Outline

• Tropical Cyclone (TC) rainfall climatology
• Factors influencing TC rainfall
• TC rainfall forecasting tools
• TC rainfall forecasting process
Tropical Cyclone Rainfall Climatology
Tropical Cyclone Tracks

Tracks and Intensity of Tropical Cyclones, 1851-2006

Saffir-Simpson Hurricane Intensity Scale

COMET (2011)
Global Mean Monthly TC Rainfall During the TC Season and Percent of Total Annual Rainfall

Data from TRMM 2A25 Precipitation Radar from 1998-2006

Jiang and Zipser (2010)
Contribution to Total Rainfall from TCs

- What percentage of average annual rainfall in southern Baja California, Mexico comes from tropical cyclones?
  1. 10-20%
  2. 20-30%
  3. 40-50%
  4. 50-60%

Khouakhi et al. (2017)
*J. Climate*
Contribution to Global Rainfall from TCs (1970-2014 rain gauge study)

- Globally, highest TC rainfall totals are in eastern Asia, northeastern Australia, and the southeastern United States
- Percentage of annual rainfall contributed by TCs:
  - 35-50%: NW Australia, SE China, northern Philippines, Baja California
  - 40-50%: Western coast of Australia, south Indian Ocean islands, East Asia, Mexico

Khouakhi et al. (2017) *J. Climate*
Contribution to Global Rainfall from TCs (1970-2014 rain gauge study)

Khouakhi et al. (2017)
*J. Climate*
Contribution to Global Rainfall from TCs (1970-2014 rain gauge study)

- Relative contribution of TCs to extreme rainfall
- Gray circles indicate locations at which TCs have no contribution to extreme rainfall

Khouakhi et al. (2017) J. Climate
TC rainfall makes up a larger percentage of total rainfall during years when global rainfall is low.

Asymmetric - generally more TC rainfall in the Northern Hemisphere.

- TCs produce 10-17% of global rain from 15-25°N
- TCs produce 5-10% of global rain from 15-25°S
## Biggest TC Rain Producers By Country/Island

<table>
<thead>
<tr>
<th>Country</th>
<th>Rainfall (mm)</th>
<th>Rainfall (&quot;”)</th>
<th>Original Event</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belize</td>
<td>829.8</td>
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Original Source: David Roth WPC (2006)
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*Original Source: David Roth WPC (2006)*
Characteristics of TC Precipitation

Stratiform and Convective Mechanisms

Stratiform Rain ~50% of Total Rain from TC

NOAA/HRD - Daily Radar Rainfall Estimate Study

Typical warm season 1-day total

Hurricane Irene (1999) 1-day total

Primarily Convective

Stratiform & Convective

Frank Marks (HRD)
TC Rainband Complexes: Stratiform Region

• Broad stratiform band in left-of-shear half of the storm
• Mesoscale ascending outflow & descending inflow driven by latent heating & latent cooling patterns
• Increased rainfall along line where descending inflow halts
• Descending inflow strengthens the outer core of vortex
TC Rainband Complexes: Convective Cells

Cell 1
- Weaker, shallower reflectivity core
- Weaker updraft
- Shallower, but stronger inflow layer
- Tangential jet and outflow confined to lower levels

Cell 2
- More intense reflectivity, heavier rain
- Increased CAPE, more buoyant updraft
- Deeper inflow layer
- Tangential jet and outflow extend deeper into the troposphere

Didlake and Houze (2013)
Factors Influencing Tropical Cyclone Rainfall
What Factors Influence Rainfall from Tropical Cyclones?

• Which of the following is NOT a primary factor in determining rainfall from tropical cyclones?
  1. TC Track
  2. TC Size
  3. TC Intensity
  4. Topography
What Factors Influence Rainfall from Tropical Cyclones?

- **Movement** – slow forward motion can produce more rain
- **Storm size** – the larger the storm, the greater the area typically receiving rain
- **Storm track** – determines the location of the rain
- **Diurnal cycle** – heaviest rainfall generally near the storm center overnight, outer band rainfall during the day
- **Topography** – enhances rainfall in upslope areas, but decreases rainfall past the spine of the mountains
- **Moisture** – entrainment of dry air can redistribute and/or reduce the amount of precipitation; increased moisture can increase rainfall
- **Interaction with other meteorological features** (troughs, fronts, jets) and extratropical transition can greatly modify rainfall distribution
Factors Influencing TC Rainfall

Storm Motion
- Slow vs. fast moving TCs
- TCs with a turning or looping track vs. straight mover

Hurricane Mitch fatalities:
- Honduras: 5,677
- Nicaragua: 2,863
- Guatemala: 258
- El Salvador: 239

Rainfall in Inches
1 Inch = 25.4 mm

Tegucigalpa, Honduras river flooding

Vulcan Casita, Nicaragua - debris flows

David Roth WPC
## Factors Influencing TC Rainfall

### Storm Size

Determined by distance from center to outermost closed isobar

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<tr>
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<th>Description</th>
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<td>&lt;2 degrees</td>
<td>“Very small/midget”</td>
<td>Marco (2008)</td>
</tr>
<tr>
<td>2-3 degrees</td>
<td>“Small”</td>
<td>Ida (2009)</td>
</tr>
<tr>
<td>3-6 degrees</td>
<td>“Average”</td>
<td>Frances (2008)</td>
</tr>
<tr>
<td>6-8 degrees</td>
<td>“Large”</td>
<td>Wilma (2008)</td>
</tr>
<tr>
<td>&gt;8 degrees</td>
<td>“Very large”</td>
<td>Sandy (2012)</td>
</tr>
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*Original Source: Joint Typhoon Warning Center*
Factors Influencing TC Rainfall

Time of Day
Alberto, July 4-5, 1994

04/18z
00z
05/06z
12z
18z
Factors Influencing TC Rainfall

Time of Day
Alberto, July 4-5, 1994
Factors Influencing TC Rainfall

Terrain Impacts
Heaviest rainfall favors mountains perpendicular to the wind

Hurricane Georges in Puerto Rico
$1.75 billion in damage
28,005 homes destroyed
Factors Influencing TC Rainfall

Vertical Wind Shear – Northern Hemisphere

Shear directed **across** the storm track leads to more uniform distribution of the rainfall.

Shear directed **parallel** to the storm track leads to a distribution of the rainfall asymmetry on the left side of the track.

Rogers et al, 2003
Factors Influencing TC Rainfall
Shear, Mesovortices, and Topography

• Downshear region of strong convection associated with Erika (2015) passed directly over Dominica, producing over 500 mm of rainfall
  • Driven by 500-850 mb shear rather than deep layer shear

• Mesovortex on the scale of ~ 100 km developed within Erika’s circulation and persisted over Dominica for 3 hours, likely due to topographic effects, enhancing heavy rainfall

Nugent and Rios-Berrios (2018, MWR)
Factors Influencing TC Rainfall

Environmental Steering in Northern Hemisphere

- Very slow moving TCs and symmetrical TCs produce the most rainfall *near the center*
  - Maximum rainfall at night (especially when over land)
  - Weak steering flow

- TCs that move into a break in the subtropical ridge often produce most of the rain *right* of their track

- TCs that recurve due to significant upper troughs in the westerlies often produce most of their rain *left* of their track
  - Rainfall may spread well in advance of the TC due to interaction with the upper jet on the leading edge of the trough
Factors Influencing TC Rainfall

Predecessor Rainfall Events

- Moisture transport well ahead of TC itself
- Coherent area of rain displaced north of the TC (near a front or over terrain)
- Maximum rainfall rates can exceed 200 mm in 24 hr
- Occurs for approximately 1 of 3 landfalling TCs in U.S.
Factors Influencing TC Rainfall

“Twin” Disturbance or Other Secondary Features
Where is Flooding from Tropical Cyclones Likely to Occur?

- Areas where the ground is already saturated (low flash flood guidance values)
- Valleys/watersheds
- Areas of orographic enhancement
- Areas with poor drainage or prone to runoff
- Areas with directed drainage that can be overwhelmed
TC Rainfall Forecasting Tools
NHC Rainfall Product

*Incorporates microwave (MW) satellite data rainfall rates*

- NHC uses two different merged satellite rainfall estimation techniques:
  - **NRL-Blend** and **QMORPH** incorporate available MW data and propagate precipitation forward in time via IR
  - Training on the NRL-Blend technique: [http://www.nrlmry.navy.mil/training-bin/training.cgi](http://www.nrlmry.navy.mil/training-bin/training.cgi)
- As a third product, NHC uses the last applicable GFS forecast
  - A model forecast has the advantage of dynamics, topography, moisture, etc.
NHC Rainfall Product: Why Microwave?

- Geostationary IR data provides excellent spatiotemporal resolution, but is not optimal for rain estimation
- Microwave provides improved rainfall accuracy but at low temporal resolution
- Quantitative precipitation estimate (QPE) products leverage each method’s strength...
Satellite Rainfall Estimates

International Precipitation Working Group (IPWG) has an exhaustive list of data sources for precipitation information, some of it in real time.

http://www.isac.cnr.it/~ipwg/data/datasets.html
Satellite Rainfall Estimates

International Precipitation Working Group (IPWG) has an exhaustive list of data sources for precipitation information, some of it in real time.

http://www.isac.cnr.it/~ipwg/data/datasets.html

NRL-Blend
http://www.nrlmry.navy.mil/sat-bin/rain.cgi

TRMM MPA
http://pmm.nasa.gov/node/171

Meteosat

Hydro-Estimator

SCaMPER
http://www.star.nesdis.noaa.gov/smcd/emb/ff/SCaMPR.php
NHC Rainfall Product: Text

Created for every “invest” system
Can be created for any disturbance
Rainfall product still available in text format like the old product

Differences in content and format compared to the old product:

- 6-hour quantitative precipitation estimates from 3 methods
- Presented as a range of rainfall within a $1^\circ \times 1^\circ$ box
- Covers total area of $6^\circ \times 6^\circ$ centered near disturbance

- Earth-relative coordinates (i.e. no reference to “left-of-center”/”right of center”)
- Available at: http://www.nhc.noaa.gov/marine/rainfall/

<table>
<thead>
<tr>
<th>SYSTEM NAME</th>
<th>DATE/TIME</th>
<th>LOCATION</th>
</tr>
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<tbody>
<tr>
<td>13W ANDRES</td>
<td>05/3000 UTC</td>
<td>17N 102.2W</td>
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<th>RAINFALL ESTIMATED BY SATELLITE VIA (ORPHON)</th>
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<td>24-HOUR RAINFALL MAXIMUM (from 00-00 UTC) - 235 MM AT 23.3N 89.2W</td>
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Differences between the satellite and model derived rainfall estimates indicate uncertainty in the amount of rain received.

Rainfall may be underestimated on the upwind side of the disturbance.

For additional information, please visit:
http://www.nhc.noaa.gov/rainfall

Forecast: Helton
**New NHC Rainfall Product: Text**

- **Lat-lon grid of rainfall accumulation**
- **6-h accumulation ranges (in mm)**
- Differences in the 3 rainfall estimates reveal uncertainty
- Available at: [http://www.nhc.noaa.gov/marine/rainfall/](http://www.nhc.noaa.gov/marine/rainfall/)
Ensemble Tropical Rainfall Potential Product (eTRaP)

- 6-hourly Day 1 forecasts: Extrapolates polar orbiting satellite rain rate along TC forecast tracks (AMSU, SSMI, AMSR, GPM)
- A satellite “member” is included when its path passes over the TC
- “Members” are weighted according to age of pass and past performance of sensor
- Official forecast of TC track & at least 2 members needed to create a forecast
- Updated daily at 0315, 0915, 1515, and 2115 UTC

http://www.ssd.noaa.gov/PS/TROP/etrap.html
eTRaP: http://www.ssd.noaa.gov/PS/TROP/etrap.html

Typhoon Ului
06-12 hr eTRaP forecast
CLIQR: Picking an Analog for a TC Rainfall Event

www.wpc.ncep.noaa.gov/tropical/rain/web/cliqr.html

Looks at:

- The current rain shield size and compare it to TCs from the past
- How fast is the TC moving?
- Vertical wind shear in current/past events?
- Look for storms with similar or parallel tracks
- Is topography a consideration?
- Look for nearby fronts and examines the depth of nearby upper troughs for current event and possible analogs

Not all TC events will have a useful analog
Available for active TCs at:
www.wpc.ncep.noaa.gov/tropical/rain/web/cliqr.html
GOES-16/17 Products
GOES-16 launched in 2016
GOES-17 launched in 2017

Rainfall Rate Algorithm
Rainfall Potential Algorithm
Probability of Rainfall Algorithm
Algorithm generates estimates of instantaneous rainfall rate at each IR pixel

- Uses IR brightness temperatures and calibrated in real time against microwave-derived rain rates to enhance accuracy

- The higher spatial and temporal resolution available from GOES-16 will be able to automatically resolve rainfall rates on a finer scale
GOES-16/17 Products
Rainfall Potential

- Predicted rainfall accumulation for the next 3 hours at the satellite pixel scale
- Extrapolation from current and previous rainfall rates from the GOES-R Rainfall Rate Algorithm
GOES-16/17 Products

Probability of Rainfall

- Generates a gridded probability of at least 1 mm of rainfall during the next 3 hours at the satellite pixel scale
- Uses intermediate rainfall rate forecasts from the Rainfall Potential Algorithm as input to a statistical model calibrated against estimates from the Rainfall Rate Algorithm
Model Forecasts

GEFS Prob. of Exceedence

NAM QPF

GFS QPF

NAEFS Prob. of Exceedence

HWRF QPF
NCEP Model QPF Biases

• NCEP models are updated frequently which makes it difficult to isolate distinct biases

• Run-to-run consistency increases confidence of occurrence
Model TC QPF Skill
Marchok et al, 2007

1998-2004 U.S. landfalling TC QPFs from the GFS, GFDL hurricane model, the NAM, and the R-CLIPER (Rainfall Climatology and Persistence)

Three elements of TC rainfall forecasts used as a basis for comparing models:

• model ability to match the large-scale rainfall pattern,
• model ability to match the mean rainfall and the distribution of rain volume, and
• model ability to produce the extreme amounts often observed in TCs
Model TC QPF Skill
Marchok et al, 2007

- Compared to R-CLIPER, all numerical models showed comparable or greater skill for all attributes
- GFS performed the best of all of the models for each of the categories
- GFDL had a bias of predicting too much heavy rain, especially in the core of the tropical cyclones
- NAM predicted too little of the heavy rain.
- R-CLIPER performed well near the track of the core, but predicted much too little rain at large distances from the track
Compared to R-CLIPER, all numerical models showed comparable or greater skill for all attributes.

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GFDL had a bias of predicting too much heavy rain, especially in the core of the tropical cyclone.

NAM predicted too little of the heavy rain.

R-CLIPER performed well near the track of the core, but predicted much too little rain at large distances from the track.

Track forecast error was a primary determinant of tropical cyclone QPF error.
Where to Find Model QPFs

- **NHC Tropical Rainfall Webpage** (storm-specific GFS, hindcasts)
  http://www.nhc.noaa.gov/marine/rainfall/

- **NCEP models** (GFS, NAM, GEFS, NAEFS) including tropical guidance (HWRF and HMON)
  http://mag.ncep.noaa.gov

- **Canadian Global GEM**
  http://www.weatheroffice.gc.ca/model_forecast/global_e.html

- **Canadian Global GEM Ensembles**
  http://www.weatheroffice.gc.ca/ensemble/index_e.html

- **NAVGEM**
  http://www.nrlmry.navy.mil/metoc/nogaps/

- **ECMWF**
  http://schumacher.atmos.colostate.edu/weather/ecmwf.php

- **Penn State Tropical Atlantic E-Wall**
  http://mp1.met.psu.edu/~fxg1/ewalltropatl.html
TC QPF Forecast Process
NWS Tropical Cyclone Quantitative Precipitation Forecasts (QPF)
Production of Tropical Cyclone Quantitative Precipitation Forecasts

A good place to start is the model closest to the NHC track forecast.

“a primary determinant of tropical cyclone QPF errors is track forecast error”
– Marchok et al 2007
Production of Tropical Cyclone Quantitative Precipitation Forecasts

How well do the models match the NHC rainfall statement?

Day 1 QPF
24-h ending 12Z 21 Aug 2008 – T.S. Fay

6-7 inch maximum rainfall forecast over 24 hours

TROPICAL STORM FAY ADVISORY NUMBER 20
NWS TPC/NATIONAL HURRICANE CENTER MIAMI FL
1100 AM EDT WED AUG 20 2008

FAY IS EXPECTED TO PRODUCE RAINFALL ACCUMULATIONS OF 6 TO 12 INCHES OVER EAST-CENTRAL AND NORTHEASTERN FLORIDA...WITH 3 TO 6 INCHES OVER SOUTHEASTERN GEORGIA. ISOLATED MAXIMUM AMOUNTS OF 20 INCHES ARE POSSIBLE IN FLORIDA. ACCUMULATIONS OF 3 TO 5 INCHES ARE POSSIBLE IN THE NORTHWESTERN BAHAMAS. AN UNOFFICIAL REPORT OF NEAR 16 INCHES OF RAIN WAS MEASURED AT SATELLITE BEACH JUST TO THE NORTHEAST OF MELBOURNE FLORIDA.
Production of Tropical Cyclone Quantitative Precipitation Forecasts

Use observations and recent model data to determine the current structure/rainfall rates.
Production of Tropical Cyclone Quantitative Precipitation Forecasts

Locate relevant synoptic scale and meso-scale boundaries

Hurricane Rina (2011)
Production of Tropical Cyclone Quantitative Precipitation Forecasts

Use conceptual models and pattern recognition as well as the forecast upper level winds to further adjust QPF
Production of Tropical Cyclone Quantitative Precipitation Forecasts

Identify areas of orographic enhancement
Production of Tropical Cyclone Quantitative Precipitation Forecasts

Identify areas of orographic enhancement

Slopes Favored For Heavy Precipitation
Determine how a change in available moisture could increase, decrease, or redistribute rainfall.
Production of Tropical Cyclone Related QPF

Use climatology (CLIQR, R-CLIPER, TC Rainfall Climatology) and data from past storms to:

- Increase/decrease amounts
- Adjust numerical guidance biases
- Reality check
- Highlight areas significantly impacted by terrain effects

INVEST_AL96

Results ranked from best match to worst match, with ties being won by the earlier storm.

BETA 2005: No graphic available.
GERT 1999
HAITIE 1981: No graphic available.
IGAN 1988
MARCO 1996: No graphic available.
NOT NAMED 1964: No graphic available.
GORDON 1994
KATRINA 1999
MARTHA 1969: No graphic available.
THIRTEEN 1985: No graphic available.
BRET 1999: No graphic available.
ALMA 1970
IRENE 1971: No graphic available.
UNNAMED 1981: No graphic available.
FOURTEEN 2002: No graphic available.
SIX 1969: No graphic available.
LAURA 1977: No graphic available.
SEVENTEEN 1975: No graphic available.
CESAR 1968: No graphic available.

Ex-Hurricane Florence
September 13-14, 2006
14 sites

- 10
- 25
- 50

Maximum: 67 mm
Salt Pond, Nfld
In Conclusion

• Remember factors that influence TC rainfall
  – Size of storm, time of day, speed etc.

• Evaluate quality of the model data compared to current conditions

• Assess the amount of shear in the environment
  – How will it influence rainfall?

• Are there past TCs that resemble the rainfall distribution and forecast of the TC?

• Use all of the tools available
  – Satellite rainfall products, NWP models, etc.

• Remember, heavy rain can also occur well away from the TC itself
  – PREs, secondary disturbances, etc.
Thank You

Questions?