

ESCI 344 – Tropical Meteorology
Lesson 11 – Tropical Cyclones: Formation, Maintenance, and Intensification

References: *A Global View of Tropical Cyclones*, Elsberry (ed.)
Global Perspectives on Tropical Cyclones: From Science to Mitigation,
Chan and Kepert (ed.)
The Hurricane, Pielke
Tropical Cyclones: Their evolution, structure, and effects, Anthes
Forecasters' Guide to Tropical Meteorology, Atkinson
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'Tropical cyclogenesis in a tropical wave critical layer: easterly waves',
Dunkerton, Montgomery, and Wang *Atmos. Chem. and Phys.* 2009.
Global Guide to Tropical Cyclone Forecasting, Holland (ed.), online at
http://www.bom.gov.au/bmrc/pubs/tcguide/global_guide_intro.htm

Reading: *An Introduction to the Meteorology and Climate of the Tropics*, Chapter 9
A Global View of Tropical Cyclones, Chapter 3, Frank
Hurricane, Chapter 2, Pielke

GENERAL CONSIDERATIONS

- **Tropical convection acts as a heat engine, taking warm moist air from the surface and converting the latent heat into kinetic energy in the updraft, which is then exhausted into the upper troposphere.**
- **If the circulation can overcome the dissipating effects of friction it can become self-sustaining.**
- **In order for a convective cloud cluster to result in pressure falls at the surface, there must be a net removal of mass from the air column (net vertically integrated divergence).**
 - **Since there is compensating subsidence nearby, outside of a typical convective cloud, there really isn't much integrated mass divergence.**
 - **Pressure really won't fall unless there is a mechanism to remove the mass that is exhausted well away from the convection.**
 - **Compensating subsidence near the convection also serves to decrease the buoyancy within the clouds, because the subsiding air will also warm. This reduces the temperature difference between the in-cloud and outside air.**
 - **This illustrates the importance of upper-level outflow in tropical cyclones.**
 - **Even if there are pressure falls at the surface, the atmosphere could just generate gravity waves and readjust back to the original pressure, unless the**

Rossby radius of deformation is small enough to allow a residual circulation to form.

- Frictional effects will work against formation as well.
- The mechanisms by which a tropical cloud cluster can overcome the above effects and develop a sustained circulation are complex, and much is still unknown.
- Some literature refers to these mechanisms as providing a ‘crank-start’ for the tropical cyclone, in analogy to starting internal combustion engine.

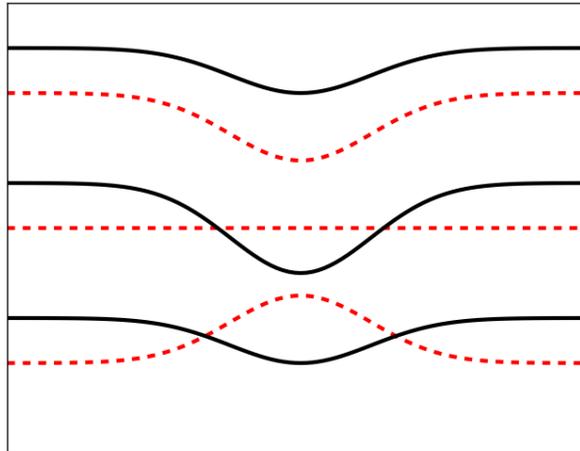
CONDITIONAL INSTABILITY OF THE SECOND KIND (CISK)

- An older theory for how tropical convection develops into a sustained tropical circulation is that of *conditional instability of the second kind* or *CISK*.
- In its simplest form, CISK can be explained as follows:
 - Latent heating of the atmosphere leads (through the hypsometric relationship) to a lowering of surface pressure.
 - The lowering of the surface pressure leads to enhanced radial inflow and convergence, which enhances the convection and latent heat release, which further decreases the surface pressures.
- CISK is then a positive feedback loop.
- There are several difficulties with using CISK to explain tropical cyclone formation.
- One problem is that in order for a circulation to form from the latent heating, the scale of the heating must be of the order of the Rossby radius of deformation ($L \sim 2\pi\lambda_R$).
 - In the Tropics, λ_R is large even for the baroclinic modes, so the mass field disturbances caused by latent heating from cloud clusters aren’t large enough to form circulation.
- In order to excite modes with a small enough Rossby radius of deformation, a heating profile that is concentrated in the lower levels is ideal.
 - However, the latent heating profile in most tropical cloud clusters is concentrated in the middle and upper levels, so it doesn’t excite the modes with low Rossby radius of deformation.

- Most studies of CISK have involved a linear approximation in which the different wavelengths, or modes, do not interact and exchange energy.
 - It is also possible that the non-linear interaction of the wave modes is important, which would allow energy that is input into one mode to be transferred into other modes that do have a horizontal scale closer to their Rossby radii of deformation.
- Although CISK has trouble explaining how cloud clusters form into a tropical cyclone, it can be used to explain how a tropical cyclone, once formed, intensifies, since as the vortex becomes stronger the Rossby radius of deformation in the core can become small enough to allow a mass-field disturbance to force a velocity field adjustment.

MESOSCALE CONVECTIVE VORTICES AND SYSTEMS

- Three relatively recent (1990's) theories for the development of tropical cyclones from tropical cloud clusters focus on the dynamics of mesoscale convective vortices which are mid-level vortices found in many tropical cloud clusters.
- Before discussing these theories a very brief review of mesoscale convective vortices is presented.
- *Mesoscale convective vortices* (MCV) are formed through the adjustment of the troposphere to convective heating. They occur both in mid-latitude and tropical mesoscale convective systems.
- The figure below shows an idealized vertical cross-section through an MCV. The solid lines are isobars and the dashed lines are lines of constant potential temperature.



- In the diagram the maximum in vorticity is in the middle, with decreasing intensity above and below.
- Since the MCV is in thermal wind balance there is a cold anomaly below, and a warm anomaly above the vorticity maximum.
- Mesoscale convective vortices often form in and are associated with *mesoscale convective systems* (MCS).
- An idealized mesoscale convective system contains two regions:
 - A *convective region* where new convective cells are formed and progress to maturity
 - In the convective region there is generally low to mid-level convergence, with divergence aloft.
 - A *stratiform region* formed from the remnants of the old cells from the convective region.
 - In the stratiform region there is generally mid-level convergence, with low-level and upper-level divergence.
- The three recent theories all attempt to explain how an MCV associated with an MCS can result in the formation and/or amplification of a vortex at the surface, which can then further develop into a tropical cyclone.
 - The three theories are broadly classified as: *Top-down Merger*; *Top-down Showerhead*; and *Bottom-up Development*

TOP-DOWN MERGER THEORY FOR DEVELOPMENT

- In the *Top-down Merger* theory, two or more smaller mid-level vortices merge into a larger mid-level vortex. The influence of this larger vortex is then felt through a deeper depth of the atmosphere, influencing development at the surface.
- The depth or vertical thickness to which a vortex penetrates is given by the *Rossby penetration depth*,

$$D_R = \omega L / N \quad (1)$$

where ω is the inertial frequency, L is the horizontal scale of the vortex, and N is the Brunt-Vaisala frequency.

- The larger in horizontal extent, or the more intense a vortex is (more intense vortices have higher inertial frequencies), the deeper the Rossby penetration depth.
- If two or more smaller, mid-level vortices merge then they will form a larger vortex that has a deeper Rossby penetration depth, and can therefore build down to lower levels.

TOP-DOWN SHOWERHEAD THEORY FOR DEVELOPMENT

- In the *Top-down Showerhead* theory we start with an existing mid-level vortex in the stratiform region of an MCS.
- Rain falling from mid-level stratiform clouds causes evaporative cooling in the low levels, and results in subsidence, which advects positive vorticity downward.
- The evaporative cooling also cools the lower levels, resulting in a cold anomaly that bows the isentropes upwards. Through thermal wind balance, this requires the pressure surfaces to bulge downward, extending the mid-level circulation downward.
- The lower levels have become humid and cool due to the evaporation of the rain falling through them. Once the downdrafts abate, convection can now fire in the low levels, resulting in low-level convergence and spin-up of low-level cyclonic vorticity.

BOTTOM-UP DEVELOPMENT THEORY FOR DEVELOPMENT

- In the theory of *Bottom-up Development* a low-level potential vorticity (PV) anomaly produced from a separate convective updraft moves underneath the MCV.
- The interaction between the PV anomaly and the MCV shifts the profile of divergence and convergence such that there is enhanced low-level convergence and spin-up of a low-level vortex, at the expense of the original MCV.

NEED TO ELIMINATE CONVECTIVE DOWNDRAFTS

- Another general consideration for development is the need to eliminate convective downdrafts.
- Regions with convective downdrafts are not favorable for development.
 - This is because convective downdrafts lead to low-level divergence, which will reduce, rather than enhance, cyclonic spin up.
- Having moisture in the mid and low levels will reduce convective downdrafts by reducing the evaporative cooling and entrainment which lead to downdrafts.

THE MARSUPIAL PARADIGM

- Regardless of which theories, Top-down Merger, Top-down Showerhead, or Bottom-up Development, explain development, it is important to have the region of development remain in a favorable environment long enough for the circulation to become self-sustaining.
- One very recent theory attempting to explain why some cloud-clusters develop into tropical cyclones while others don't is the *Marsupial Paradigm*.
- In the marsupial paradigm the favorable environment is located where the mean wind speed is equal to the phase speed of the tropical wave.
 - In this location, air parcel trajectories in a reference frame moving with the wave are nearly closed curves and are isolated from entrainment from the outside.
 - A vortex residing in this location can develop through the continual moistening and latent heat release of the air parcels 'trapped' within favorable location.

- **Once the vortex is strong enough to maintain itself on its own it breaks away from the parent wave.**
- **The marsupial hypothesis gets its name from an analogy to how a marsupial such as a kangaroo rears its young in a protective pouch until the young are ready to fend for themselves.**

MAINTAINING INTENSITY

- **There is a coupling between the winds in the boundary layer and the transfer of latent and sensible heat into the air as it spirals into the cyclone.**
 - **Frictional convergence of the tangential winds plays a key role in transporting latent heat into the core of the vortex.**
 - **The stronger the winds, the greater the frictional convergence into the core.**
 - **Also, the stronger the winds, the greater the transfer of latent and sensible heat from the sea surface into the inflowing air.**
- **The formation of an anticyclone aloft by latent heating aids in the upper-level mass divergence which is necessary to sustain and intensify the cyclone.**
- **Tropical cyclones can maintain themselves as long as there is sufficient inflow of warm, moist air into the cyclone, and there is adequate outflow aloft. Factors that can cause a tropical cyclone to fluctuate in intensity (either up or down) are:**
 - **Variations in SST.**
 - **Interaction with land, which can result in less evaporation and latent heat inflow.**
 - **Tropical cyclones can momentarily increase in intensity as they make landfall due to enhanced low-level convergence due to the increased friction over land.**
 - **Enhanced or suppressed outflow.**
 - **Increased vertical shear.**
 - **Vertical shear can cause the upper-level anticyclone and outflow to decouple from the low-level inflow. If the outflow is weakened, then the mass that is ejected into the upper troposphere by the convection can subside in the vicinity of the tropical cyclone and weaken the convection, as well as limit the surface pressure falls.**

SYNOPTIC SCALE INFLUENCES

- **Since tropical cyclone formation requires a pre-existing cyclonic disturbance, they normally form in**
 - **Monsoon troughs**
 - **Tropical waves**
 - **Old frontal zones or shear lines**
- **Any enhancement of vorticity is favorable for formation.**
 - **A cold surge in the wintertime hemisphere often will enhance the Equatorial westerlies, and is favorable for formation.**
- **Existing storms can influence the formation and development of new storms.**
 - **For storms that have not yet recurved, the path ahead of the storm is unfavorable for formation of another tropical cyclone, while the wake area behind it is favorable.**
 - **This is due to the large scale vertical motion pattern forced by the tropical cyclone.**
 - **The outflow from an existing storm can also sometimes provide too much shear over a region and suppress formation and development.**
- **Formation of upper-tropospheric outflow jets is key for development, since the upper-level mass divergence must be larger than the lower-level mass convergence.**
- **A north-east quadrant outflow jet is enhanced by linking with**
 - **the subtropical jet**
 - **a tropical upper-tropospheric trough (TUTT)**
 - **a deep mid-latitude trough**
 - **an upper-level cold low**
- **The position of the cyclone in relation to the above features is crucial for an enhanced north-east outflow jet. Although they enhance outflow, which aids deepening of the surface low, if they are too close then the increased westerly shear can inhibit growth.**
- **A south-west quadrant outflow jet is enhanced by an intense upper-level anticyclone in the opposite hemisphere.**