Reassessing Nonstationary Risk from Heavy Rainfall

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Introduction: The Challenge of Changing Rainfall

Problem: Escalating impacts of climate change on extreme rainfall events

Traditional Approach: Stormwater infrastructure designed based on historical data (e.g., NOAA Atlas 14)

Reality: Historical records are increasingly insufficient due to:

- Increased frequency and intensity of extreme rainfall
- New weather extremes set annually

Consequence: Underestimation of risk, inadequate local planning, and challenges for the insurance industry

The Problem: Nonstationary Risk & Pluvial Flooding

Climate-Driven Intensification: Mounting evidence of flood intensification

Pluvial Flooding: Flooding from excessive rainfall overwhelming drainage

- Often underestimated and inadequately mitigated
- Major cause of U.S. flood insurance claims (1978-2021 data)

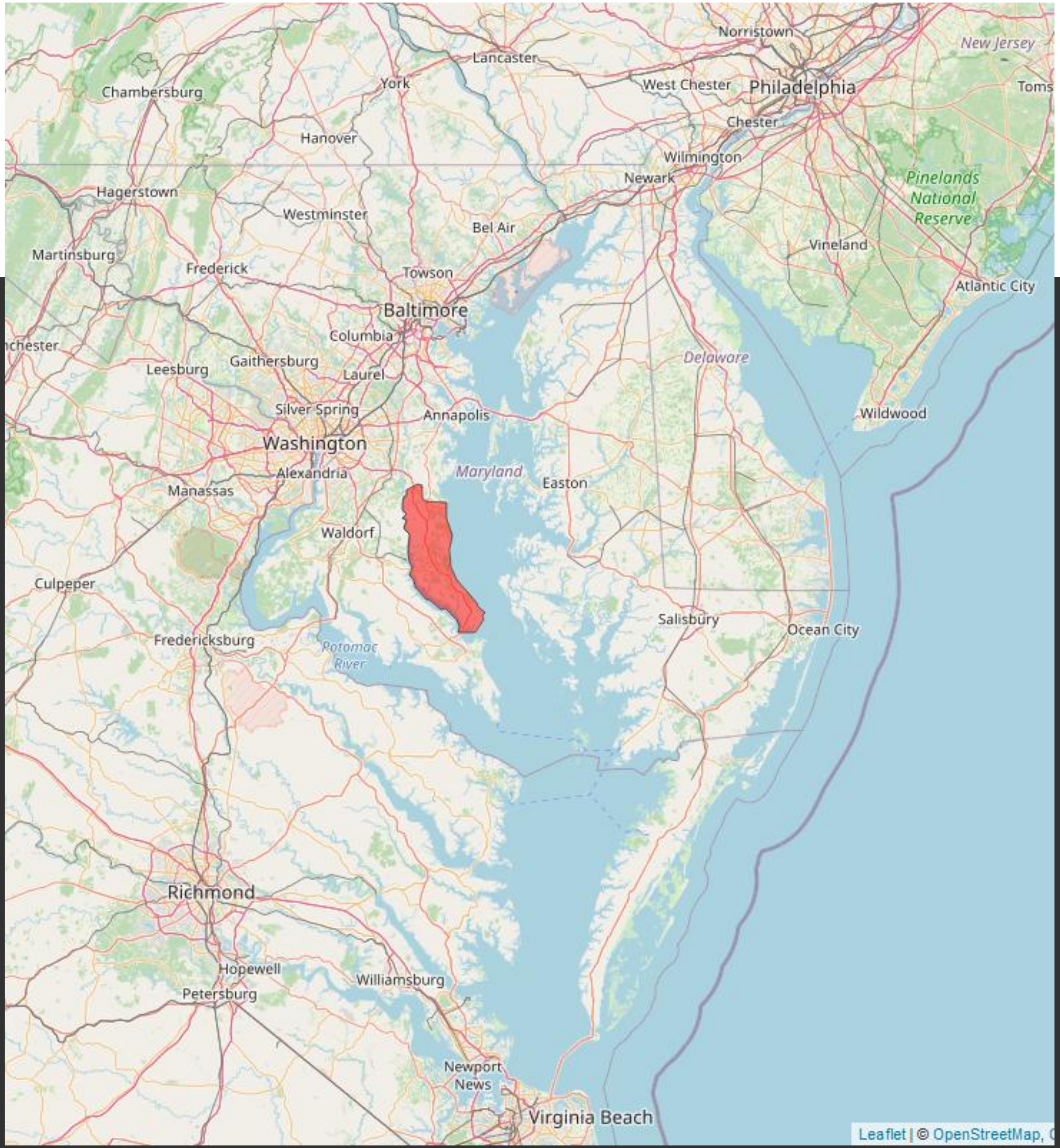
Exacerbating Human Factors

- Increased Impervious Surfaces: Reduced infiltration, enhanced runoff
- Inadequate Stormwater Infrastructure: Catastrophic failures (e.g., Hurricanes Katrina, Harvey, St. Louis 2022)
- Climate Warming: Directly increases rainfall rates and pluvial flooding frequency

Study Area: Calvert County, Maryland

Location: Coastal entity on the western shore of Chesapeake Bay

Due to the cliffs at its shores and its many rivers, *pluvial* (rain-induced) and *fluvial* (river-induced) flooding are arguably more impactful here than *coastal* flooding related to sea-level rise



Project Objectives

1. **Assess Trends:** Evaluate trends in heavy rainfall statistics relevant for stormwater management designs in Calvert County
2. **Suggest Modifications:** Propose revisions to design thresholds by incorporating the most recent regional climate dynamics and uncertainties
3. **Overall Goal:** Enable Calvert County to adjust regulatory standards, thereby reducing flood risks and impacts

Data Sources: A Multi-Dataset Approach

Purpose: Combine historical records with future projections to assess trends

1. NOAA Global Hourly Precipitation (ISD DSI-3505)
Station-based hourly time series (1945–2023); from Calvert, Anne Arundel, St. Mary's Counties; used for long-term trend analysis (24-hour rainfall maxima)

2. NOAA Atlas 14 Annual Maxima
Cleaned and processed historical data (1892–2000); also from the 3 counties; used to assess differences with future expectations using the same IDF estimation methods

3. NASA IMERG Product
Satellite-derived, ground-truthed gridded precipitation (2001–2022); 30-minute temporal, 0.1° (10 km) spatial resolution; represents recent observational period

4. Convection-Permitting Model (CPM) Control Run
Highly-resolved (1-hour, 4 km) historical simulation (2000–2013); baseline for bias correction and comparison with observations. **Novel component:** Explicitly includes thunderstorms

5. CPM Climate Projections (RCP 8.5)
"Business as usual" climate trajectory (average conditions over 2071–2100); used for future rainfall estimates

Methods: Trend Assessment in Observational Data

1. Generalized Additive Model for Location, Scale, and Shape (GAMLSS) with Generalized Extreme Value (GEV) distribution

$$Precipitation_t \sim GEV(\mu_t, \sigma_t, \nu_t)$$

2. Nonparametric Mann–Kendall Test (Sieve-Bootstrapped)
   - Tests for monotonic trend, accounting for autocorrelation
   - AR(p) model filters autocorrelation; residuals are bootstrapped

Methods: Bias Correction of Climate Model Output

Purpose: Match the distribution of observed precipitation and climate model output for the same period

- Enables accurate estimation of future climate dynamics

Method Selection: 10-fold cross-validation using NASA (observed) and CPM control run (model) hourly precipitation (2001–2012)

Quantile Mapping Methods Assessed

- PTF (Parametric Transformations): Exponential tendency to an asymptote
- DIST (Distribution Derived): Bernoulli-Gamma mixture distribution
- QUANT / RQUANT (Nonparametric Quantile Mapping): Empirical and robust empirical quantiles
- SSPLIN (Smoothing Spline): Smoothing spline fit to quantile-quantile plot

Evaluation Criteria: Smallest Mean Absolute Error (MAE) and Root Mean Square Error (RMSE)

Methods: IDF & DDF Estimation and Uncertainty Quantification

Fit a **Generalized Extreme Value (GEV)** distribution to the annual maxima for each duration

- DDF Curves: Calculate return levels for durations and return periods (2, 5, 10, 25, 50, 100 years)
- IDF Curves: Derived from DDF curves by adjusting return levels for intensity

Uncertainty Quantification (Bootstrap Procedure)

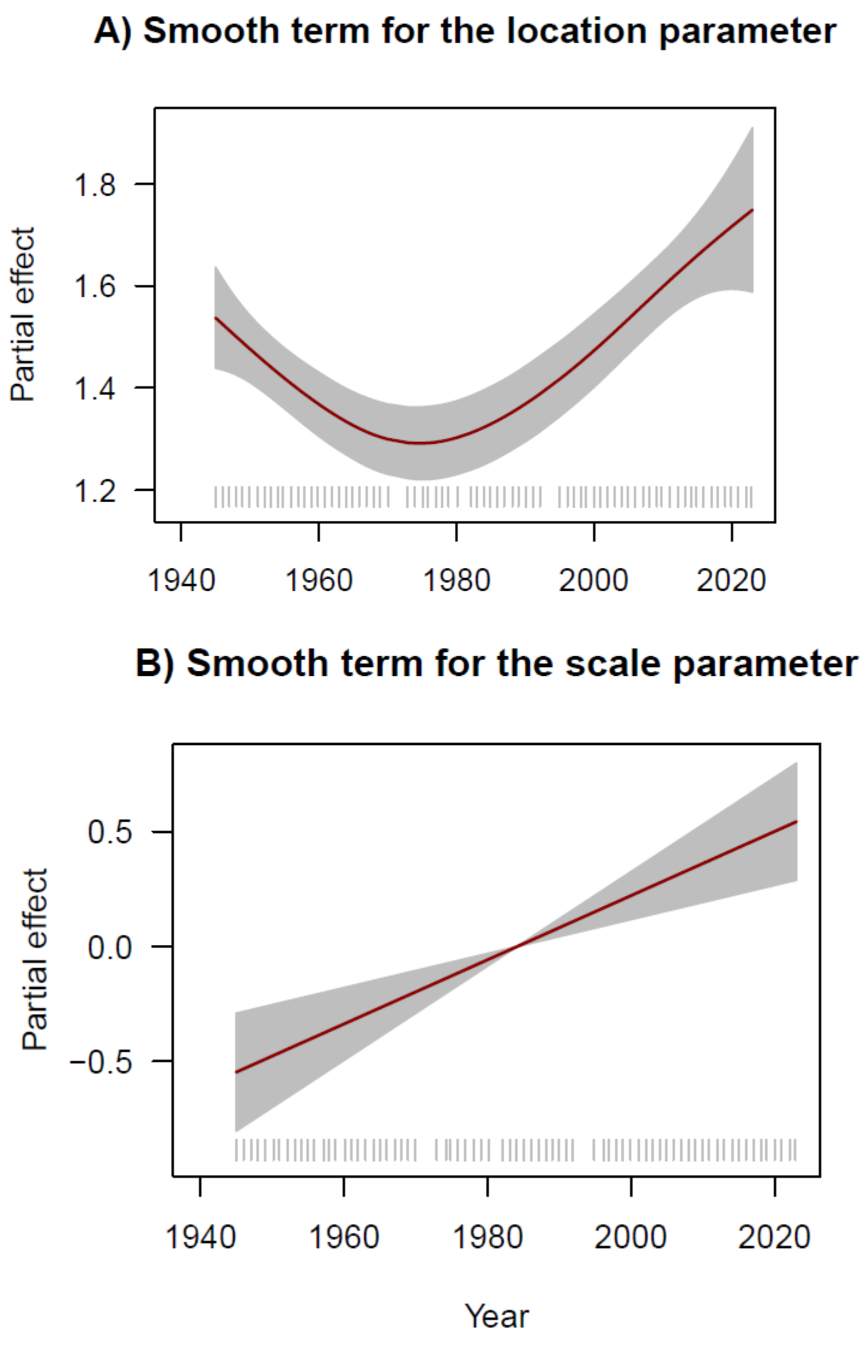
- **Resampling:** Resample spatial grid cells with replacement 1000 times
- **Re-estimation:** Re-estimate IDF and DDF curves (fitting GEV) for all durations on each dataset
- **Confidence Intervals:** Calculate 2.5th/97.5th percentiles (95% CI) and 10th/90th percentiles (80% CI) from the distribution of estimated return levels

Results: Trend Assessment

Significant **increase in both magnitude and variability** of extreme precipitation over time

$$Precipitation_t \sim GEV(\mu_t, \sigma_t, \nu_t)$$
$$log(\mu_t) = a_0 + s_1(Year_t)$$
$$log(\sigma_t) = b_0 + b_1 Year_t$$
$$\nu_t = c_0$$

Sieve-bootstrapped Mann–Kendall test τ = 0.158, with an associated p-value of 0.047 --> presence of a statistically significant monotonically increasing trend



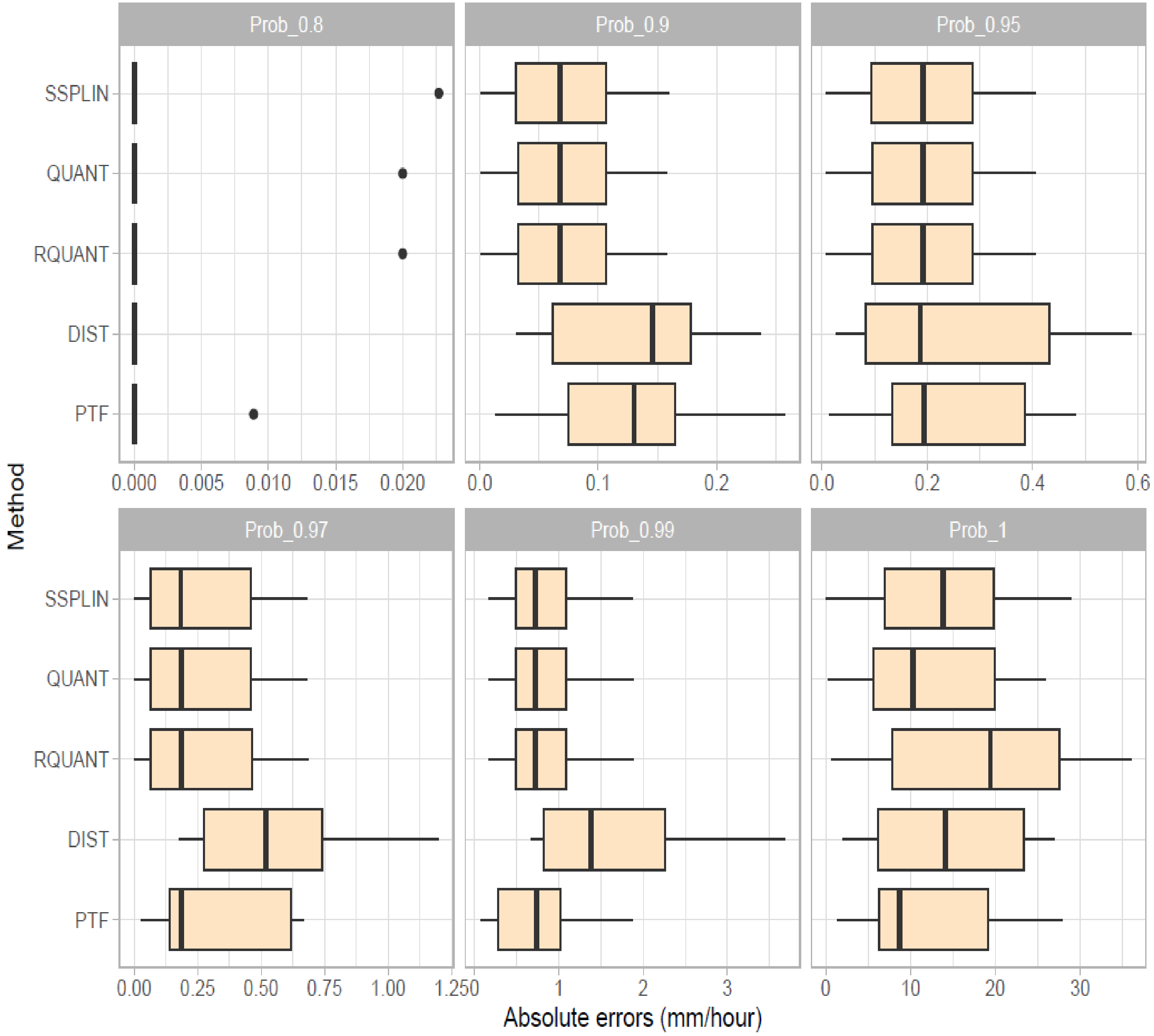
Results: Bias Correction

QUANT method consistently yielded the lowest MAE and RMSE

Verification: Trivial difference between NASA data and bias-corrected model control run quantiles in the 2001–2012 training period

Key Observation: For probabilities > 0.9, bias-corrected control run quantiles were lower than observed quantiles from the full 2001–2022 NASA data

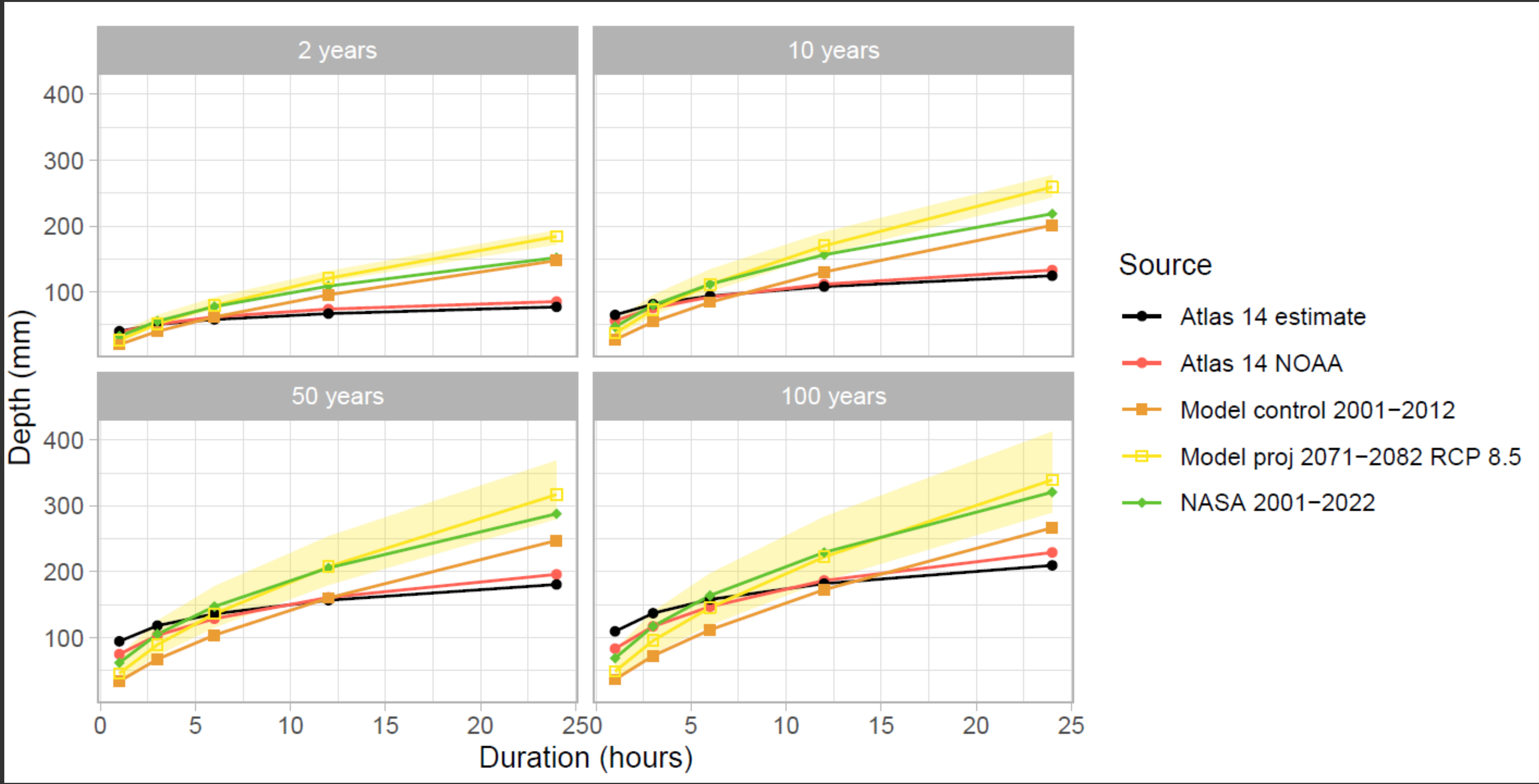
- Suggests an increase in extreme precipitation during 2013–2022, supporting trend inference
- Bias-corrected model projections show a further expected increase in the most extreme precipitation



Results: IDF and DDF Curves

Estimates from **bias-adjusted model projections are consistently higher** than observed or control run data

Suggests a **clear pattern towards more extreme rainfall in the future**, warranting further exploration



Discussion: Key Insights

Consistency with Atlas 14: General consistency but notable differences at varying durations

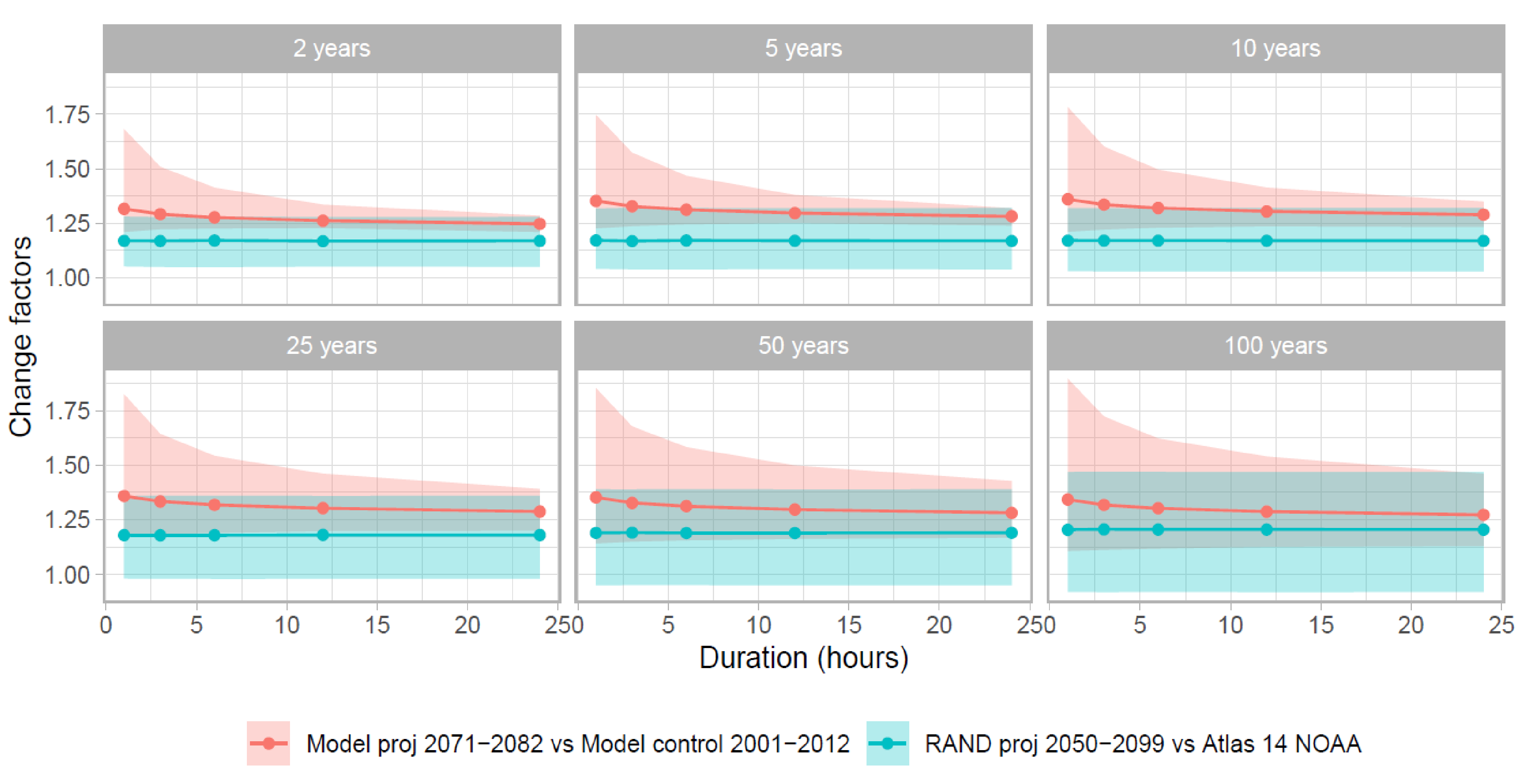
- Recent NASA data (2001–2022) show substantially steeper DDF curves for longer durations (12 and 24 hours) compared to historical Atlas 14 (pre-2000)
- Confirms nonstationary nature of extreme rainfall; historical records underestimate current conditions

Importance of Temporal Consistency: Bias correction effectively aligns quantiles over matched timeframes

- Comparisons must be done over the same period to avoid confounding temporal changes with other data differences

Discussion: Comparison with RAND Study

- RAND (lower-resolution, no convective precipitation): Median change factor of **1.18**
- Our study (CPM, accounts for convection): Median change factor of **1.30**
- Our study's 80% confidence intervals consistently remain above 1, suggesting a consistent increase in rainfall



Conclusion & Future Directions

Key Findings Confirmed: Recent extreme rainfall in Southern Maryland significantly exceeds 20th-century levels, and high-resolution models project even greater future intensities

- Underscores nonstationary nature of extreme precipitation
- Highlights inadequacy of historical Atlas 14 data for stormwater management design

Implications for Risk Management

- Quantitative estimates of current and future risk dynamics are crucial for actuaries and the public
- Current property insurance contracts should integrate up-to-date estimates to maintain viability
- Estimated trends should compel insurers to adjust future products and advocate for climate mitigation

Broader Applicability

- This project offers a science-based template for other jurisdictions nationally
- Fosters dialogue on adopting new methods for developing regulatory standards and risk reduction strategies that explicitly account for projected climate change

Thank you!

Questions?

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