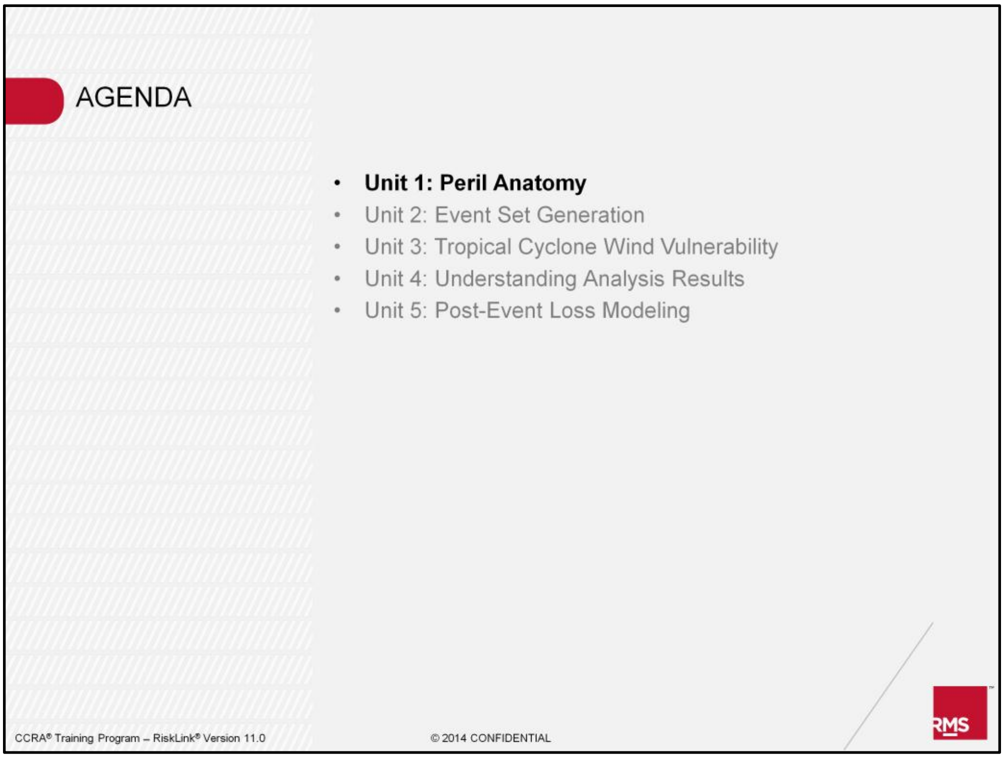
TROPICAL CYCLONE MODELING

UNIT 1

RMS® CCRA® Training Program

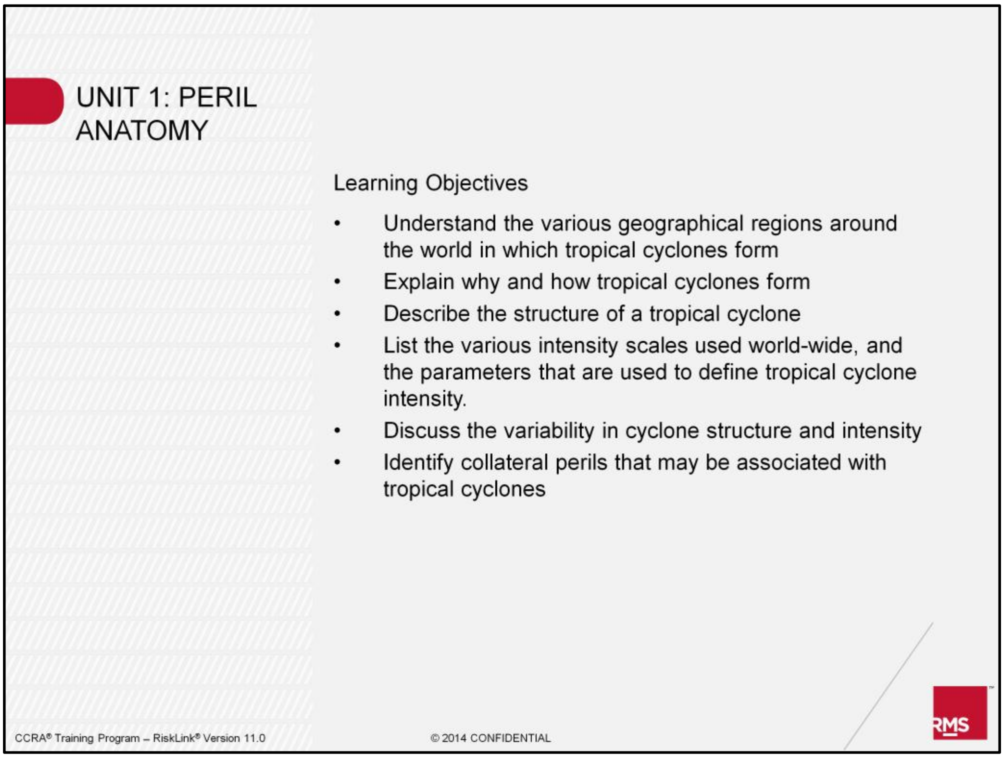
Certified Catastrophe Risk Analyst



This is the agenda for the Tropical Cyclone Modeling course. The first of five presentation units in the course covers the anatomy of tropical cyclones. The following units cover the creation of tropical cyclone event sets for use in modeling, how damage is assessed given a particular location and wind speed (vulnerability), understanding tropical cyclone modeling results, and how models can be used to estimate losses after an event has made landfall.

This unit includes the following sections:

- Tropical Cyclone Formation: Ingredients and Processes
- Tropical Cyclone Structure
- Tropical Cyclone Intensity Measures
- Tropical Cyclone Variability
- Collateral Perils



At the end of this unit you should have a good understanding of each of the six learning objectives listed on this slide.

TOP TEN INSURED CATASTROPHE LOSSES
1991-2010

Insured Loss ($billions)	Year	Event	Country
66.3	2005	Hurricane Katrina	U.S.
23.0	1992	Hurricane Andrew	U.S., Bahamas
21.4	2001	World Trade Center Attack	U.S.
20.0	2008	Hurricane Ike	U.S.
19.0	1994	Northridge Earthquake	U.S.
13.7	2004	Hurricane Ivan	U.S., Caribbean
13.0	2005	Hurricane Wilma	U.S., Caribbean, MX
10.4	2005	Hurricane Rita	U.S., Caribbean
8.6	2004	Hurricane Charley	U.S., Caribbean
8.4	1991	Typhoon Mireille	Japan

Swiss Re Sigma

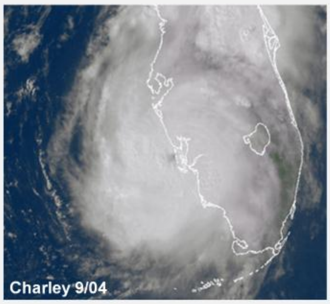
These are the ten largest insured catastrophe losses since 1991. Eight out of the top ten cat losses since 1991 were related to tropical cyclones. Seven were hurricanes that struck the U.S. and the Caribbean, and one was a typhoon that struck Japan. The losses shown can vary from report to report; however, comparing insured earthquake versus tropical cyclone losses, we do notice that globally tropical cyclones caused several times as much loss as did earthquakes, while, especially in the U.S., hurricanes cause ten times as many fatalities.

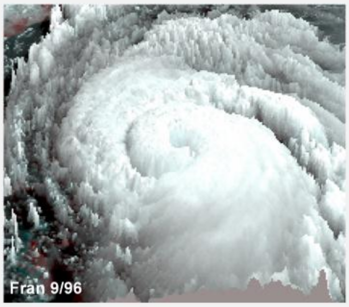
As a historical example, the great hurricane that struck Galveston, Texas on September 8, 1900 had a storm surge of 15 feet, which was responsible for the deaths of 8,000 people. More recently, Hurricane Katrina’s storm surge at landfall, in combination with inland flooding and resultant levee breaks, led to the deaths of more than 1,300 people.

Improved forecasting of tropical systems has obviously lowered the risk of tropical cyclone deaths, especially in the U.S. This is related to the advances in the infrastructure as well as in science, specifically our increasing ability to forecast tropical cyclone tracks and intensity.

WHAT IS A TROPICAL CYCLONE?

- Low-pressure systems that develop into intense cyclonic storms with strong horizontal winds.
- Cyclones in different regions are named differently; however, the formation mechanisms are similar.
- Need several pre-existing conditions before a tropical cyclone can develop successfully
- Form over warm tropical oceans
- Vertical wind circulation also exists

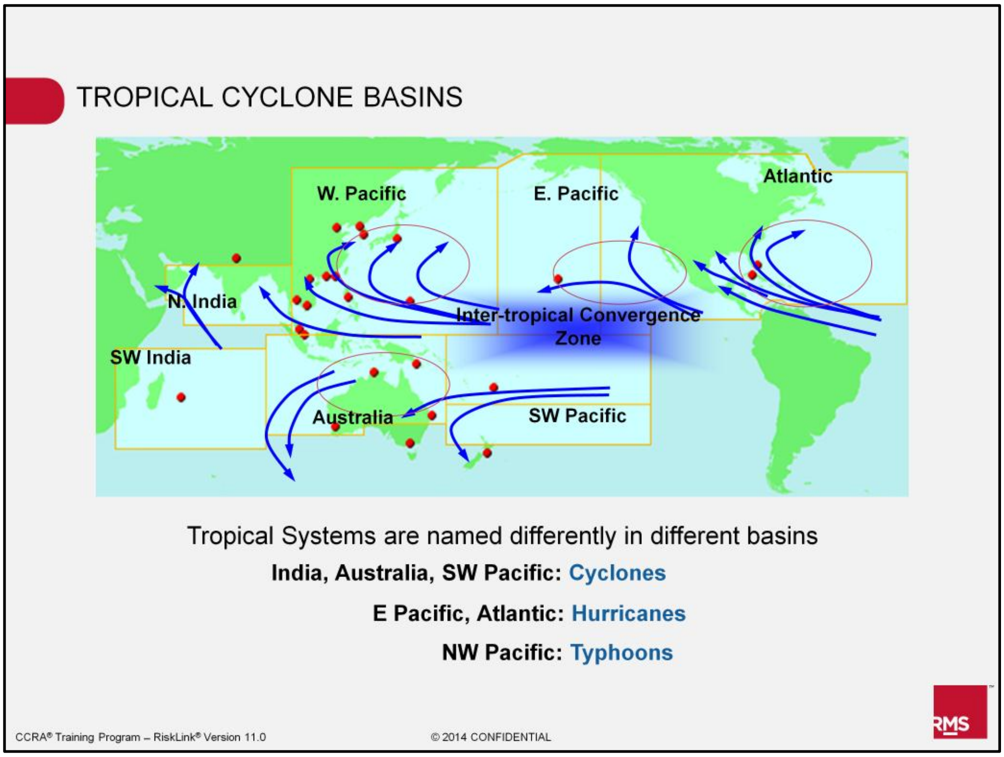




So what is a tropical cyclone? Tropical cyclones are intense cyclonic low pressure systems that form in the tropics or subtropics where sea surface temperatures are generally above 26 degrees centigrade (79 degrees Fahrenheit) throughout the upper 50 meters (164 feet) of the ocean. These low pressure systems derive their energy from the underlying warm seas.

Tropical cyclones are regions of localized low pressure and contain a closed circulation. In order to form, tropical cyclones need a variety of favorable environmental conditions, which will be discussed later in this presentation. Each year, an average of nearly 80 tropical systems form somewhere on the globe with low-level sustained winds of greater than 17 meters per second (38 miles per hour). About two thirds of them obtain hurricane intensity at 33 meters per second (74 miles per hour). Tropical cyclone activity in the Atlantic basin averages one eighth of the global total, with approximately ten tropical cyclones per year.

The satellite pictures shown here are of Hurricane Fran in the Gulf of Mexico, just east of Florida, in September 1996 and Hurricane Charley making landfall on the Florida Peninsula in 2004.

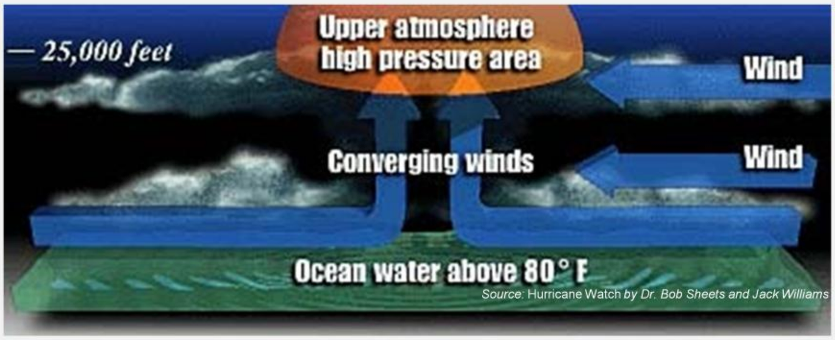


There are seven tropical cyclone basins where storms occur on a regular basis. The Atlantic basin, including the North Atlantic Ocean, the Gulf of Mexico, and the Caribbean Sea; the East Pacific basin from Mexico to approximately the dateline at 180 degrees west; the West Pacific basin including Japan, South Korea, Taiwan, and the Philippines; the North Indian basin, including the Bay of Bengal and the Arabian Sea; the Southwest Indian basin; the Southeast Indian or Australian basin from 100 to 142 degrees east, and the Australian/Southwest Pacific basin.

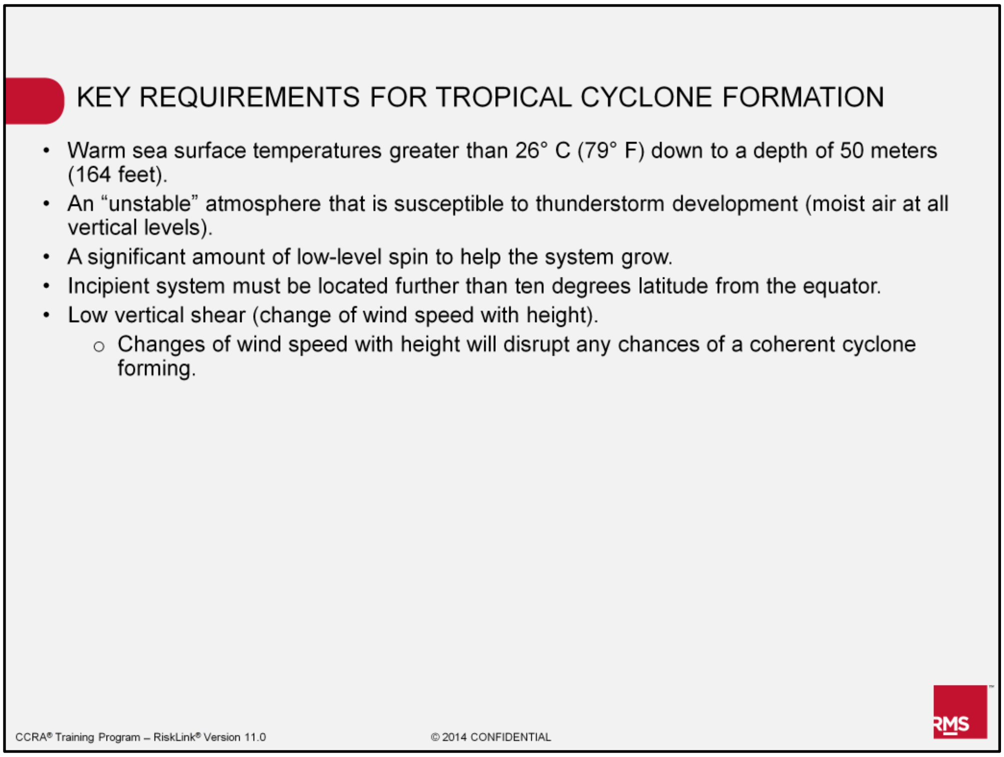
According to the National Oceanic and Atmospheric Administration's (NOAA) National Hurricane Center, approximately 69% of tropical cyclones occur in the northern hemisphere, while only 31% can be found in the southern hemisphere. Approximately 12% occur in the Atlantic ocean, 57% in the Pacific, and the remaining 31% occur in the Indian Ocean. You will notice that the Southern Atlantic Ocean appears to have been left off this list.

Why does the South Atlantic Ocean rarely experience tropical cyclones? Meteorological conditions are usually unfavorable for tropical systems to form in this basin, although we did see the first ever recorded tropical system off the coast of Brazil in March 2004. Though many people might speculate that the sea surface temperatures are too cold, the primary reasons that the South Atlantic Ocean rarely experiences tropical cyclones are that the troposphere (lowest layer of the atmosphere) vertical wind shear is much too strong and there is typically no inter-tropical convergence zone (ITCZ) over the ocean (Gray 1968). Without an ITCZ to generate synoptic vortices and convergence (i.e., large scale spin and thunderstorm activity), and without strong wind shear, it becomes very difficult to nearly impossible to have genesis of tropical cyclones.

TROPICAL CYCLONE FORMATION



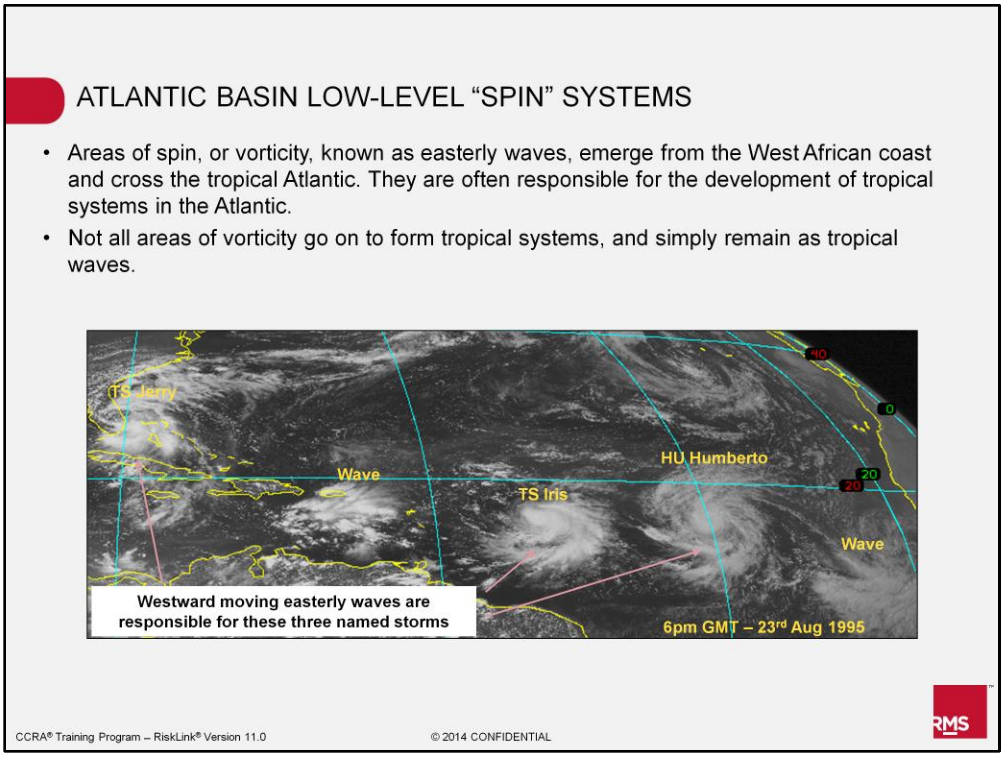
We will now take a look at how tropical cyclones form and how they intensify into potentially dangerous systems.



A number of conditions have to be met for a tropical cyclone to form and to have the potential to intensify.

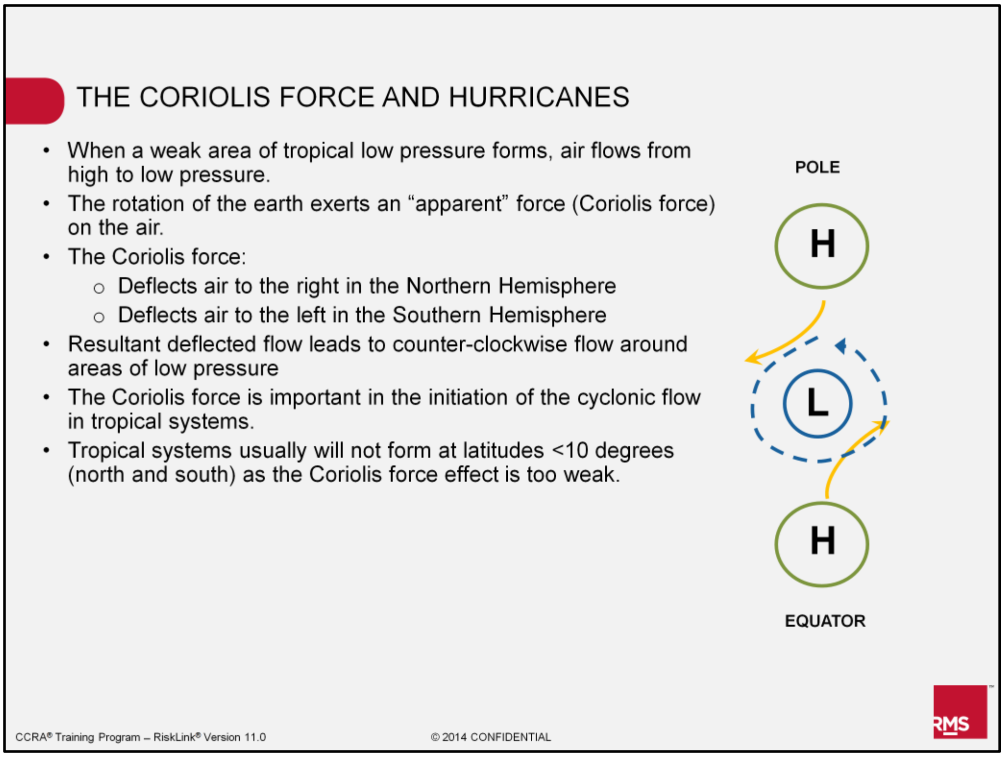
- First, tropical systems extract their energy from the sea. As a result, warm seas are required. Typically over 26 degrees Celsius (or 79 degrees Fahrenheit) is necessary to sustain a tropical cyclone.
- Next, the atmosphere above the sea surface (the troposphere) must cool relatively quickly with height such that the atmosphere is susceptible to thunderstorm development.
- Third, there has to be a pre-existing source of spin or vorticity present in the atmosphere at low-levels to help initiate the tropical cyclone development.
- Fourth, systems can normally only develop away from the equator, where the Coriolis force is significant, which we will address later in this presentation.
- Finally, the winds in the atmosphere should not increase with height too much. This will inhibit any developing tropical systems as increasing winds with height disrupt the circular symmetry, which is a hallmark of an intense tropical system.

We will now look at some of these factors in more detail.



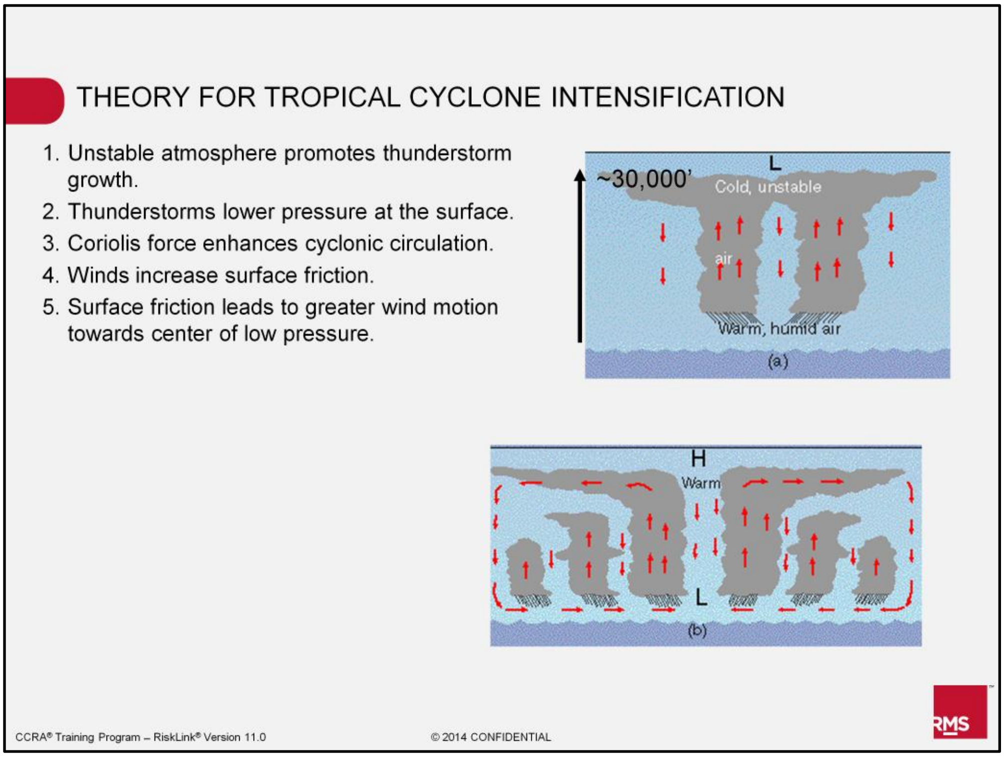
The Atlantic Basin has a source of low-level spin, or vorticity in meteorological terminology, which is often the seed for tropical systems to develop. These are known as African easterly waves that push west across the Atlantic Ocean. They tend to be most prominent from June to October when sea surface temperatures tend to be highest and are the seed for more than half of the tropical cyclones in the Atlantic. This picture shows a remarkable example of a chain of five easterly waves, three of which went on to form tropical systems that were intense enough to be named.

While easterly waves can contribute to hurricane formation across the globe, several basins also have additional formation mechanisms. For example, in the western North Pacific, hurricanes can form out of semi-permanent monsoon "gyres", which are a result of an enhanced ITCZ. Additionally, across all basins, mid-latitude storm systems can sometimes have a cold front that reaches near the tropics. An area of vorticity on this cold front, if remaining over warm sea surface temperatures (SSTs), can eventually make a transition into a tropical cyclone.



This is a slightly more technical slide explaining the Coriolis force, which is often mentioned regarding hurricane development. When a weak region of low pressure forms at the surface, the surrounding air will naturally move towards it because air moves from high to low pressure. However, since the earth is spinning, the air that moves north from a high pressure region towards a low pressure region is seen to deflect to the right. Similarly, the air that moves south from a high pressure region to a low pressure region is seen to deflect to the left. Hence the air rotates anti-clockwise (counter-clockwise), or cyclonically, around the low. This apparent force grows stronger as you move closer to the poles.

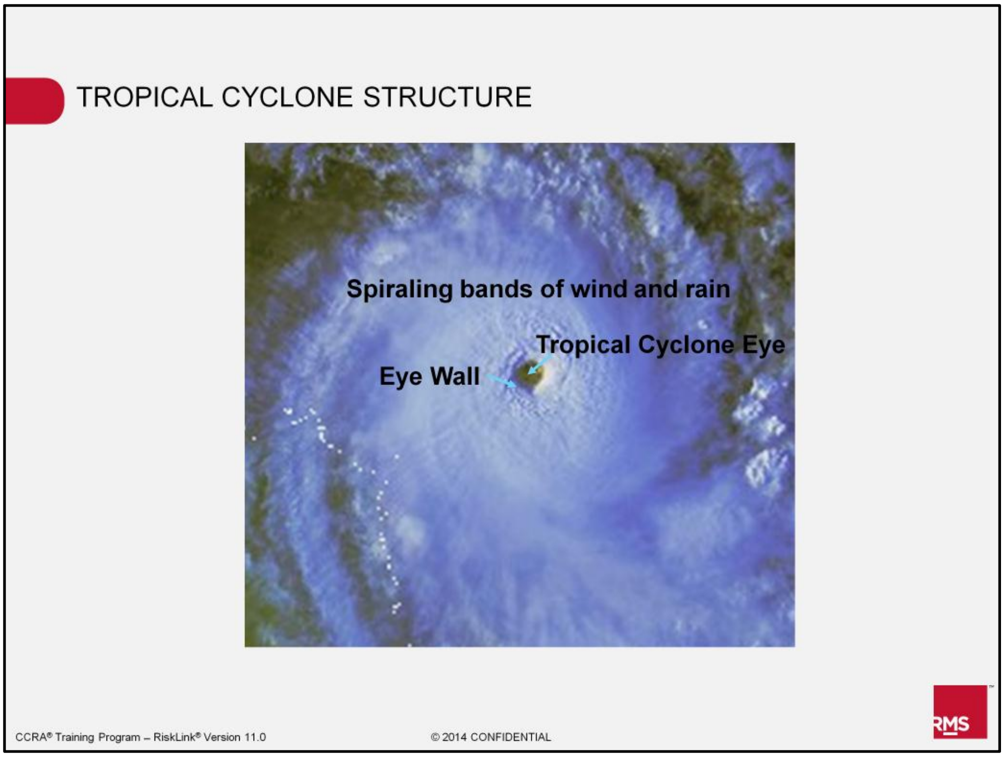
The main issue here is to understand why this is important in the early stages of hurricane formation. Close to the equator, the Coriolis force is weak, so cyclonic systems (i.e., those that may go on to form hurricanes) form less readily, which is why most hurricanes are found north of 10 degrees North and south of 10 degrees South.



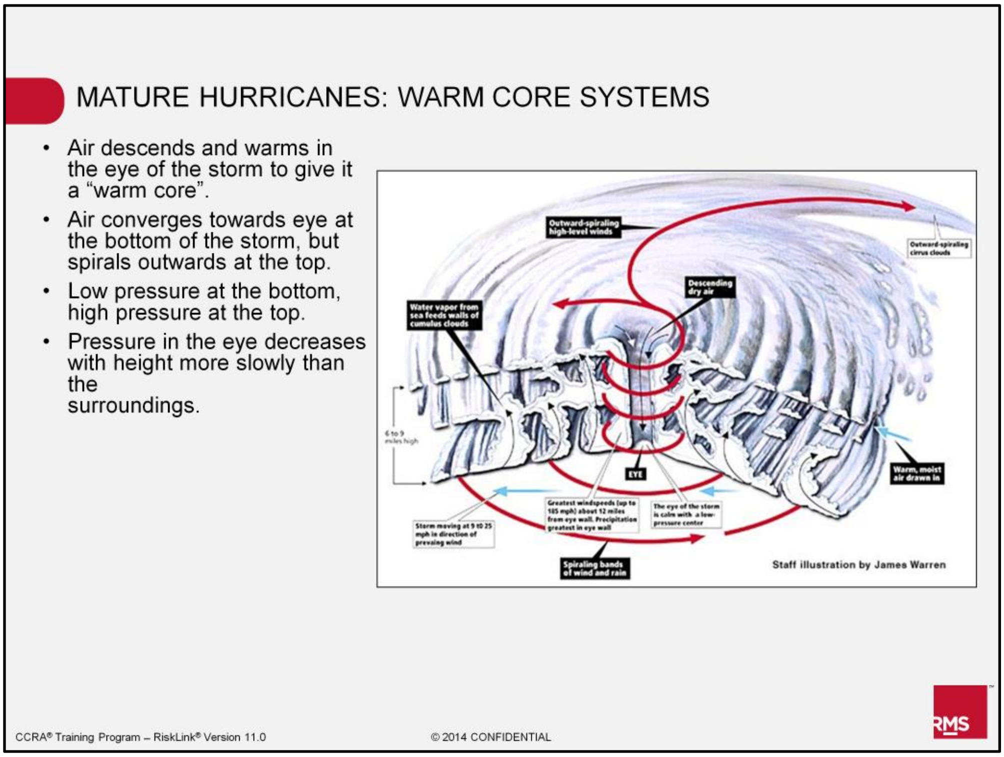
As mentioned, an area of spin or vorticity is required for hurricane formation. In addition, the atmosphere needs to be susceptible to thunderstorm formation in order for a tropical system to intensify. Typically this means that the air above the ocean needs to become cold very quickly as you move up through the atmosphere, rendering it unstable so that thunderstorms can develop readily. This also relies on the temperature of air at the surface to be significantly warm enough, hence the need for high sea surface temperatures in the hurricane development process.

When thunderstorms form, latent heat is released when the clouds form, which acts to decrease the pressure at the surface. Latent heat describes the amount of energy in the form of heat that is required for a material to undergo a change of phase, in this case from a gaseous state to a liquid state. As the billions of molecules of water vapor release latent heat as they condense into water, this warms the air enough to make it rise faster. As the air rises, more air flows in, creating wind. This also results in a decrease in surface pressure locally, which then acts to enhance the air spin at the surface.

Cyclonic circulation is enhanced by the influence of the Coriolis force around low pressure at the surface. The resultant increase in wind increases surface friction, leading to greater wind motion towards the center of low pressure. This has the effect of enhancing the thunderstorms and the whole process can become more intense, leading to lower surface pressure if the conditions detailed on the first slide of this section of the unit continue to be met.

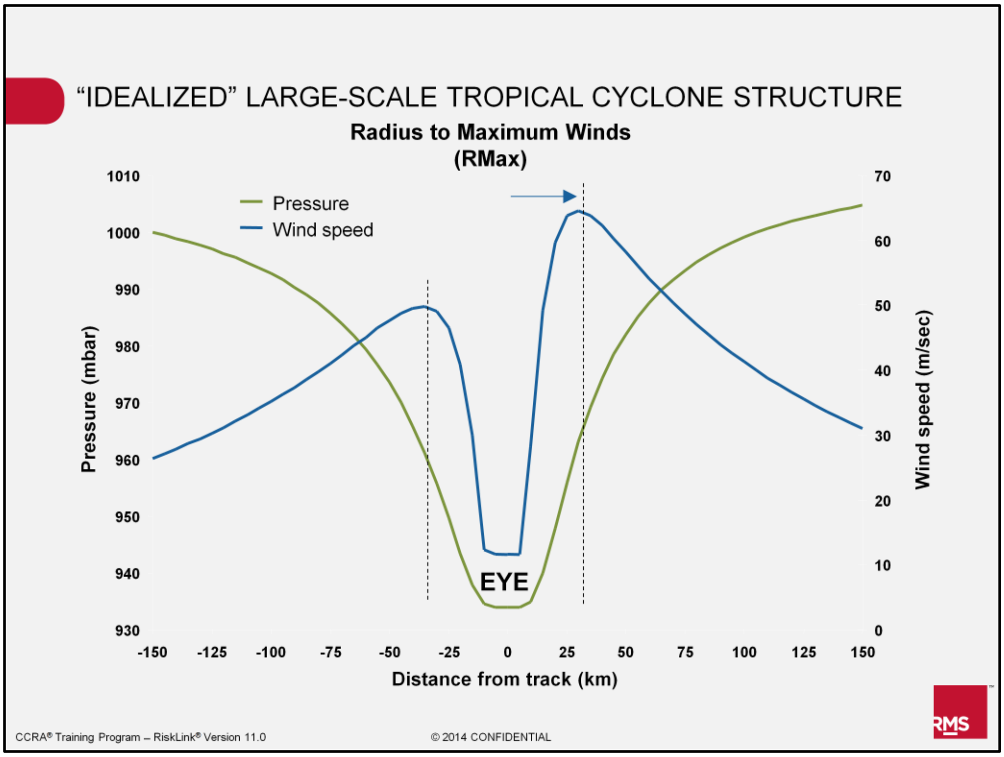


This next section looks at the structure of an intense tropical cyclone.



Well-developed tropical cyclones extend throughout the depths of the troposphere. The troposphere is the part of the atmosphere closest to the surface, which in tropical regions is typically about 16 kilometers (10 miles) in height. As mentioned earlier, the friction across the sea means that at the surface the air spirals inwards towards the center of the storm. Surrounding the center (or eye) of the storm, there is a wall of extremely intense thunderstorms. This is known as the eyewall. The air spiraling inward around the periphery of the tropical cyclone will also typically contain thunderstorms in features often called spiral rain bands.

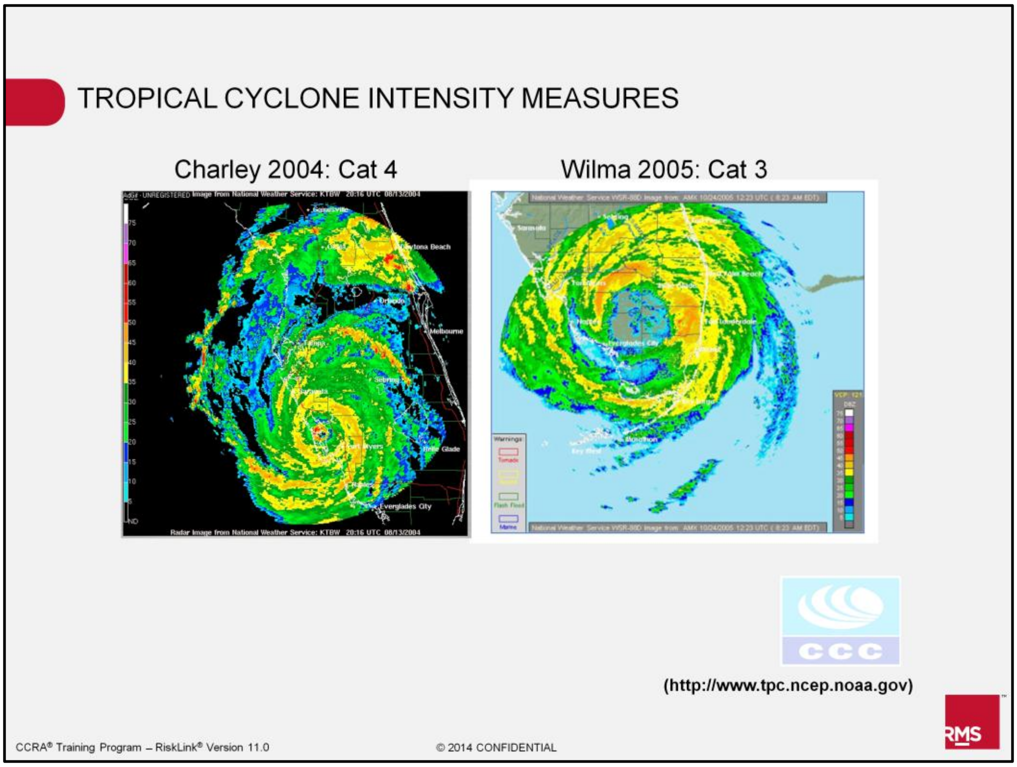
The center of the storm has a relatively cloud-free eye that is characterized by air that descends and warms. This air is warmer than the surrounding air, hence the fact that tropical cyclones are "warm core" systems. The eye itself is characterized by very weak winds, whereas the eyewall sees the strongest winds associated with the tropical system.



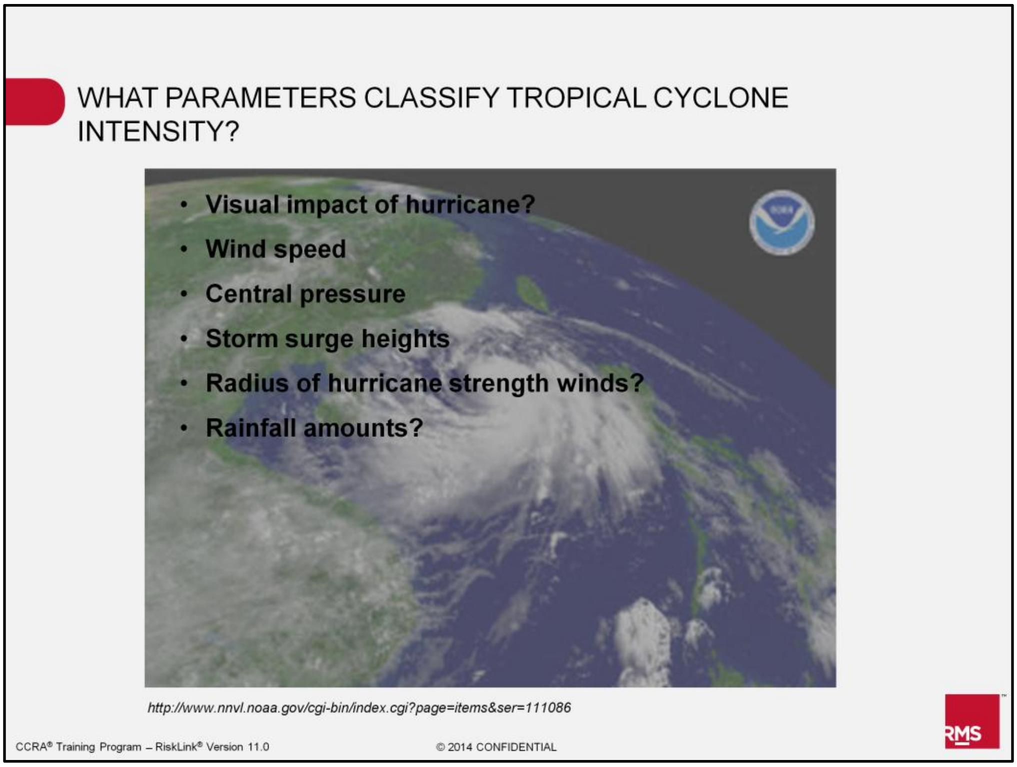
We can simplify the illustration shown in the previous slide by taking a slice through a well-developed tropical system to look at a cross-section of the hazard across the system. The cross-section shown in this example is perpendicular to the track of the storm. In this example we are showing a cross-section based on the RMS hurricane model parameters. Note that the graphed variation in these parameters approximate the structure of a hurricane.

The storm's pressure is indicated on the left y-axis. The green line shows how the pressure changes across the storm. It is lowest within the eye (at the center of the storm), but increases as one moves away from the center. To a good approximation, the rate at which the pressure changes as one moves away from the center of the storm is proportional to the wind speeds, which are shown with the blue curve, whose scale is on the right y-axis. The pressure drops off most quickly at the Rmax, the radius to maximum winds (highlighted by the blue arrow), where the winds are their strongest. The RMax is a good proxy for the size of a storm. Furthermore, the pressure changes very little in the eye of the tropical cyclone, which explains why the winds are very calm in the eye.

Another important thing to remember is that in this case, winds on the right-hand side of the storm are stronger than those on the left-hand side of the storm. We have to take into account the storm's forward speed of motion when calculating the wind speed. The speed of motion is additive to the wind speed on the right-hand side of the storm, and subtractive on the left-hand side. This additive/subtractive value is understandably more pronounced for faster moving tropical cyclones, and negligible if a tropical cyclone is stationary.



This next section reviews tropical cyclone intensity measures.



In 1969 when Herbert Saffir was asked by the UN to prepare a study on aspects of design and construction to mitigate damage caused by tropical cyclones, he proposed a hurricane scale to measure the storm's structural affects. Prior to that time, storm classifications were empirical, such as the Beaufort wind scale (1805), which is similar to the earthquake modified intensity scale in that it relies on visual observations to estimate wind speeds and impacts, rather than measured storm parameters to classify storms. The Beaufort scale starts at 0 and extends to 12 (hurricane force winds).

Saffir developed a scale based on central pressure and sustained wind speeds. Later, Robert Simpson, then director of the National Hurricane Center, modified Saffir's work, adding measurements for storm surge flooding heights. The result was the Saffir-Simpson Hurricane Rating scale, which is used today for Atlantic hurricanes.

More recently, there has been some discussion about creating a tropical cyclone classification that includes both rainfall amount and the size of the tropical cyclone. The thought is that these parameters should be included to better classify the level of damage that would be expected.

Interestingly, the Beaufort scale is still widely used in China. Taiwan also uses the Beaufort scale, which was extended in 1944 with Forces 13-17, to better represent the wind caused by typhoons. Hong Kong and Macau continue to use Force 12 as the maximum. As a recent example, Typhoon Prapiroon (shown on this slide) made landfall at the coastal area between Yangxi County and Dianbai County in western Guangdong at 7:20 p.m. Thursday, August 3, 2006. With a speed of 33 meters per second (74 miles per hour), the wind power near its eye reached 12 degrees on the Beaufort Scale.

SAFFIR-SIMPSON HURRICANE SCALE FOR ATLANTIC HURRICANES

- The Saffir-Simpson Hurricane Wind Scale was updated in early 2010 to remove storm surge, following Hurricane's Ike and Katrina where the storm surge was disproportionately larger than the hurricane intensity at landfall.

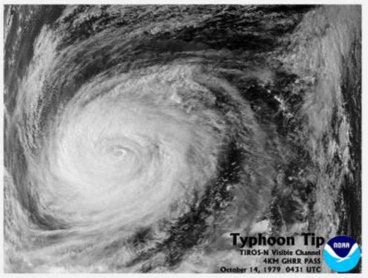
	Category	Wind (mph)	Wind (m/s)	P_{eye} (mb) (hPa)
	Tropical Depression	<38	<17	n.d.
	Tropical Strom	38-73	17-32	n.d.
Hurricane	1	74-95	33-42	>980
Hurricane	2	96-110	43-49	965-979
Hurricane	3	111-130	50-57	945-964
Hurricane	4	131-155	58-69	920-944
Hurricane	5	>155	<69	<920

P_{eye} = Sea-level pressure in the eye

The Saffir-Simpson Scale is commonly used today to classify the strength of Atlantic hurricanes. The scale is divided into five intensities as shown on this slide. We have also included the tropical storm and tropical depression classification as well. The scale defines the ranges of wind speeds and central pressure values. The wind speeds refer to the one-minute sustained wind speed at 10 meters; a standard wind observing instruction. Commonly, meteorological agencies will refer to wind speeds in knots (nautical miles per hour). The conversion of knots to mph is 1 knot = 1.15 mph. Note that the wind speed of Typhoon Prapiroon (74 mph) just classifies it as a hurricane of category 1 on the Saffir-Simpson scale.

DIFFERENT SCALES IN DIFFERENT BASINS

Category	Australia Definition	U.S. Definition
0	< 37	< 74
1	37 – 60	74 – 95
2	60 – 88	96 – 110
3	88 – 115	111 – 130
4	115 – 143	131 – 155
5	> 143	> 155



JTWC Classification		WMO - Western Pacific	
<38	Tropical Depression	<38	Tropical Depression
38 - 74	Tropical Storm	38 - 54	Tropical Storm
74 – 150	Typhoon	54 - 74	Severe Tropical Storm
> 150	Super Typhoon	> 74	Typhoon

Note: Numbers are sustained wind speeds in miles/hr.

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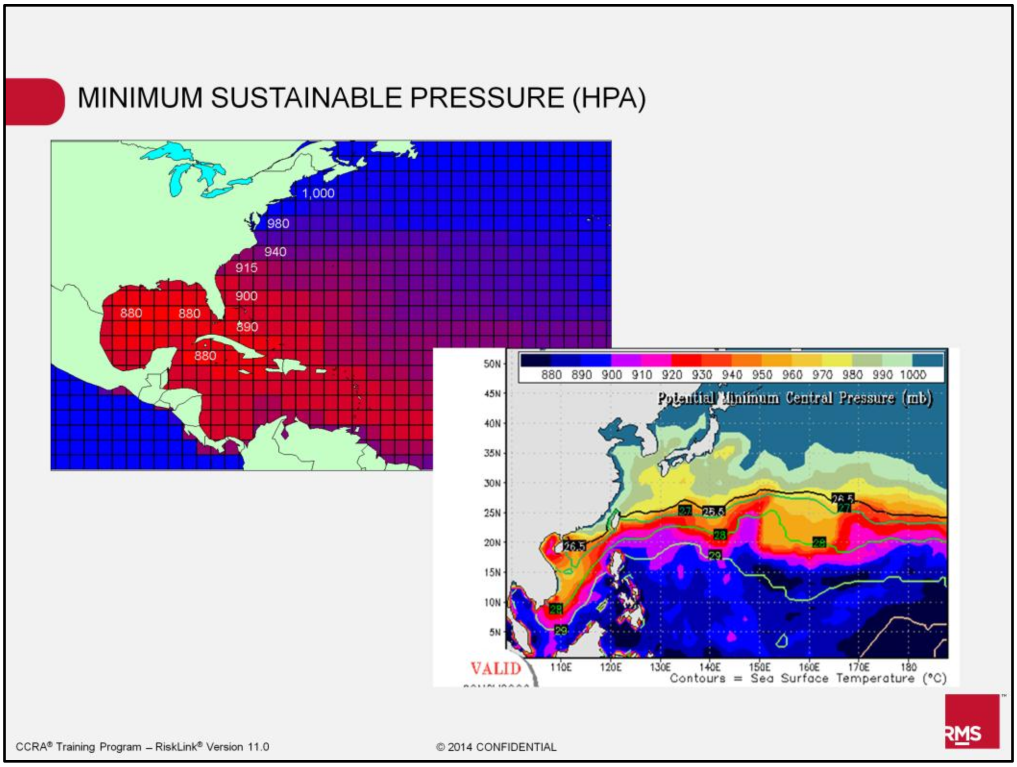
While the Saffir-Simpson scale refers to intensities in the Atlantic Basin, there are also scales for tropical cyclones in other basins as shown on this slide. Units shown here are sustained winds in miles per hour. Note that tropical cyclones become hurricanes in the Atlantic and Typhoons in the NW Pacific at the same (74mph) wind speed.

Wind speed advisories differ between scales. As an example, the Joint Typhoon Warning Center (JTWC) uses the U.S. criteria of one-minute mean to designate maximum sustained winds, while the Japan Meteorological Agency (JMA) uses the ten-minute mean wind criteria to designate tropical cyclone maximum sustained winds. This difference generally means that JTWC maximum winds will appear to be higher than the maximum winds described by the JMA for the same cyclone. Thus, it is critical to understand the underpinnings and definitions used in the classification of tropical cyclones.



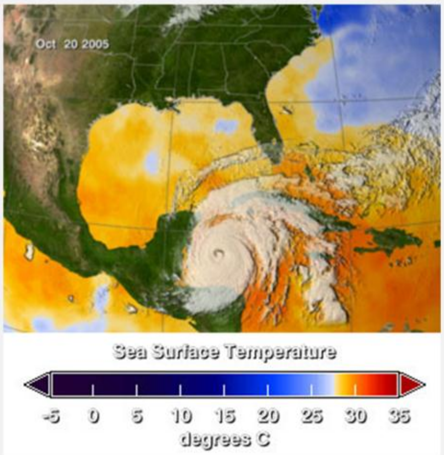
Modeling any natural peril risk requires not only an understanding of the mean and variability of the phenomenon, but also the extremes. The sea surface is the main source of energy for hurricanes, and thus, work has been carried out by meteorologists to look at the underlying sea surface temperature as well as the thermodynamics and physics of hurricanes to predict the lowest potential minimum pressure of hurricanes.

The upper left graphic on this slide shows the minimum sustainable pressure for a hurricane during the month of September using the mean sea surface temperatures and atmospheric conditions for that month. Clearly there is a trend here; stronger hurricanes with lower central pressures are possible in the Caribbean and the Gulf of Mexico where the sea surface temperatures are warmest (often exceeding 30 Celsius/86 Fahrenheit), and the lowest possible pressure increases as you move north and the sea surface temperatures decrease.

Real-time potential intensity products are also readily available via the internet during the course of tropical cyclone seasons, as shown for the Western Pacific in the bottom right hand graphic. These maps are available for all ocean basins at: http://wxmaps.org/pix/hurpot.html.

It should be noted, however, that hurricanes can develop over regions with high sea-surface temperatures and can hit regions with underlying sea-surface temperatures that are *not* high enough to support hurricane development. For example, the 1938 Hurricane that hit New England moved north from the region of high sea surface temperatures, and was quickly carried towards Long Island, hitting it with a central pressure of 938mb. There will be more about this storm in Unit 2.

TROPICAL CYCLONE INTENSITY SCALES



Microwave Scanning Radiometer (AMSR-E) instrument on NASA's Aqua satellite. +High resolution print still (8.9 Mb) Credit: NASA

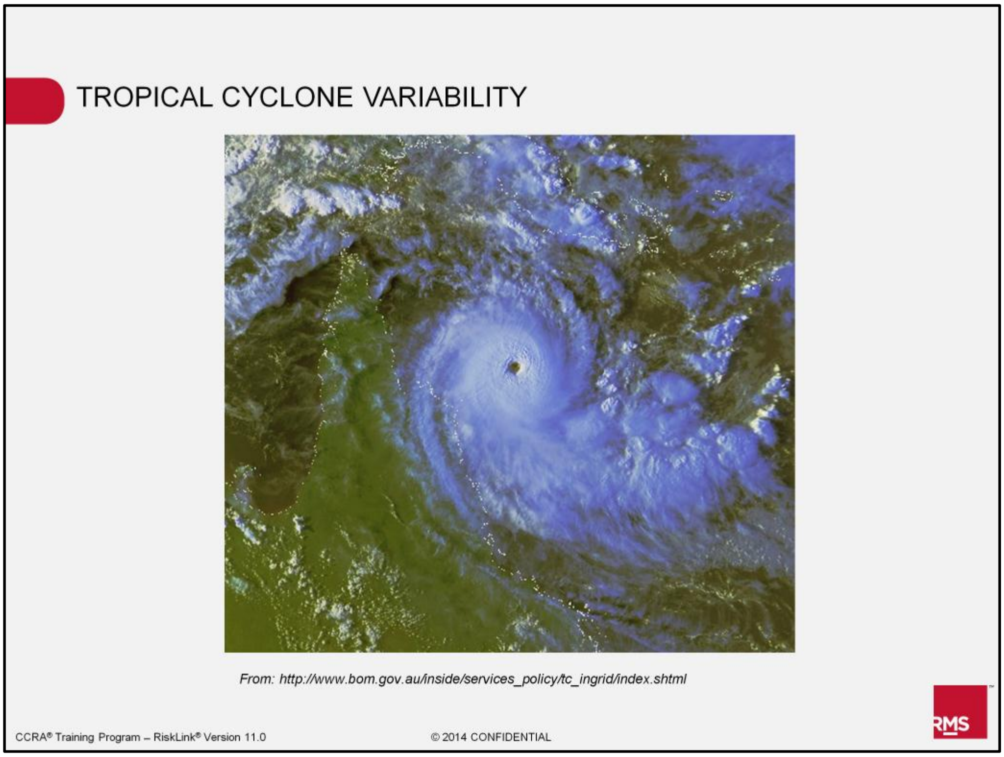
- Increasing SSTs increases frequency and intensity.
  - Increases the proportion of cat 3-5 hurricanes
  - e.g., Hurricane Wilma in 2005 strongest recorded Atlantic hurricane.
- As SSTs increase, the geographic pattern of hurricane formation can also be expected to change.
  - Shifts in activity towards the eastern part of the region (such as the so-called Cape Verde hurricanes) and western Caribbean Sea .
  - e.g., Hurricane Julia in 2010 set the record for the most intense storm the furthest east in the Atlantic Basin.

Based on current ocean and atmospheric conditions on Earth, the estimated maximum wind speed potential for hurricanes is about 190 mph. It is important to note that very intense storms are at the limit of our current observational and technological capabilities to accurately measure storm parameters, making accurate wind speed measures difficult.

Climate change and warming of sea surface temperatures may have the impact of increasing the estimated maximum wind speed potential, thus leading some to suggest introducing a higher hurricane category of 6 with a 176 – 196 wind speed range. In fact, in 2006, mainland China extended their version of the Beaufort scale to Force 17 the day (May 16) that Super Typhoon Chanchu was forecast to make landfall at Guangdong. It ultimately made landfall as a Saffir-Simpson category 1 typhoon on May 17th.

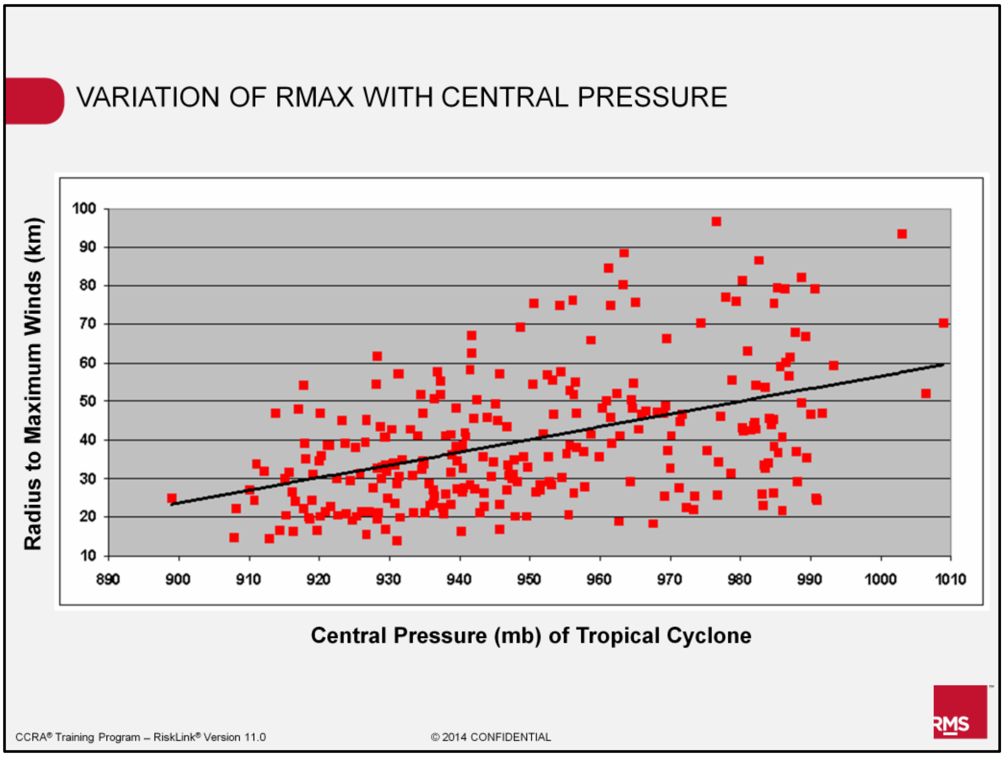
To date the strongest recorded Atlantic tropical cyclone is Hurricane Wilma (2005), which had maximum recorded wind speeds of 185 mph. Shown on the image are ocean temperatures surrounding Wilma, which hovered near 85 degrees F, about three degrees higher than the temperature required to fuel a hurricane. This image shows the sea surface temperatures (SSTs) from Oct. 15 - 20. Every area in yellow, orange, or red represents temperatures of 82 degrees F or above.

In the Western North Pacific, Super Typhoon Tip is the strongest tropical cyclone ever recorded since the beginning of the use of reconnaissance aircraft. On October 12, 1979, a central pressure of 870 mb was recorded. Using pressure/wind relationships, this extrapolates to winds gusting as high as 190 mph (306 km/h). The size of the circulation around Typhoon Tip was approximately 1,350 miles (2,174 km) across. If placed over the continental U.S., it would almost cover the western half of the country.



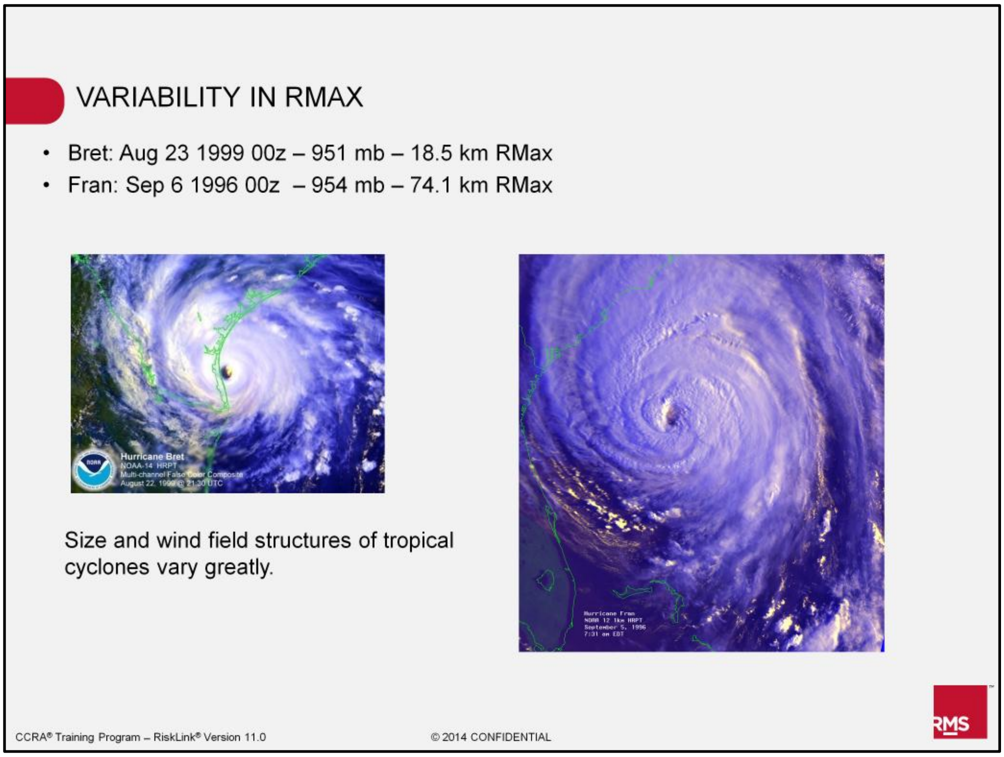
This next section looks at the variability in tropical cyclones. Although the mechanisms and basic structure of tropical cyclones are quite similar, they can vary in size and intensity, which can make quite a difference from storm to storm.

This is a photo of Cyclone Ingrid. Ingrid was a small cyclone in size, but very intense, not unlike Cyclone Tracy (the smallest diameter tropical cyclone recorded) that devastated Darwin, Australia in 1974. For this reason, communities more than 100 km from Ingrid's path (like Darwin) were affected only slightly. Also, while some significant rainfall was reported, (e.g., 445 mm in 24 hours at Emma Gorge in the Kimberley) the amounts were not as remarkable as those reported after some other larger, but less intense cyclones in the past.

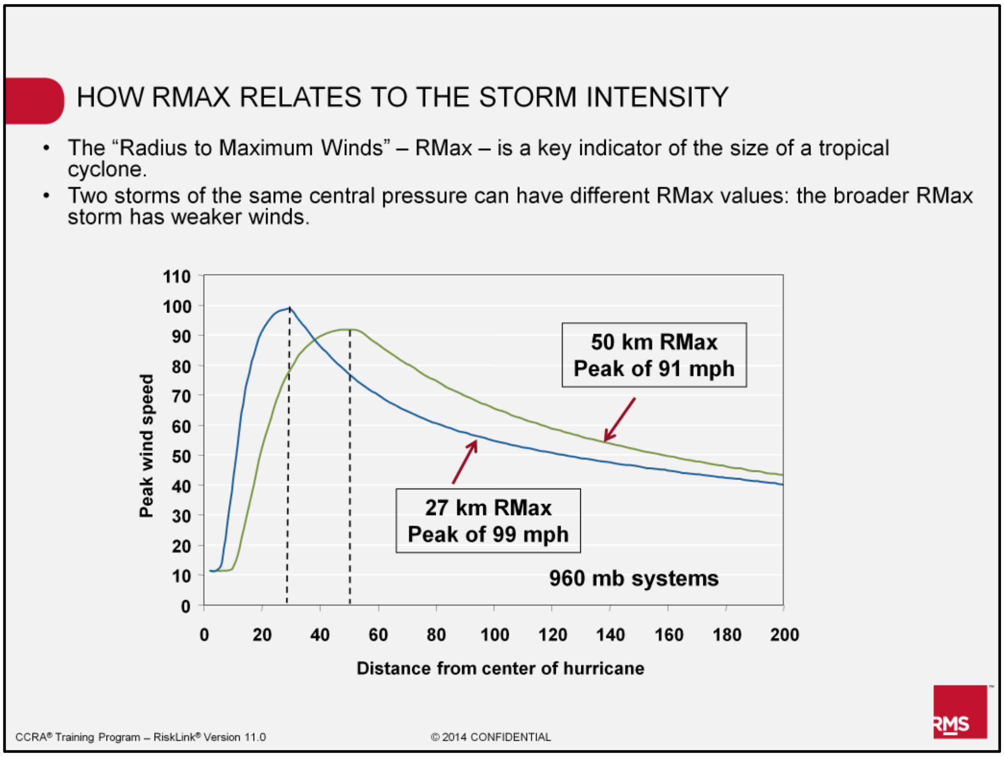


There are general trends between tropical cyclone size and intensity. Generally, the lower the central pressure of the storm (shown here on the horizontal, X-axis), the smaller the storm. The size of the RMax, the radius-to-maximum winds, is plotted here on the vertical Y-axis for a sample of simulated storms in the RMS hurricane model, which uses a large amount of observed hurricane structure data in its development so the data is a good representation of hurricane size-to-intensity relationships. For instance, the dangerous, 920mb, Category 5 hurricanes in this selection have a range of 15-50km for their Rmax (9-31 miles), whereas weak, borderline Category 1 hurricanes range from 25-90km in size (15-56 miles).

Clearly for any particular hurricane intensity there is a range of sizes, which leads us to the next slide.



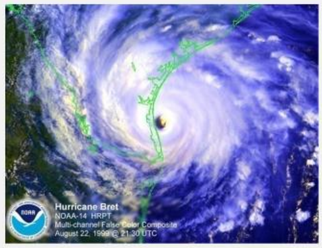
Here we see two satellite pictures of hurricanes to further illustrate this subject of variability – Bret on the left, which hit Texas in 1999, and Fran on the right, seen here near Florida in 1996. Both storms had very similar central pressures, but their RMax varied by a factor of approximately four. Bret was a small, tight-cored system with an 18.5 km Rmax (11.4 miles), but Fran's RMax was much broader at 74.1 km (46 miles).



It is also important to realize that for storms of similar central pressure, the size of the storm will help to govern the strength of the winds. The example we show here is of two 960 mb hurricanes with differing RMax values. The wider storm has a peak wind speed of 91 mph (147 km/h), but the smaller, tighter storm has stronger peak winds, with a wind speed of 99 mph (159 km/h). This demonstrates that although two storms can be very similar in central pressure, the size of the storm itself will in part dictate how strong the winds will be. In other words, there is no completely reliable one-to-one relationship between wind speed and pressure.

THE TRACK OF THE CYCLONE

- Correlation between tropical cyclone intensity and potential damage
- But the track of the cyclone is also important!
- 1999 - Bret, Cat 3
  - $15 million damage
- 2005 - Katrina, Cat
  - First landfall in Florida - $1 billion damage



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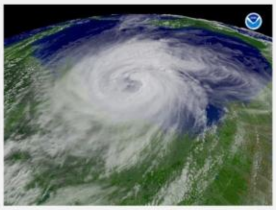
Lastly, the intensity of a tropical cyclone is clearly related to the potential for damage it can cause. However, for all a hurricane's potential, the track that the tropical cyclone finally takes will obviously have the greatest bearing on the insured losses.

To demonstrate this we will look at Hurricane Bret, which hit Texas in 1999 as a Category 3 hurricane on the Saffir-Simpson Scale. Though it was a Category 3 hurricane, it caused only $15 million in loss because it passed largely over uninhabited or underdeveloped regions. Hurricane Katrina, on the other hand, was only a weak-to-moderate Category 1 hurricane when it made its first landfall on Florida. However, because of the high underlying exposure that it passed over, losses were on the order of $1 billion, which is a loss of about 60 orders of magnitude higher than Hurricane Bret even though it was two scales lower on the Saffir-Simpson scale. Slight changes in the track of a tropical cyclone on the edges of large metropolitan regions can have huge impacts on the amount of loss that can be caused.

STORM SURGE – RECENT EVENTS



- HU Katrina, 2005

  Caused orders of magnitude more storm surge damage than anticipated by the NHC.

- HU Ike, 2008

  Storm surge generated by this Cat 2 hurricane was far greater due to large size and time spent over Gulf of Mexico.

- NOAA, 2010

  The Saffir Simpson Scale no longer uses storm surge as part of its classification of landfalling storms-decoupled from wind.

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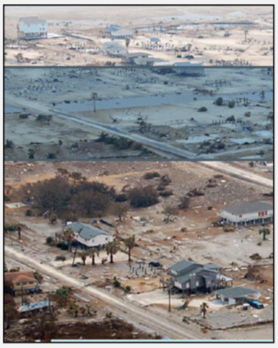
A tropical cyclone also has an effect on the underlying sea surface – it creates a storm surge. Storm surge modeling has in recent years taken a great leap forwards compared to the early to mid 2000s.

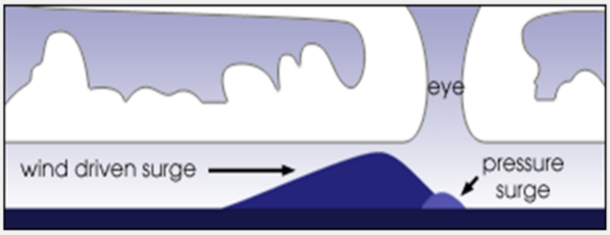
Katrina and Ike both produced storm surges much greater than expected based on the landfall characteristics of the hurricane, due to their offshore characteristics. They were much larger and more intense out at sea. In response, NOAA removed storm surge from its saffir-simpson scale in 2010, in recognition that landfall characteristics are not a good predictor of the surge size and extent.

Storm surge is now modeled as a primary model, not a secondary peril within the RMS modeling framework

KEY CHALLENGES IN MODELING SURGE

Storm surge is the water driven on land by a combination of pressure drop and wind stress.





Key Challenges:

- There are some observations from past events (sea surface heights/flood stage), but somewhat limited complete gauge records.
- Areas affected includes a wide range of geological characteristics.
- Surge is the combination of the offshore & onshore storm characteristics, tides, and geology, ***not just landfall parameters.***

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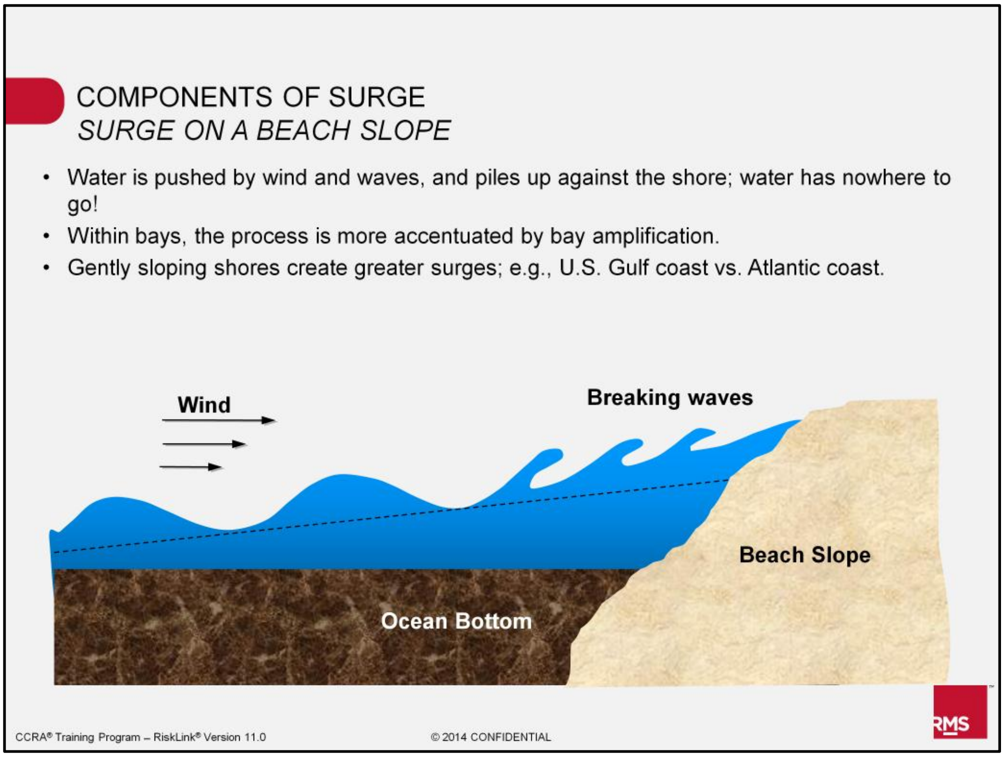
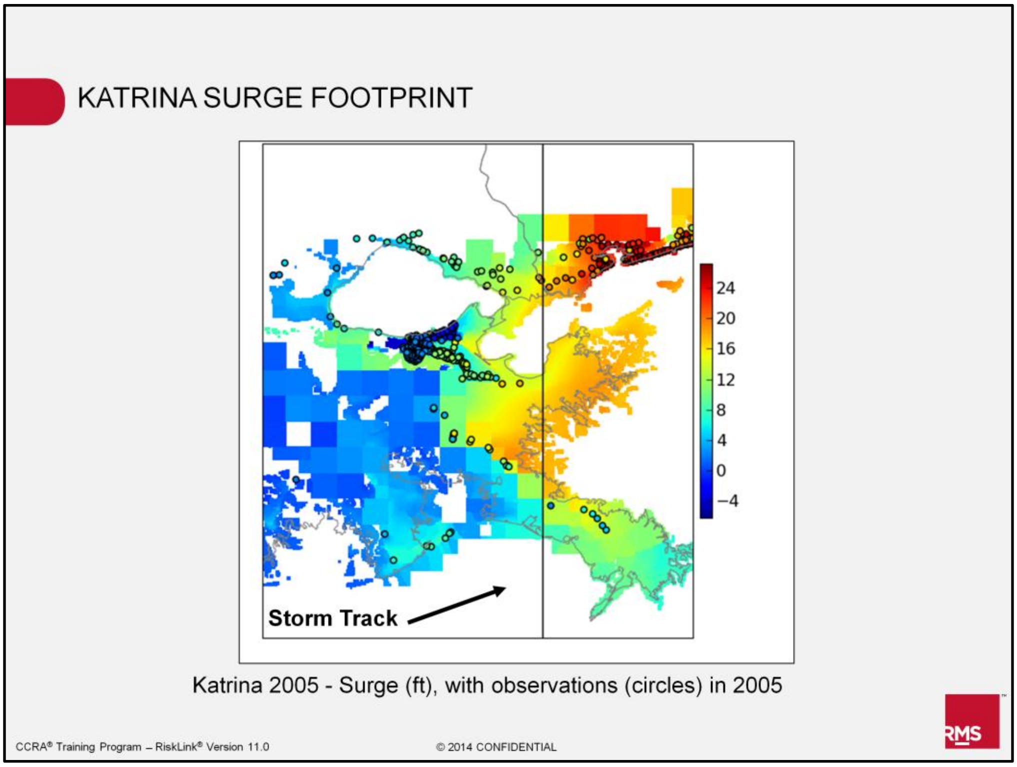
Some of the challenges in modeling storm surge are listed on this slide. There are some observations from past events but they are somewhat limited in the number of complete gauge records. In addition, an area affected could include a wide range of geological characteristics. Finally, storm surge is not just about landfall parameters; surge is the combination of the offshore and onshore storm characteristics, tides, and geology.



The wind drives the surge towards the shores, and the water effectively piles up against the shoreline; it has nowhere to go. This process is more accentuated with enclosed bays, where the process is known as bay amplification. Interestingly, the wind-driven wave action by surge increases with wind speed up to hurricane force, but does not increase beyond because the wave tops become partially chopped off by the winds above hurricane force, limiting the growth of waves beyond this wind speed.



Here is the surge footprint produced for Hurricane Katrina. Katrina was an interesting storm in that although it was only classified as a Category 3 storm when it made landfall on the Gulf Coast, the surge that accompanied the storm was more akin to a Category 5 storm in places.

COLLATERAL PERILS

- Tree Damage
- Power Outages
- Inland Flooding

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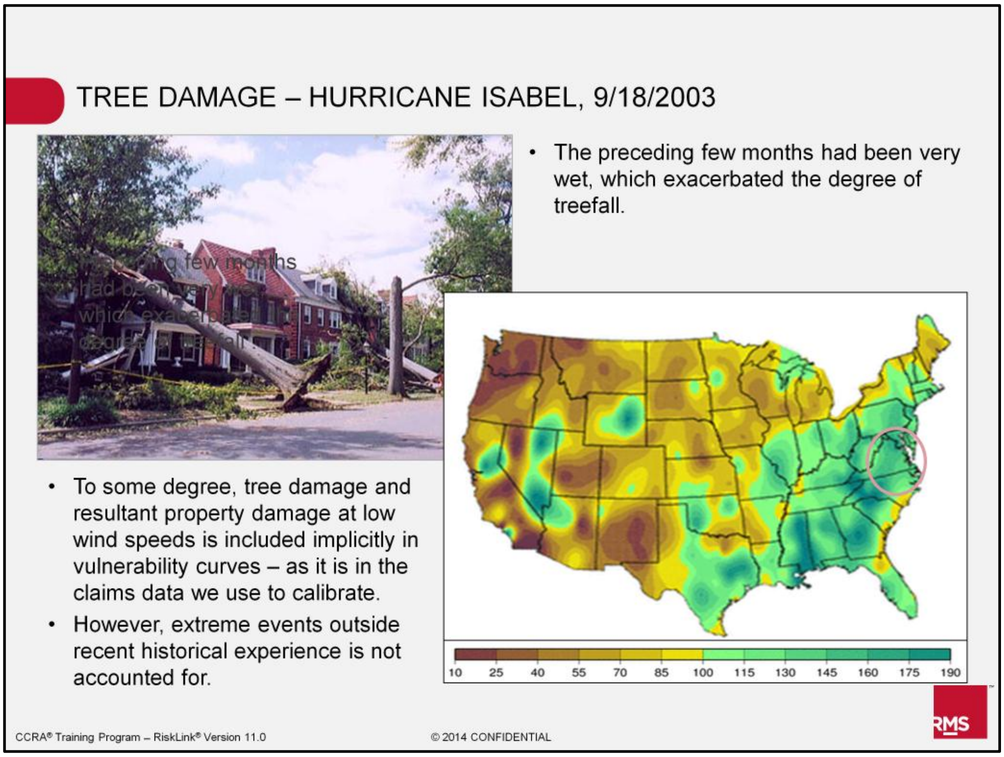
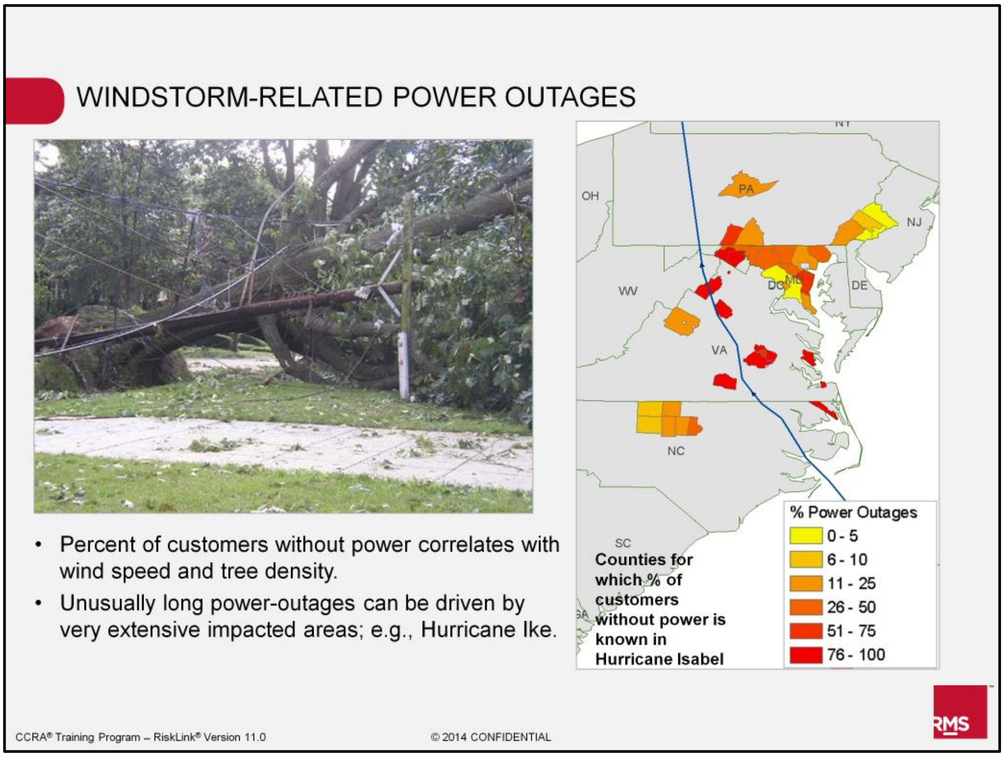
Having discussed the wind damage issues for tropical cyclones, we now move on to look at other sources of loss and damage that these systems can inflict. We have listed three of the main perils that are collateral to tropical cyclones: tree damage, power outages, and inland flooding.



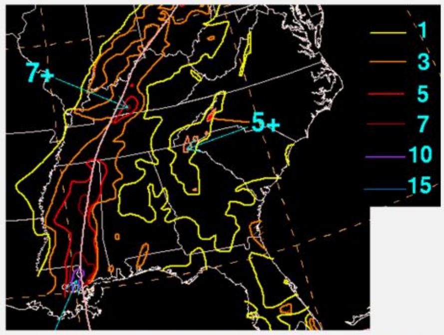
Damage due to trees was highlighted with Hurricane Isabel where significant losses occurred at very low wind speeds that normally are right on the threshold for causing damage. It has been quoted that tree loss may have caused more than 10% of the losses experienced during Isabel. These losses were incurred not only from trees falling on properties, but also the expenses from the removal of fallen trees. The map on the right highlights the percent difference from the mean of the rainfall from the three months prior to Isabel, indicating that the area around Isabel's landfall, shown by the red circle, had received well-above average rainfall prior to Isabel. This resulted in weakened root systems, making trees more susceptible to falling at lower wind speeds than one would expect. Tree density in urban areas was also higher in the landfall area of Isabel, which compounded the issue even further.



Another threat related to falling trees during a tropical cyclone is power outages. Although tropical cyclone winds might be severe enough to destroy some structures, it is unlikely that wind is the direct cause of a power outage. The figure on the right shows counties for which the percentage of customers without power was known after Hurricane Isabel. There is an obvious correlation between the distance to the track and the percentage power outage. The relationship of power outages to fallen trees is common for many storms, but was more pronounced after Isabel given the circumstances preceding the event.

INLAND FLOODING

- Not included within the hurricane model
- Heavy hurricane-related rainfall causes rivers to overflow and flash flooding
- Can be a relatively big proportion of the loss for tropical storms (e.g., TS Alison, 2001), and for the remnants of Hurricanes inland (e.g., HU Ivan, 2004 and Floyd, 1999)
- Additional impacts
  - Contaminates fresh water supplies
  - Erosion
  - Threat to vessels



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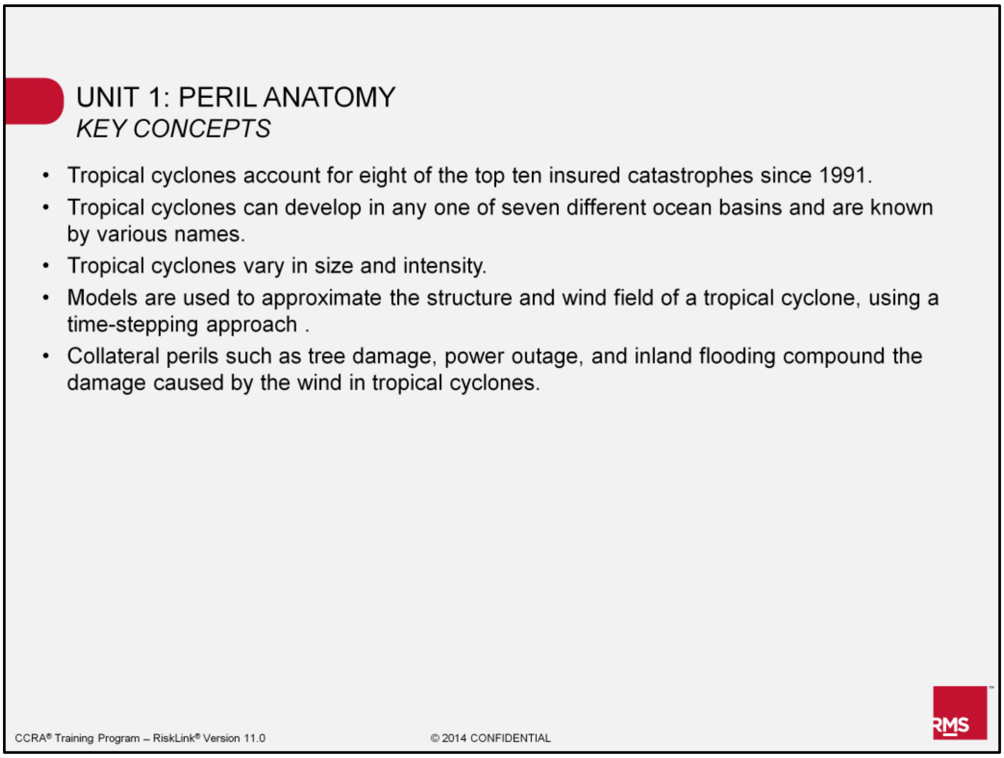
RMS

Lastly, inland flooding is another cause of additional damage. RiskLink® does not yet cover this collateral peril, but it may be included in the future. The amount of loss related to inland flooding tends to be especially heavy late in the life cycle of a storm, when storms interact with the jet stream and start to transition into extra-tropical cyclones. Among the threats related to inland flooding are the blocking of river mouths, contaminated fresh water, and enhanced erosion.



This slide highlights the key points from Unit 1. We encourage you to review these topics to ensure that you have a good understanding of each one before proceeding to Unit 2.