Evaluating the efficacy of ten snow-to-liquid ratio algorithms to predict snowfall in the Northeast United States

Brian Filipiak[1,2], Ummul Khaira[1,2], Michael Walters[1,2] and Marina Astitha[1,2,3]
[1]School of Civil and Environmental Engineering, University of Connecticut, CT, USA
[2]Eversource Energy Center, University of Connecticut, CT, USA
[3]NSF National Center for Atmospheric Research, CO, USA

Societal Impacts

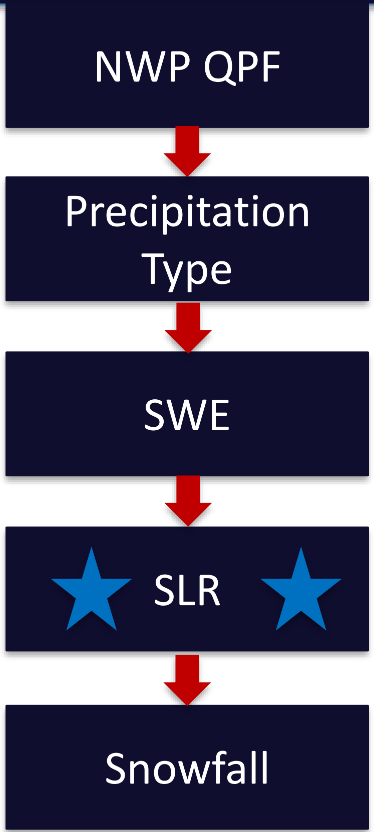
- Winter storms create numerous hazards to society including power outages, travel disruptions and economic losses
- The most important factors in winter storm related power outages are snow density, ice accumulation and foliage cover[1]
- Not all wet, heavy snow sticks the same to power lines

Damaged power lines in Brewster, MA from February 24, 2026 (masslive.com)

1: Cerrai et al. 2020: "Outage prediction models for snow and ice storms." J. SEGAN

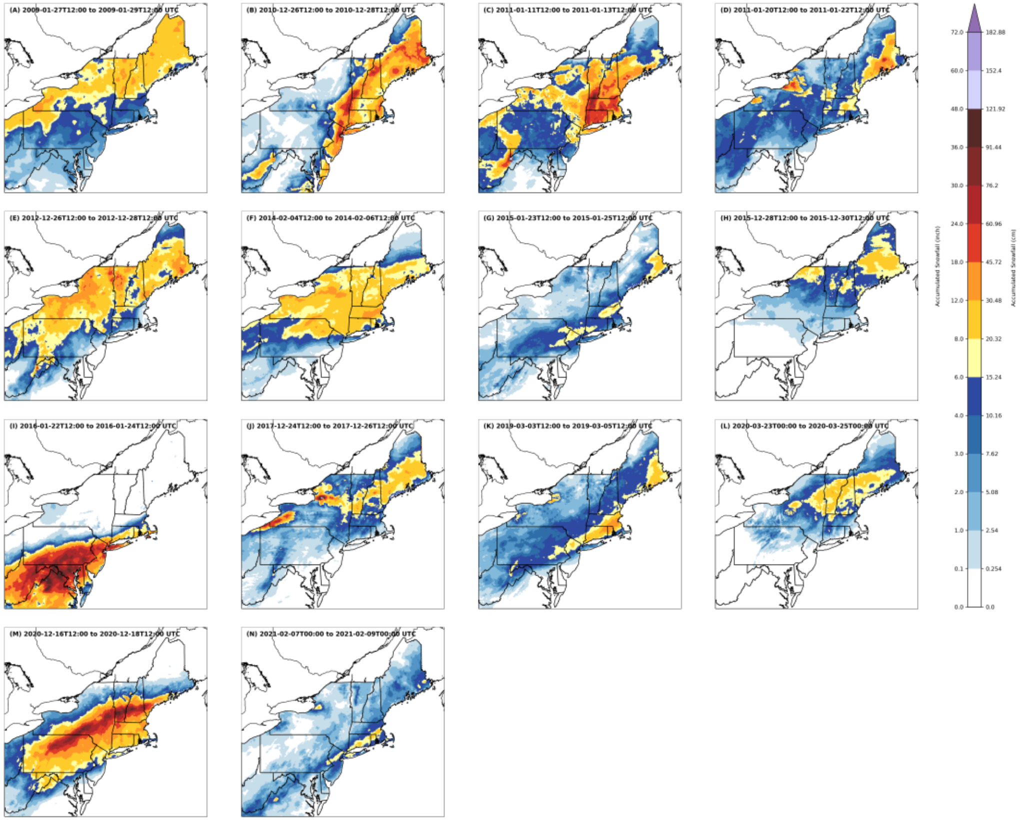
Snowfall Forecasting

- Snow-to-Liquid Ratios (SLRs) are an important component in the snowfall forecasting process
- SLRs have a wide range of possible values (2:1 to 100:1) due to the thermodynamic environment and microphysical processes
- Many approaches to estimating SLR that range in complexity
- **Research Goal:** Assess bulk accuracy of 10 SLR algorithms via snowfall accumulations for 14 impactful winter storms in the Northeast United States to establish a baseline comparison across numerous types of algorithms



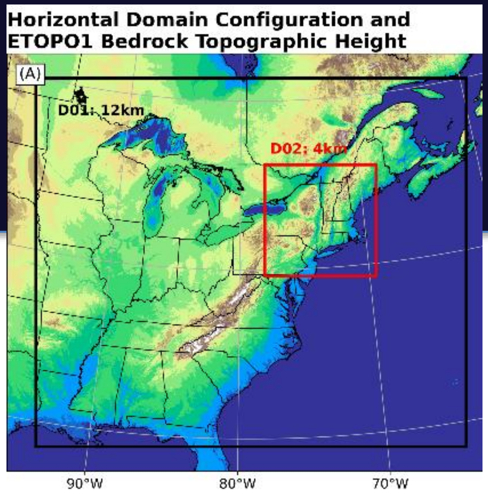
Storm Selection

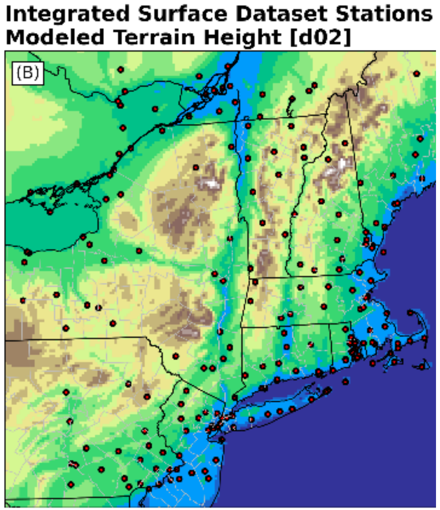
- Simulated 14 significant snowstorms between 2009-2021
- Similar to RSI (Squires et al. 2014), multiple GHCN-D snowfall observations > 4 inches were required in major cities in NE US
- Started in 2009 to coincide with National Snowfall Analysis data

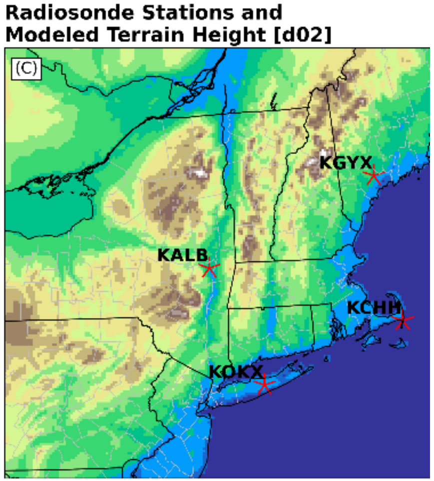


Datasets

- WRF Simulations
  - WRFv4.2.2, 60-hour simulations
  - GFS initial and boundary conditions
  - Domains: 12 and 4km
- Evaluation Datasets
  - NOAA Integrated Surface Database
  - NWS Radiosondes
  - Stage IV Precipitation: 4km, radar-derived gauge-corrected QPE

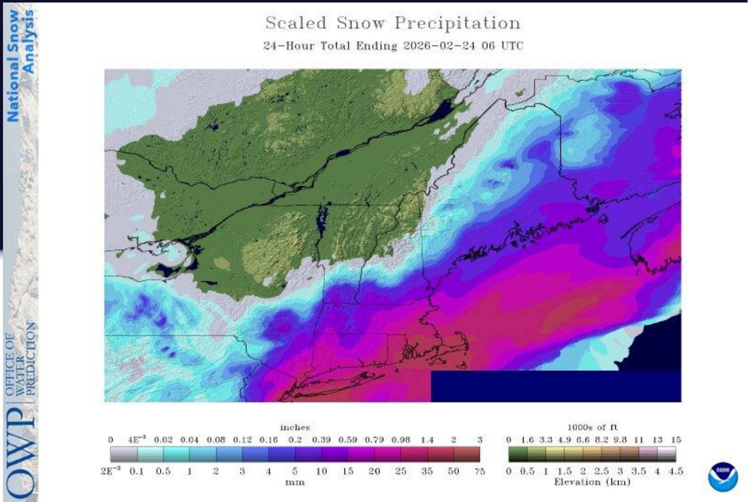


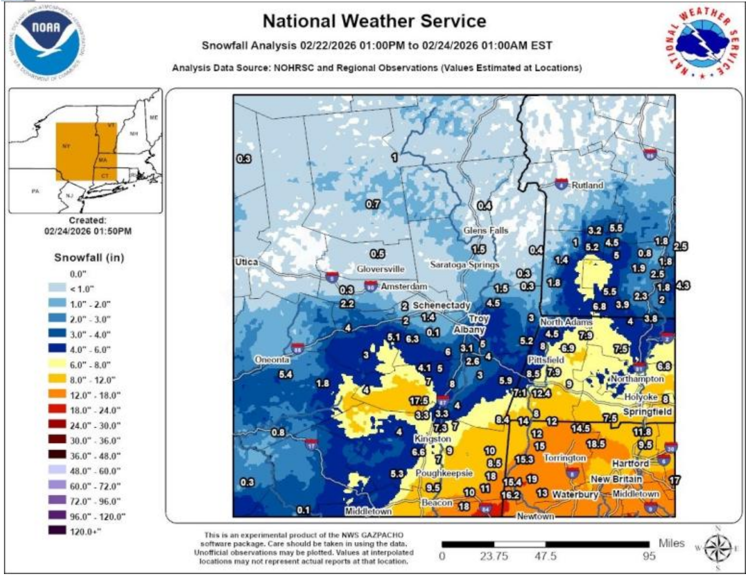




Datasets

- NOHRSC National Snowfall Analysis (NSA)
  - 0.04° gridded 48-hour accumulations
  - SNODAS assimilates multiple observational data sources
    - Snowfall- NWS COOP, CoCoRaHS, & NWS Spotters
    - Precipitation- 24-hr Stage IV QPE & HRRR
    - 2m Temperature- NSA
    - First Guess Climatological 30yr SLR
  - Background analysis combined with snowfall observations via ordinary Kriging interpolation





Snowfall Methodology

Standard Method

NWP QPF

Precipitation Type

SWE

SLR

Snowfall

WRF Adapted

WRF QPF

Use Microphysics Scheme

WRF SNOWNC

SLR

Event Snowfall= $\sum$ SWE∗SLR

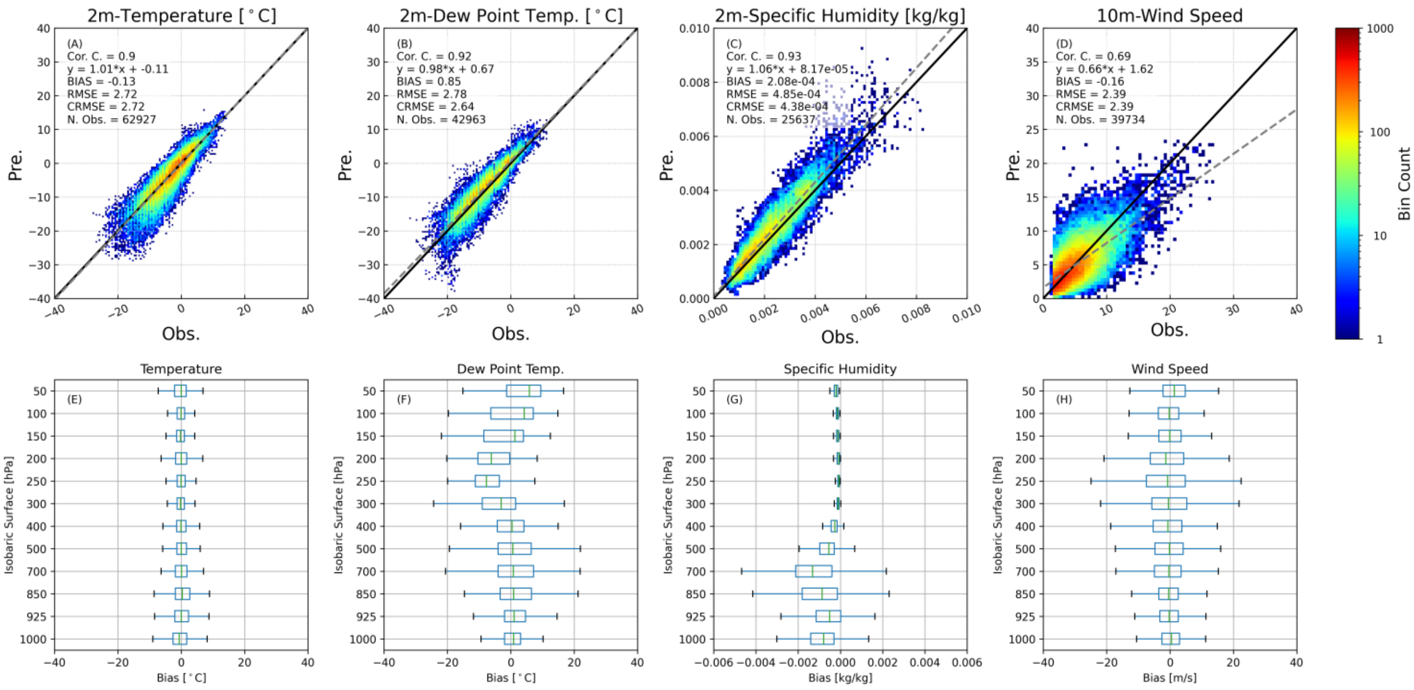
Hourly snowfall accumulations

1. Retrieve WRF SWE
2. Calculated SLR for different methods
3. Hourly Snowfall= SWE∗SLR

SLR Methods

SLR Method	Required WRF Variables
Method 1: 10:1	None
Methods 2 & 3: Baxter Monthly & Annual Climotologies	None
Method 4: NWS Conversion Table	T_2
Method 5: NOAH-LSM	T_2
Method 6: AFWA	T_{2m}; SW_{down}
Method 7: KAKQ	Atmospheric thickness between 850 & 700 mb (dz in m)
Method 8: Kuchera	T_{max} in the layer 1000-500hPa
Method 9: Byun	T_2; 3-hourly precipitation rate
Method 10: Cobb and Waldstreicher (from NBMv4.1)	Upward vertical velocity (ω), Temperature, geopotential height (Φ), and relative humidity at 25hPa intervals

WRF Performance



- ✓Temperature: Unbiased at both the surface and throughout the atmosphere
- ✓Wind Speed: Unbiased both at the surface and throughout the atmosphere
- ✓Humidity: WRF overestimates at the 2-meters and underestimates humidity above the surface until 500hPa

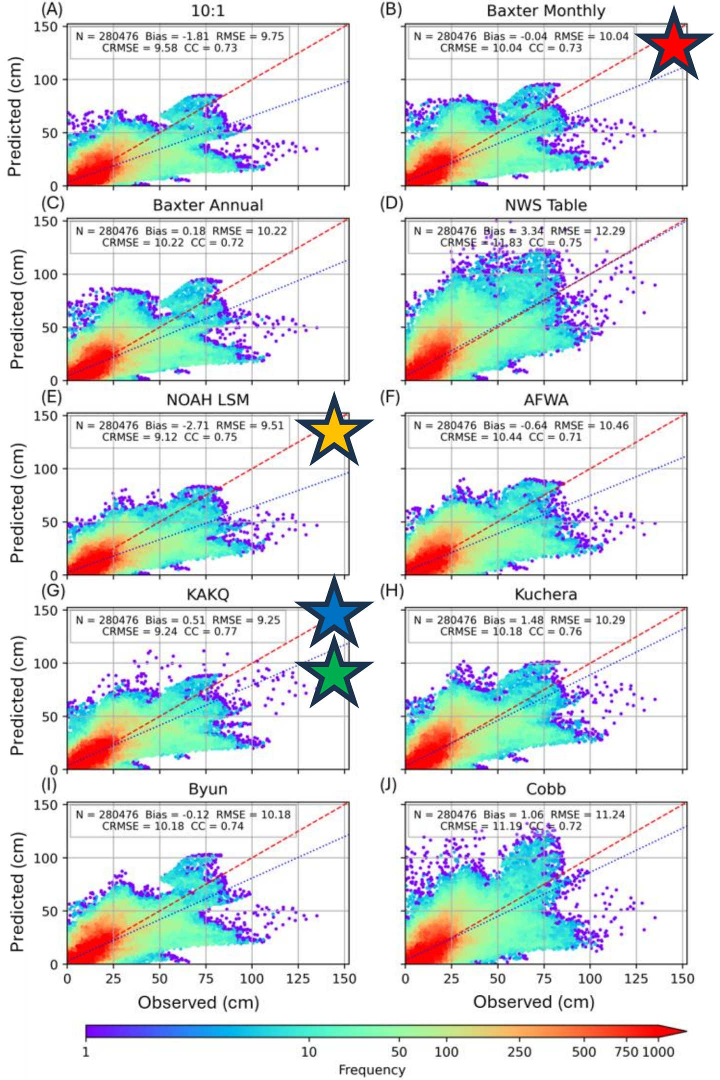
SLR Performance

Here, results represent the accuracy of SLR methods without knowing the QPF biases that contribute to snowfall biases

- ✓**KAKQ had the best RMSE and CC**
- ✓**NOAH-LSM had best CRMSE but a significant negative bias**
- ✓**NWS Table had worst bias and error metrics**

Statistically Significant metrics:

Bias RMSE CRMSE CC



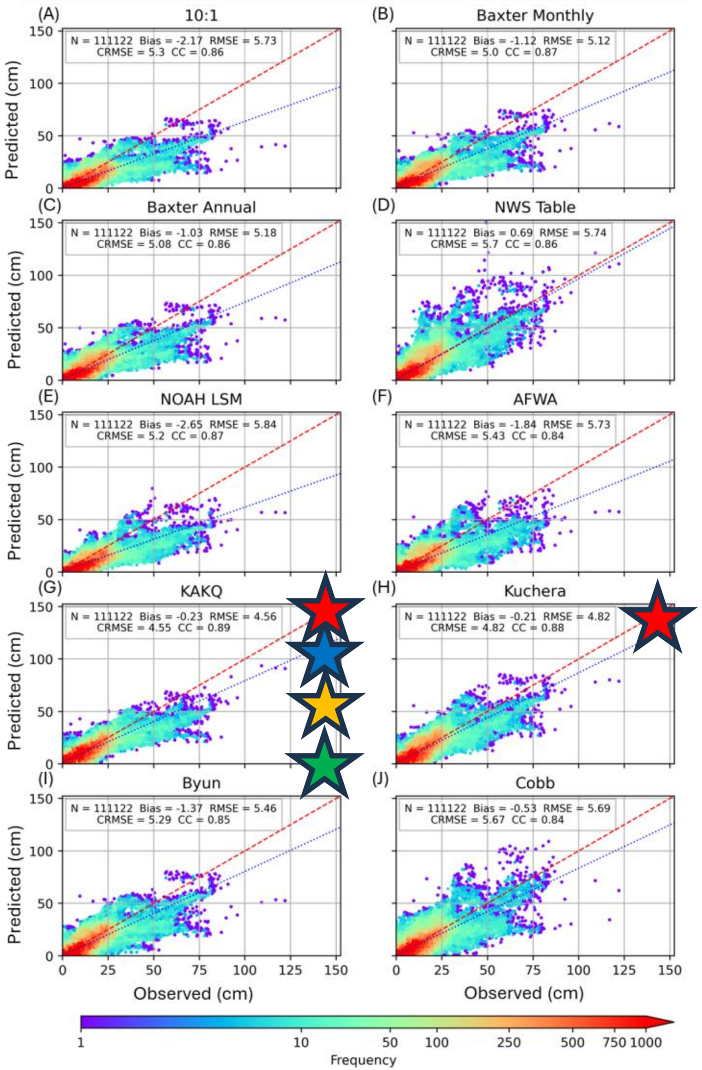
SLR Performance

To remove biases in precipitation forecasts, only grid cells with ≤0.1in biases were kept

- ✓**Error metrics improved by >50% and CC increased by around 0.1**
- ✓**All methods (except NWS Table) underestimated snowfall**
- ✓**KAKQ and Kuchera performed best across the different statistical metrics**
- ✓**Kuchera had less underestimation for accumulations > 50 cm (~20 in)**

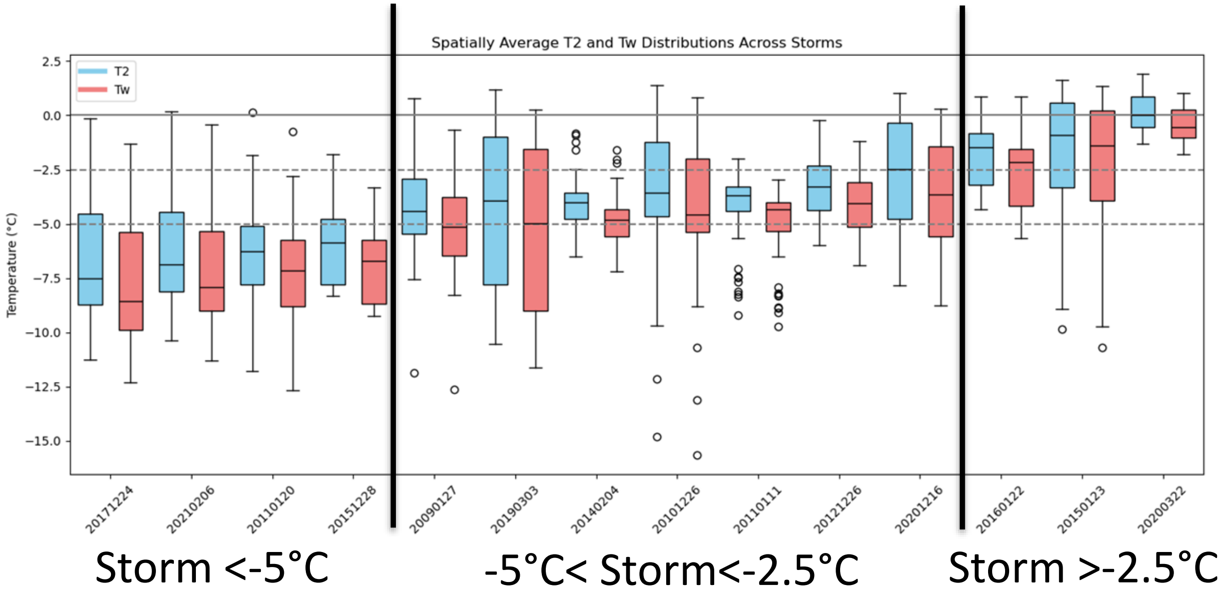
Statistically Significant metrics:

Bias RMSE CRMSE CC



Impact of Temperature

- Examined the accuracy of SLR algorithms depending on storm conditions
- Separated storms by median T_2 and T_{2wet} during snowy hours



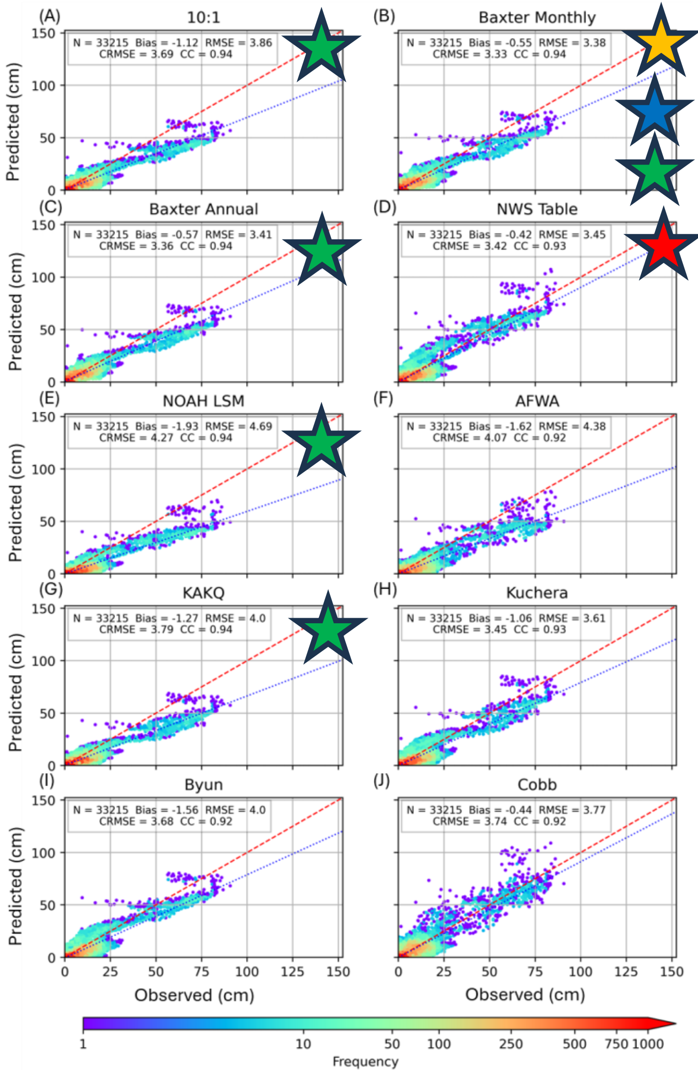
SLR Performance

For the storms with a median T_2 and T_{2wet} >-2.5°C

✓**The climatology methods performed very well**
✓**Narrower range and better values of CRMSE (3.33-4.27cm) and CC (0.92-0.94) compared to the overall analysis**
✓**Less variability between the different SLR methods**

Best Performing metrics:

Bias RMSE CRMSE CC



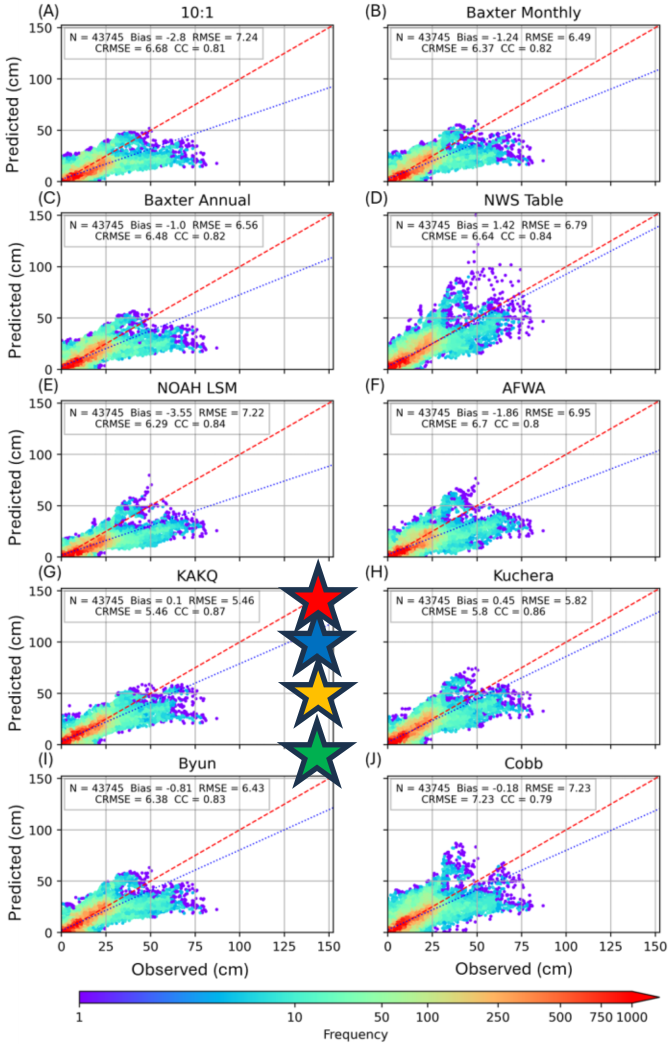
SLR Performance

For the storms with a median T_2 and T_{2wet} >-5°C and <-2.5°C

✓**Overall SLR performance decreased with higher CRMSE (5.46-7.23cm) and lower CC (by 0.05-0.13)**
✓**KAKQ was the best algorithm followed by Kuchera**
✓**Cobb has second best bias, largest CRMSE**
✓**Largest deviations in snowfall accumulations occurred with snowfall >50cm (~20 in)**

Best Performing metrics:

Bias RMSE CRMSE CC

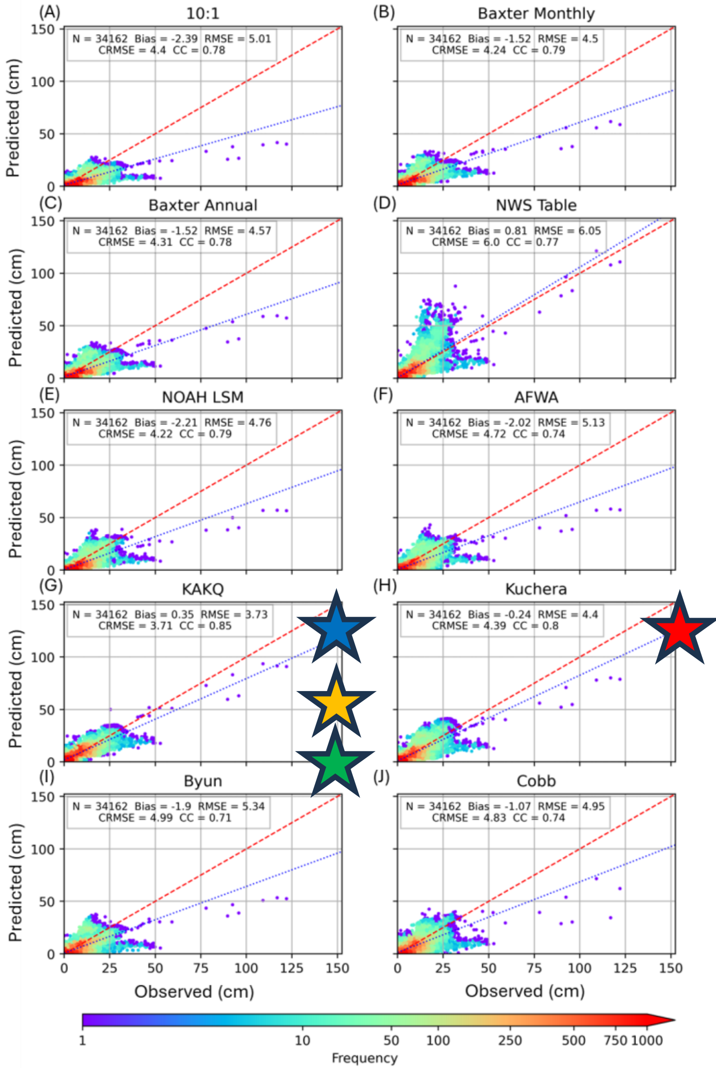


SLR Performance

For the storms with a median T_2 and T_{2wet} <-5°C

✓**Snowfall accumulations were lower overall**
✓**KAKQ and Kuchera performed the best of all methods**

✓**Overall: There was more variability and reduced accuracy with the SLR algorithms as T_2 and T_{2wet} decreased.**



Best Performing metrics:

Bias RMSE CRMSE CC

Research Summary

- 10 SLR methods were evaluated over 14 snowstorms in the Northeast United States
- QPF biases contributed to ≈50% of snowfall error
- KAKQ and Kuchera methods were the most accurate SLR
  - Both methods used temperature above the surface
- SLR algorithms showed more variability in colder temperatures
- Future work should focus on evaluate SLR algorithms for different regions and types of winter storms

Use in Operations

- Not all the methods shown before are widely used in operational forecasting
- WFOs have a sense of what methods tend to work best in the different situations (storm type, temperatures) in their area
- Challenge is expanding to larger regional and CONUS scale forecasts
- What SLR methods are currently being used operationally and how can these results give us context to these methods?

Operational Models

- HRRRv4, RAPv5, RRFSv1
  - Snow accumulation with variable SLR (5-17:1)
  - Lowest model level temperature
- RRFSv1
  - New instantaneous falling snow density field
    - Linear-regression from Pletcher et al. 2026
    - Simpler, faster version of Random Forest model

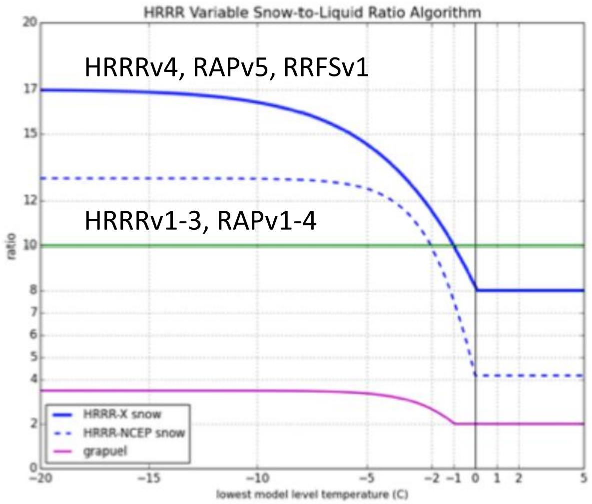


TABLE 2. Descriptions of atmospheric and geographic features used for RF training.

Feature	Levels	Group
Temperature (T, K)	300, 600, 900, 1200, 1500, 1800, 2100, 2400 m AGL	Atmospheric
Wind speed (SPD, m s^{-1})	300, 600, 900, 1200, 1500, 1800, 2100, 2400 m AGL	Atmospheric
RH (R, %)	300, 600, 900, 1200, 1500, 1800, 2100, 2400 m AGL	Atmospheric

Operational Models

- National Blend of Models (NBM)
  - Blending guidance from multiple methods applied to multiple numerical model
  - Weighting of methods and numerical models vary by forecast hour

Model	SLR Techniques
HRRR	50% Cobb | 50% MaxTAloft
HRRRX	50% Cobb | 50% MaxTAloft
RAP	50% Cobb | 50% MaxTAloft
RAPX	50% Cobb | 50% MaxTAloft
HiResARW	50% Cobb | 50% MaxTAloft
HiResARW2	50% Cobb | 50% MaxTAloft
HiResFV3	50% Cobb | 50% MaxTAloft
NAMNest	50% Cobb | 50% MaxTAloft
GFS	33% Cobb | 33% MaxTAloft | 33% Roebber (through model 84-H)
GEFS	33% Cobb | 33% MaxTAloft | 33% 850–700mb Thickness
ECMWFE	33% Cobb | 33% MaxTAloft | 33% 850–700mb Thickness
CMC GDPS	33% Cobb | 33% MaxTAloft | 33% 850–700mb Thickness
CMC RDPS	33% Cobb | 33% MaxTAloft | 33% 850–700mb Thickness
CMC REPS	*50% MaxTAloft | 50% 850–700mb Thickness*
CMC GEPS	*50% MaxTAloft | 50% 850–700mb Thickness*

Operational Models

MaxTAloft- between 2000ft to 400hPa AGL

$$\mathrm{SLR}_{\mathrm{MaxTAloft}} = 0.000\,004\,5 \times T_{\mathrm{Max}}^{5} + 0.000\,443\,2 \times T_{\mathrm{Max}}^{4} + 0.013\,090\,3 \times T_{\mathrm{Max}}^{3} + 0.058\,596\,8 \times T_{\mathrm{Max}}^{2} - 1.815\,080\,9 \times T_{\mathrm{Max}} + 5.980\,572\,2, \quad (1)$$

850-700 Thickness

$$\mathrm{SLR}_{\mathrm{Thickness}} = -(0.165\,59 \times \mathrm{Thickness}_{850-700\mathrm{mb}}) + 263.35, \quad (2)$$

Roebber- Integrated at WPC, utilized Artificial Neural Network to predict SLR (Roebber et al. 2003)

Cobb- Modified with melting factor since NBMv4.2

- Utilizes 25hPa pressure levels between 925-300hPa
- Vertical velocity is scaled by RH to avoid dry layers
- Initial guess SLR at each level based on temperature
- Final SLR is a weighted summation of the initial guess with weighing of the layers' scaled vertical velocity

Model	SLR Techniques
HRRR	50% Cobb | 50% MaxTAloft
HRRRX	50% Cobb | 50% MaxTAloft
RAP	50% Cobb | 50% MaxTAloft
RAPX	50% Cobb | 50% MaxTAloft
HiResARW	50% Cobb | 50% MaxTAloft
HiResARW2	50% Cobb | 50% MaxTAloft
HiResFV3	50% Cobb | 50% MaxTAloft
NAMNest	50% Cobb | 50% MaxTAloft
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CMC REPS	*50% MaxTAloft | 50% 850–700mb Thickness*
CMC GEPS	*50% MaxTAloft | 50% 850–700mb Thickness*

Implications for Forecasters

- HRRR/RRFS snow accumulation could have worse performance due to reliance on lowest model level temperature
  - RRFS snow density field could provide improvement in snowfall accumulations due to the variables incorporated
- NBM SLR methods utilize methods similar to those that showed more consistent results for the Northeast US
  - Due to regionality and spatial heterogeneity of SLR methods, the method used in the NBM seems more representative

Overall Summary

- Research Findings:
  - 10 SLR methods were evaluated over 14 snowstorms in the Northeast United States
  - QPF biases contributed to ≈50% of snowfall error
  - KAKQ and Kuchera methods were the most accurate SLR
- Operational impacts
  - The different NBM SLR methods utilize techniques that have been shown to produce more representative SLRs across different environments

Contact: Brian Filipiak, brian.filipiak@uconn.edu