Estimating the Value of Weather Radars in Reducing Flash Flood Casualties

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Motivation

- **What's next after NEXRAD?**
  - **Polarimetric phased array radar?**
  - **Denser network of smaller radars?**
  - **Targeted gap-filling sites?**
  - **Continued incremental upgrades?**
- **Benefit estimates are needed to support decision process**
  - **Build business case through cost/benefit analyses**
- **Top 3 weather-related casualty sources in U.S.**
  - **Excessive heat (no direct weather radar impact)**
  - **Tornadoes (Cho and Kurdzo, 2019: JAMC, *58*, 971-987)**
  - **Flash floods (this talk)**

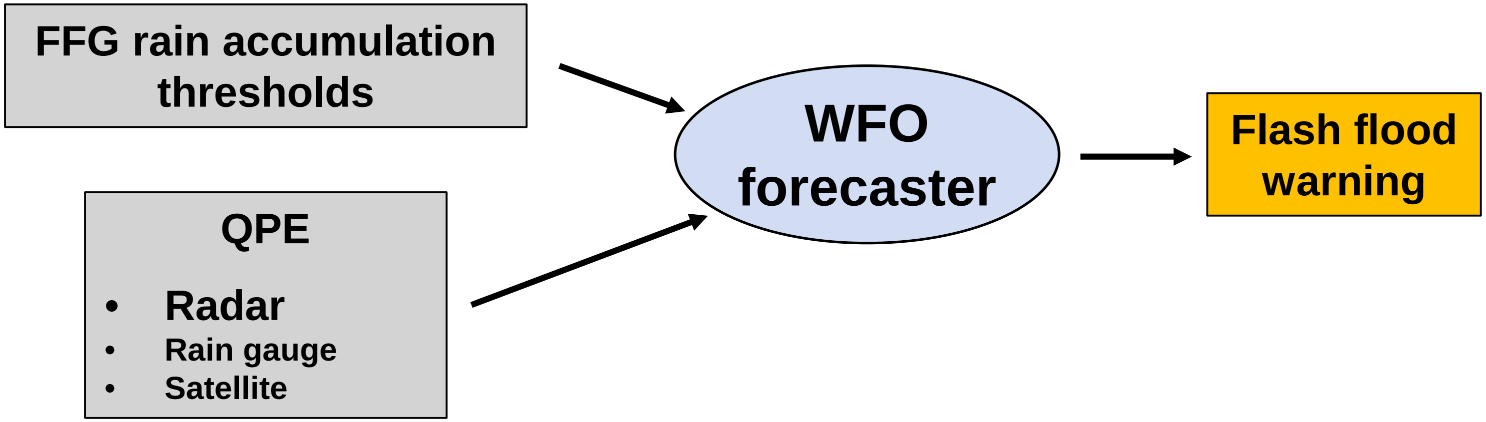
Goal: Quantify the impact of radar network configurations in reducing flash flood casualties

JAMC = Journal of Applied Meteorology and Climatology

Outline

- Motivation
- Model development
  - Basic concept
  - Coordinate transformation: Flood location ⇔ source basin
  - Radar coverage vs. flash flood warning performance
  - Flash flood warning performance vs. casualty rate
- Model Results
- Summary

Basic Model Concept



- **Poor radar coverage is a significant source of QPE error**
- **Hypothesize:**
  - – **Flash flood warning performance depends on radar coverage**
  - – **Casualty rate depends on warning performance**
  - ∴ **Flash flood casualty rate depends on radar coverage**

Use statistical analyses of historical data to develop model of weather radar network's impact on flash flood casualty cost reduction

FFG = Flash Flood Guidance **WFO = Weather Forecast Office**
QPE = quantitative precipitation estimate

Flash Flood Data Sets

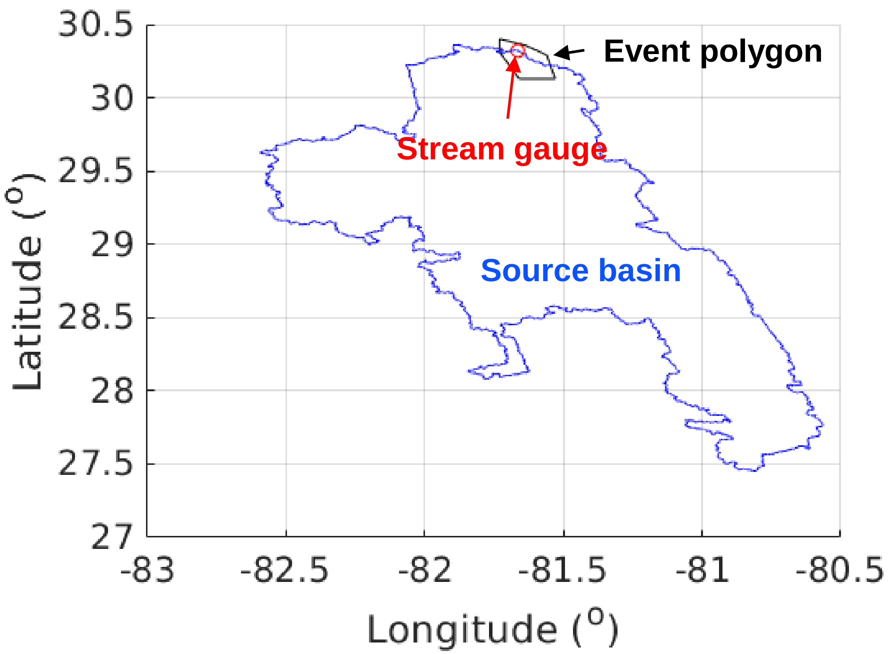
- NWS storm reports (FLASH and NCEI archives)
  - Event time and location (polygons and points)
  - Cause: Heavy rain, tidal, dam break, etc.
  - Casualties: Fatalities and injuries
  - Caveat: Not every flooding event is recorded
- NWS storm warnings (IEM archive)
  - Warning time and location (polygons since October 2007)
- Data period used: October 2007 – December 2018
- Only keep flash floods caused by heavy rain
- For every event search for matching warning: POD, lead time
- For every warning search for matching event: FAR

NWS = National Weather Service
FLASH = Flooded Locations and Simulated Hydrographs Project
NCEI = National Centers for Environmental Information
IEM = Iowa Environmental Mesonet
POD = probability of detection
FAR = false alarm ratio

Matching Flood to Source Basin

- **Compute mean radar coverage parameters over upstream drainage basin, not downstream flooded area**
  - **Find stream gauge(s) inside event/warning polygon or nearest if event is point**
  - **Use USGS NHDPlus database: 19,031 stream gauges with corresponding source basin characteristics**

Flood of St. Johns River, FL (2007-10-3)



Total Matched in Study Period (CONUS)

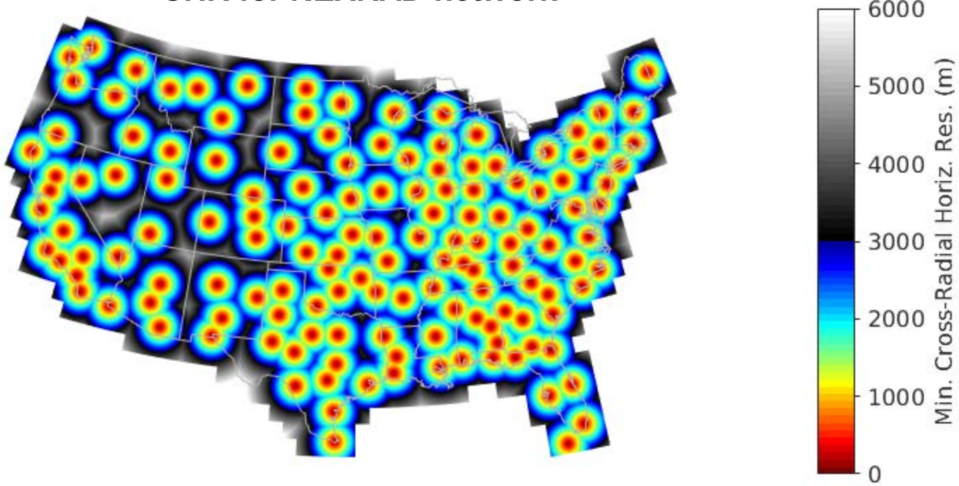
24,236 flash flood events
32,438 flash flood warnings

USGS = United States Geological Survey
NHDPlus = National Hydrography Dataset Plus

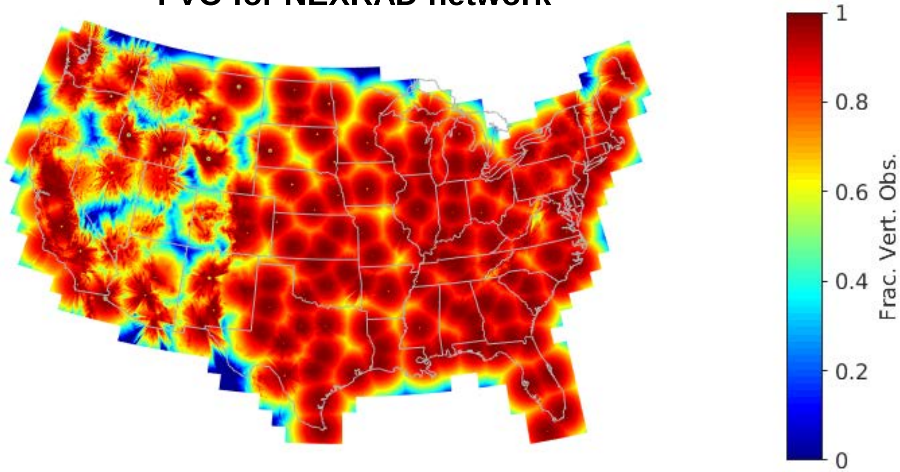
Radar Coverage Metrics

- **Key weather radar data characteristics for QPE**
  - **Cross-radial horizontal resolution (CHR)**
  - **Low-altitude coverage**
    - **Compute fractional volume coverage (FVO) between surface and 20kft AGL**

CHR for NEXRAD network

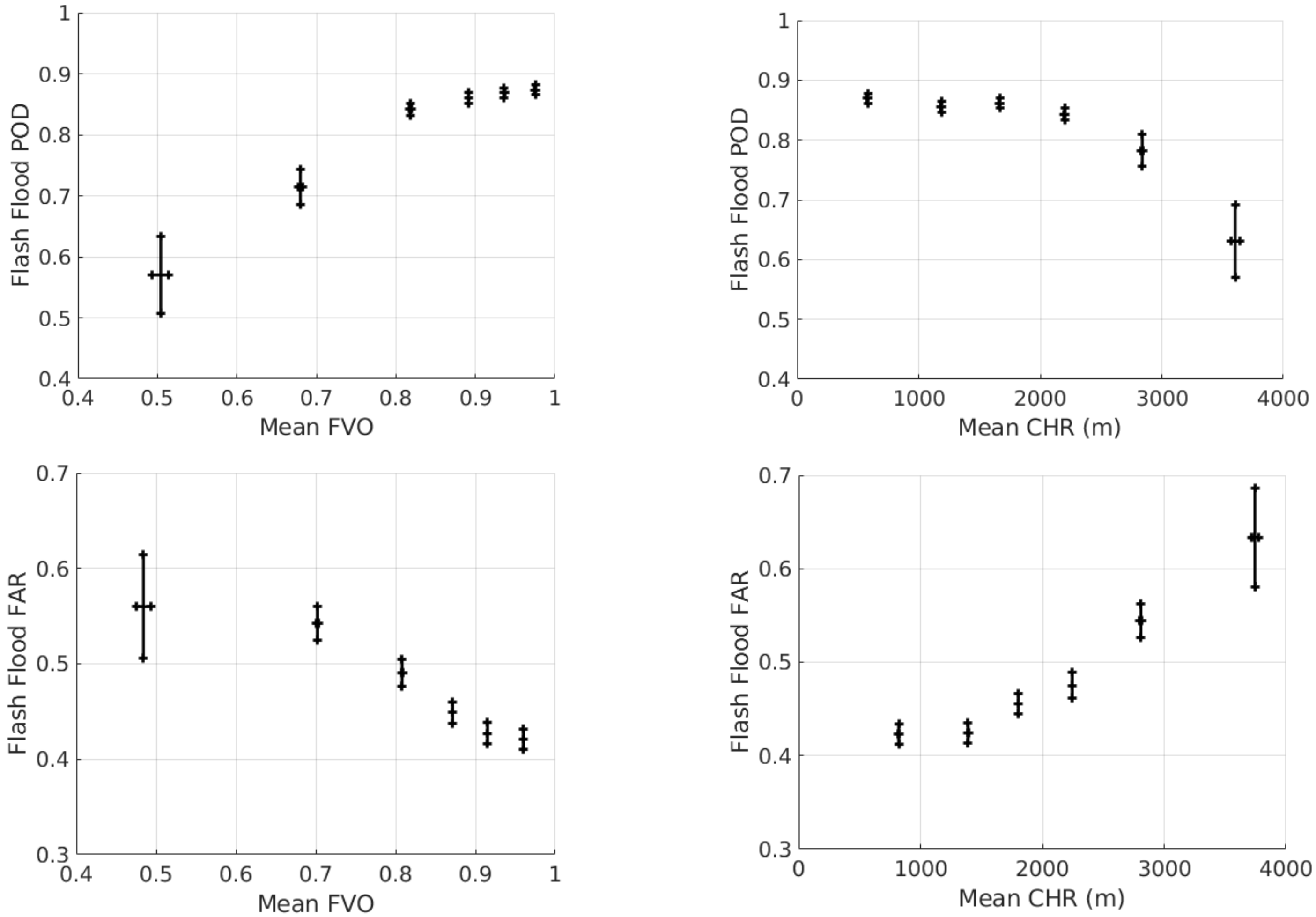


FVO for NEXRAD network



FVO includes Earth curvature, terrain blockage, and cone-of-silence effects in one metric

Flash Flood Warning vs. Radar Coverage



Better radar coverage improves flash flood warning performance

Flash Flood Casualty Regression Model

- **Negative binomial statistical flash flood casualty model**

Casualty → $C \sim \text{NegBin}(\mu, \theta)$ (Mean: μ; Overdispersion parameter: θ)

$$\ln \mu = k + \sum_i a_i x_i$$

Predictor Variable (x_i) Tested	Most Significant Results With
Population in event area	√
Flash flood warning presence	√
Flash flood warning lead time	
Historical flash flood warning FAR in event area	
Catchment basin size (proxy for basin response time)	
Flood flashiness* (limited number of cases available)	
Fraction of population in mobile housing	√

- Flashiness* = Peak flow above flood stage / (basin area × time to peak)
- Calculated from USGS streamflow data (only small subset of NWS events matched up)

Saharia et al., 2017: *Mapping flash flood severity in the United States, J. Hydrometeorology, 18, 397–411

Flash Flood Casualty Regression Model

- **Negative binomial statistical flash flood casualty model**

Mean

Casualty → $C \sim \mathrm{NegBin}(\mu, \theta)$ ← Overdispersion parameter

$$\ln \mu = k + \sum_i a_i x_i$$

Predictor Variable (x_i)	Coefficient	Estimate	P-value
Population in event area	a_1	0.17 ± 0.02	4×10^{-16}
Warning presence	a_2	-0.57 ± 0.16	3×10^{-4}
Fraction of population in mobile housing	a_3	2.2 ± 0.4	4×10^{-7}
Intercept constant	k	-4.6 ± 0.2	$< 2 \times 10^{-16}$
Overdispersion parameter	θ	0.11 ± 0.0007	N/A

Presence of flash flood warning reduces casualty rate by 44%

Gridded Casualty Rate Computation

- **Casualty rates (per year, per grid cell*)**

$$R_{ij}^{F,H,R} = Y^{F,H,R}\left[r_{ij}(1)B_{ij} + r_{ij}(0)\left(1 - B_{ij}\right)\right]O_{ij}$$

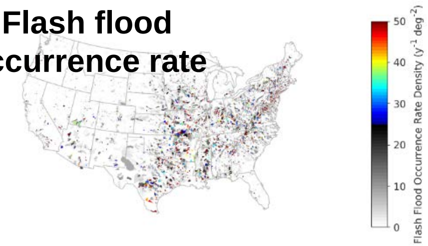
Casualty type fraction — $Y^{F,H,R}$

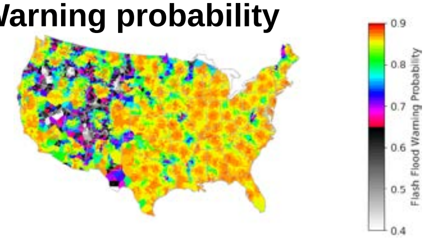
Casualty rate with warning — $r_{ij}(1)$

Casualty rate without warning — $r_{ij}(0)$

Warning probability — B_{ij}

Flash flood occurrence rate — O_{ij}



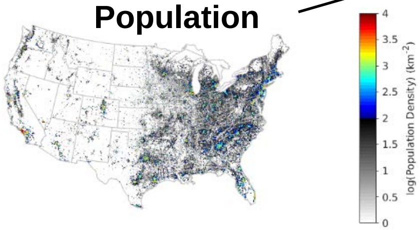


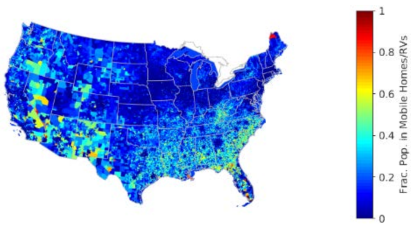
$$r_{ij}(W) = \exp\left[a_1 \ln\left(P_{ij}\right) + a_2 W + a_3 M_{ij} + k\right]$$

Population — P_{ij}

Warning presence: 0 or 1 — W

Fraction in mobile housing — M_{ij}





Fatal fraction: $Y^F = f$
Hospitalized injury fraction: $Y^H = (1 - f)h$
Treated and released fraction: $Y^R = (1 - f)(1 - h)$

Historical Averages

$f = 0.61$
$h = 0.43$

- **Sum over all grid cells to get total casualty rate per year**

***Grid cell size = 1/120° x 1/120°**

Outline

- **Motivation**
- **Model development**
- **Model Results**
  - **Basic scenarios**
  - **Benefit pool mapping**
- **Summary**

Annual CONUS Flash Flood Casualty Rates: Modeled vs. Actual

Scenario	Fatal	Injured (hospitalized)	Injured (treated and released)	Total	Delta baseline
0% warned	83.6	23.1	30.6	137.2	50.9
No radar coverage	77.6	21.4	28.4	127.4	41.1
NEXRAD network	52.6	14.5	19.2	86.3	——
Perfect radar coverage	51.5	14.2	18.9	84.6	-1.7
100% warned	47.2	13.0	17.3	77.4	-8.9
Actual mean (2007–2018)	63 ± 10	41 ± 15		104 ± 20	N/A
Actual median (2007–2018)	59 ± 7	23 ± 8		86 ± 13	N/A

No radar coverage: FVO = 0 and CHR = ∞ everywhere
Perfect radar coverage: FVO = 1 and CHR = 0 everywhere

Modeled casualty rates closely match actual rates

- **Use value statistical life* (VSL) to monetize casualties**
  - **$11.6M (fatality), $3.1M (injury—hospitalized), $0.55M (injury—treated and released)**

***"Guidance on treatment of the economic value of a statistical life in U.S. Department of Transportation analyses—2016 adjustment," Memorandum to secretarial officers and modal administrators**

Annual CONUS Flash Flood Casualty Cost Model Results

Scenario	Fatal ($M)	Injured (hospitalized) ($M)	Injured (treated and released) ($M)	Total ($M)	Delta baseline ($M)
0% warned	969.6	71.2	16.7	1057	392
No radar coverage	899.8	66.1	15.5	981	316
NEXRAD network	609.9	44.8	10.5	665	——
Perfect radar coverage	597.7	43.9	10.3	652	-13
100% warned	547.0	40.2	9.4	596	-69

Current radars provide over $300M per year in flash flood benefits

- Remaining benefit pool for radar network upgrade is modest
  - On average, current radars provide good coverage for flash flood warning guidance
  - Pool may increase if rapid scan benefit can be claimed but ultimately limited by 100% warned limit
  - Other aspects of casualty reduction should be addressed, e.g., warning dissemination, public education, etc.

Remaining Benefit Pool Map

- **Difference between “perfect coverage” case and NEXRAD network case**
- **Guidance for placing gap-filling radars with respect to flash flood benefits**

Summary

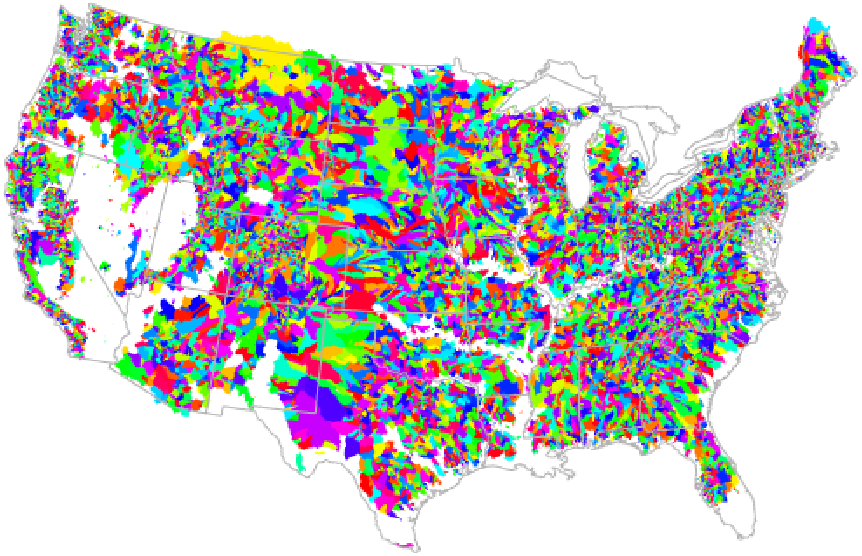
- Statistical geospatial model developed for flash flood casualty reduction benefits associated with weather radar coverage
- Model yields ~$320M per year benefit for current CONUS NEXRAD network
- Remaining benefit pool for radar coverage enhancement is modest
- Follow-up question: Do faster scan updates improve warning performance?
  - Investigate with existing (MESO-)SAILS, MRLE data

MESO = multiple elevation scan option
SAILS = supplemental adaptive intra-volume low-level supplemental scan
MRLE = mid-level rescan of low-level elevations

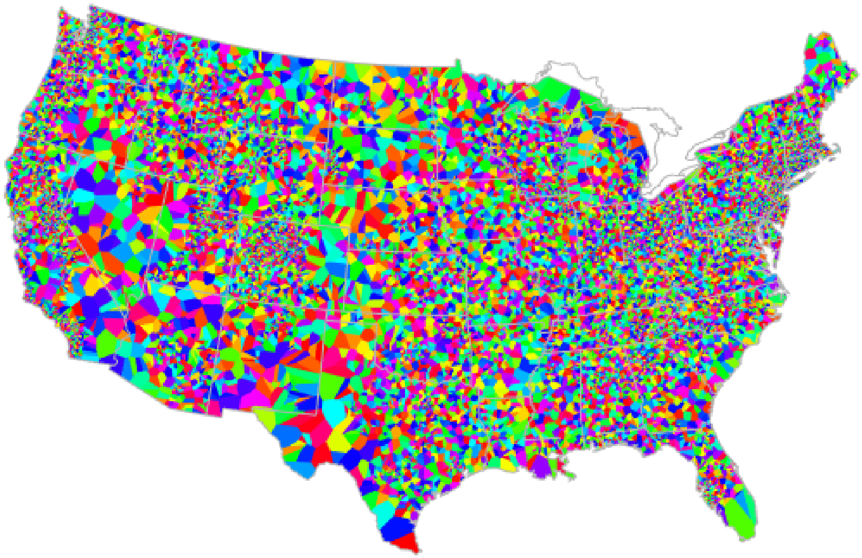
Backup Slides

Stream Gauge and Source Basin: Geospatial Mappings

Source Basins Associated with Stream Gauges

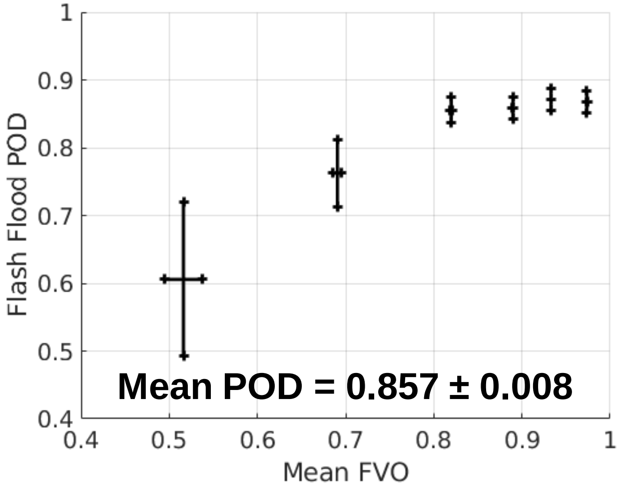


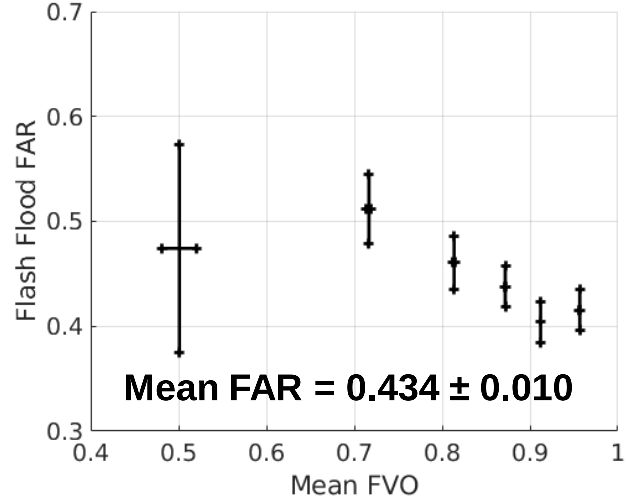
Areas Associated with Closest Stream Gauge



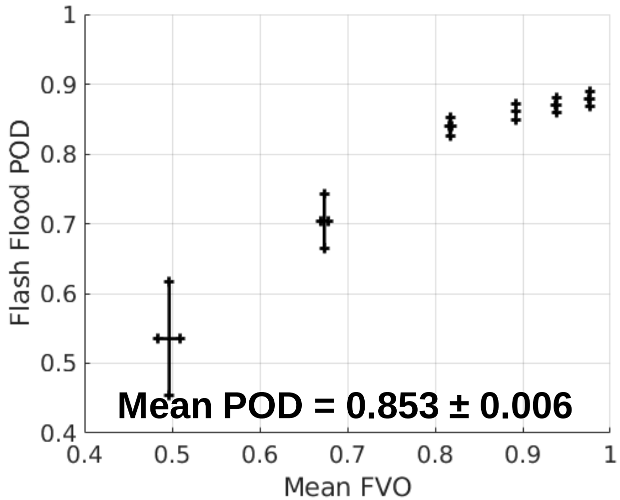
Flash Flood Warning Statistics Before and After Dual-Pol Upgrade

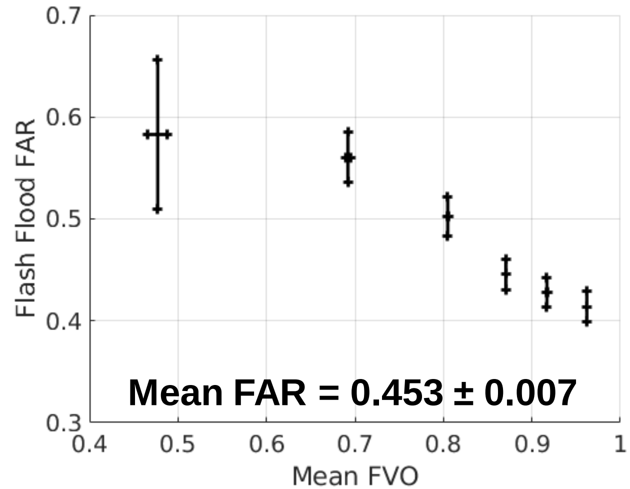
Pre-Dual Pol
2007-10-1 to 2011-3-7





Dual Pol
2013-5-16 to 2018-12-31





Radar coverage vs. flash flood warning performance relation is robust

Combined Annual CONUS Tornado and Flash Flood Cost Model Results

Scenario	Tornado ($M)	Flash flood ($M)	Total ($M)	Delta baseline ($M)
No radar coverage	3904	981	4885	851
NEXRAD	3385	665	4050	16
NEXRAD, TDWR	3369	665	4034	——
NEXRAD, TDWR, rapid scan	3036	665	3701	-333
Perfect coverage	3186	652	3838	-196
Perfect coverage, rapid scan	2693	652	3345	-689

Benefits and benefit pools are dominated by tornado cost avoidances

Publications

- **Cho, J. Y. N., and J. M. Kurdzo, 2019: Weather radar network benefit model for tornadoes. *J. Appl. Meteor. Climatol.*, 58, 971-987**
- **Cho, J. Y. N., and J. M. Kurdzo, 2019: Monetized weather radar network benefits for tornado cost reduction. Project Rep. NOAA-35, MIT Lincoln Laboratory, Lexington, MA, 88 pp.**
- **Cho, J. Y. N., and J. M. Kurdzo, 2019: Weather radar network benefit model for flash flood casualty reduction. *J. Appl. Meteor. Climatol.*, under review**

TDWR = Terminal Doppler Weather Radar