Case Studies of Extreme Tropical Cyclone Precipitation in the Southern Appalachians: Observational & Modeling Challenges

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NASEM: Extreme warm-season rainfall in mountainous terrain: modeling and observational challenges

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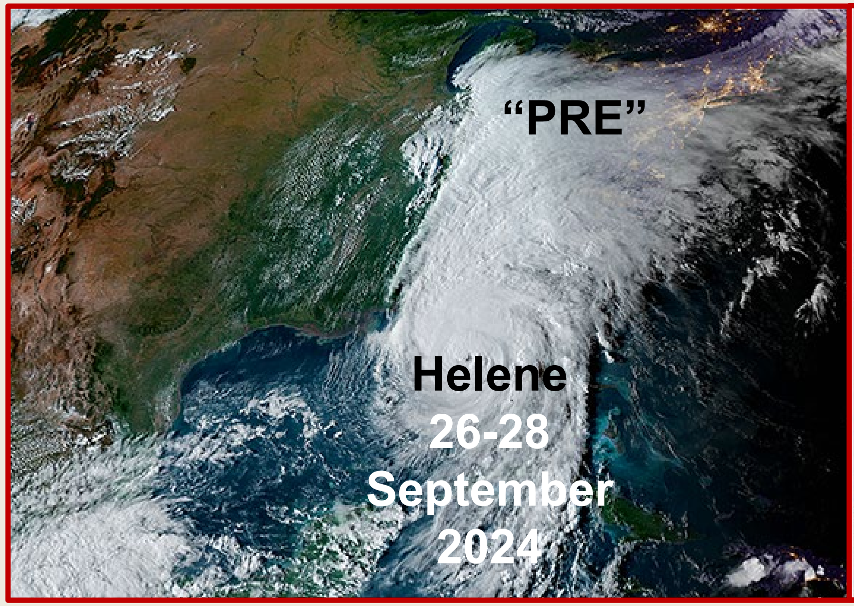
With contributions from: **Amanda Sinning (now Munro-Foulis) and Sawyer Smith**



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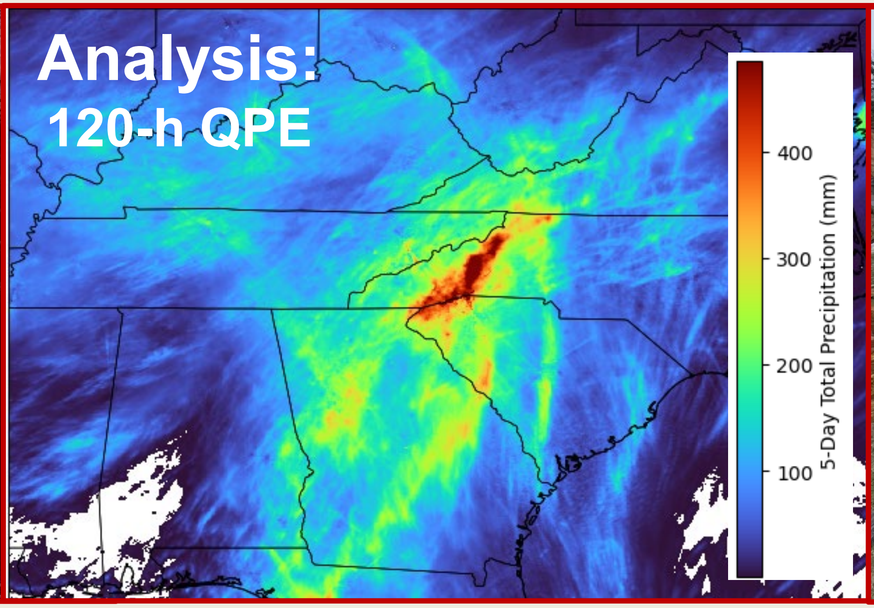


MRMS 120-h accumulated precipitation, 25 – 29 Sept. 2025


Craig Dam, Swannanoa River in Asheville, pictured in February 2025. Image by Jack Igelman/Carolina Public Press.

Focus topic: Extreme tropical cyclone (TC) precipitation in the Southern Appalachians

- The tropical cyclone (TC) - orographic precipitation problem presents challenges from both observational and modeling standpoints

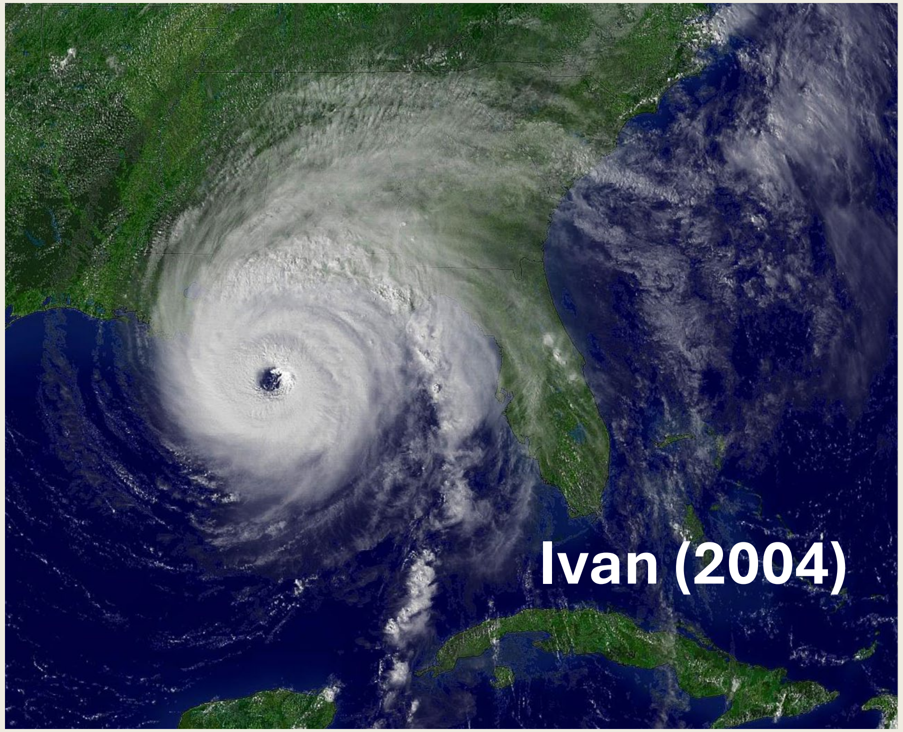
- Share experiences from ongoing, applied projects with PMP-relevant goals:
  - North Carolina Department of Transportation (NC DOT):
    - Simulated "design storms", including Frances and Ivan (2004) and Helene (2024)
    - Used convection-allowing ensembles to simulate past extreme events associated with TCs in the Southern Appalachians
    - Goal: Provide precipitation data for transportation engineering purposes
  - Center for Western Weather and Water Extremes (CW3E):
    - Atmospheric River (AR) predictability study, examined sensitivity of orographic precipitation to the parameterization of cloud and precipitation

- Discuss uncertainty sources and "lessons learned" based on experience developing the kind of historical case-study event catalog that is recommended for PMP modernization

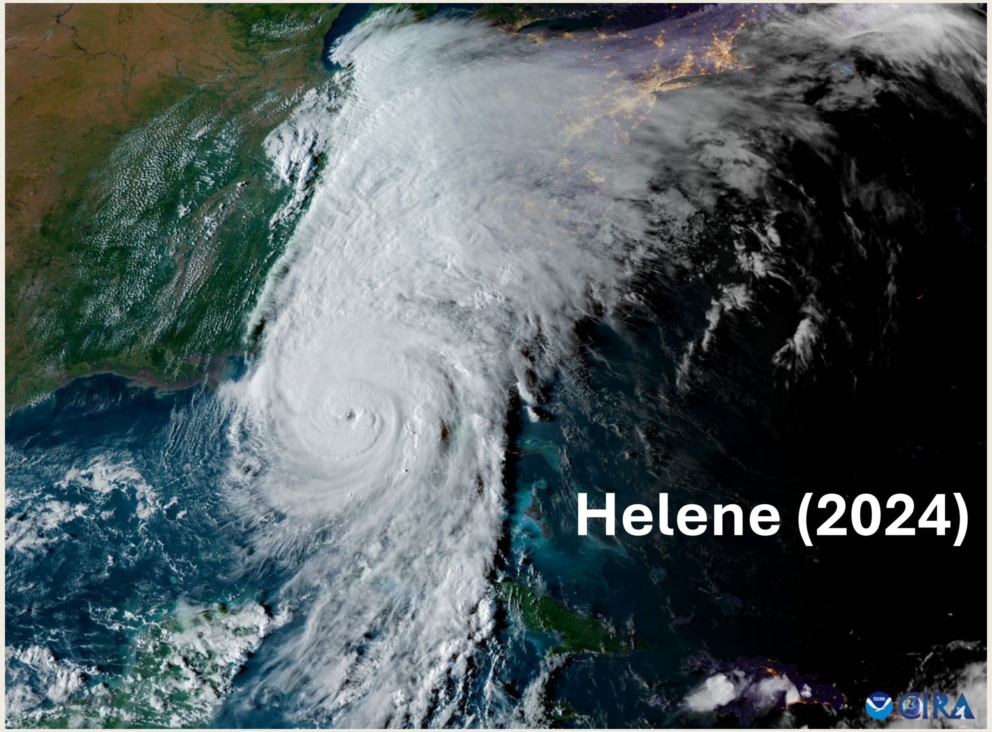
Case Studies of Extreme Tropical Cyclone Precipitation in the Southern Appalachians: Observational & Modeling Challenges

Building a catalog of extreme Southern Appalachian TC flooding: Many candidate events:

- 1916 Asheville flood event (e.g., downscale using 20th Century Reanalysis with dynamical model)
- Camille (1969, VA)
- Frances and Ivan (2004), back-to-back storms
- Tropical storm Fred (2021)
- Helene (2024)

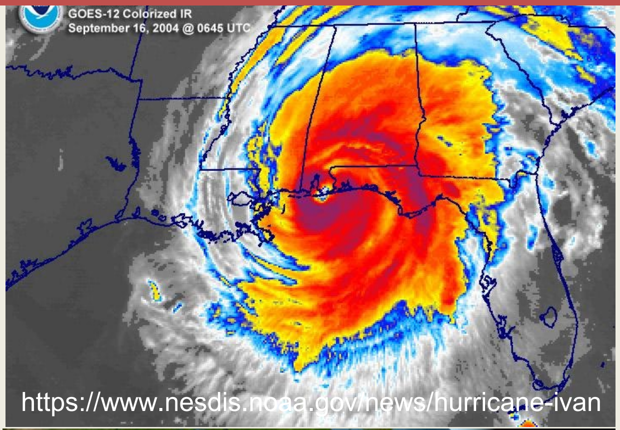


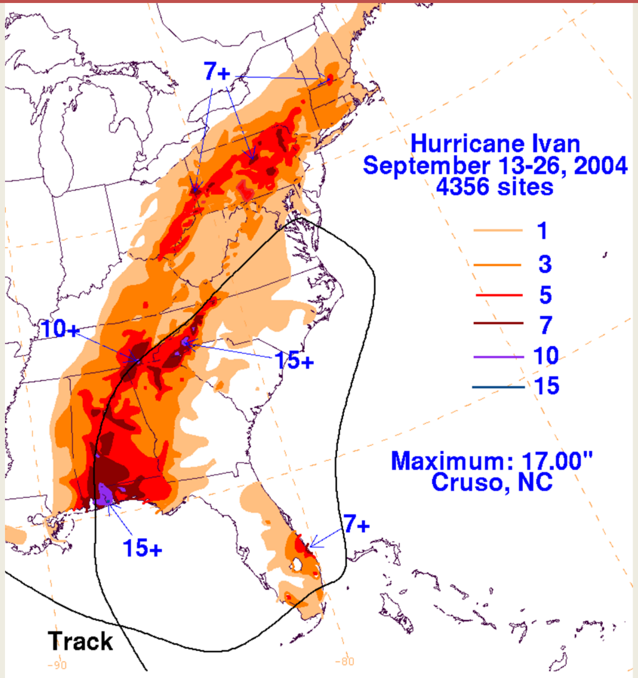
Ivan (2004): https://www.nesdis.noaa.gov/news/hurricane-ivan



Helene (2024): https://satlib.cira.colostate.edu/event/hurricane-helene/

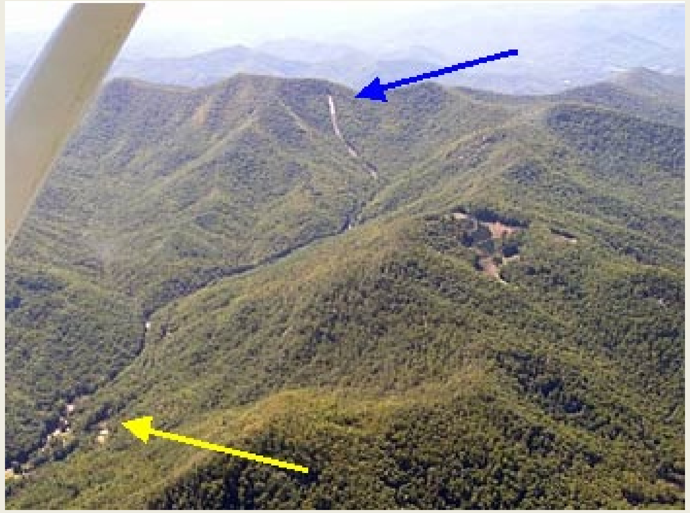
Case Study Example: Ivan (2004)





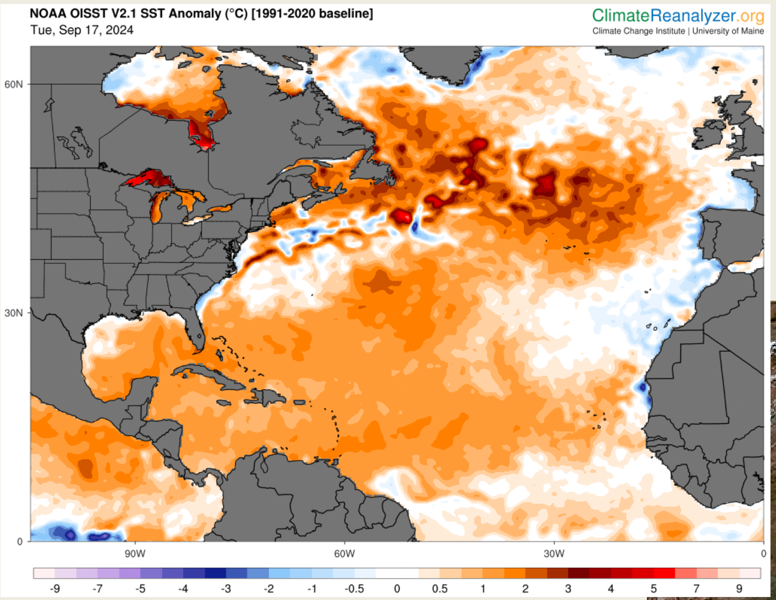
- $26B (2004 USD)
- [54 US fatalities]
- In Appalachians 16-17 Sept 2004
- Frances affected area ~10 days before

Peeks Creek flow alone destroyed 15 homes, 4 fatalities



Peeks Creek debris flow in Macon County. (Photo by Leif Skoogfors/FEMA).

Case Study Example: Helene (2024)

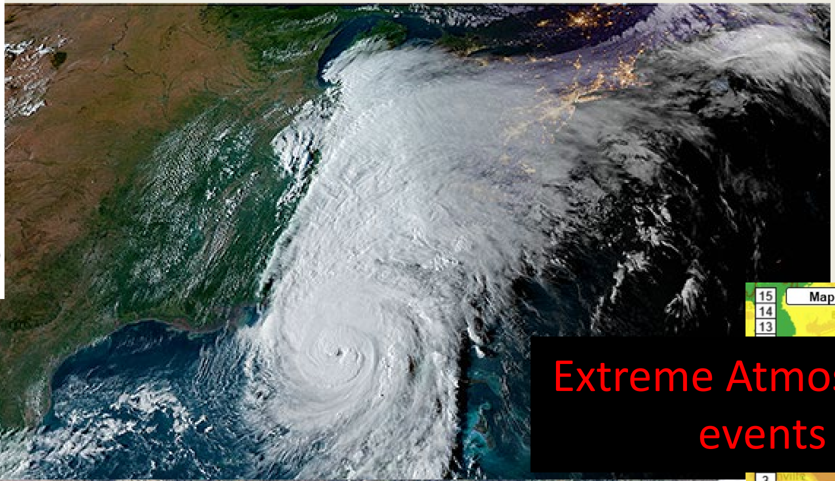


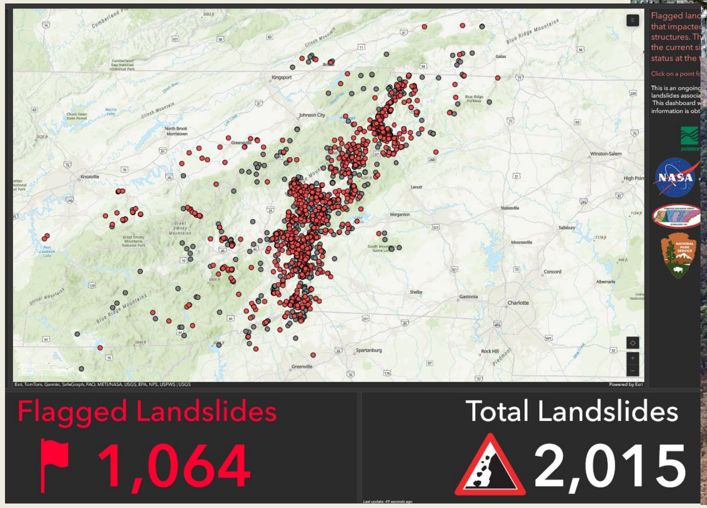
Extreme ocean warmth led to record atmospheric vapor content

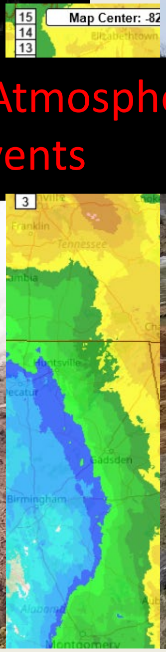
- $78.7B (2024 USD); 252 US fatalities
- In Appalachians 24-28 Sept 2024
- Predecessor Rain Event (PRE) affected area in days preceding

Nolichucky Dam, Greeneville TN

https://nypost.com/2024/09/28/us-news/tennessee-dam-narrowly-avoids-failure-after-heavy-rain-from-hurricane-helene/







Extreme Atmospheric events

Craig Dam, Swannanoa River in Asheville, pictured in February 2025. Image by Jack Igelman/Carolina Public Press.

https://pulitzercenter.org/stories/not-silver-bullet-nc-dams-problematic-during-helene-flooding-future-role-unclear

Case Studies of Extreme Tropical Cyclone Precipitation in the Southern Appalachian Mountains: Observational & Modeling Challenges

Challenges in simulating a “catalog” of cases of this type:

1) Must simulate some portion of the **TC lifecycle** for model storm to be realistically structured

Tropical Cyclones (TCs) are challenging to model:

- Simulate **TC intensification, landfall, and post-landfall evolution** prior to storm reaching terrain
- Synoptic circulation with “mesoscale power plant”: **Convection-allowing grid length** needed
- Large **convection-allowing domain** to capture TC development (moving nest not ideal)
- **Air-sea interactions** (at least **ocean mixed-layer model** for slow-moving TCs, or coupled model)
- Modeling experience (e.g., with WRF*: “isftcflx”, initial condition issues, digital filter, etc.)
- Results sensitive to physics, especially PBL & **microphysics (MP)**: **Ensemble**
- TCs may be **transitioning**, interacting with synoptic features, further complicating simulation
- Use of nudging can help replicate (e.g., with TC track), but limits physical realism

* WRF = Weather, Research, and Forecasting model from NSF NCAR

Case Studies of Extreme Tropical Cyclone Precipitation in the Southern Appalachian Mountains: Observational & Modeling Challenges

Challenges in simulating a "catalog" of cases of this type:

2) Additional complexities await once simulated TC reaches orographic region:

- Uncertain precipitation observations:
  - Extreme rainfall in complex terrain, large spatial variability
  - **Precipitation measurement** at high wind speed **problematic** for many gauges
  - Topography and **radar beam-blockage** can limit analysis accuracy
- Another set of numerical model physical dependencies and sensitivities

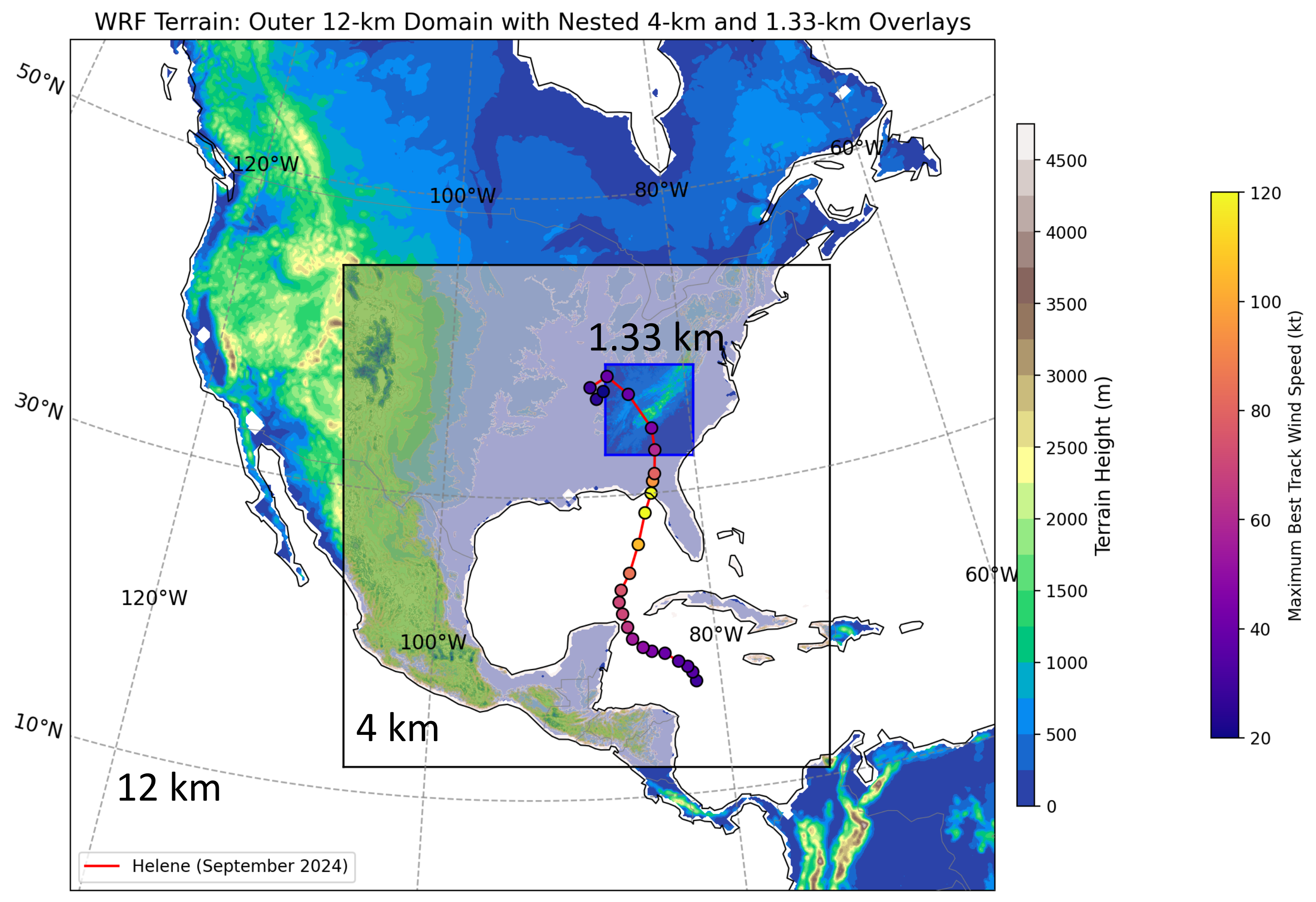
What are some "best practices" for this category of case study?

Model Methods: Domain, Terrain, Resolution

Simulations of Hurricane Helene (2024):

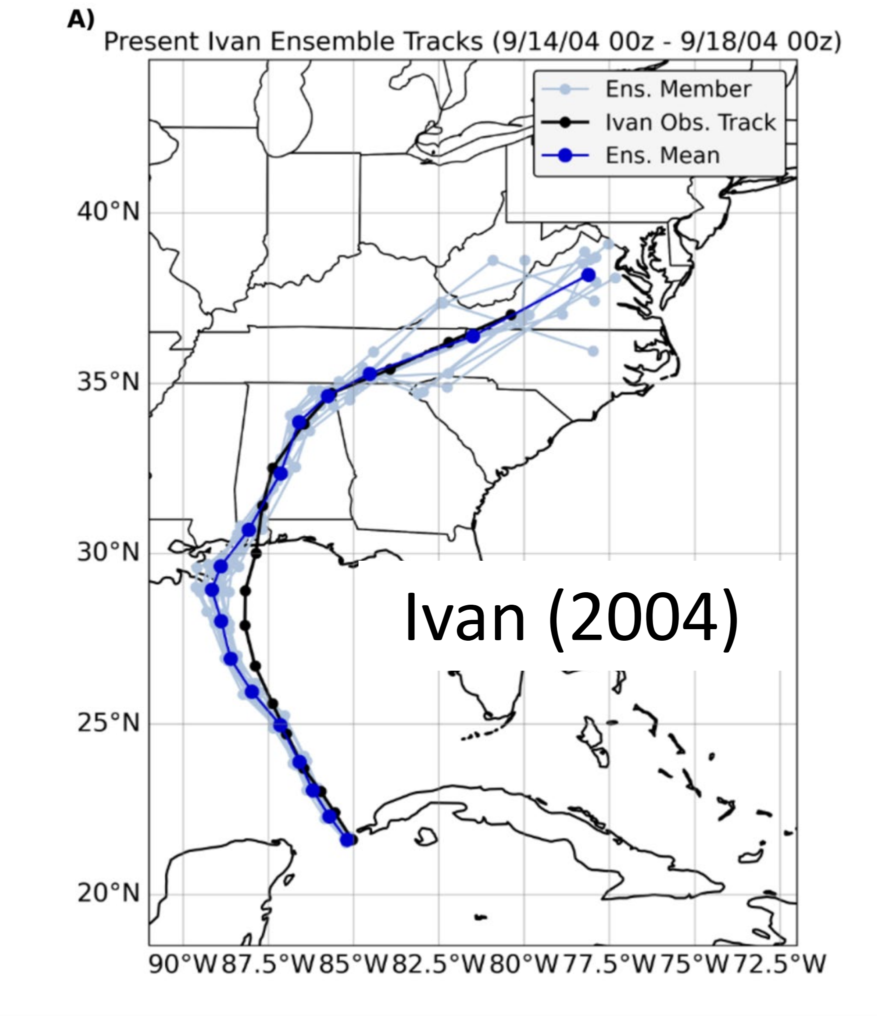
- Triple nested domains to 1.33 km, 1 and 2-way nesting
- Residence time in high-resolution domain (with strong flow)?
- Physics and time-lagged ensemble

- Storm intensity and track well represented on 4-km domain
- GFS initial, boundary conditions
- Digital filter initialization (DFI) to reduce spin-up, balance initial fields

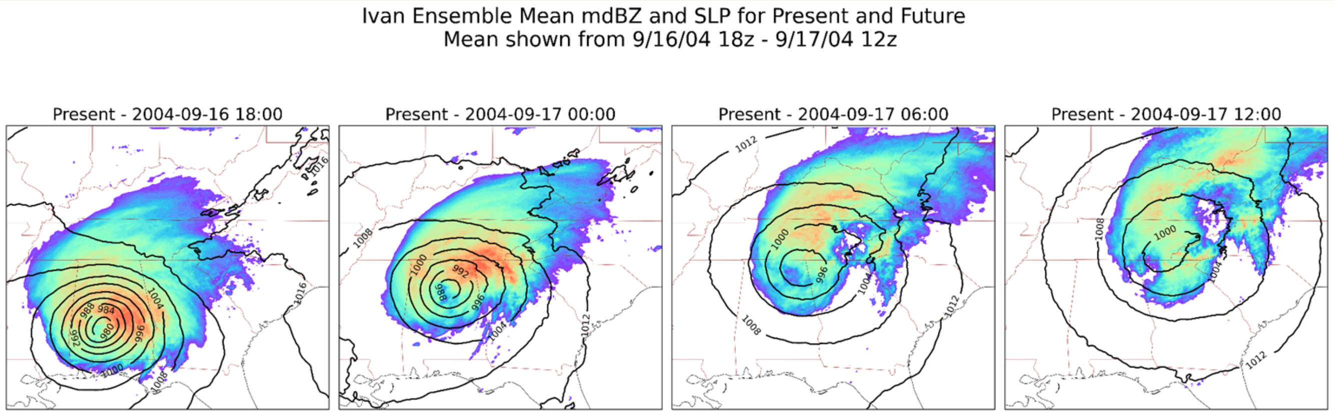


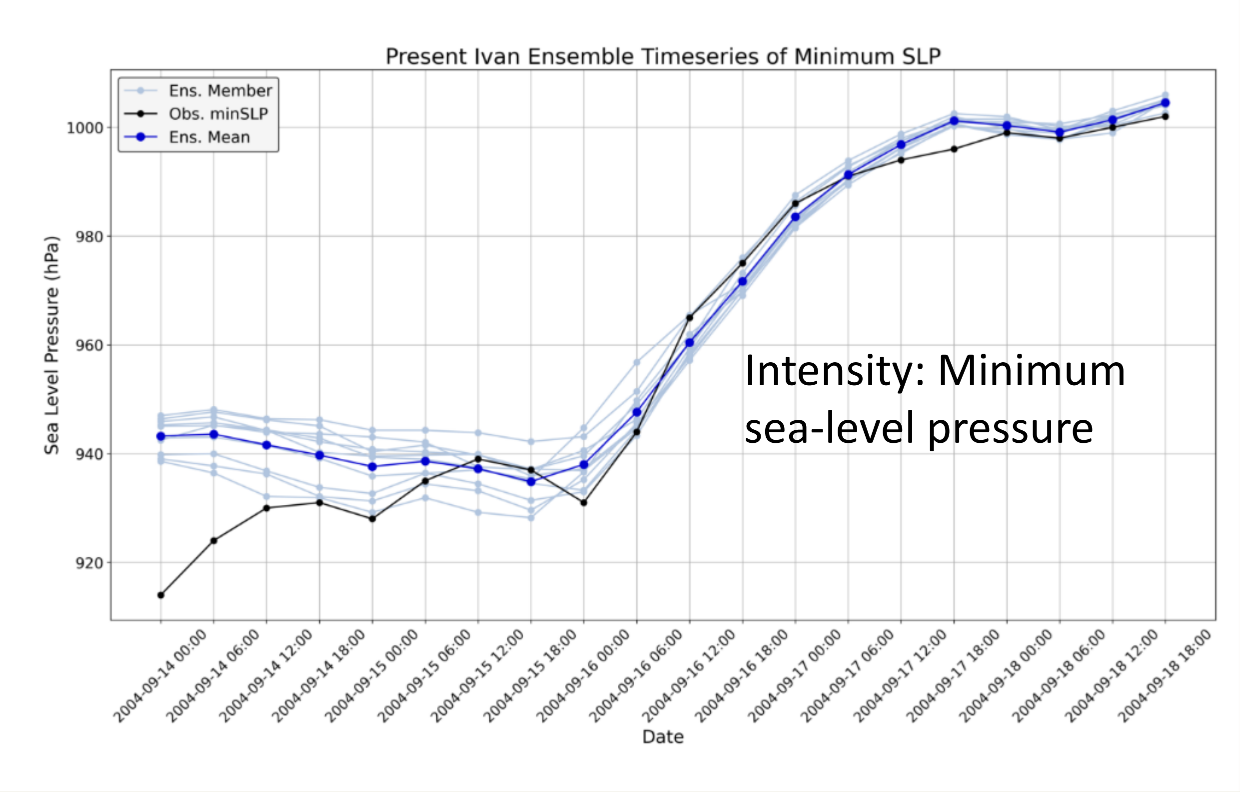
Example model domain setup: **Helene (2024)**
30 Arc-Second (~1-km grid) model terrain

Methods: Convection-Allowing Ensemble



Ivan (2004)





Intensity: Minimum sea-level pressure

Observations plotted in **black**
Ensemble mean plotted in bold **blue**

Methods: Ensemble Configuration?

Many choices for high-resolution ensembles:

1. Lagged-average (vary initial times)
2. Initial condition variations
3. Physics ensemble (e.g., PBL, microphysics)
4. Perturb energy, parameter, or physics tendencies
5. Vary boundary conditions

Leverage experience from operational NWP community

- ***Combination*** of physics, SKEB[a], SPPT[b], and SPP[c] gave best spread-skill ratio (e.g., Jankov et al. 2017)

For cloud and precipitation (microphysics) sensitivity:

- Consider higher-moment, newer schemes at high resolution (more on this soon)

A Performance Comparison between Multiphysics and Stochastic Approaches within a North American RAP Ensemble

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ABSTRACT

A stochastic parameter perturbation (SPP) scheme consisting of spatially and temporally varying perturbations of uncertain parameters in the Grell–Freitas convective scheme and the Mellor–Yamada–Nakanishi–Niino planetary boundary scheme was developed within the Rapid Refresh ensemble system based on the Weather Research and Forecasting Model. Alone the stochastic parameter perturbations generate insufficient spread to be an alternative to the operational configuration that utilizes combinations of multiple parameterization schemes. However, when combined with other stochastic parameterization schemes, such as the stochastic kinetic energy backscatter (SKEB) scheme or the stochastic perturbation of physics tendencies (SPPT) scheme, the stochastic ensemble system has comparable forecast performance. An additional analysis quantifies the added value of combining SPP and SPPT over an ensemble that uses SPPT only, which is generally beneficial, especially for surface variables. The ensemble combining all three stochastic methods consistently produces the best spread–skill ratio and generally outperforms the multiphysics ensemble. The results of this study indicate that using a single-physics suite ensemble together with stochastic methods is an attractive alternative to multiphysics ensembles and should be considered in the design of future high-resolution regional and global ensembles.

[a] Stochastic kinetic energy backscatter (SKEB)
[b] Stochastic parameter perturbation (SPP)
[c] Stochastic Perturbation of Physics Tendencies (SPPT)

Methods: Ensemble Configuration

Sample configuration (Ivan study, from Amanda Sinning's 2025 thesis)

	Ens1	Ens2	Ens3	Ens4	Ens5	Ens6	Ens7	Ens8	Ens9	Ens10
Microphysics	Thompson	P3 Opt.52	WDM-7	Jensen-ISHMAEL	P3 Opt.53	Jensen-ISHMAEL	WSM6	Thompson	Morrison	P3 Opt.51
Boundary Layer	YSU	YSU	YSU	YSU	Shin-Hong	Shin-Hong	Shin-Hong	MYJ	YSU	YSU
Surface Layer	MM5	MM5	MM5	MM5	MM5	MM5	MM5	MYJ	MM5	MM5
Cumulus	Multi-Scale KF	Multi-Scale KF	Multi-Scale KF	Multi-Scale KF	Multi-Scale KF	Multi-Scale KF	Multi-Scale KF	KF	Multi-Scale KF	Multi-Scale KF
Sh. Mixing None	None	None	None	None	None	None	None	GRIMS	None	None
Ocean Physics	Off	On	On	On	Off	Off	Off	On	On	On

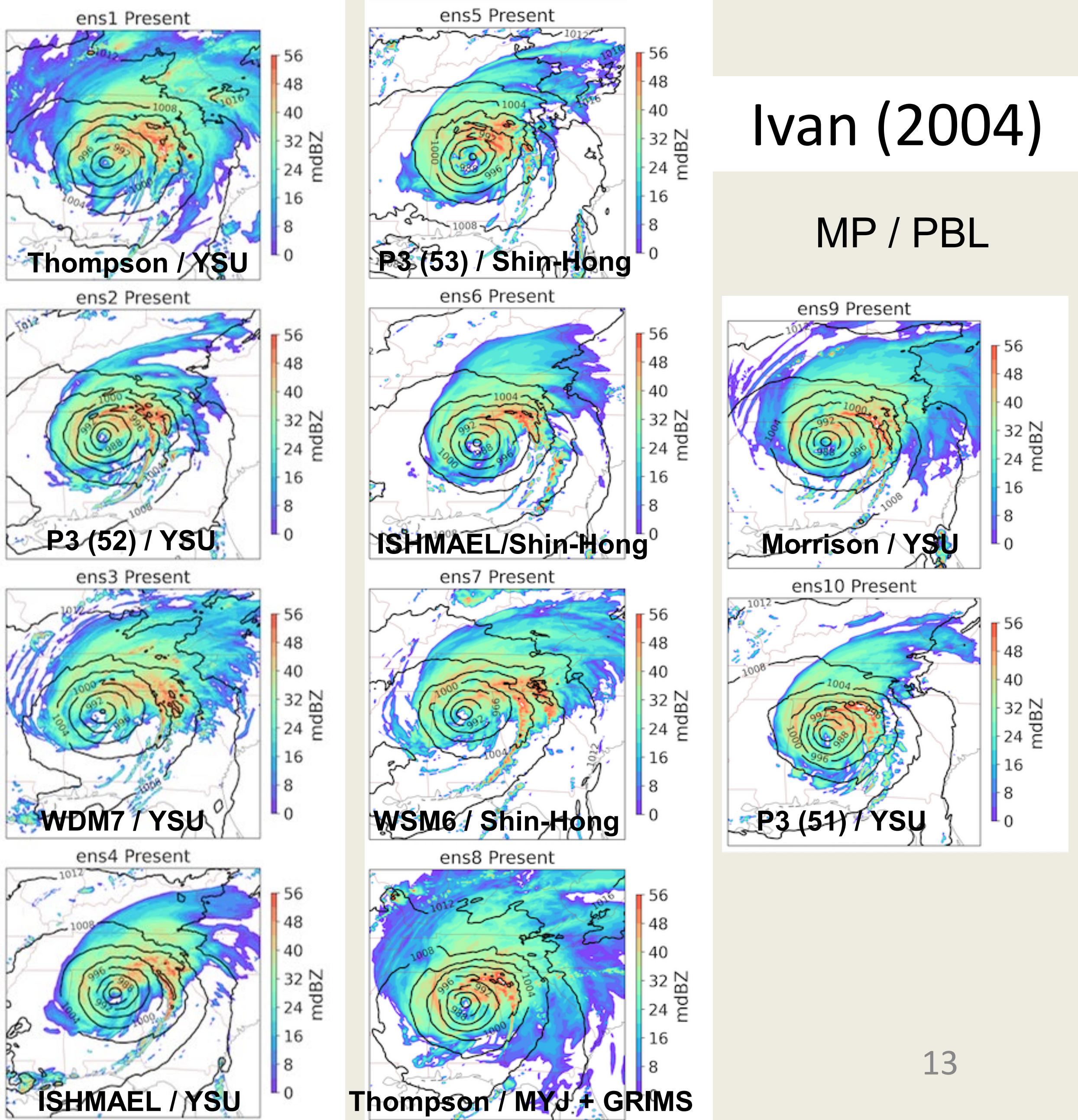
Table 2.1: WRF physics choices used for each ensemble member of both Hurricanes Frances and Ivan. All simulations use RRTMG Radiation Schemes and the Noah-MP Land Surface Model.

Cloud and Precipitation (“microphysics”) Parameterization

- Watershed-level precipitation simulation sensitive to microphysical parameterizations (Grubišić et al. 2005)
- Windward/leeward precipitation distribution, hydrometeor transport, depend on accurate depiction of size distribution, sedimentation, etc.
- At high resolution over complex terrain, some newer MP schemes show advantages over older in some test cases (e.g., atmospheric river cases)
- MP sensitivity also demands ensemble approach to case-study simulation

Methods: Sensitivity to Physics

- Strong sensitivity of TC size, intensity, precipitation to model physics choices
  - Cloud & precipitation (microphysics parameterization, “MP”)
    - WRF model features > 30 MP choices (+ sub-configurations)
  - Also varied boundary layer (“PBL”), ocean model, shallow convection representation
  - Note variations in storm size in simulated reflectivity (shaded)



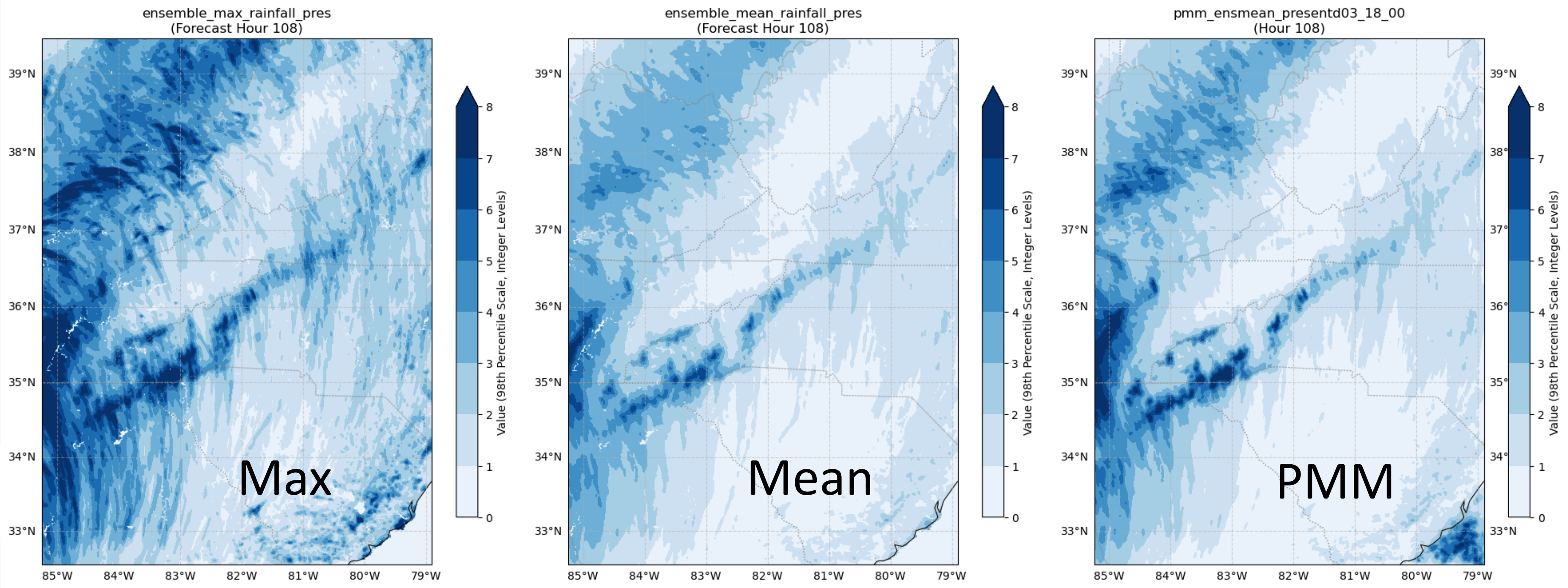
SLP (black contours), simulated reflectivity (shaded) 00 UTC 17 Sept. 2004, 4-km domain

Methods: Ensemble Output

- Simulations: **Ensemble mean not optimal for PMP** (excess coverage, damped extrema)
- Ensemble **maximum** may be good for PMP applications

- Weather prediction literature suggests **probability matched mean** (PMM; Ebert 2001)
  - Percentile matching preserves extremes
  - Retains ensemble spatial structure, avoids coverage bias

Ivan (2004)

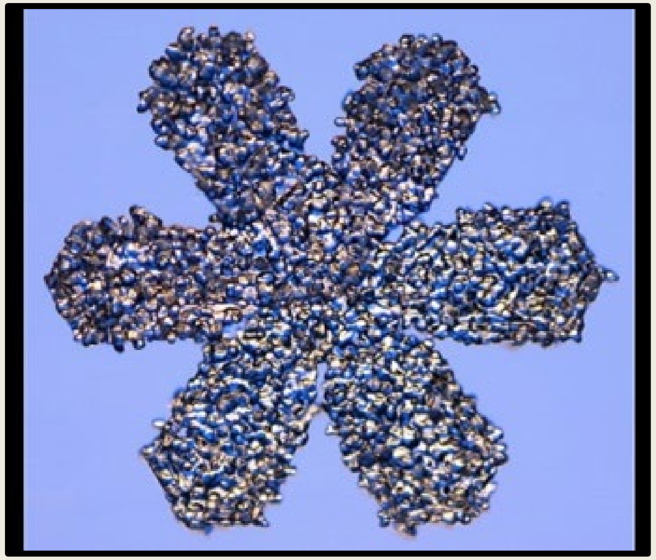


- Comparison of ensemble maximum, ensemble mean, and probability match mean (PMM)
- 4.5 day simulated totals from Helene simulations on 1.33 km domain (NASA MP)

Microphysical Considerations

Traditional bulk MP: Separate snow, graupel/hail class

Predicted Particle Properties (P3): ice evolves in time and space

Fall speed and other properties evolve *gradually* on a continuum

Predicts 4 ice categories: ice mass, rime mass, rime volume, number

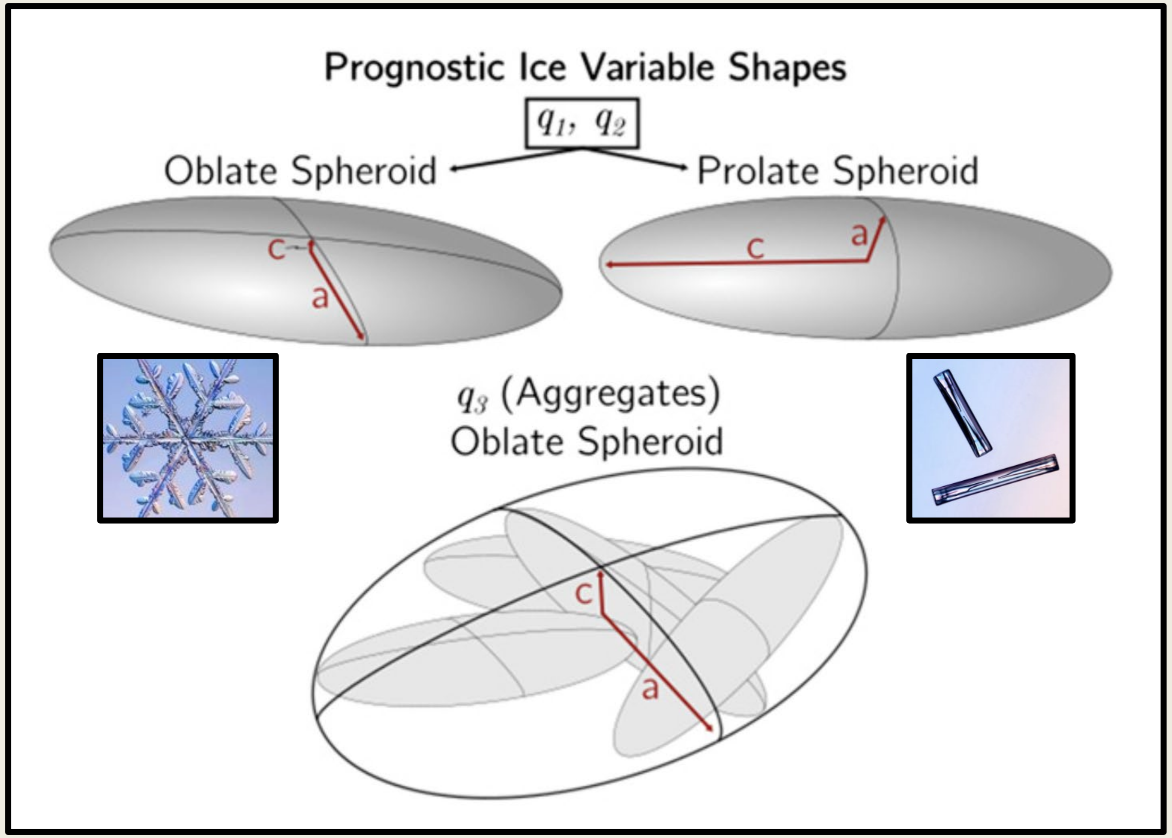
Image credits: http://www.inscc.utah.edu/~tgarrett/Snowflakes/WASHARX.html

Microphysical Considerations

Center for Western Weather and Water Extremes
SCRIPPS INSTITUTION OF OCEANOGRAPHY AT UC SAN DIEGO

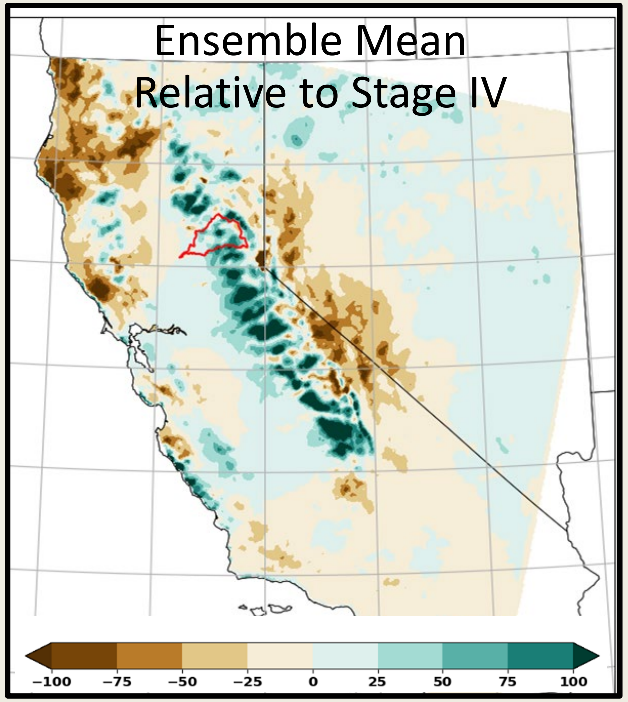
ISHMAEL (Ice Spheroid Habit Model with Aspect-ratio EvoLution)

- Extends P3 to account for ice shape
- Predicts aspect ratio, mass, number, size, and density
- Ice shape impacts vapor deposition rates
- Allows for evolution of 3 ice species/grid cell
- Effective for orographic precipitation (Jensen et al. 2018)

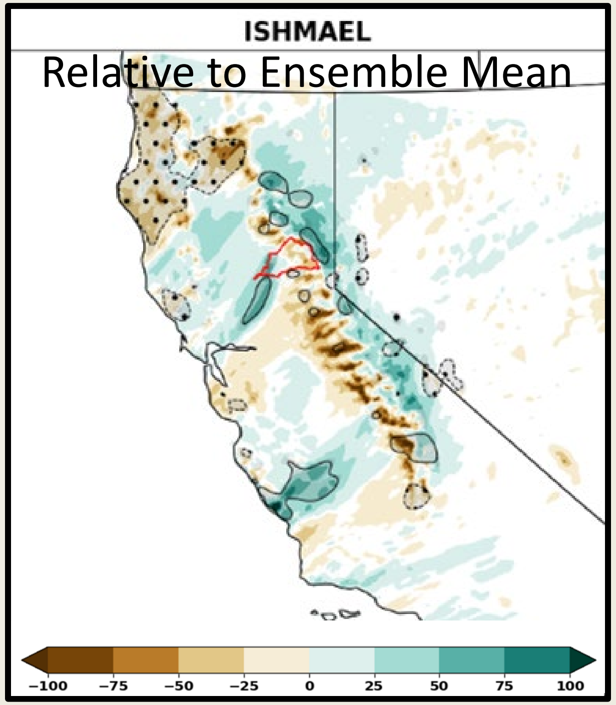


Schematic from Jensen et al. (2017); their Fig.1. Snowflake photo Credit: Kenneth G. Libbrecht.

Parameterization and Precipitation Distribution



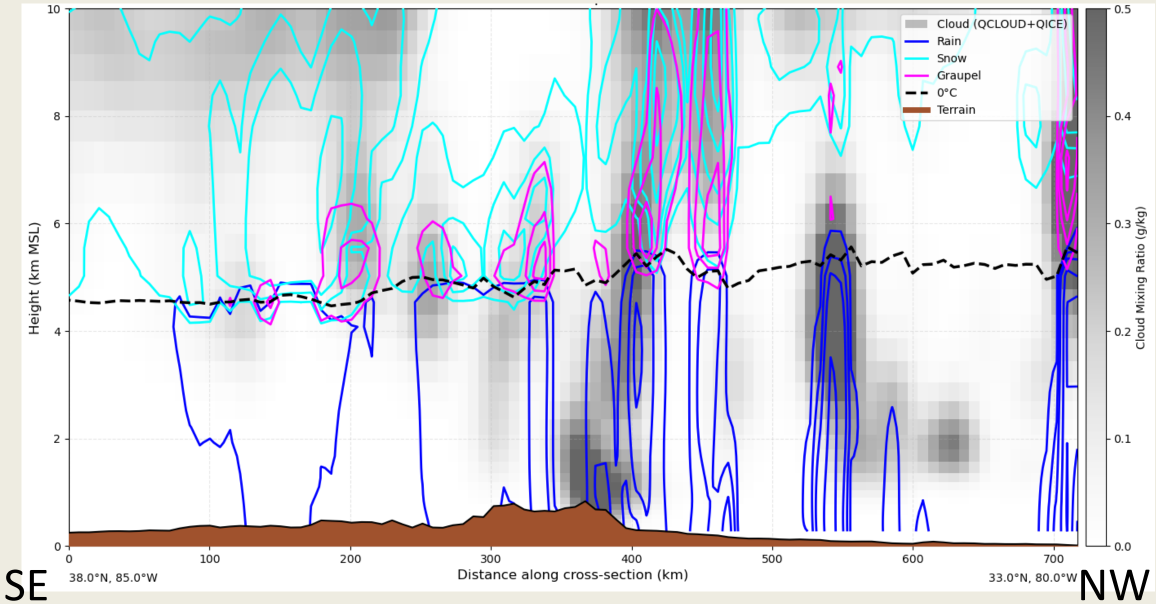
Ensemble mean cross-barrier bias (vs. Stage IV analysis)



ISHMAEL MP member: Reverses bias

For atmospheric river (AR) case study (Smith et al. 2025, in review) from January 2017:

- ISHMAEL, Morrison, SBU, P3 2cat, P3 3moment show reduced windward bias
- ISHMAEL, Morrison also generate heavier lee precipitation (**reduced bias**)
- Relevant for TC cases?



Helene (2024) cross section 09 UTC 27 Sept: Cloud (shaded), freezing level, terrain, snow, graupel, and rain mixing ratios (NASA MP)

Ensemble Performance

Center for Western Weather and Water Extremes
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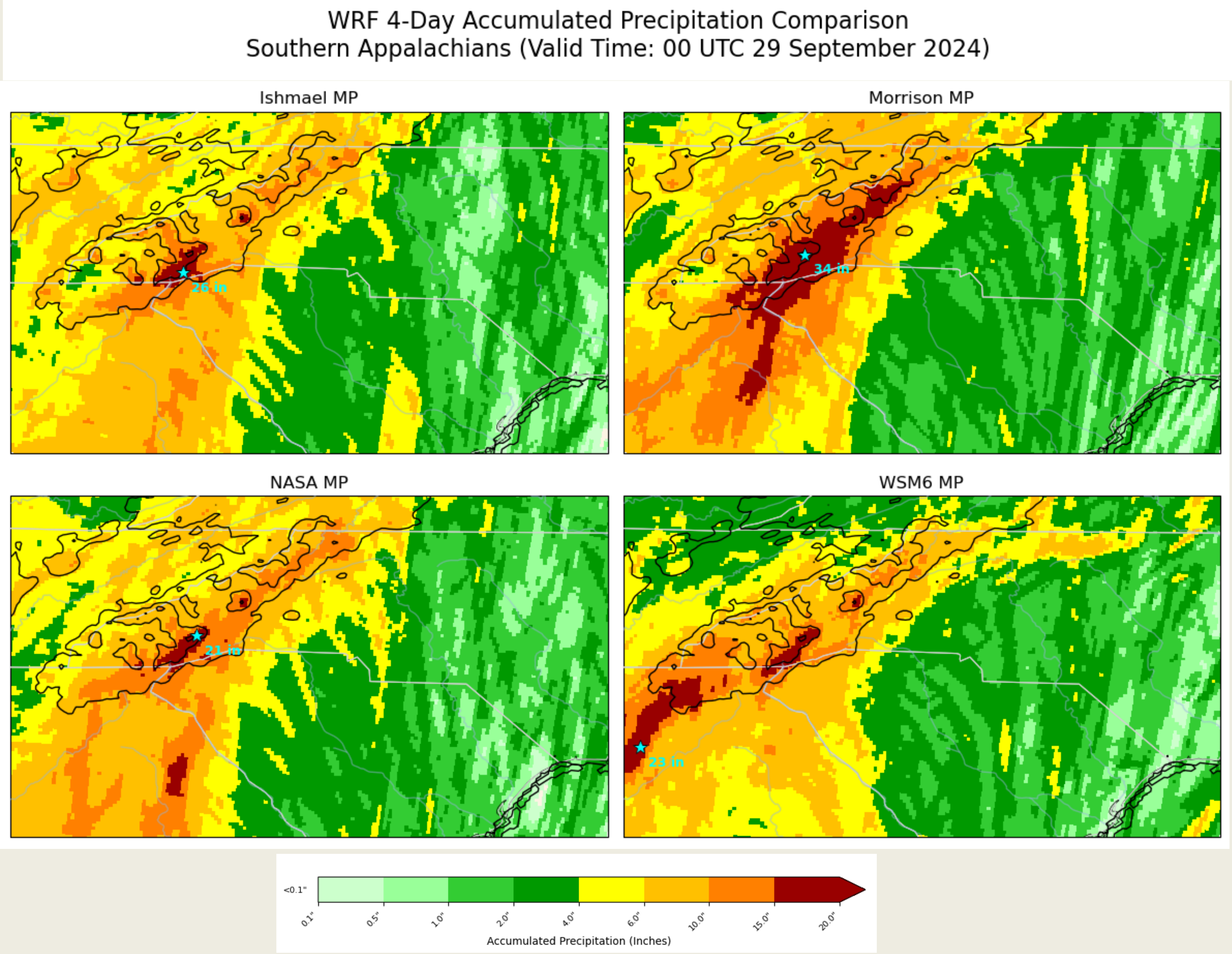
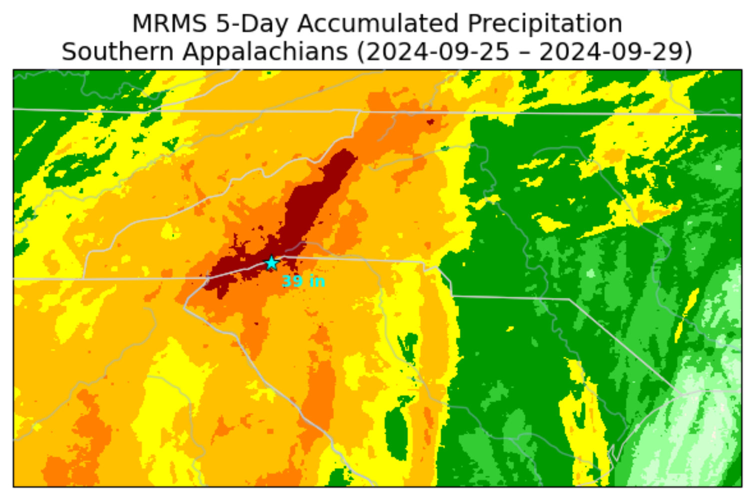


Helene (2024):

Strong MP sensitivity evident over Appalachians

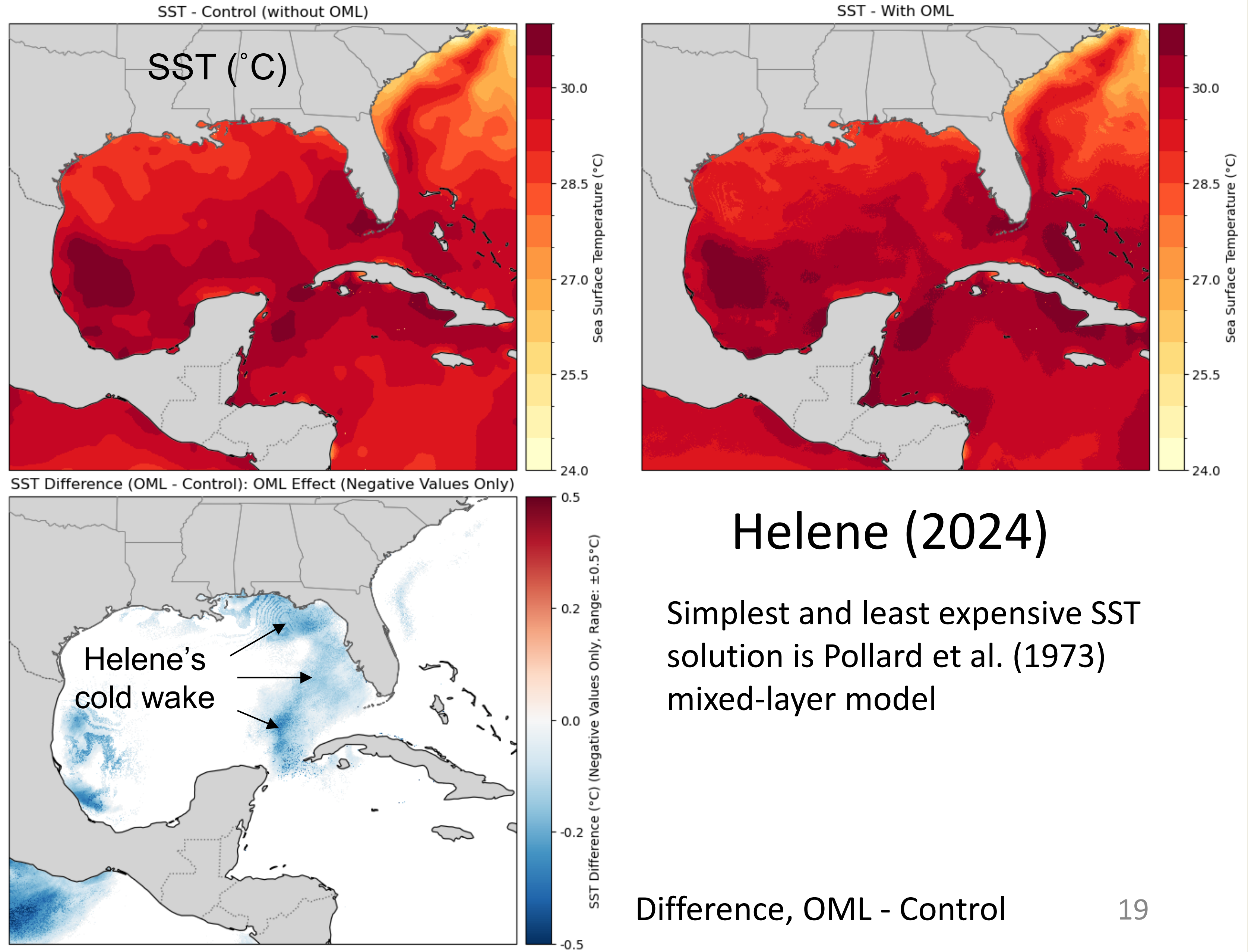
Simulated maxima: 21” to 34” depending on MP choice



Methods: Air-Sea interaction

Representing TC cold wake:

- For realistic SST evolution, TC intensity affected
- Especially slow-moving TCs
- WRF: Several options
    - Mixed-layer model (OML) option, slab, mixing only
    - Price 1981 3-D model
    - Groups run fully coupled ocean/wave models
- Namelist *isftcflx* important for strong TCs (exchange coef.)



Helene (2024)

Simplest and least expensive SST solution is Pollard et al. (1973) mixed-layer model

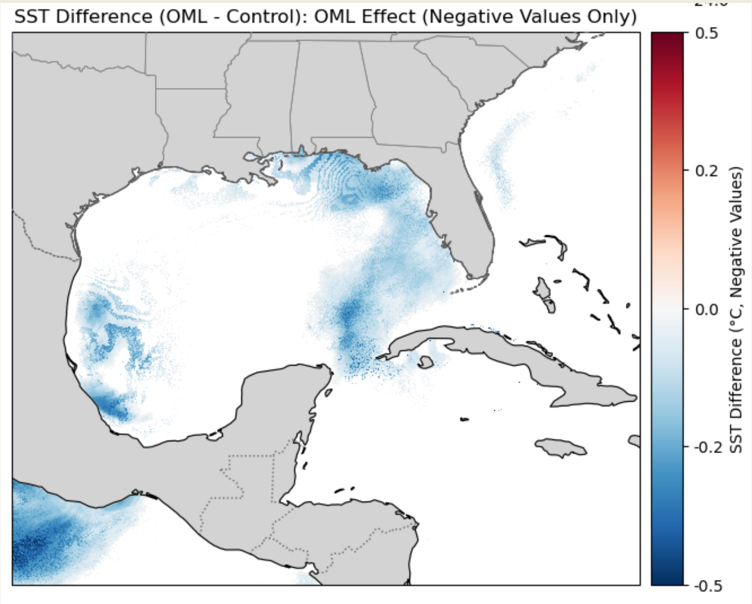
Difference, OML - Control

Methods: Air-Sea interaction

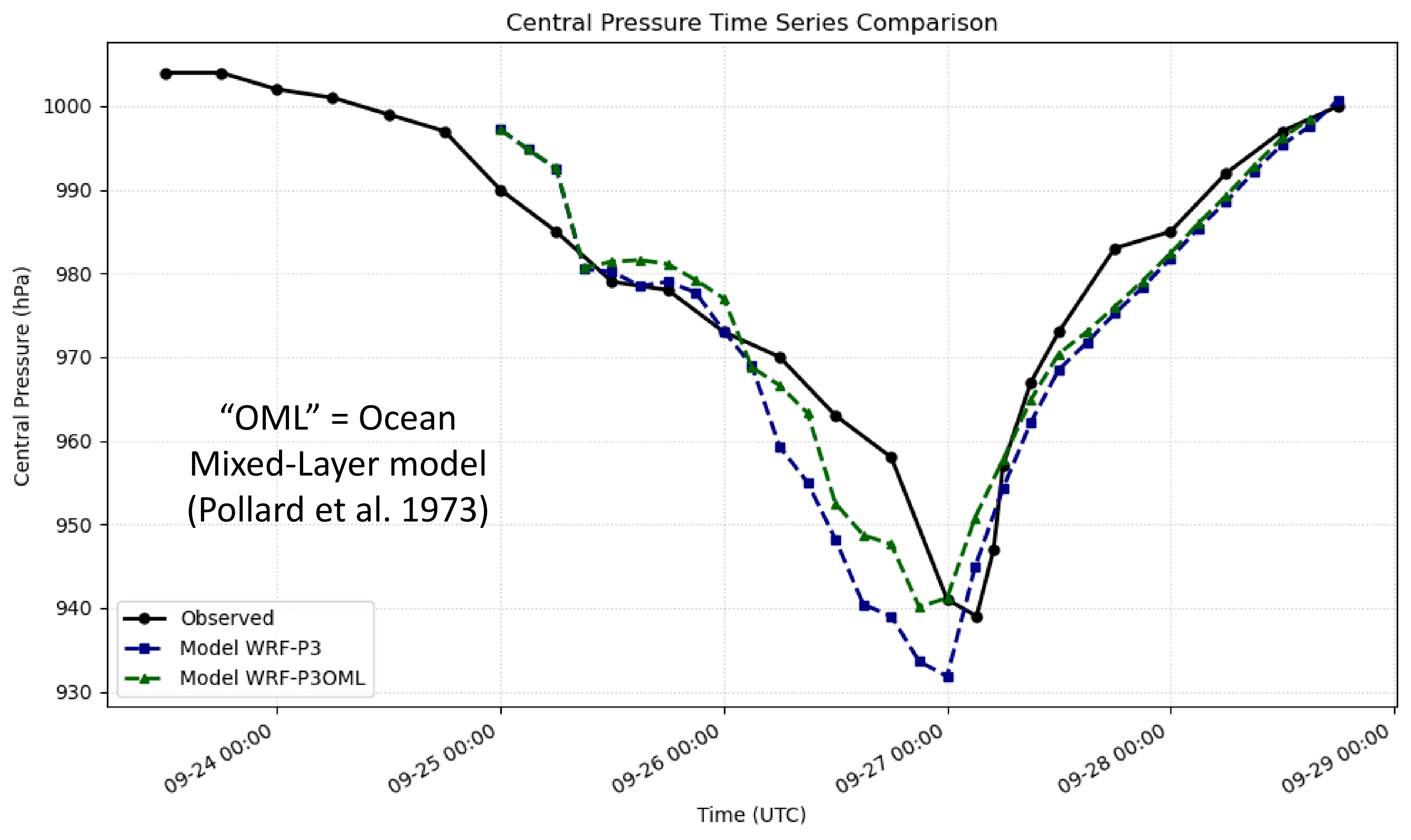
Without OML, simulation over-intensifies Helene by ~8 hPa

With OML, intensity improved

(note other errors, including landfall timing)



Helene (2024)



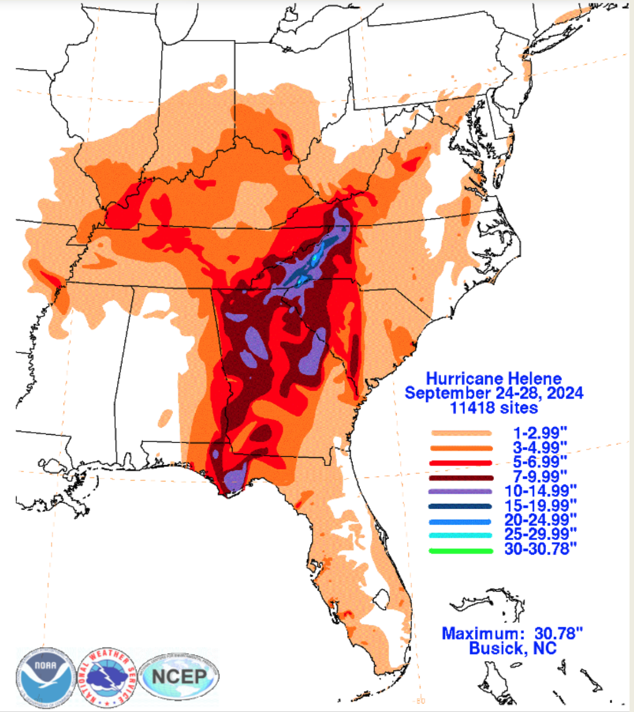
"OML" = Ocean Mixed-Layer model (Pollard et al. 1973)

Methods: Verification

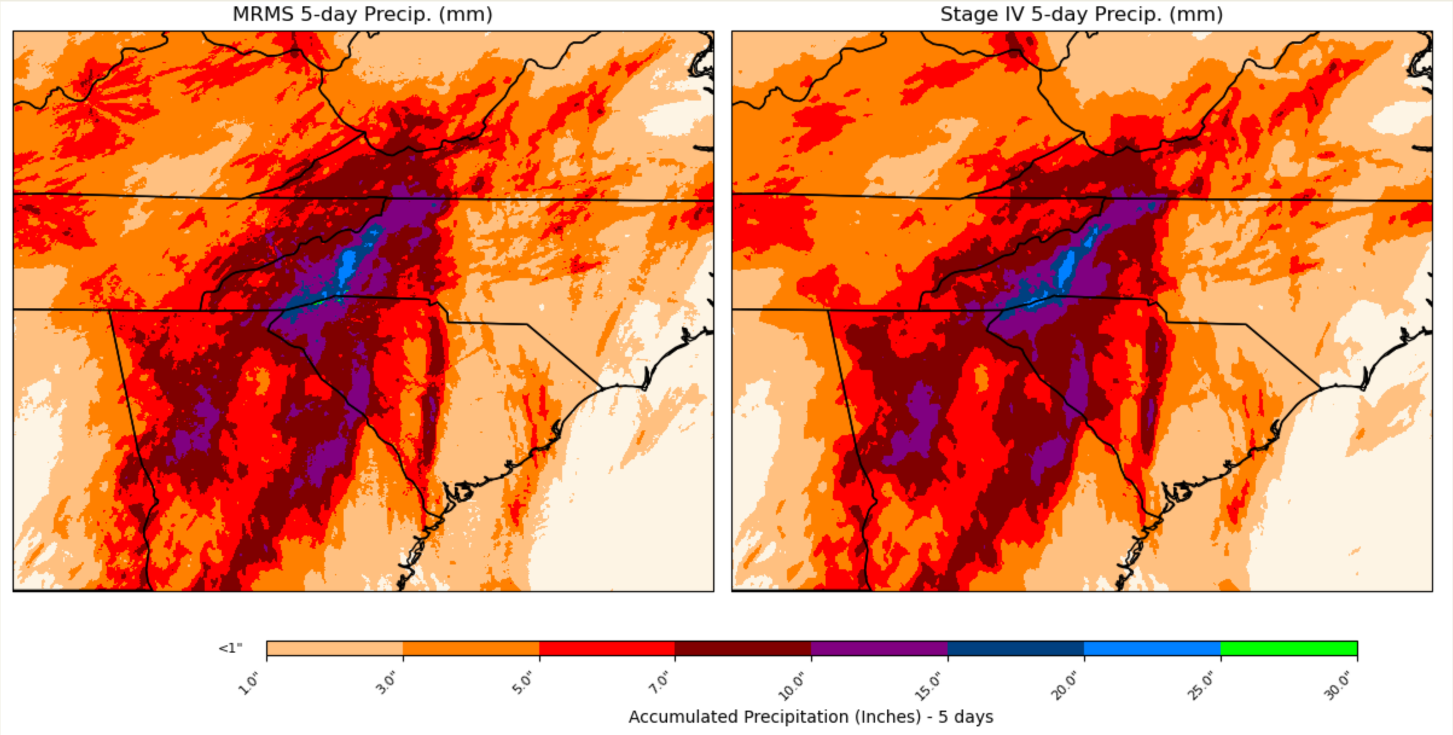
- Precipitation data sources for historical events:
  - MRMS (1 km, since 2012)
  - Stage IV (4 km, since 2002)
  - PRISM (4 km, daily since 1981)
  - Gauge data (back to 1800s)

- PRISM (Parameter-elevation Relationships on Independent Slopes Model; Daly et al. 1994, 2002, 2008)
  - Local elevation-variable relations
  - Designed to handle complex terrain

Helene (2024)



Analysis of storm total rainfall (inches).
Courtesy of David Roth of the NOAA WPC

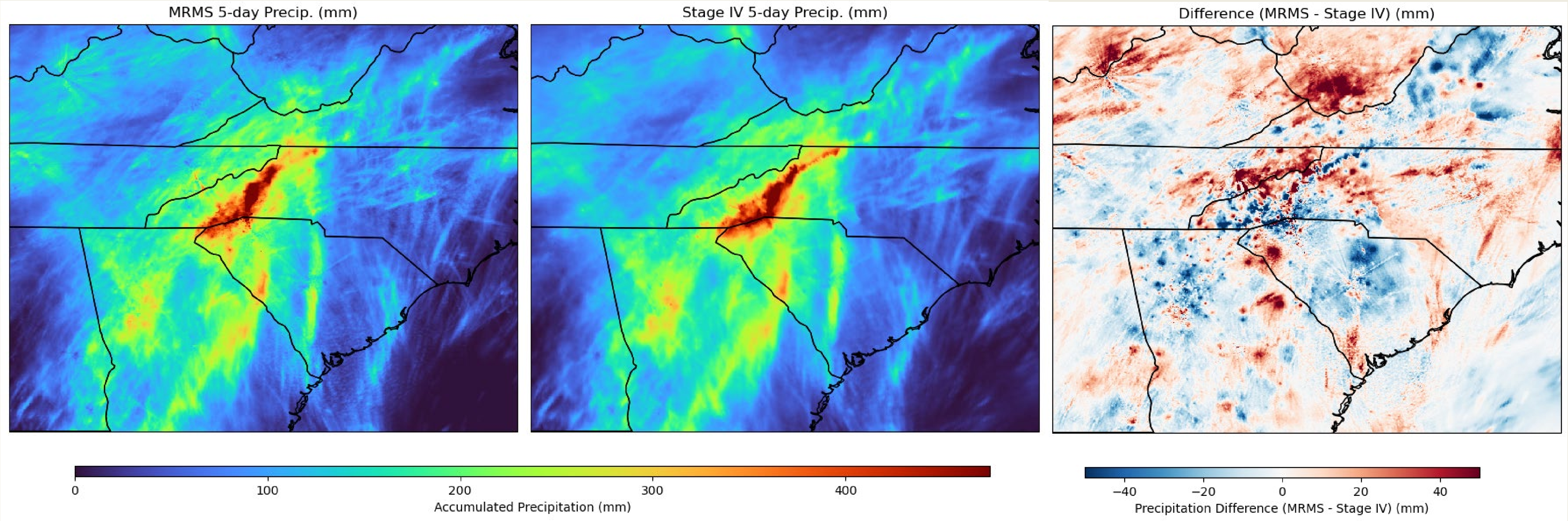


MRMS & Stage IV 5-day precipitation total ending 29 September 2024

Methods: Verification

- QPE variation can be substantial between high-resolution sources
- Must account for observational QPE uncertainty (Bytheway et al. 2020, *J. Hydromet.*, examine QPE in complex terrain)

Helene (2024)



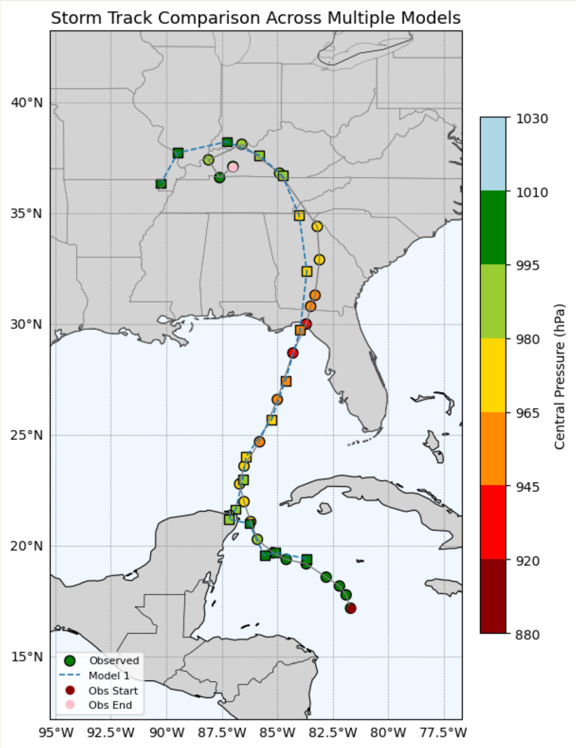
MRMS vs Stage IV 5-day precipitation total ending 29 September 2024

Difference, MRMS – Stage IV

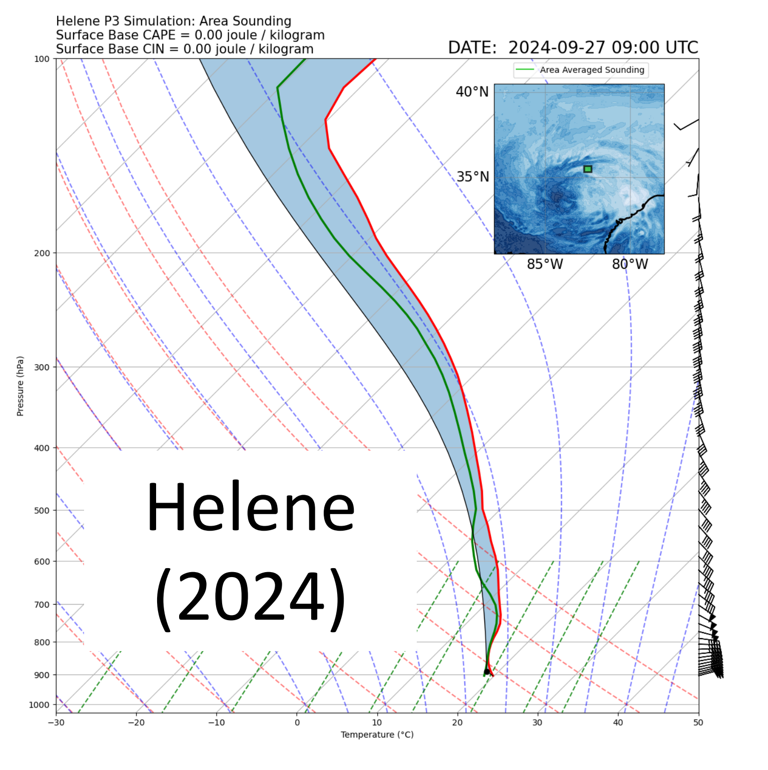
Meteorology: Static stability

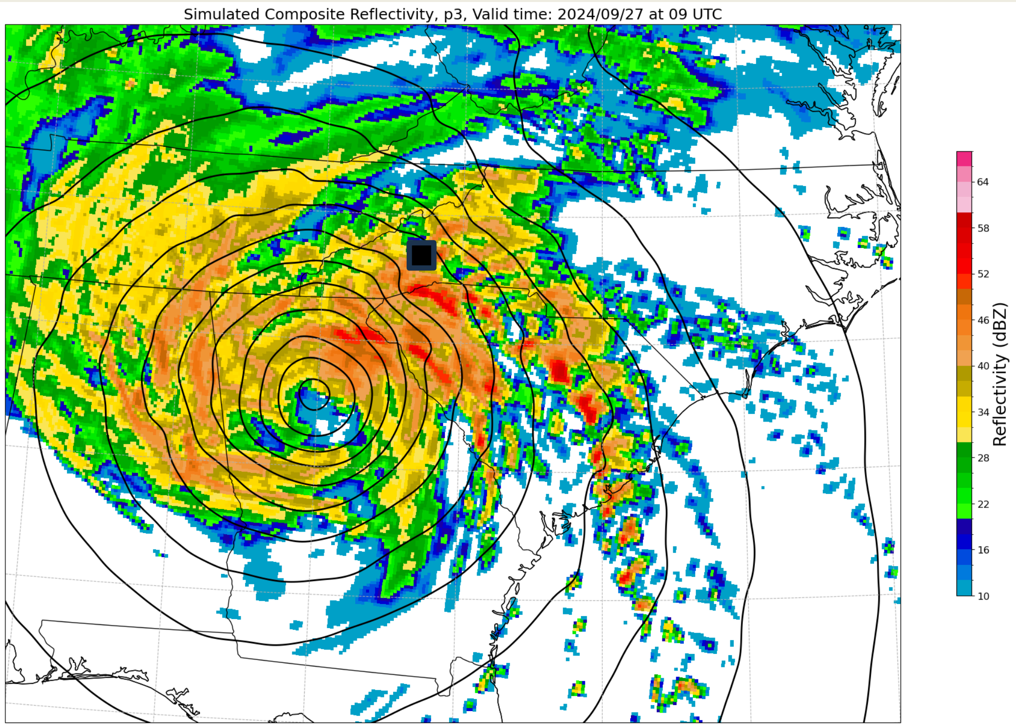
Key meteorological factors:

- Strength of orographic ascent
- Mountain waves
- Orographic convection / static stability (e.g., Rotunno and Houze 2007)



Character of extreme orographic TC precipitation?





Helene (2024) example:

- **Limited or no instability at times** during heavy precipitation
- CAPE 0 - 500 J Kg^{-1}

Challenges and Next Steps for Orographic Tropical Cyclone Precipitation Modeling (and PMP more generally)

Transition to high-resolution, physics-based simulations of extreme historical events is an essential step forward but presents significant challenges.

Key Challenges:

- **Computational Expense:** Convection-allowing ensembles are expensive; numerous case studies are needed. AI/ML offers potential for expanding?
- **Modeling Complexities:** Challenges in parameterization (especially MP schemes), TC initial conditions, accurate physical process representation (e.g., offshore TC evolution, environmental interactions).
- **Data & Verification:** Acute observational challenges exist for precipitation verification (e.g., using PRISM in complex terrain). Strategies for gap filling, accounting for climate non-stationarity are needed.
- **Community Consensus:** The NASEM-recommended model evaluation project is critical to establish best practices and community agreement.

Methodological Needs & Decisions:

- **Ensemble Strategy:** Define best practices for configuration (e.g., physics/parameter perturbation, etc.) and output presentation (e.g., Probability Matching (PMM), ensemble maximum)
- **Further Research:**
    - Targeted experimentation with orographic precipitation distribution using newer MP schemes
    - Account for phenomenological sensitivity for various extreme precipitation categories/locations

Acronyms

AR: Atmospheric River
CAPE: Convective Available Potential Energy
CW3E: Center for Western Weather and Water Extremes
DFI: Digital filter initialization
GFS: Global Forecast System (model)
ISHMAEL: Ice Spheroid Habit Model with Aspect-ratio EvoLution (MP)
MP: Microphysics
MRMS: Multi-Radar, Multi-Sensor precipitation products
NCDOT: North Carolina Department of Transportation
NWP: Numerical Weather Prediction
OML: Ocean Mixed Layer model
PBL: Planetary Boundary Layer
PMM: Probability Matched Mean
PMP: Probable Maximum Precipitation
P3: Predicted Particle Properties
PRE: Predecessor Rain Event
PRISM: Parameter-elevation Relationships on Independent Slopes Model
QPE: Quantitative Precipitation Estimate
SBU: Stony Brook University
SKEB: Stochastic kinetic energy backscatter
SPP: Stochastic parameter perturbation
SPPT: Stochastic Perturbation of Physics Tendencies
TC: Tropical Cyclone
WRF: Weather Research and Forecasting Model

References and Sources

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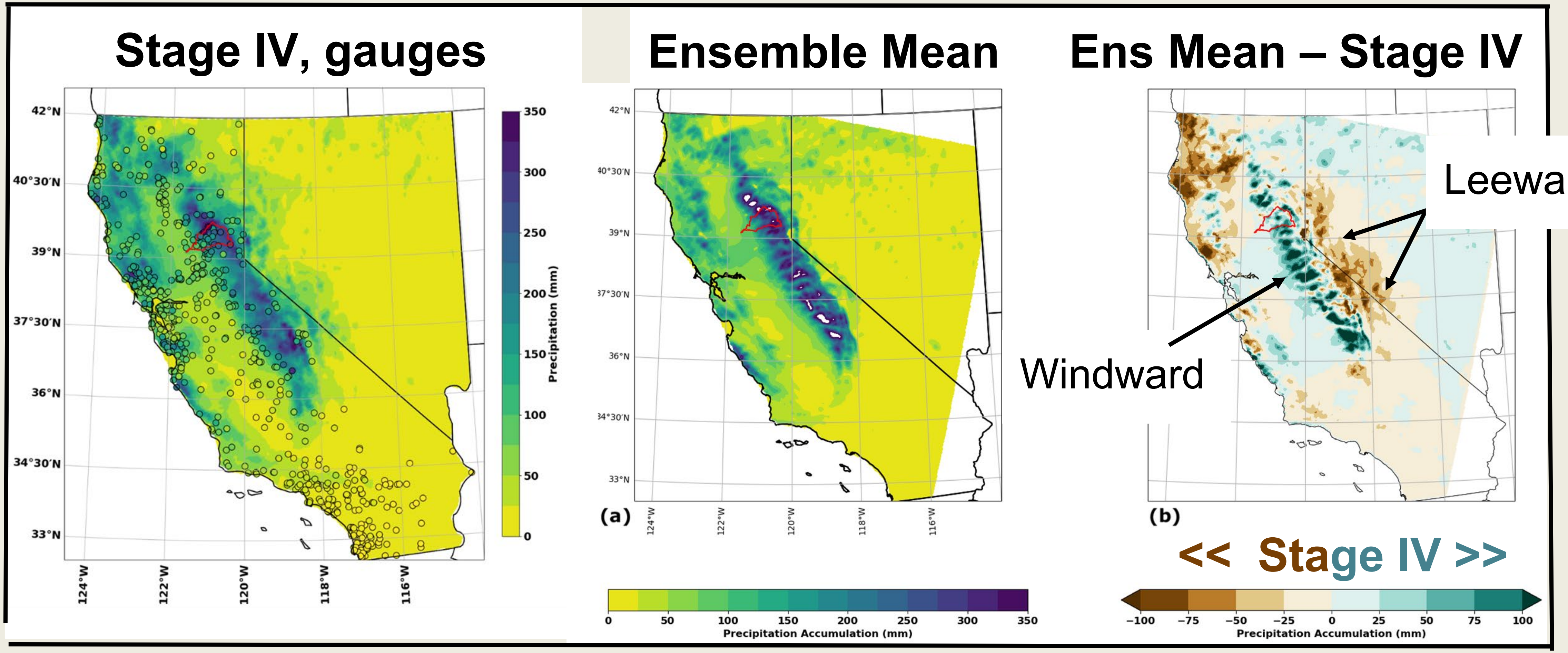
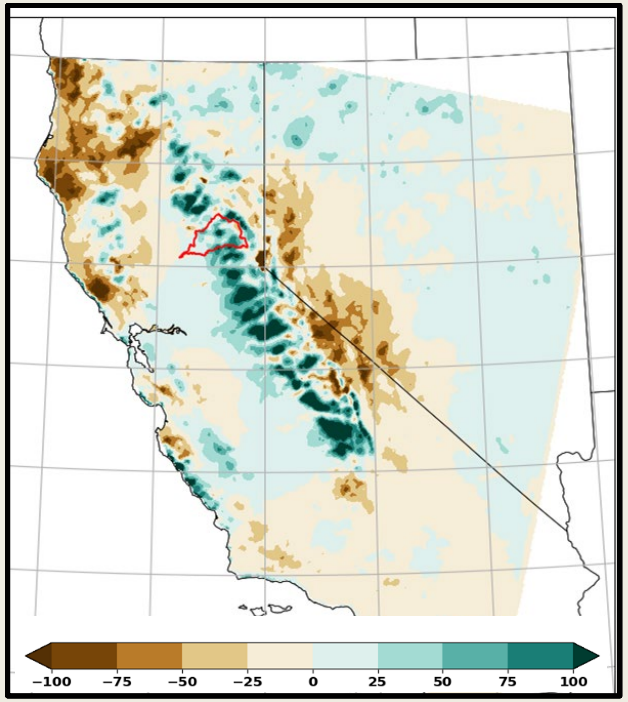
Extra Slides

Ensemble Performance

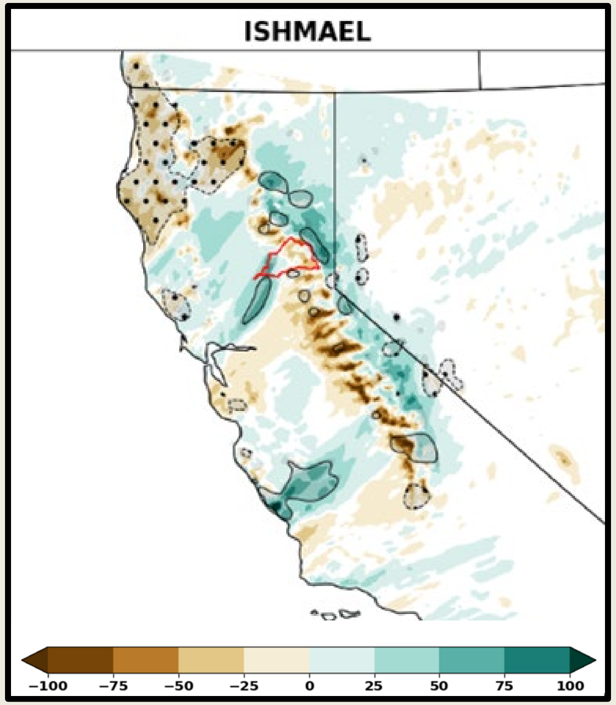
Relative to analysis (Stage IV + gauges), positive (negative) model precipitation bias on windward (leeward) slopes of Sierra Nevada range (Smith et al. 2025, in review)



Ensemble Performance



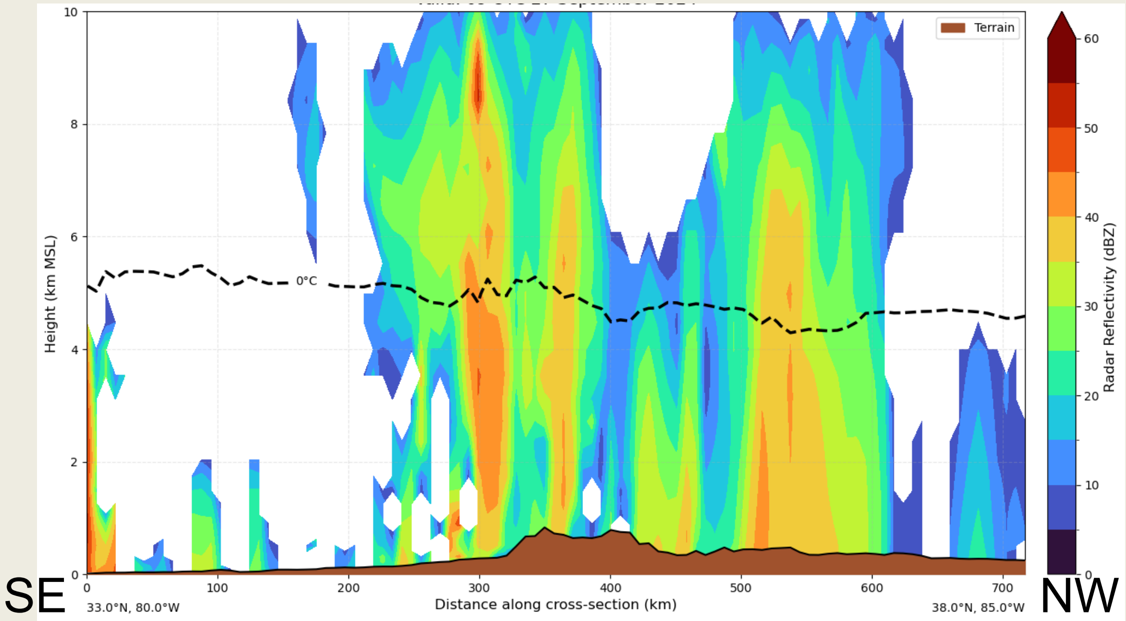
Ensemble mean cross-barrier bias (vs. Stage IV analysis)



ISHMAEL ensemble member vs Ensemble mean: Reverses bias

For an atmospheric river (AR) case study from January 2017:

- ISHMAEL, Morrison, SBU, P3 2cat, P3 3moment show reduced windward bias
- ISHMAEL, Morrison also generate heavier lee precipitation (**reduced bias**)
- Relevant for TC cases?



Helene (2024) cross section 09 UTC 27 Sept: Reflectivity (shaded), freezing level, terrain

NASEM 2024 Report: Modernizing Probable Maximum Precipitation (PMP) Estimation

- Traditional PMP methods: Based on concept of "upper bound"; outdated, subjective, and ignore climate change and uncertainty
- NASEM Recommendation:
  - Implement a probabilistic, climate-aware PMP definition
  - Transition to high-resolution (~1 km), physics-based simulations of extreme historical events
- Implementation:
  - Requires a phased modernization (data digitization, radar integration, storm reconstruction)
  - Implement a Model Evaluation Project (MEP) for performance assessment
- Goal: Reliable, reproducible framework supporting better risk-based infrastructure design and enhanced national resilience featuring sustained collaboration

Summary: Extreme TC Precipitation in the Appalachians

Case studies of extreme orographic precipitation associated with tropical cyclones in this region are essential, but challenging:

- Need to capture offshore TC evolution, and environmental interactions
- Numerical modeling complexities: Parameterization, initial condition issues
- Acute observational challenges for precipitation verification
- Require convection-allowing ensembles: Expensive
- Further experimentation with orographic precipitation distribution using newer MP parameterizations is needed

Method-related questions and decisions:

- How to configure ensemble? Physics, parameter perturbation recommended
- Presenting ensemble output: Probability matching (PMM) or ensemble max?
- Observational verification data: PRISM best in complex terrain?

Overall PMP Takeaways

Transition of PMP to high-resolution, physics-based simulations of extreme historical events is an excellent step forward

Needs:

- Numerous case studies with large, convection-allowing ensembles
- Model configuration best practices (e.g., ensemble strategy, output)
- Attention to physical process representation, parameterization studies
- Account of phenomenological sensitivity for various categories, locations
- Convection-allowing scale reanalysis that includes precipitation?

Challenges:

- Computational expense; AI opportunities?
- Sample size: Strategies for gap filling, accounting for climate non-stationarity
- Model evaluation project critical to establish community agreement