Cloud Dynamics - Hurricanes

Take Home Messages

Chapter

1 Overview and Introduction

- naming conventions for TCs depend on the region: **Hurricane** in North Atlantic and Northeast Pacific, **Typhoon** in Northwest Pacific, **Severe Tropical Cyclone** in Southwest Pacific and near Indonesia, **Tropical Cyclone** in the southern Indian and **Severe Cyclonic Storm** in northern Indian Ocean

Prerequisites for TC formation

THERMODYNAMIC	DYNAMIC
1. SST > 26.5 °C to at least 50 m depth → fuel for TC	1. at least 5° from the equator → Coriolis effect induces rotation
2. sufficient moist mid-troposphere	2. pre-existing weather disturbance with sufficient vorticity and convergence, e.g. a tropical easterly wave
3. conditionally unstable atmosphere $\Gamma_s < \gamma < \Gamma_d$	3. low vertical wind shear between surface and upper troposphere

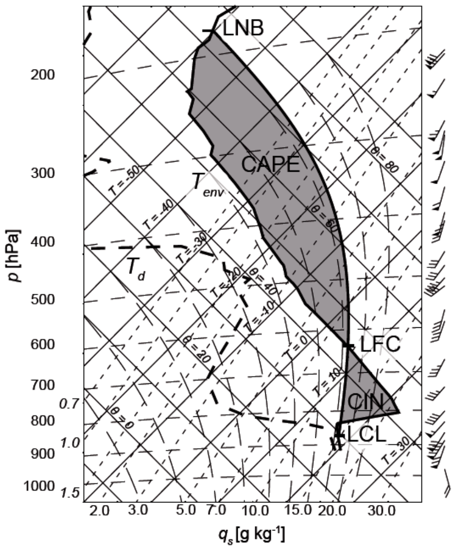
- Hurricane hazards include **storm surges** (most devastating hazard), **high winds** (esp. in the eyewall and the NE-quadrant), **heavy rain** (including Predecessor Rain Events which are sustained by deep tropical moisture that is transported poleward directly in front of the TC) and **tornado activity** (NE-quadrant favored and they are usually weaker than their non-tropical counterparts)

4 Thunderstorms I

- **horizontal vorticity** (η and ξ) is generated by the **shear** of the horizontal wind and vertical vorticity ζ by **conversion** of η and ξ **in the presence of buoyancy** source
- vertical vorticity is produced by tilting of horizontal vorticity → $\frac{\partial \zeta}{\partial t} \approx \frac{\partial U}{\partial z}\frac{\partial w}{\partial y}$
- the **dynamic pressure minima** associated with the vortices are **both negative**: $p^*_{D_z} \sim -\Delta p^*_{D_z} \sim -\zeta^2$ where the strong mid-level rotation acts to lower pressure → inducing updraft growth on each flank thus maintaining updrafts
- as the splitting progresses and the two updraft centers move apart, the downdraft (and associated precipitation development) tilts the vortex lines downward and **a two-vortex pair** develops
- **clockwise directional** shear produces pressure gradients that favour **ascent** on the **southern flank** and **descent** on the **northern flank** → enhancing the development of the storm moving south and suppressing the development of the storm moving north, thus promoting right-turning supercells

5 Thunderstorms II

- tilting of horizontal vorticity creates vertical vorticity: $\frac{\partial \zeta}{\partial t} \approx \frac{\partial U}{\partial z}\frac{\partial w}{\partial y}$ → vorticity couplets are 90° to shear vectors
- fluid shear terms create horizontal pressure perturbations $p^*_{D_{xy}} = 2\rho_0 S \nabla_h w = 2\rho_0\left(\frac{\partial U}{\partial z}\frac{\partial w}{\partial x} + \frac{\partial V}{\partial z}\frac{\partial w}{\partial y}\right)$
- **supercell prerequisites** include ample low-level **moisture**, sufficient **CAPE** (instability) and **clockwise turning shear** of < 20 ms^{-1} within a deep layer (0-6 km)
- gust fronts as the leading edge of a mesoscale pressure dome separating the outflow air in a convective storm from the environmental air can help generate new TS cells and cut off buoyant air supply for old cells
- downbursts due to negative buoyancy driven by θ_e (strength can be explained by DCAPE)



Prerequisites for Tornadogenesis

- **mesocyclone** (i.e. a deep cyclonic updraft that is persistently rotating around a vertical axis)
- rapid **increase** in low-level **rotation** inducing low p (remember: $p^*_D \propto -\zeta^2$)
- formation of rear-flank downdraft (**RFD**) due to precipitation formation
- **acceleration** of **RFD** as it approaches the ground and dragging of the mesocyclone with it

- **cool downdraft** and **warm updraft** air become intertwined and create a rotating wall cloud
- RFD focuses mesocyclone's base sucking air from an increasingly smaller area on the ground → intensification of updraft → **low pressure at ground**

→ mesocyclone is pulled down and a visible condensation **funnel** appears

Ingredients for Tornadogenesis

- **shear** of > 10 ms^{-1} between surface and 1 km
- needs large storm-relative helicity (**SRH**: velocity times vorticity):

$$SRH = \int_0^d (v - c) * w_h dz$$

where (v-c) = storm-relative wind

- SRH in low levels (0 – 1 km) of 100 to > 200 m^2s^{-2} caused by **tilting of horizontal vorticity** is needed to create vertical vorticity (ζ) here
- **CAPE** at low levels (0 – 3 km) is important to determine updraft strength
- height of **LCL**: best < 1000 m

w_h = horizontal vorticity	**CIN**: best < 100 Jkg^{-1} → however CIN is **good to prevent** that **instability is removed** earlier in the day

- large-scale flow determines the frequency of tornadoes in the US with moisture supply from the Gulf of Mexico, the Rocky Mountains providing deep dry adiabatic mixed layer which makes the loaded gun and the jet stream driving the divergence aloft

6a Atmospheric Dynamics Needed for TC Formation

- TCs consist of a superposition of the **primary azimuthal** (i.e. axisymmetric circulation around the TC center, reversing with height from cyclonic to anticyclonic) and **secondary "in-up-and-out"** circulation
- Summary of TC circulation: **friction**ally induced **inflow** inside the BL → outflow induced by **supergradient** wind **above** the **BL** near the RMW $\left(-\frac{1}{\rho}\frac{\partial p}{\partial r} < \frac{v^2}{r} + fv\right)$ → weaker, vertically extended diabatically-induced inflow above the BL → strong outflow above z = 10 km in region of weak inertial stability → **maximum winds** located **inside** the **BL** due to the effect of frictional convergence that is able to overtake frictional dissipation → **winds** get weaker and **weaker with height** → ascent along the eyewall, with secondary maximum above the BL at the RMW (frictionally induced convergence)
- the **boundary layer spin-up** process can be described as follows:
    - friction leads to convergence towards the storm center
    - reduction in *r* increases the velocity, which in turn increases friction
    - this leads to further convergence and *v* increases, and so on...
- the **Saywer-Eliassen equation** describes the **shape** of the **secondary circulation** that is generated as a result of some forcing:
    1. radial variation in **diabatic heating**
    2. vertical variation of circulation and **diabatic heating**
    3. vertical variation of **momentum sources** (friction, etc.)

Storm Type Comparison

Thunderstorm	Supercell	Tropical Cyclone
large CAPE	large CAPE	no CAPE
CIN as a barrier	CIN as a barrier	no CIN
over land	over land	over ocean → dissipates over land due to missing energy source
$\frac{1}{\rho}\frac{\partial p}{\partial r} = fv + \frac{v^2}{r}$ & $\frac{1}{\rho}\frac{\partial p}{\partial r} = fv$	strong wind shear (preferentially clockwise turning)	
gradient & cyclostrophic balance	gradient & cyclostrophic balance	geostrophic & gradient wind balance
energy source: CAPE due to baroclinicity	energy source: stretching/tilting of horizontal vorticity	energy source: latent heat release by evaporation of water
	non-symmetric: separation between up- & downdraft regions	symmetric
lifetime: ~1 hour since downdraft or gust front undercuts the updraft and leads to storm dissipation	lifetime: several hours	lifetime: ~10 days
size: ~tens of km	size: ~50 km	size: ~10^3 km
well-mixed surface layer	warm, moist low level inflow from South	
	cold, dry mid-troposphere flow from West	requires moist mid-troposphere
		env. conditions close to saturated conditions (RH_w ~100 %, i.e. temperature is following the moist adiabat

Differences between Tropical and Extratropical Cyclone

TC	ETC
presence of warm core at storm center, especially at mid- and upper levels	presence of cold core at the storm center
axial symmetry	asymmetric structure
absence of fronts: no baroclinicity	presence of warm and cold sector, separated by fronts (strong temp. gradient at the surface)
no tilted structure	vertically tilted structure (westward)
anticyclonic shear with height	cyclonic shear with height
dimensions: hundreds of km	dimensions: thousands of km
energetically driven by sensible / latent heat fluxes from the sea	energetically driven by baroclinicity (strength of latitudinal thermal gradient)
presence of a clearly defined eye, surrounded by conv.	

6b Paradigms in TC Science

- **CISK** → heat removed from the ocean is the true source of energy of TCs where strong **convergence of moist air provides fuel** to maintain the convection **–** drawback since moisture **convergence** does **not imply convection**, there is **no conditional instability in the tropics**, in reality the instability is more efficiently released by small TSs than by aggregation into vortex and CISK could be as large over land as over the ocean

- **WISHE** → **positive feedback** between **circulation and heat fluxes**, assumes **gradient wind** balance **everywhere** and concludes that ↑wind ≙ more evaporation ≙ higher LH release which increases winds
- **VHT** → Vortical Hot Towers as the current theory and focuses on the role of **convective clouds** in **generating vorticity** via vortex stretching in deep convective cloud – VHT tend to **merge** with each other and with MCV to create mesoscale convective systems (MCS) – these MCSs have two inflows which promote convergence towards the low pressure system center, causing **vorticity anomalies** to **merge at the center** of the storm

7 Hurricanes I – General Features

- TCs can be described using a **Carnot process** with heating due to moisture from the BL (WISHE; isothermal expansion), adiabatic expansion as the air rises in the eyewall (↓p, θ_e const.), isothermal compression as the air is being cooled (↑p, i.e. ↓θ_e) and adiabatic compression with no heat exchange (↑p, i.e. θ_e const.)

9 Hurricanes II – Genesis and Extratropical Transition

- ET can occur if TCs move to higher latitudes after an **initial transformation stage**, where the TC weakens due to increased wind shear, the **cyclone may re-intensify as an extratropical storm**, as it recurves ahead of an upper level trough or interacts with the midlatitude baroclinic zone
- Interaction with the mid-latitude flow can occur via the three following ways: **large-scale ascen**t as the TC enters a region of an **upper-level trough**, intensification as it enters a region of **enhanced baroclinicity** or **ascent** at the baroclinic zone **and heavy precipitation**
- re-intensification is generally accompanied by an increase in the size of the storm, heavy rain and strong winds
- ET has often an impact downstream: it is linked to **reduced forecast skill** and may trigger Rossby Wave Trains that propagate downstream → This situation, linking together forecast uncertainty and **potential for high impact weather**, may be risky and challenging to forecast
- African Easterly Waves (**AEWs**) are mesoscale weather systems responsible for the **genesis** of the majority of Atlantic and East Pacific hurricanes → in Western Pacific we have a similar feature, related to local monsoon systems
  - **disturbance** must be **isolated by the shear** and relatively dry environment in order for convection to organize → this can happen for the AEWs that find themselves in **Kelvin's cat eyes** associated with the African Easterly Jet (AEJ); a "**kangaroo pouch**" forms, where the **system** is kinematically **isolated from the environment** and where the TC embryo is preserved inside (i.e. the marsupial paradigm)
- **many TCs** develop **from** initially **cold core systems** → these systems acquire tropical chacteristics (warm core, symmetry, no fronts, etc...) via the tropical transition process
  - a possible mechanism for trough-induced development is explained in the case of anticyclonic wave breaking
  - in this case, a significant upstream water vapor transport by the northward anticyclone is beneficial for the TT process which can be visualized in a Hart Diagram (i.e. amount of tropicality / extratropicality of the storm)

10 Steady State Model

- lines of angular momentum *m* coincide with θ_e^* surfaces, i.e. we have **symmetric neutrality** within the vortex above the boundary layer: $\frac{\partial \theta}{\partial z}|_M = 0 \leftrightarrow \frac{\partial M}{\partial y}|_\theta$
- the raduis increases with decreasing pressure on an m-surface and thus explains the wideningof the eye with increasing altitude
- the central equation of Emanuel's steady state model is a relationship for the radial extent r_0 of the storm in terms of θ_e, T_B and p:

$$r_0^2 = \frac{16 c_p T_B}{f^2 r_0^2} \int_0^{r_0} \eta * ln\left(\frac{\theta_e}{\theta_{ea}}\right) r dr$$

→ the geometric area r_0^2↑ as its moist entropy surplus (ln $\theta_e/\theta_{ea} > 0$)↑. as f↓ and T_B↑

- the boundary layer exerts a strong thermodynamic control of the storm above it (WISHE paradigm)
- the tangential velocity *v* is related to the Carnot efficiency, the temperature at cloud base and the saturated moist entropy: $v = v(\eta, T_B, ln(\theta_e/\theta_{es}^*))$
- the RH inside the eye increases inwards at least in the absence of strong subsidence in the eye → warm core
- the pressure deficit is a function of ΔRH, T_s, T_B and $T_{out}(\eta)$
- the larger the evaporation rate, the larger the pressure deficit in the eye π_{CS}
- the highest tangential winds *v* occur when T_{out} is high and we have a high SST

Limitations of the Steady State Model

ASSUMPTIONS	VIOLATED
conservation of energy	at landfall at the latest or by intrusion of dry air
environmental parameters (RH, T, ...) do not change	yes, b/c every TC evolves
axisymmetry	in the outflow → rainbands, cloud bands
hydrostatic balance	in the presence of buoyancy (eyewall)
gradient wind balance: $\frac{1}{\rho}\frac{\partial p}{\partial r} = fv + \frac{v^2}{r}$	ignores friction (subgradient) ignores BL-spin-up (supergradient)

- symmetric neutrality: $\frac{\partial\theta}{\partial z}|_M = 0 \leftrightarrow \frac{\partial M}{\partial y}|_\theta$
- conservation of angular momentum m

- ok in the eyewall
- violated in the BL
- unlikely

11 Tropical Cyclones in the Reinsurance Concept

- the **5-box modelling approach** involves the following aspects: i) **import** any portfolio with **entities**, ii) **encode** geography and **vulnerability**, iii) **rate assets** using a **hazard set** by simulating events, iv) **apply** any **insurance** conditions and v) **calculate** expected **loss**, **adaptation measures**, **cost-benefit analysis**, etc.

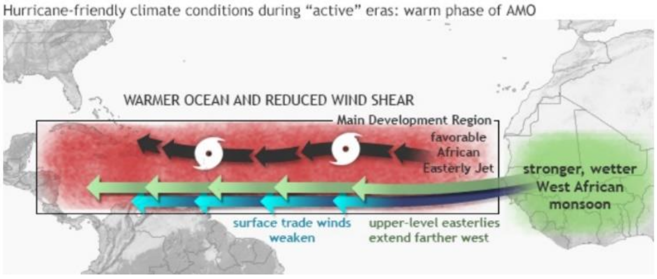
12 Hurricanes IV – Intensification and Tracks

- there are two possibilities for changing TC intensities: external and internal effects
  - **external intensification** via **ocean interaction**, impact of clouds, little vertical shear
  - **internal intensification** via production of stronger gradients (same as frontogenesis) in the eyewall
- the eyewall propagates towards the center of the TC, thus shrinks in radius, after 1-2 days collapses, disappears and is replaced by a new one (at r_m ~50-100 km)
- **vertical wind shear** has detrimental effects on a TC: **loss of symmetry**, **reduction in fuel** η and **reduction in tangential wind speed** v
- ocean interaction involves adding turbulence to the mixed layer (through breaking waves), strong winds inducing ocean mixed layer currents (reduction in SST) as well as Ekman pumping (most pronounced on the northside due to superposition of the TCs circulation and its translational movement
- there are additional (non-linear) effects which can also affect the tracks of TCs dramatically
  - interaction of the vortex with the ambient flow (steering effect)
  - Coriolis effect
  - effect of non-uniform flow (horizontal wind shear)
  - baroclinic effects (vertical wind shear, diabatic heating, etc.)
  - vortex assymmetries

13 Hurricanes V – TC Forecasts, Projections (and Tornadoes)

- **seasonal TC forecasts** are based on
  - ocean observations of **SST** (Argo buoys sparse, esp. in 3D ocean)
  - state of the **NAO** (negative = weaker westerlies which do not act as much as a conveyor belt and thus do not prevent as many landfalls) → NAO$^-$ = more TCs in US East Coast
  - state of the **ENSO** (**El Niño = less TCs in the Atlantic** and **more in the Pacific** due to stronger vertical wind shear, stronger trades and greater atmospheric stability in the Caribbean Sea) → neutral ENSO = more TCs in US East Coast
- **TC forecasts more difficult** than forecasting ETCs since:
  - **path** can change drastically
  - **more lead time** for **evacuation** is needed
  - TCs have lots of **indirect components** (SST, AEWs, etc.)
  - **initial conditions less precise** (no airplanes in TC, Argo buoy resolution limited)
  - ideally you need an **AOGCM** with **high ocean** model **resolution** and correct **Cu parameterization**
  - you need to have polar-orbiting satellites
- IPCC AR5 concludes *low confidence* in assessment that TC changes occurred since 1950, that humans contributed to changes and it is *more likely than not* that further increase in intense TC activity until 2100 will happen
  - on global scale including all basins, it is estimated there will be an overall decrease in all TC frequencies, an increase in Cat. 4-5 TC frequency and a slight increase in associated precipitation rate

Colorado State University - TC Forecast as of 1 June 2017



- 2017 = approx. average activity
- **ENSO** model prediction ensemble equally favour neutral and El Niño conditions through 2017
  - **neutral** = weaker shear, weaker trades and less atm. stability in the North Atlantic which means **average TCs**
  - **El Niño** = stronger vertical shear, stronger Atlantic trades and greater atm. stability (**less TCs**) in the North Atlantic while also **increasing** likelihood of **TCs in the North Pacific** (Camargo et al., 2004)
- **AMO** in **positive** phase since 1992, i.e. warmer North Atlantic SST and reduced wind shear → favouring **more TCs**
- **NAO** in slightly **negative** phase which means weaker westerlies → weak westerlies = winds do not hinder TCs from landfall at the US East Coast as much, resulting in **more TCs** hitting the coast