Stages of a typical Tropical Cyclone Lifecycle

This information has been summarised from the Introduction to Tropical Meteorology (2nd Edition) which can be accessed, free of charge, on the MetEd/ COMET website (requires free registration).

The key stages in the lifecycle of a typical tropical cyclone are:

1. **Incipient disturbance.**
2. **Tropical storm.**
3. **Tropical cyclone** (hurricane, typhoon).
4. (possibly) **Severe tropical cyclone** (major hurricane, super-typhoon).
5. **Decay / extratropical transition.**
6. **Post-landfall structure.**

Having reached its peak intensity at one of these stages the storm will either decay or undergo **extratropical transition** (the movement of the tropical cyclone from the tropics to the mid-latitudes). These stages are associated with changes in the storm intensity and structure.

This review of the physical stages of the storm lifecycle is illustrated by the stages of Hurricane Rita (2005).

Stage 1 - Incipient Disturbances

A tropical cyclone will not develop instantaneously: some intermediate, weaker disturbance is needed to provide the "seed" from which a tropical cyclone can develop (Fig. 1). In contrast to our expectations for a tropical cyclone, the incipient disturbance can be very **asymmetric**.

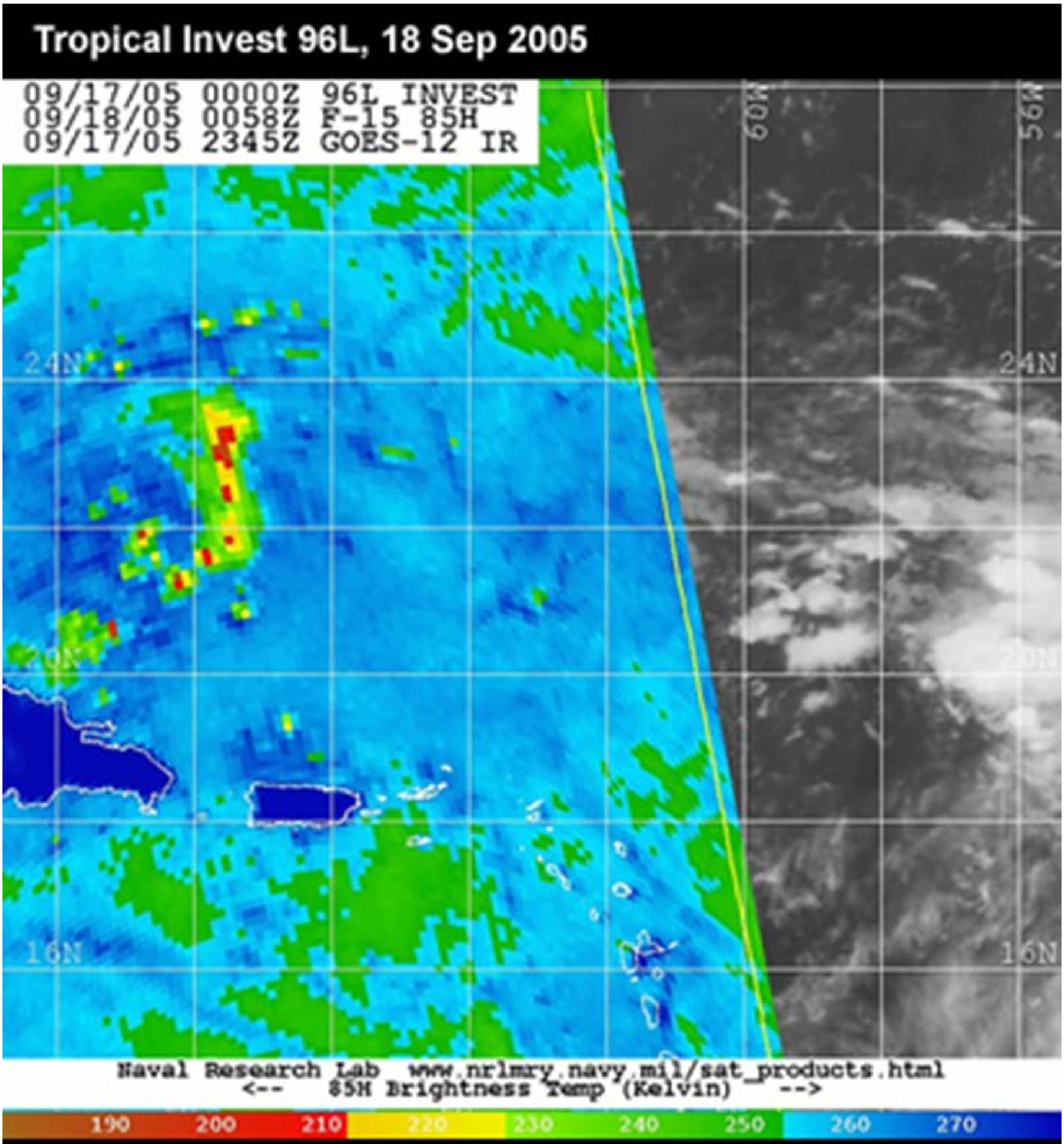

Figure 1 *Combined infrared and SSM/I satellite image for Tropical Invest 96L, the disturbance that became Hurricane Rita (2005). Images are taken near 0000 UTC 18 Sep 2005. Note the "hook" of intense convection near the western edge of the image. The peak surface winds associated with this disturbance were estimated to be 12 m s-1 with minimum surface pressure of 1012 hPa.*

A promising incipient disturbance is one that satisfies all of the necessary, *but not sufficient*, conditions for tropical cyclogenesis:

- cyclonic circulation in the low levels of the atmosphere
- weak vertical wind shear
- association with deep convection.

Disturbances meeting these criteria differ in their own formation histories in the different tropical ocean basins:

- **Western Pacific and Indian Oceans**
  The monsoon trough is the dominant location for tropical cyclogenesis in the Pacific and Indian Oceans, but equatorial Rossby and mixed Rossby gravity waves are increasingly being recognized as potential initiators of tropical cyclogenesis (the start of the organised, rotating storm) in these basins. Furthermore, the merger of a number of smaller storms has also been identified as a mechanism for tropical cyclogenesis in the North Pacific.
- **Eastern Pacific**
  Tropical storms forming in the eastern North Pacific have been identified with both instabilities in the ITCZ and with moist easterly waves (wavelike disturbances in tropical easterlies) and equatorial waves (caused and confined by the Coriolis effect with distance from the equator) intruding from the Atlantic.
- **Atlantic Ocean**
  The monsoon in the Atlantic basin is mainly confined to West Africa. Easterly waves forming here are influenced by local convection and mesoscale (large-scale) systems that initiate near the Aïr Mountains (Northern Niger), Jos Plateau (central Nigeria), and Guinea Highlands. Another source of Atlantic tropical cyclogenesis is subtropical cyclones.

Summary

Asymmetric, unorganised incipient disturbances form due to local conditions

To have the potential to evolve into a tropical cyclones the disturbance must satisfy three conditions of cyclogenesis:

- Cyclonic circulation in the low levels of the atmosphere
- Weak vertical wind shear
- Association with deep convection.

Stage 2 – Tropical storm

Given a favourable environment, an **incipient disturbance** may organise into a **tropical storm**. Maintenance of these favourable environmental conditions for tropical cyclogenesis is ideal for further **intensification** to the tropical storm stage.

The warm ocean waters of the tropics provide the energy source for the tropical cyclone. Evaporation (latent heat flux – the heat taken up by water vapour as it evaporates and then released as it subsequently condenses) and heat transfer (sensible heat flux – commonly referred to as conduction) from the ocean surface warms and moistens the tropical storm boundary layer. Taken together the heat and moisture fluxes (flows) and the potential energy of the air comprise the **moist static energy** of the air. Conversion of this moist static energy into kinetic energy via convection is the mechanism by which a tropical cyclone intensifies. (See **Intensity** document for theories relating to the potential intensity (PI) possible for a storm based on this mechanism and the reasons why every storm does not achieve its potential intensity).

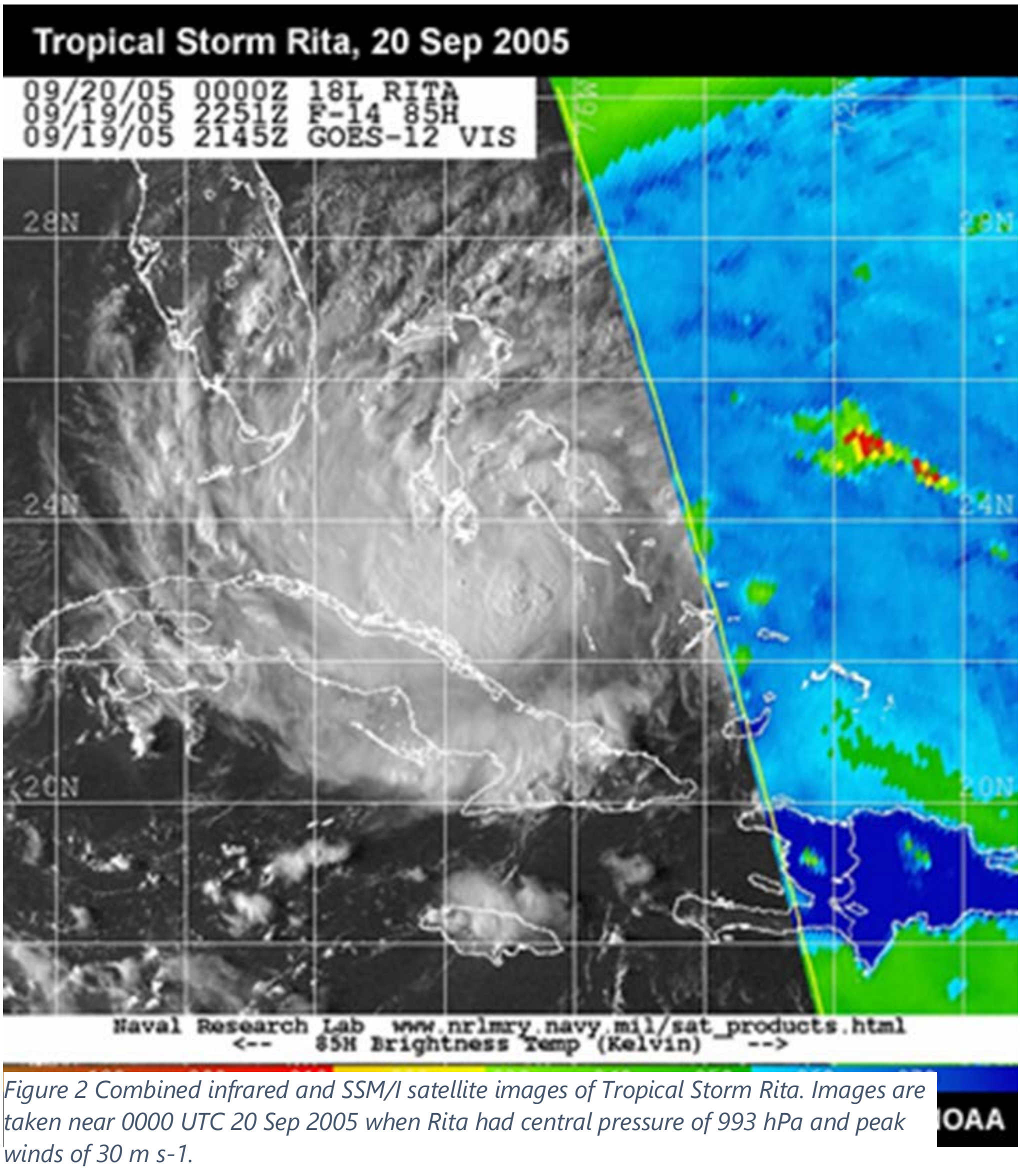

Figure 2 Combined infrared and SSM/I satellite images of Tropical Storm Rita. Images are taken near 0000 UTC 20 Sep 2005 when Rita had central pressure of 993 hPa and peak winds of 30 m s-1.

Operational centres require a consistent definition — **peak surface wind speed** — to decide when a system has become a **tropical storm**, but this is not always the most helpful definition for explaining the storm evolution as tropical disturbances require external forcing to be sustained.

For instance, a physically-based definition of the transition from a **tropical disturbance** to a **tropical storm** is that the system has become a tropical storm once it is **self-sustaining**. This means that, while external forcing might help or hinder the evolution of the tropical storm, it does not need external forcing to remain a coherent system, or even to intensify.

Summary

- An incipient disturbance may organise into a tropical storm in a favourable environment
- Intensification is driven by the flow of heat from the ocean – latent heat flux due to evaporation – and the within the atmosphere itself – sensible heat flux.
- The key physical characteristic of a tropical storm is that it is self-sustaining.

Stage 3 – tropical cyclone

The tropical cyclone is now an organised and self-sustaining system (Fig. 3). Traditionally, **vertical wind shear** (winds moving in different directions and/or at different speeds with height) has generally been considered to have a negative effect on tropical cyclone intensification though research is now challenging this view as vertical wind shear has been shown to intensify storms in marginal formation environments. (These storms must already be sufficiently intense to survive the initial disruption of their convection by the vertical wind shear, explaining why shear is still considered to be a negative effect on tropical cyclogenesis).

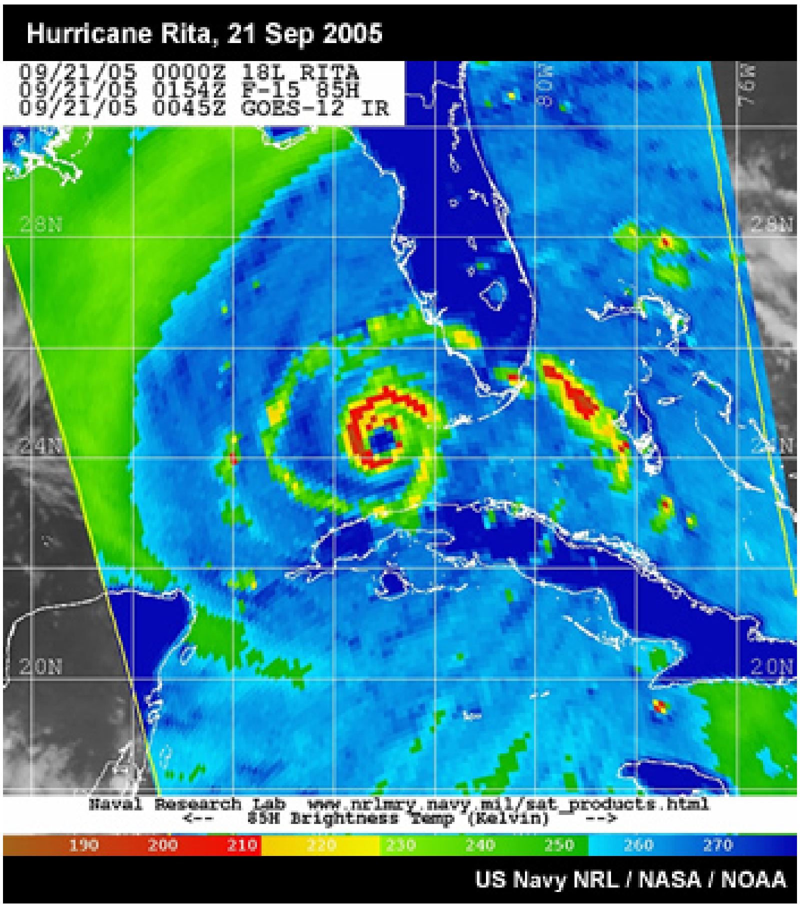

Figure 3 *- Combined infrared and SSM/I satellite images of Hurricane Rita. Images are taken near 0000 UTC 21 Sep 2005. At this time, Rita had peak winds of 45 m s-1 and central pressure of 967 hPa, making it a Category 2 on the Saffir-Simpson scale. Note the intense eyewall convection and clear eye.*

Regional differences also may provide the source of the forcing leading to this further intensification. For example, storms forming on the Northwest Shelf off the west coast of Australia may track parallel the coast for hundreds of kilometres. Warm waters on the shelf provide the ideal environment for continued intensification of these storms until they either encounter the midlatitude westerlies (and their associated strong vertical wind shear) or a dry air intrusion from the Australian deserts disrupts the convective organization of the system.

Summary

- Average wind speeds required for classification vary by basin,
- Vertical wind shear is likely to have a negative effect on storm intensification, but may not.
- Regional difference may provide forcing (external input) that lead to intensification.

Stage 4 - Severe Tropical Cyclone (super-typhoon, major hurricane)

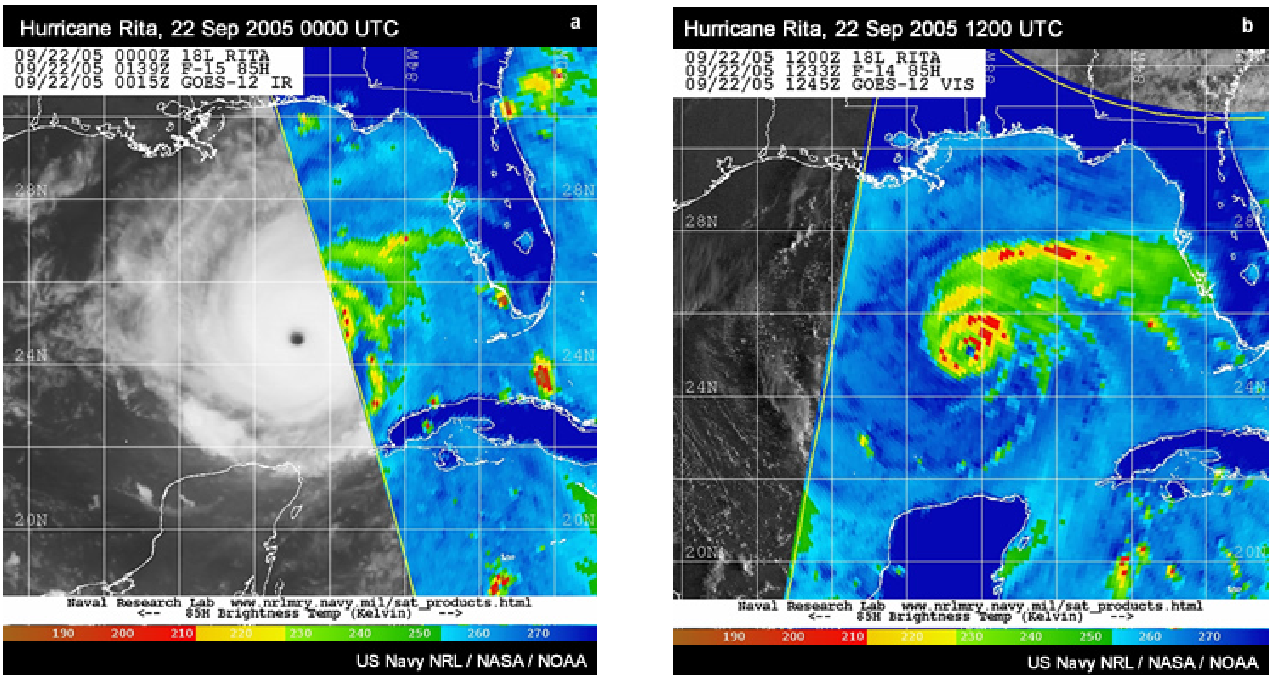

Figure 3. Combined infrared and SSM/I satellite images of Hurricane Rita at about 0000 UTC 22 Sep 2005 (a) and twelve hours later (1200 UTC; b). Rita was a Category 5 hurricane over this period, with peak surface winds of 75 m s-1 and minimum central pressure around 898 hPa (a). Note the clear eye and symmetry of the storm. The intense eyewall convection, spiral rainbands (green/red) with subsidence between (light to dark blue) and clear eye are evident in panel b.

Relatively few tropical cyclones reach this status, characterized by peak sustained surface winds in excess of 50 m/ s (Fig. 4). Intensification to **severe tropical cyclone** requires that the storm remain over the open ocean, so storms forming close to land are less likely to reach such intensities.

However, there are exceptions to every rule: the tropical cyclones off the Western Australian coast, described in the previous section, form and track relatively close to land; further, storms in the Bay of Bengal, Gulf of Mexico, and Western Caribbean have been observed to intensify rapidly into severe tropical cyclones.

One limit on the intensity of storms in the Southern Hemisphere is the relatively **zonal** (along a line of latitude) nature of the mean flow. The Southern Hemisphere has much smaller land masses and mountain ranges than the NH, providing less obstruction to the atmospheric flow. The result is more zonal mean midlatitude winds with the mean westerly zone being closer to the equator (which reduces the Coriolis effect). In contrast, the many mountain ranges and large extents of the Northern Hemisphere continents result in a large meridional (north/south) component to the mean flow, which can steer tropical cyclones to much higher latitudes. The relative susceptibility of Japan (roughly 36°N) to tropical cyclone landfalls compared to, say, New Zealand (about 42°S) illustrates this point.

Summary

- The storm has remained over open ocean to reach average wind speeds in excess of 50 m/ s
- Exceptions are Western Australia, Bay of Bengal, Gulf of Mexico, Western Caribbean.
- Storm formation and intensification is limited in the Southern Hemisphere by zonal flow (due to the lack of significant landmasses).

Stage 5 - The End of the Tropical Cyclone Lifecycle: Decay or Extratropical Transition (ET)

When a tropical cyclone moves into a **hostile environment** it will either decay (Fig. 5) or undergo extratropical transition. A hostile environment includes at least one of the following:

- **strong vertical wind shear** (in excess of 10-15 m/s over a deep layer)
- **cool ocean temperatures** under the storm core (less than 26°C)
- **dry air intrusion** (loss of moist air)
- **landfall** (increased turbulence with ground boundary layer)

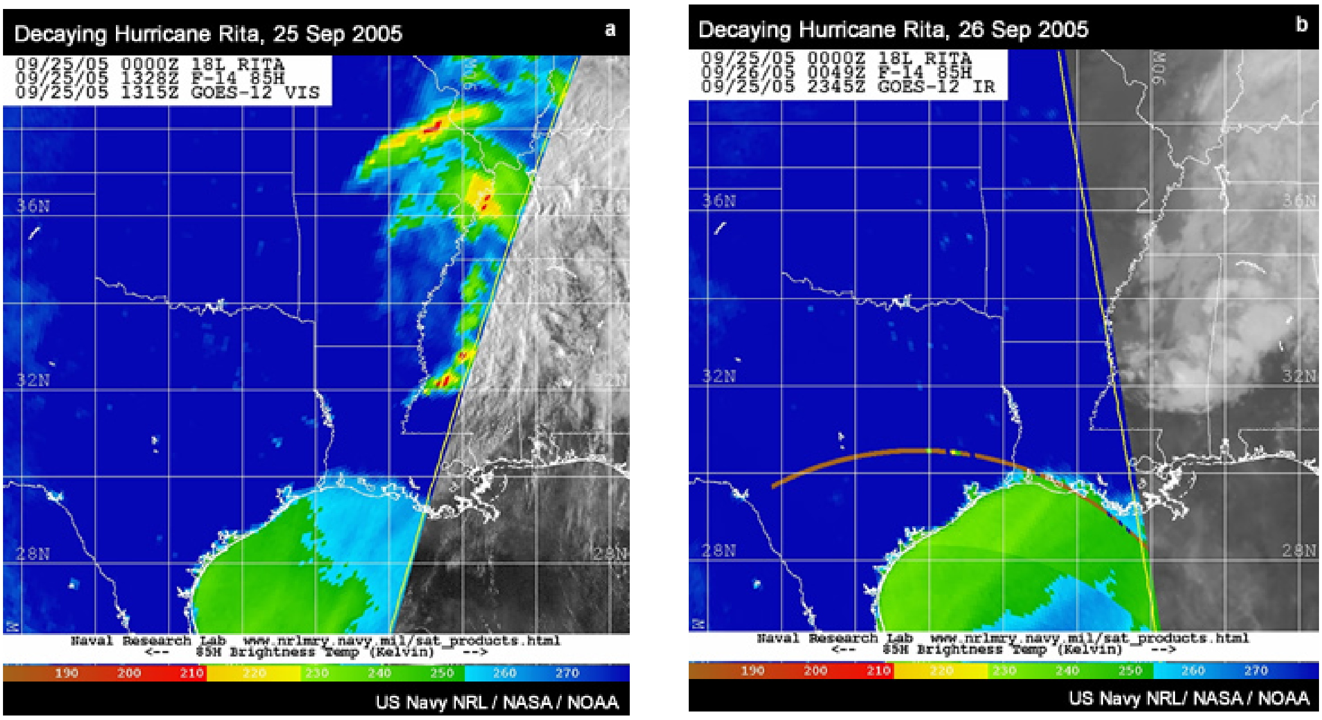

__Figure 5__. Combined infrared and SSM/I satellite images of the decaying Hurricane Rita between 1300 UTC 25 Sep (a) and 0000 UTC 26 Sep (b). Rita had decayed to 18 m s-1 peak surface winds and minimum central pressure of 983 hPa. The eyewall is no longer symmetric (a) and the eye is again overcast (b).

Cool sea-surface temperatures and strong shear are typical of a mid-latitude environment, explaining why this region is generally thought to be a tropical cyclone graveyard. The hostile environment may unbalance the storm so that it ceases to be self-sustaining—and will decay—but intense storms may instead undergo transition into an extratropical cyclone.

Summary

- A hostile environment comprising any of strong vertical wind shear, cool oceans temperatures, dry air intrusion or landfall will begin the process of decay.
- Extratropical transition will also weaken the cyclone.

Post-landfall Structure

Changes in the tropical cyclone boundary layer (the interface between the storm and the ground) when the storm crosses the coast — that is, when the storm "makes **landfall**" (Fig. 6) - critically influence the subsequent distribution of significant weather due to that tropical cyclone. From a forecasting perspective, "landfall" does not occur until the **centre (minimum pressure and winds) of** the tropical cyclone has crossed the coast.

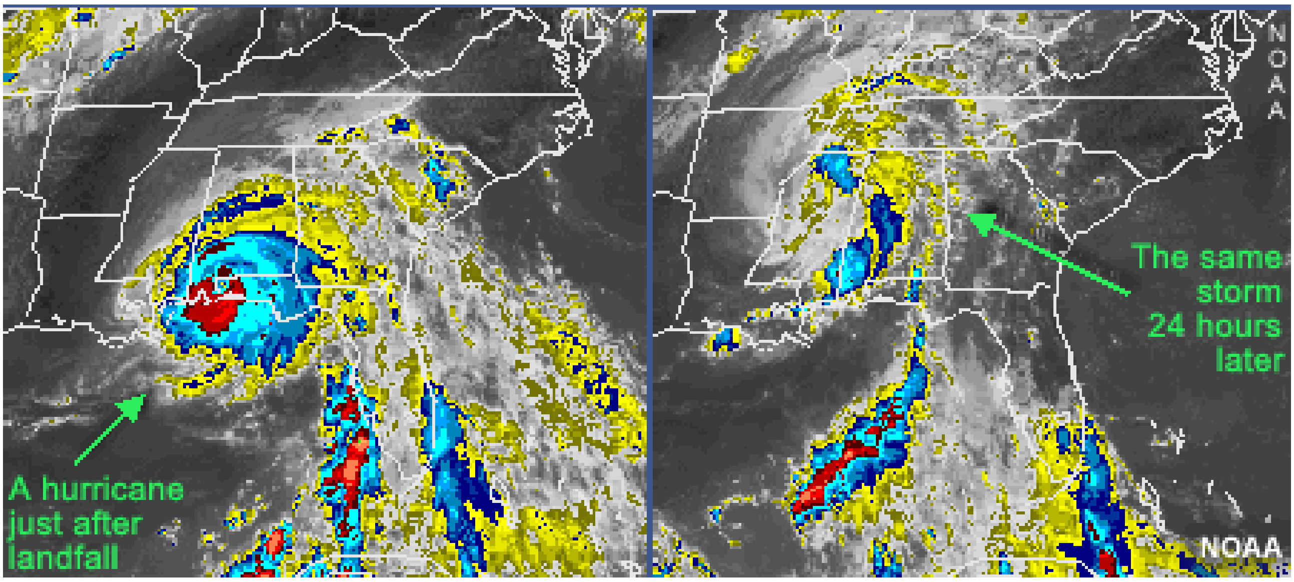

Figure 6. *An example of post-landfall structural changes.*

With rare exceptions (ships at sea, storms that stay just offshore, oil platforms and other structures), the **major impacts** from a tropical cyclone occur at, and after, landfall.

Two major changes of the storm environment at landfall cause it to weaken:

1. loss of the ocean energy source with the reduction in evaporation and therefore latent heat flux
2. increased friction (with the ground)

The resulting changes in storm structure leads to a **redistribution** of the significant weather associated with the storm.

Loss of the ocean energy source

Evaporation (latent heat flux) and **heat transfer (sensible heat flux)** from the ocean surface warm and moisten the tropical storm boundary layer, providing energy to feed the clouds that drive the tropical cyclone. When the storm loses this energy source it begins to weaken - the lack of a moisture source over land weakens the convection and associated subsidence in the eye weakens the upper tropospheric warm core, raising the central pressure of the storm. This increase in the central pressure leads to weaker pressure gradient and weaker gradient wind.

Increased friction

Surface friction effects on the atmosphere **increase significantly** after landfall. The ocean surface has less **drag** on the air than the solid land so the storm is able to sustain stronger peak surface winds over water. Land surfaces have a greater "roughness" (due to **topography** and **natural and man-made structures**) which leads to greater frictional drag and weaker winds.

These two mechanisms for slowing the surface winds **take time to act** and their influence will change with new changes to the surface. Any change in surface roughness (landfall or change in land use) will result in the formation of a new "**internal" boundary layer** that is in balance with the new surface. The (new) internal boundary layer will form in the timescale of an **inertial period of the storm** (i.e. the time for the storm to rotate 360 degrees), which is about an hour in the strong wind part of the storm.

The ultimate impact of landfall on the surface winds depends on a variety of factors. For example, if the storm comes ashore in the coastal plains and river deltas of the Gulf of Mexico, the **frictional effects** will be much less than if it makes landfall in a mountainous place like Taiwan or Central America. **Land use** also matters: all else being equal, a heavily built-up or forested area will have a larger frictional effect than a swamp—and evaporation of moisture from the swamp may delay weakening or even cause the storm to temporarily re-intensify.

A storm is generally modified differently by passage over an island compared to a continental land mass. For example, the loss of surface energy source and the increased friction will have less impact for a tropical cyclone moving over an island than if it moved completely over land. The size of the island and its **topographic** scale will cause a range of impacts on the storm.

While post-landfall structure changes generally lead to a decrease in the near-surface wind speeds as described above, the **roughness** of the terrain can contribute to regions in which the gusts are stronger than the frictionally-reduced surface winds.

The final effect of landfall on the tropical cyclone is the redistribution of its significant weather: weakening the surface pressure gradient causes the boundary layer convergence zone to shift outwards, leading to a redistribution of the convection and development of broad regions of **stratiform rain** (which feeds off the moisture transported onshore with the storm). The strong moisture gradient between the storm and its landfall environment coupled with the vertical wind shear profile can create the ideal conditions for **tornadic thunderstorms**. Tornadoes generated with the passage of Hurricane Ivan (2004) caused major damage in Florida, even though the storm made landfall further west. **Lightning** generated in the unstable coastal zone can also create a hazard (generally just offshore) to the population near the coast.

As with the frictional weakening of the storm, **topography** can play a role in these weather-related impacts: the topographic enhancement of the already intense rainfall associated with the storm. Hurricane Mitch (1998) is a terrible example of this combination of very intense rain with unstable mountain slopes leading to large-scale **mudslides** and loss of life in Central America.

Summary

- Landfall occurs when the centre of the cyclone crosses the coast.
- Major cyclone impacts occur after landfall.
- The loss of the ocean heat source (latent and sensible flux), and increased friction with the ground or the principle reasons for cyclones to weaken after landfall.
- Topography, land use, and ground roughness all influence the speed with which a storm weakens
- Ost landfall, as the cyclone loses organisation, it may generate tornados, lightning and cause secondary impacts dependent on local topography (such as mudslides).

Further information

- General overview
  http://www.wmo.int/pages/prog/www/tcp/documents/FactShtTCNames1July05.pdf
- Storm surge
  https://www.nhc.noaa.gov/pdf/sshws_statement.pdf
- Joint Typhoon Warning Centre
  https://www.metoc.navy.mil/jtwc/jtwc.html (Warnings, current map, reports, tracks, overlays)
- Australian Bureau of Meteorology – Tropical cyclones
  http://www.bom.gov.au/cyclone/index.shtml(Map, warning info/services, prep and safety, FAQs, plotting a track - http://www.bom.gov.au/cyclone/about/plotting.shtml)
  https://en.wikipedia.org/wiki/Portal:Tropical_cyclones