Using simple algebra, the evacuation decision arc (a distance) is computed by multiplying the hurricane's forward movement speed (a rate) times the ETE (a time).

> **Example**. If a Category 4 hurricane is approaching at a forward movement speed of 10 miles per hour and the ETE for Risk Areas 1 through 4 is 20 hours, then an emergency manager should begin an evacuation when the Tropical Storm force wind reaches 200 miles (20 hours multiplied by 10 miles per hour) from that county's shoreline.

An emergency manager can use information about the uncertainties in the evacuation analysis to estimate one evacuation decision arc based on the *minimum probable ETE*, another arc based on the *most probable ETE*, and a third arc based on the *maximum probable ETE* (see Figure 6). Similarly, it is possible to use information about the uncertainties about the hurricane's intensity to estimate the *minimum probable* Estimated Time of Arrival (ETA) for Tropical Storm force wind, the *most probable ETA*, and the *maximum probable ETA.*

Figure 6. Decision Arcs.