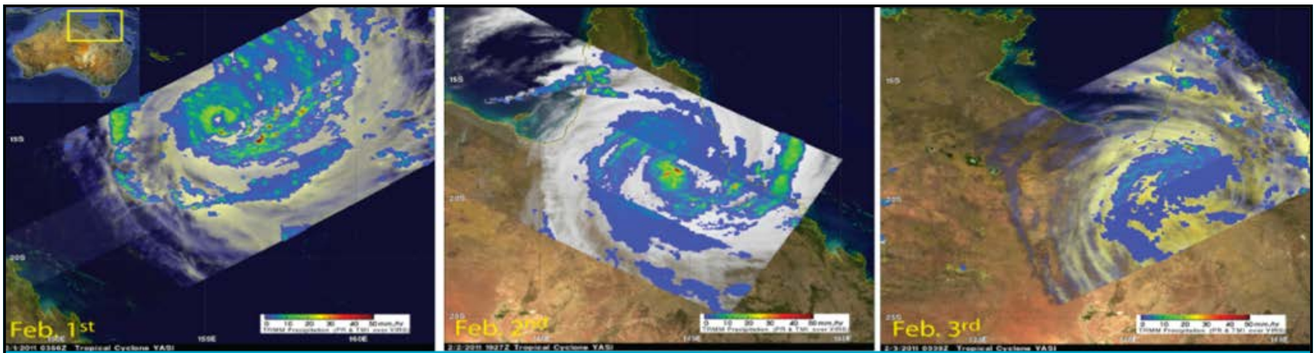


Extreme Rainfall: Tropical Cyclones

Hamish Ramsay
28 June 2018

OCEANS AND ATMOSPHERE
www.csiro.au

Overview

1. Tropical cyclone structure and dynamics
2. Climatological aspects of tropical cyclone rainfall
3. Modelling tropical cyclone rainfall
4. Climate change and future risk assessment

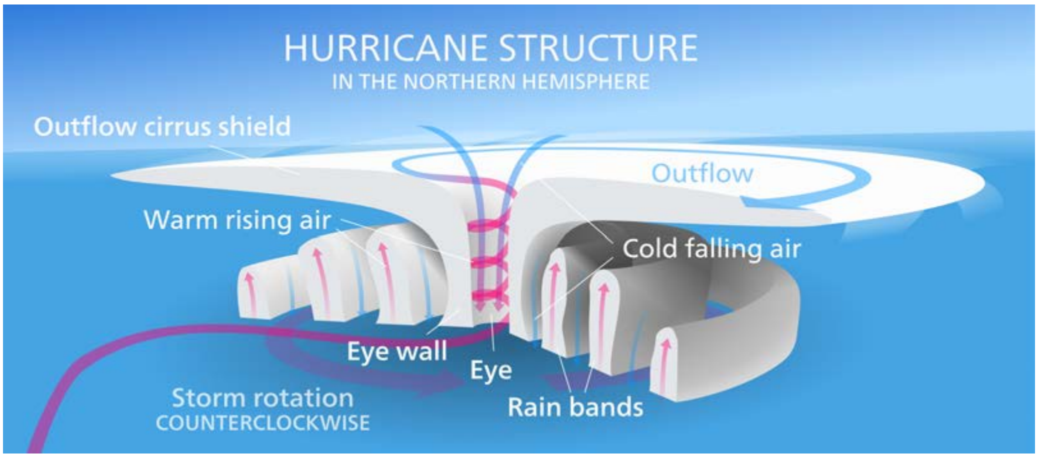
Part 1:
Tropical Cyclone Structure and Dynamics

Definition of a Tropical Cyclone

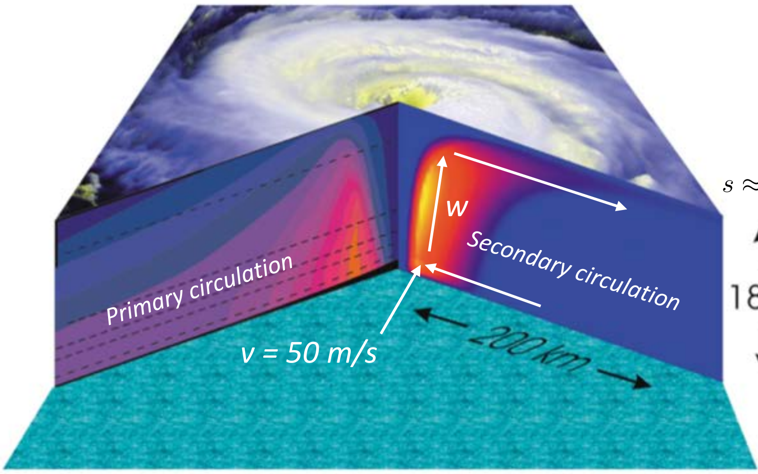
Tropical cyclones, also known as tropical storms, hurricanes, and typhoons, depending on region and intensity, are warm-cored, cyclonically rotating atmospheric vortices, driven by air-sea enthalpy fluxes, and are mostly in hydrostatic and gradient wind balance (except near the eyewall and within the boundary layer).

Hurricane Isabel, September 2003

Tropical Cyclone Structure



Tropical Cyclone Structure



Emanuel (2003)

Two important conserved variables:

1) Specific moist entropy:

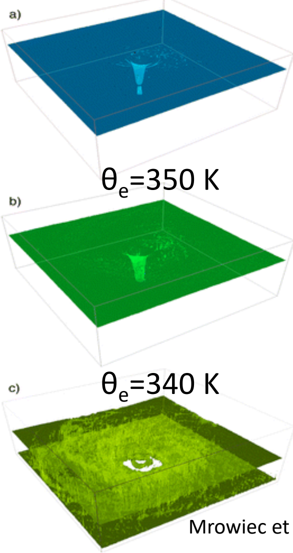
$$s \approx C_p \ln(T) - R_d \ln(p) + \frac{L_v q}{T} - q R_v \ln(H)$$

or, $s \approx C_p \ln(\theta_e)$

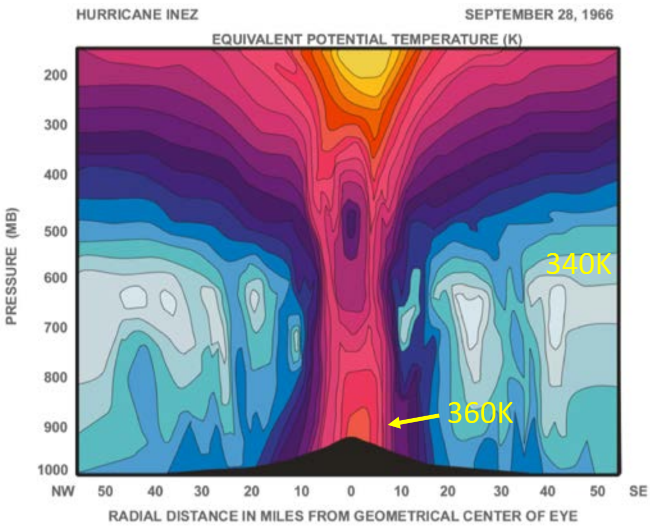
2) Absolute angular momentum:

$$M = rV + \frac{1}{2} f r^2$$

Tropical Cyclone Structure

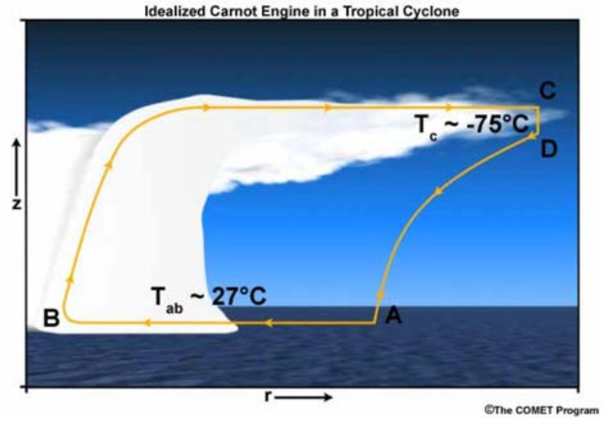


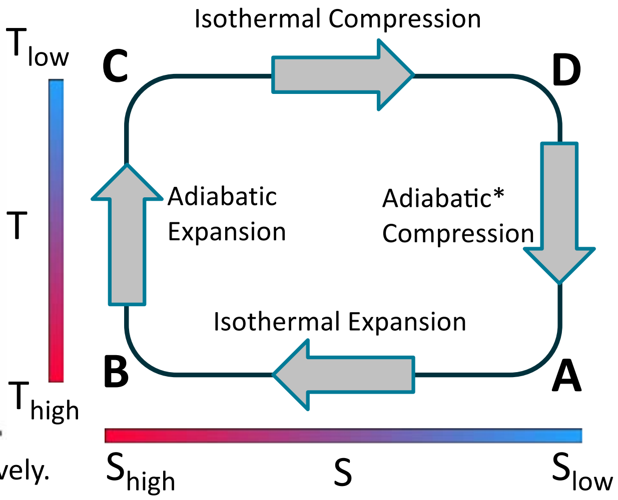
Mrowiec et al. (2016)



Emanuel (2004), adapted from Hawkins and Imbembo (1976)

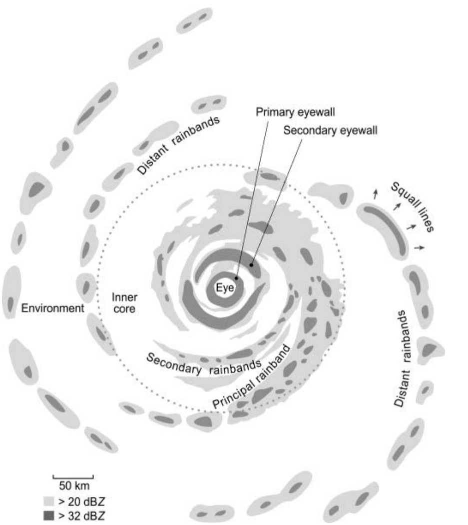
Tropical Cyclone Structure and Energetics



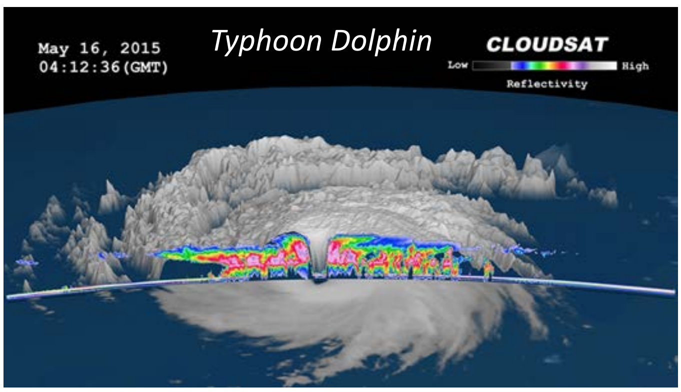


*Note: D→A is not adiabatic as air cools radiatively.

Precipitation Structure of a Mature TC

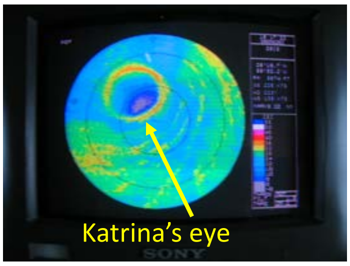


Houze (2010)

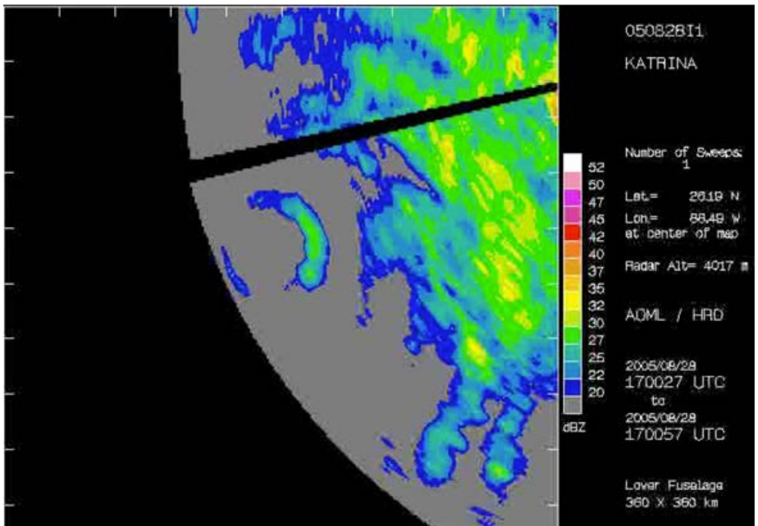


Credits: Natalie D. Tourville, CSU

Observed Tropical Cyclone Structure



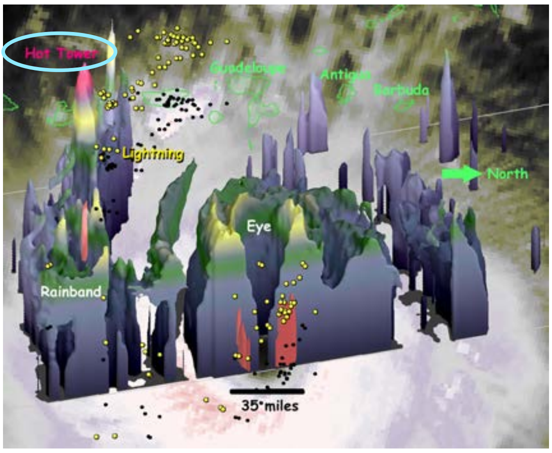
Observed Rainfall Structure in Hurricane Katrina



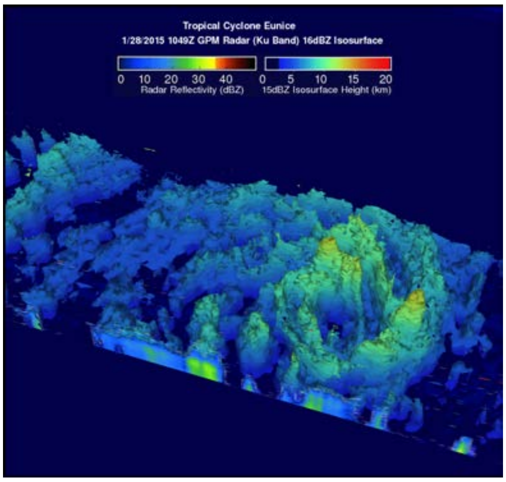
ftp://ftp.aoml.noaa.gov/pub/hrd/data/radar/2005/katrina/katrina_stm_28i1.mpeg

Katrina near peak intensity (902 hPa, 282 km/h winds), August 28, 2005.

Observed Rainfall Structure from NASA's GPM



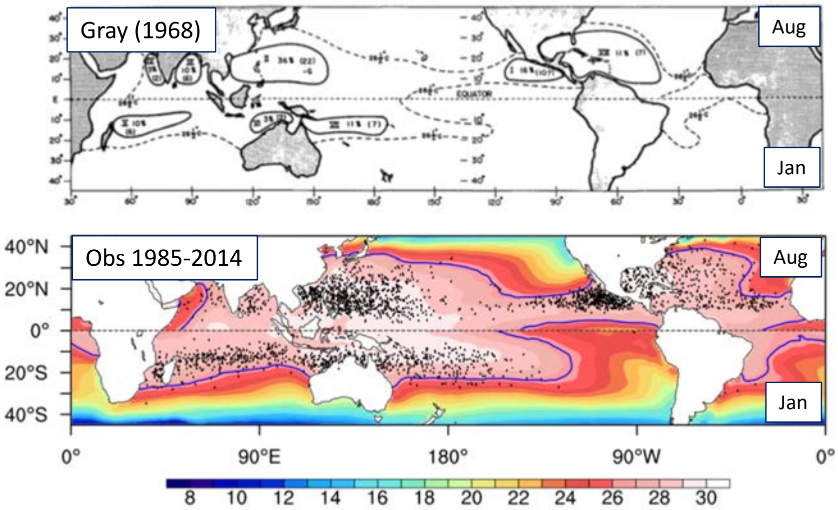
Hurricane Irma (2017), North Atlantic



TC Eunice (2015), South Indian Ocean

Part 2:
Tropical Cyclone Rainfall Climatology

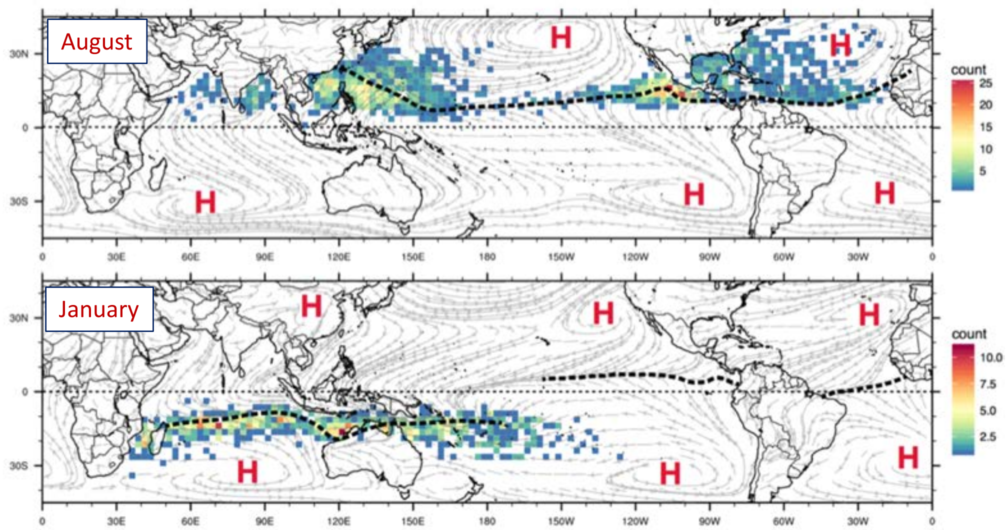
Global Tropical Cyclone Genesis Climatology



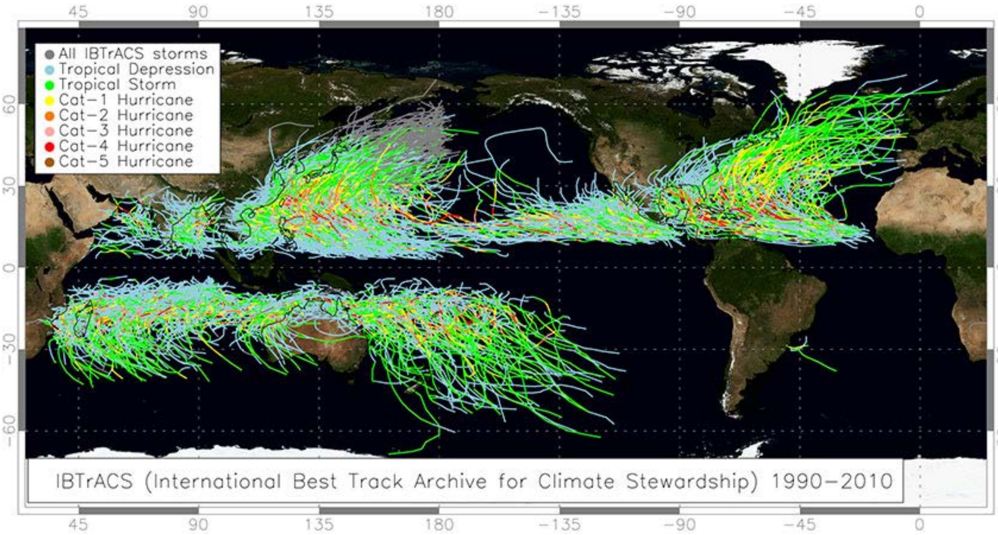
Palmén (1948): "Hurricanes can only be formed in oceanic regions outside the Equator where the surface water has a temperature above 26-27°C"

*But this threshold depends on global climate (e.g., Emanuel & Nolan 2004)

TC Formation Density and Surface Circulation



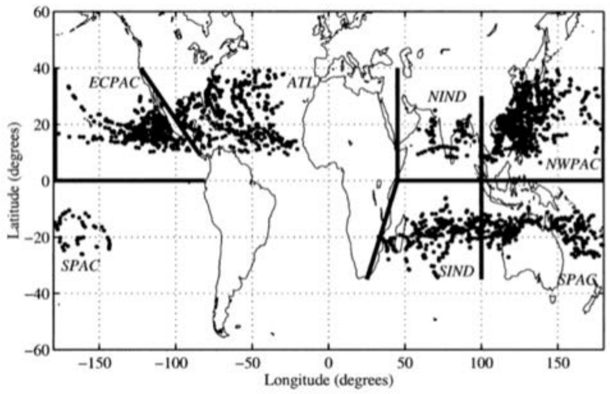
Global Tropical Cyclone Tracks



17 | Tropical cyclone rainfall | ARC CLEX Winter School 2018

TC Rainfall Climatology

260 TRMM observations 1998-2000



Lonfat et al. (2004)

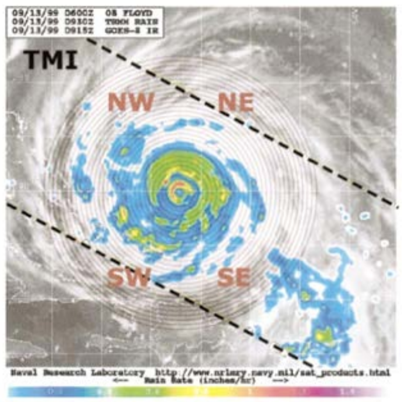
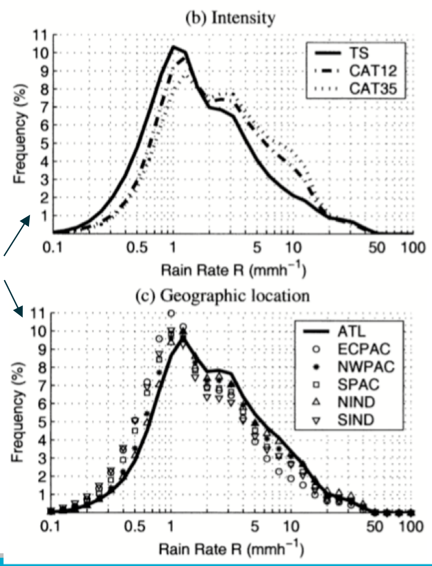


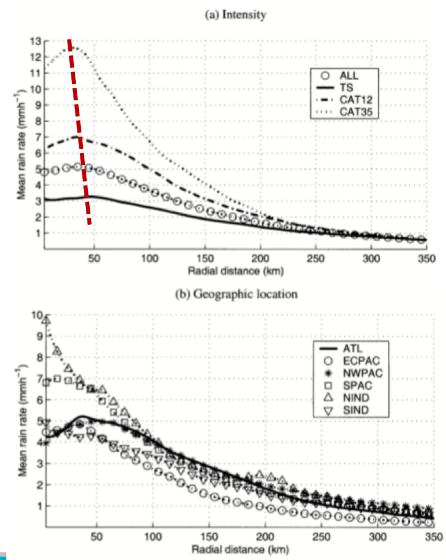
FIG. 2. Example of annuli used in the analysis. The map shows the surface rainfall for Hurricane Floyd on 13 Sep 1999.

18 | Tropical cyclone rainfall | ARC CLEX Winter School 2018

TC Rainfall Climatology

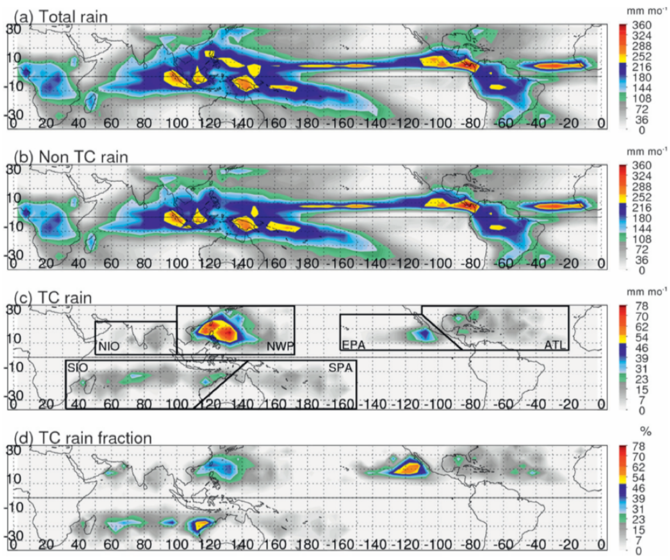
PDF within 500 km radius of TC centre

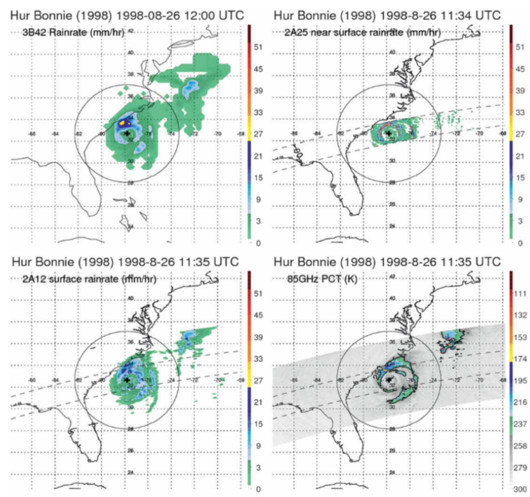




Lonfat et al. (2004)

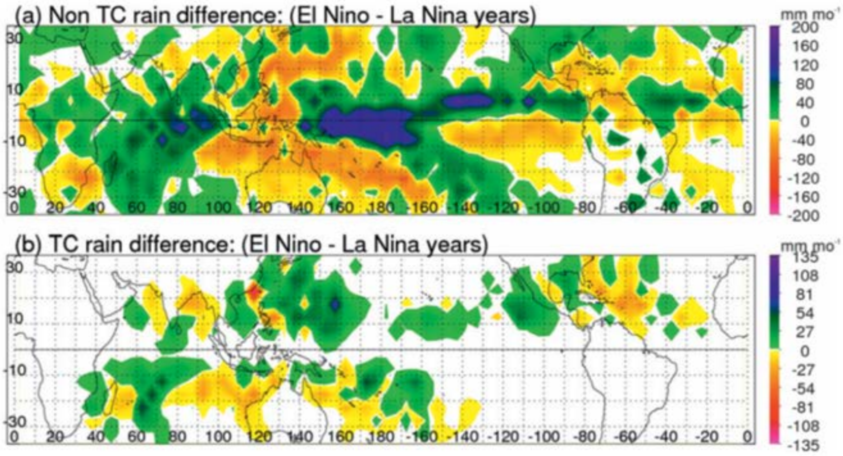
TC Rainfall Climatology





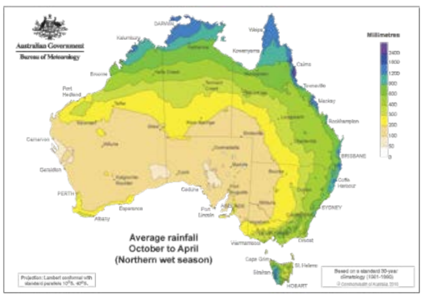
Jiang and Zipser (2010)

TC Rainfall and ENSO

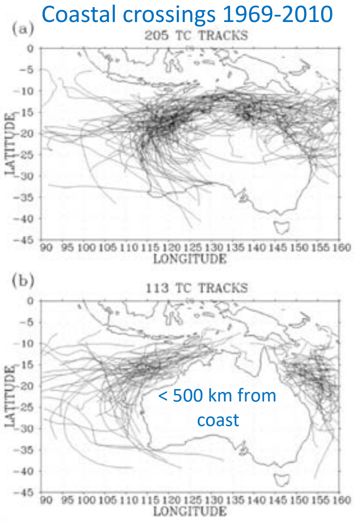


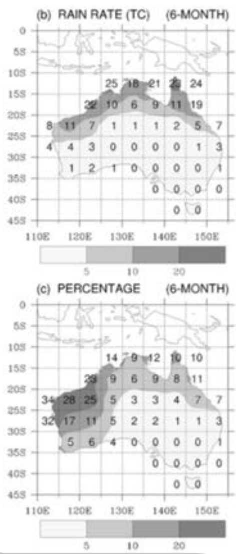
Jiang and Zipser (2010)

Contribution of TCs to Australian Seasonal Rainfall



Coastal crossings 1969-2010

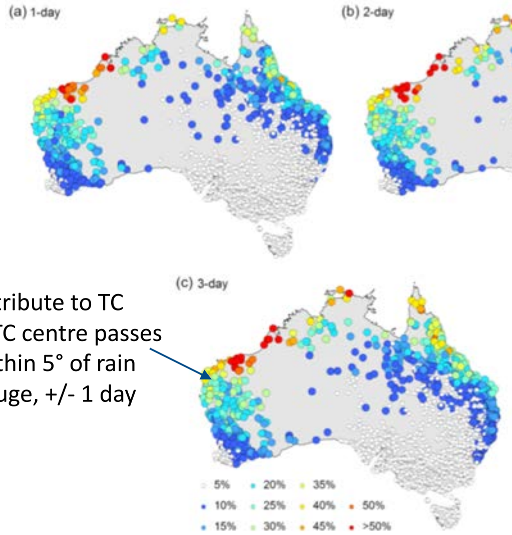




Nov-Apr
mm/month

Dare et al. (2012)

Contribution of TCs to Extreme Rainfall

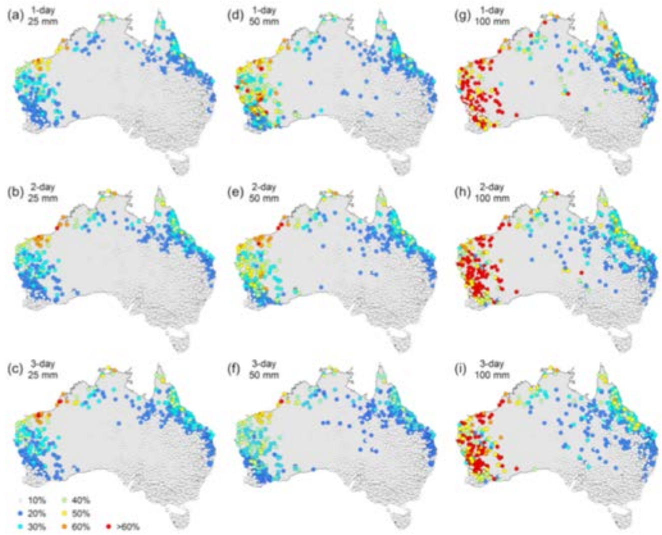


Attribute to TC if TC centre passes within 5° of rain gauge, +/- 1 day

- Rain gauge data from 1969-2012
- Analysed largest 1, 2, and 3-day rainfall totals within each year
- TCs responsible for 30-50% of annual maxima in northern coastal regions
- TC influence diminishes away from coast

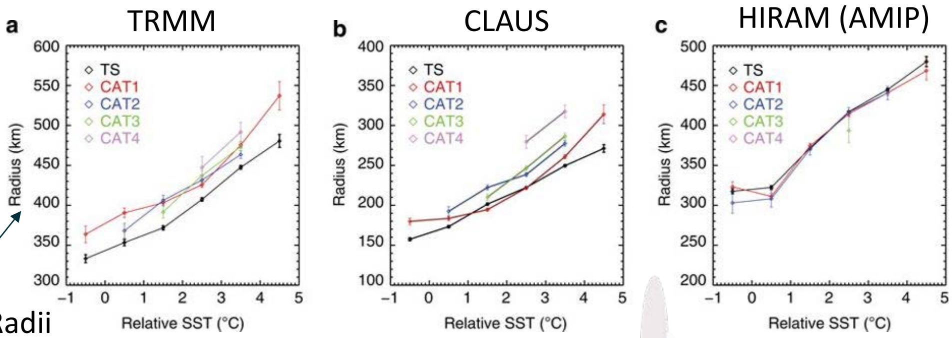
Villinari and Denniston (2015)

Contribution of TCs to Extreme Rainfall

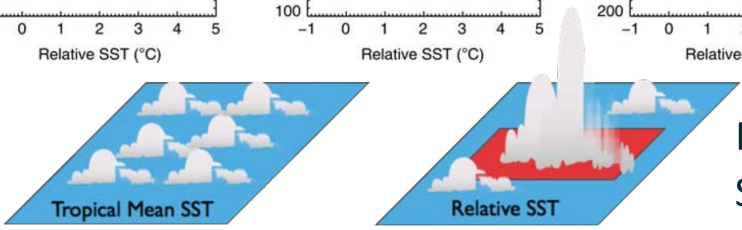


Villarini and Denniston (2015)

TC Rainfall Area Controlled by Relative SST



Average Rainfall Radii

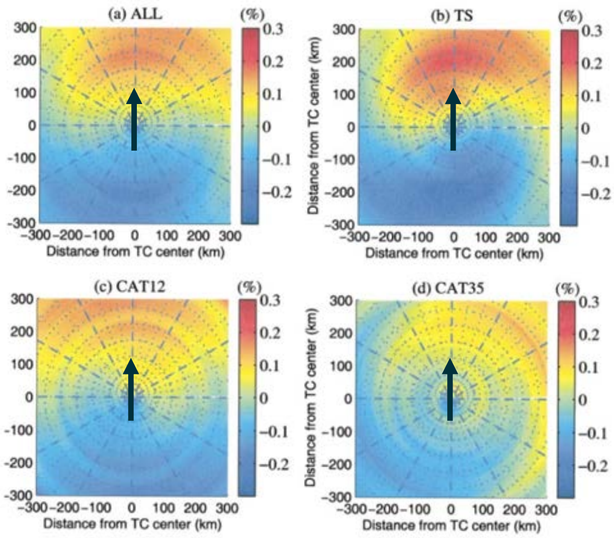


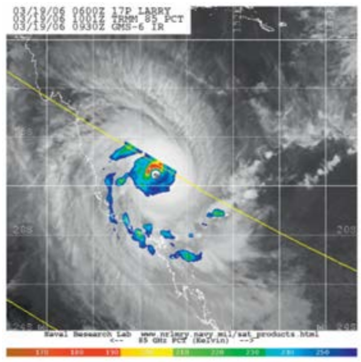
Relative SST:

$SST_{i,j} – SST_{trop\_avg}$

Lin et al. (2015)

TC Rainfall Asymmetry





Leading causes of rainfall asymmetries:

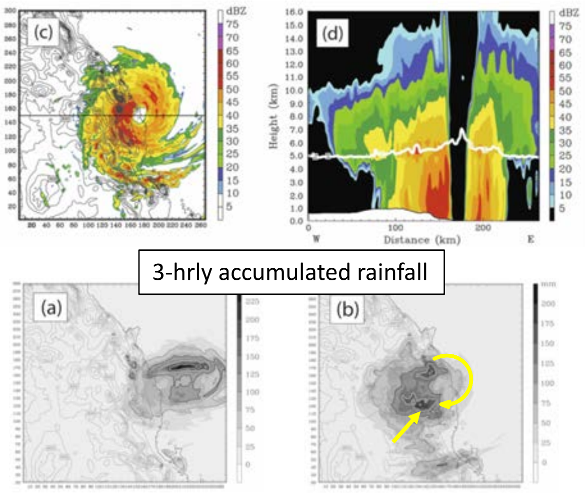
- Deep-layer vertical wind shear
  (rain concentrated downshear-left in NH)
- Boundary layer frictional convergence
- Land-sea contrast

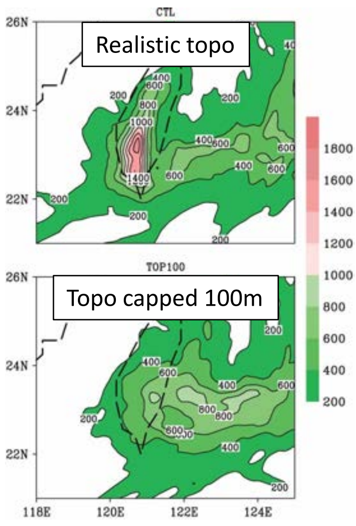
Lonfat et al. (2004)

Part 3:
Modelling Tropical Cyclone Rainfall

Orographic Enhancement of TC Rainfall

MM5 simulation of Severe TC Larry (2006)





Typhoon Morakot (2009)
2777 mm accum. precip!

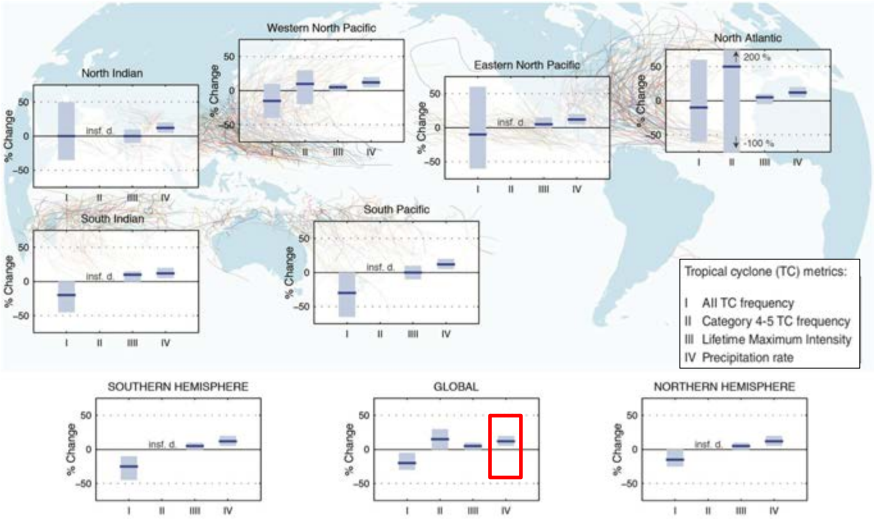
WRF model
27km→9km→3km

~1000 mm difference when topography removed

Ramsay and Leslie (2008)

Ge et al. (2010)

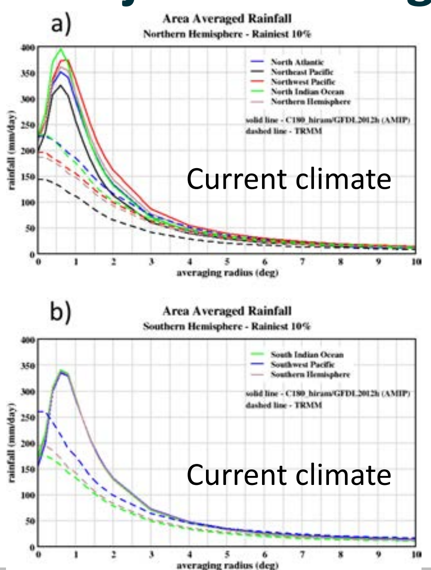
Projected Changes of TC Rainfall: IPCC AR5

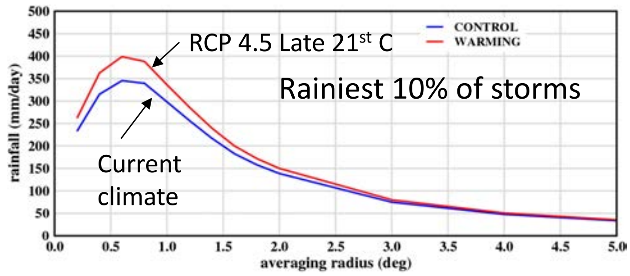


- TC-related rainfall is predicted to increase by 5-20% under greenhouse warming
- This is a consistent result across climate models
- There have been no detected global trends in TC rainfall rates

Christensen and co-authors (2013)

Projected Changes of TC Rainfall: GFDL HiRAM

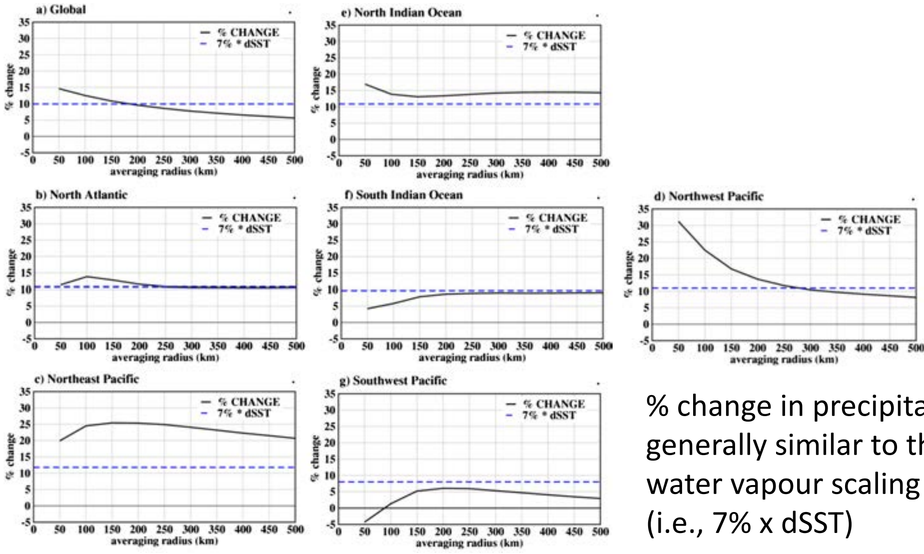




- 50-km global model downscaled to ~6 km for each TC
- Model overestimates rainfall compared to TRMM estimate (but TRMM underestimates compares to gauges)
- On average, model shows a 14% increase in rain rate across all TC intensities, globally

Knutson et al. (2015)

Projected Changes of TC Rainfall: GFDL HiRAM



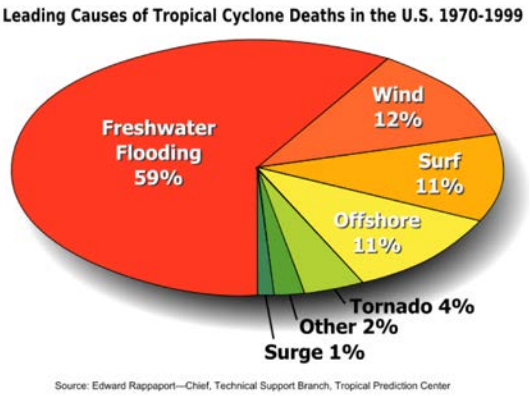
% change in precipitation is generally similar to the water vapour scaling (i.e., 7% x dSST)

Knutson et al. (2015)

Part 4:
Risk Assessment of Extreme Rainfall

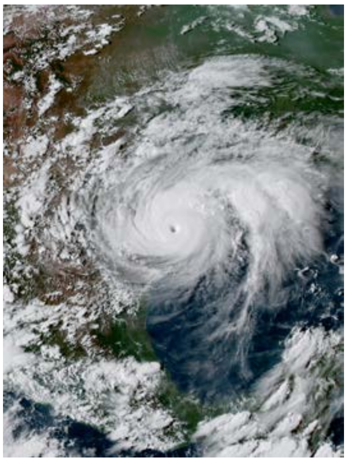
Slides 35-44 courtesy of Kerry Emanuel (MIT)

Tropical cyclone related mortality



e.g., Rappaport (2000), *BAMS*

Hurricane Harvey (2017)



Risk Assessment for Houston and Texas:

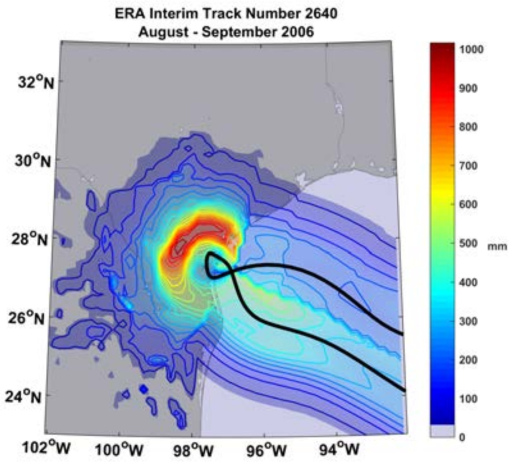
Run 100 events for each year from 1980 to 2016 (3700 events total) passing within 300 km of Houston, downscaled from three climate reanalyses

Run 100 events each year from 1979-2015 passing over the Texas coastline, downscaled from NCAR/NCEP reanalyses. Calculate storm total rainfall for each event at each of 78 points constituting a grid extending from 26° N to 31° N and from 99° W to 94° W, at increments of 0.5°, but excluding points over the Gulf

Run 100 events each year during two periods: 1981-2000 and 2081-2100, passing within 300 km of Houston, downscaled from six climate models

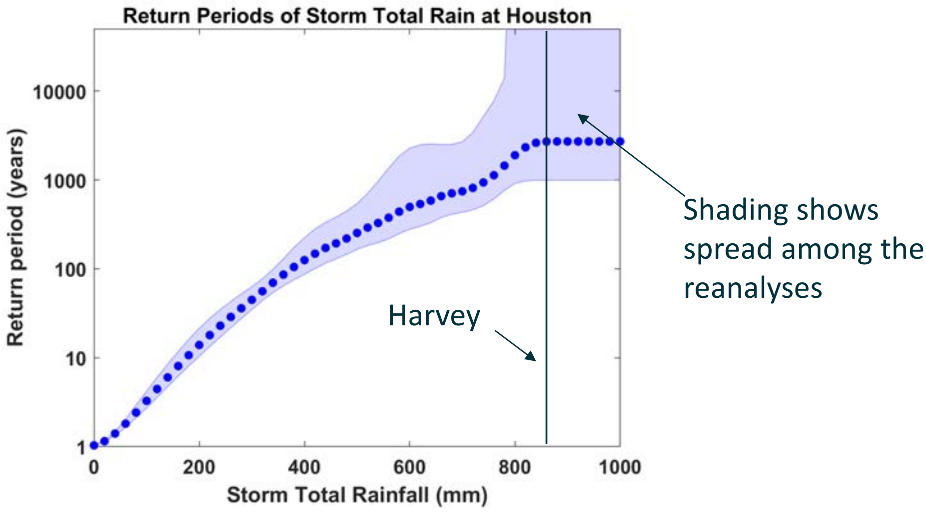
Rain algorithm described in detail in Lu et al., *J. Atmos. Sci.*, 2018

Example of Accumulated Rainfall from a Harvey-like Event Downscaled from ERA Interim Reanalysis



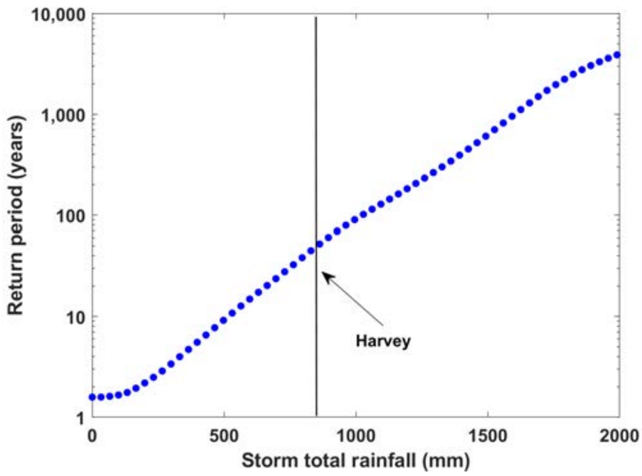
Emanuel (2017)

Probability of storm accumulated rainfall in Harris County, from 3 climate Reanalyses, 1980-2016, based on 3700 events each.



Emanuel (2017)

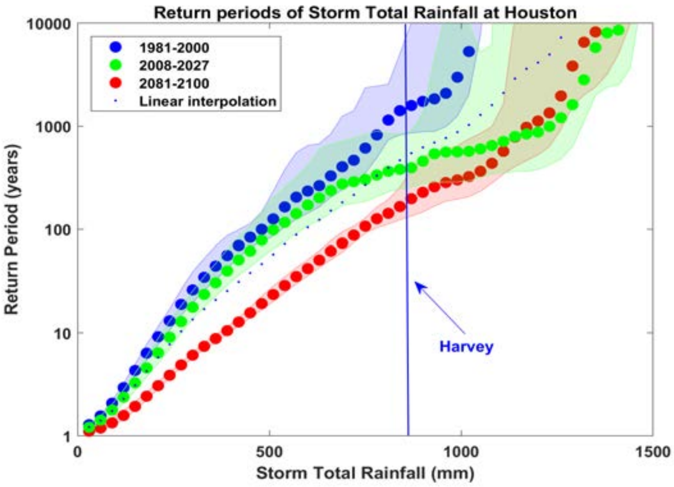
Probability of Accumulated Hurricane Rain Anywhere in Texas, based on 3700 Events Downscaled from NCAR/NCEP Reanalysis



Emanuel (2017)

Probability of Storm Accumulated Rainfall in Harris County, from 6 Climate models, 1981-2000, 2008-2027, and 2081-2100

Probability of a Harvey-like storm for Houston increases from a 1 in 2000-y event at end of 20^{th} C to a 1 in 100-y event at end of 21^{st} C



Based on 2000 events using RCP 8.5

Shading shows spread among the models

Emanuel (2017)

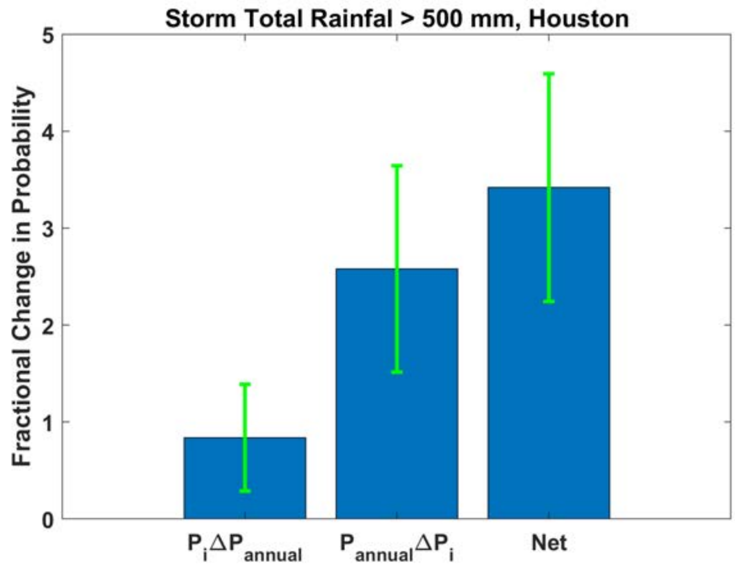
Decomposition of Storm Total Rain Exceedance Probabilities

$$P = P_{Annual} P_{R>i}$$

P_{Annual} is the annual probability of any TC rain

$P_{R>i}$ is the conditional probability of rain > i

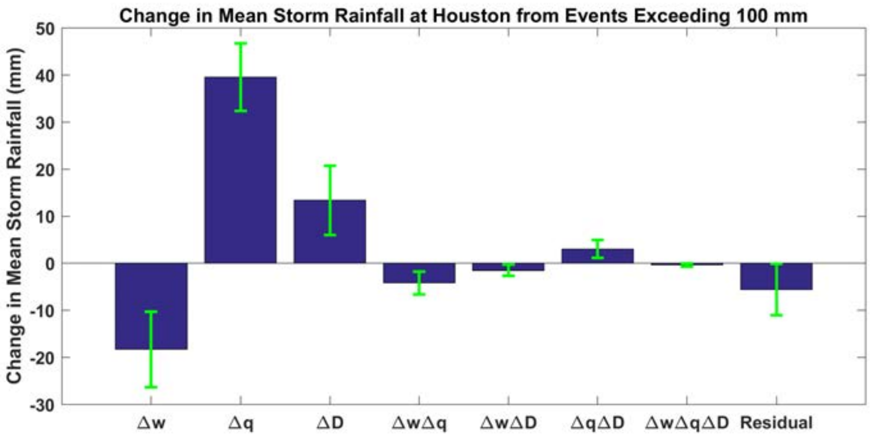
$$\Delta P = P_{R>i} \Delta P_{Annual} + P_{Annual} \frac{dP}{dR} \Delta R$$



Per-Event Storm Total Rainfall

$$R = \int_0^{\tau} (\rho w q) dt$$

Contributions to Changes in Hurricane Rainfall at Houston from Changes in Updraft Speed, Water Vapour Content, and Storm Duration

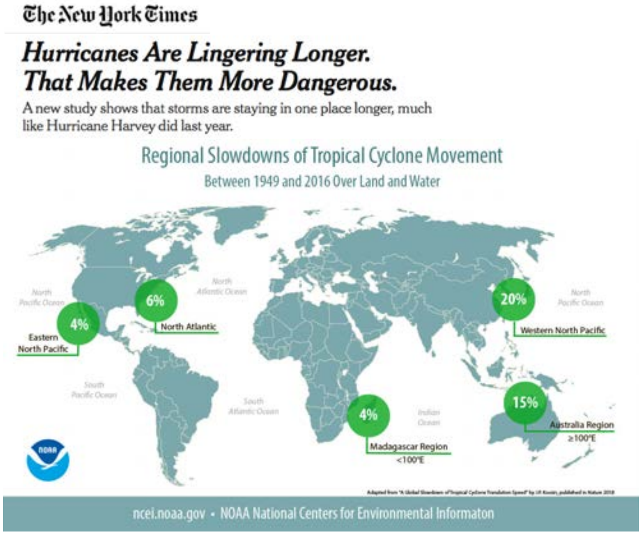


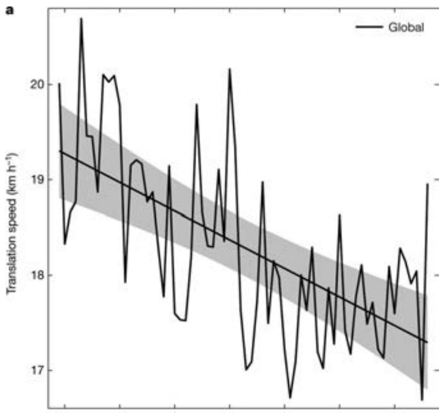
Δw = Change in updraft speed, Δq = Change in water vapour concentration, ΔD = Change in storm duration

Three studies of Harvey's rain

- This study (Emanuel 2017)**: 4-fold increase in annual probability of 840 mm rainfall in Harris County from 1990-2017**, and 9-fold from 1990-2090. Based on models only.
- Risser and Wehner, *Geophys. Res. Lett.*, 2017: **~6-fold increase in annual probability of 840 mm rainfall over eastern coastal Texas from 1950-2016**. Based on historical records only.
- van Oldenborgh et al., *Environ, Res. Lett.*, 2017: **~2-11-fold increase in Harvey-magnitude rainfall from 1880 to 2017**. Based on observations and models.

Are tropical cyclones slowing down?





Kossin (2018) *Nature*

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Thank you

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