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Advantages and Challenges of Mid-latitude Super-Ensemble Coastal Water Level Forecasting

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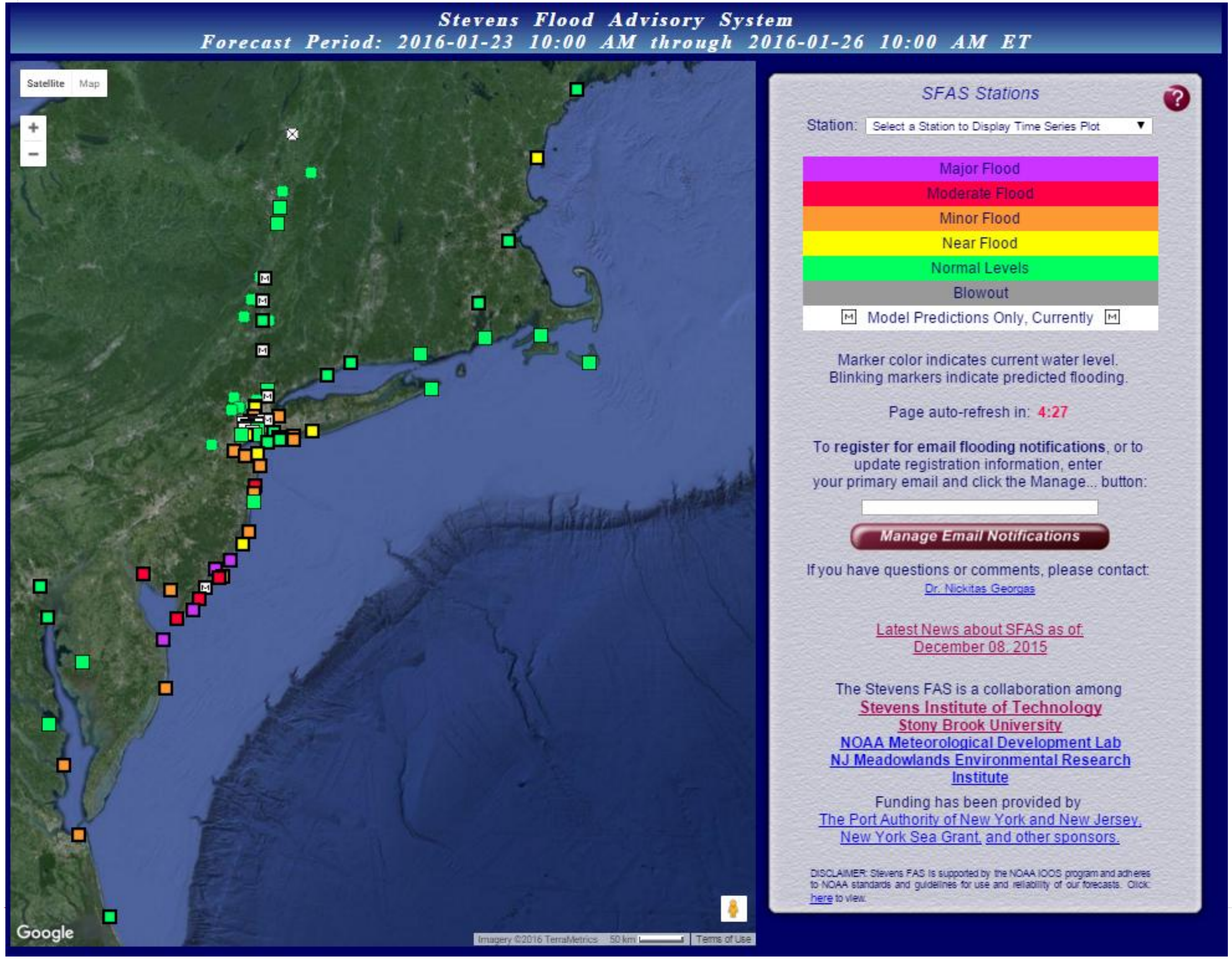
Stevens Institute of Technology

(Georgas now at TetraTech)

Funding: Port Authority of NY/NJ, NOAA-RISA, NOAA ORR via New Jersey Sea Grant Consortium

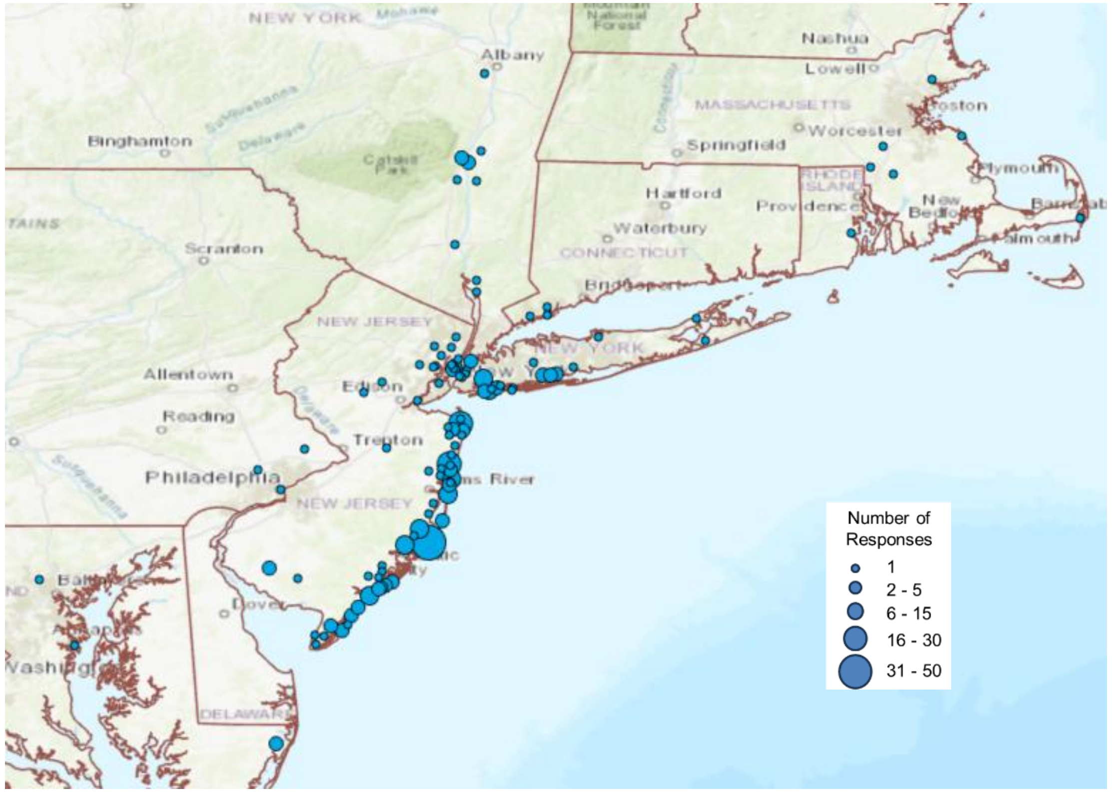
Stevens Flood Advisory System (http://stevens.edu/SFAS)



Key Features

- Time series water level forecasts with 90% uncertainty
- Station-based predictions for tidal water bodies
- Includes coastal and fluvial flood drivers
- Sends emails with 8-hour and 4-day flood alerts
- From 2017-2024 included Flood Inundation Mapping at areas of critical infrastructure (Jordi et al. BAMS)

SFAS Users: Respondents to a 2024 Poll



NWS Forecast Offices across the US Northeast and Mid-Atlantic use SFAS data behind the scenes in forming forecast guidance.

About 1600 website users are signed up for email notifications. An anonymous survey was created and distributed to them and completed by 351 (23%).

Published user survey (Orton et al., *Mendeley* 2024)

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Poll Findings

- A subset of 99 (of 351) respondents were community, company or government users that share SFAS forecasts or use it for their operations
  - Common response activities include closing flood gates or storm surge barriers, moving cars to higher elevation, closing roads, protecting industrial equipment, preparing facilities to accommodate floodwaters, triggering OEM activities, and issuing PR notices to the public
- Another 225 respondents were "household users" with similar, personal activities including adjusting travel times to/from home

→ SFAS is enabling 'micro-adaptations' to sea level rise induced high-tide flooding

Mid-Latitude Ensemble Forecast Systems

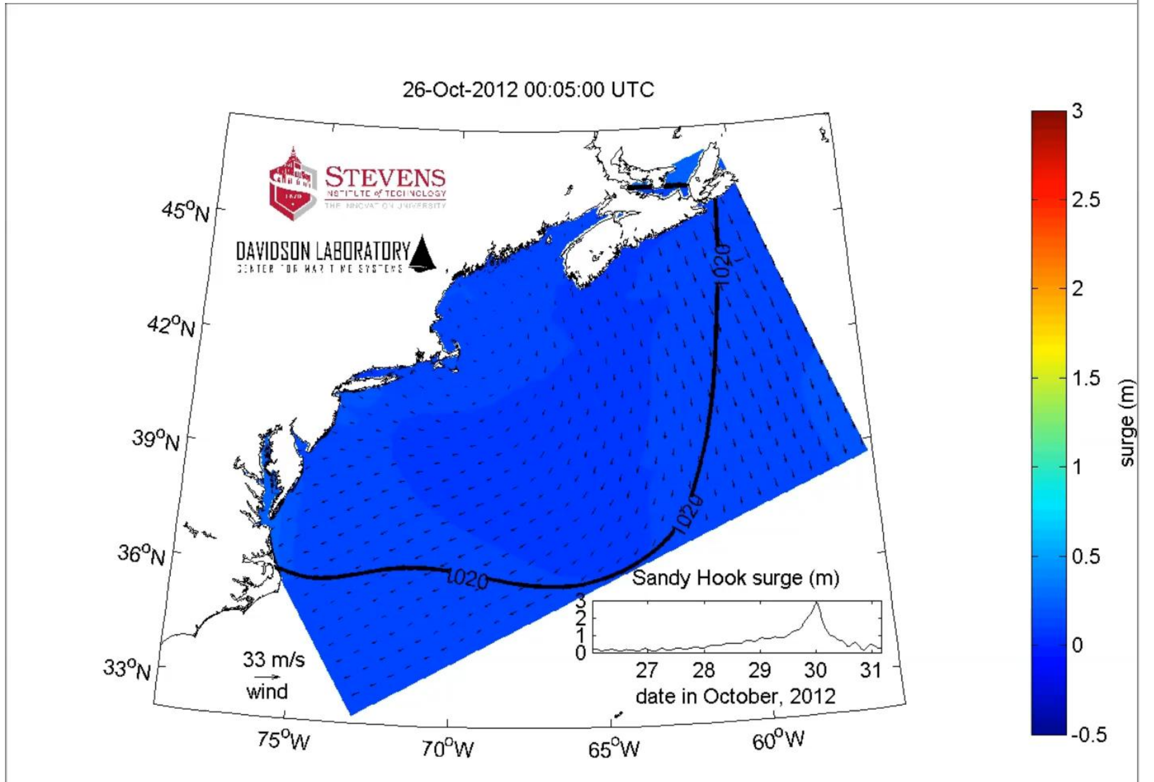
- Mid-Latitude ensemble water level forecast systems are defined as year-round operational water level (and/or flood) forecast systems
- Such systems are run only by relatively few organizations, such as:
  - Stevens (Flood Advisory System), NOAA (P-ETSS), the Dutch Meteorological Institute (KNMI) (de Vries, 2009), the UK Meteorological Office (Flowerdew et al., 2010)
- There has been relatively little detailed multi-year probabilistic assessment

Research Goals

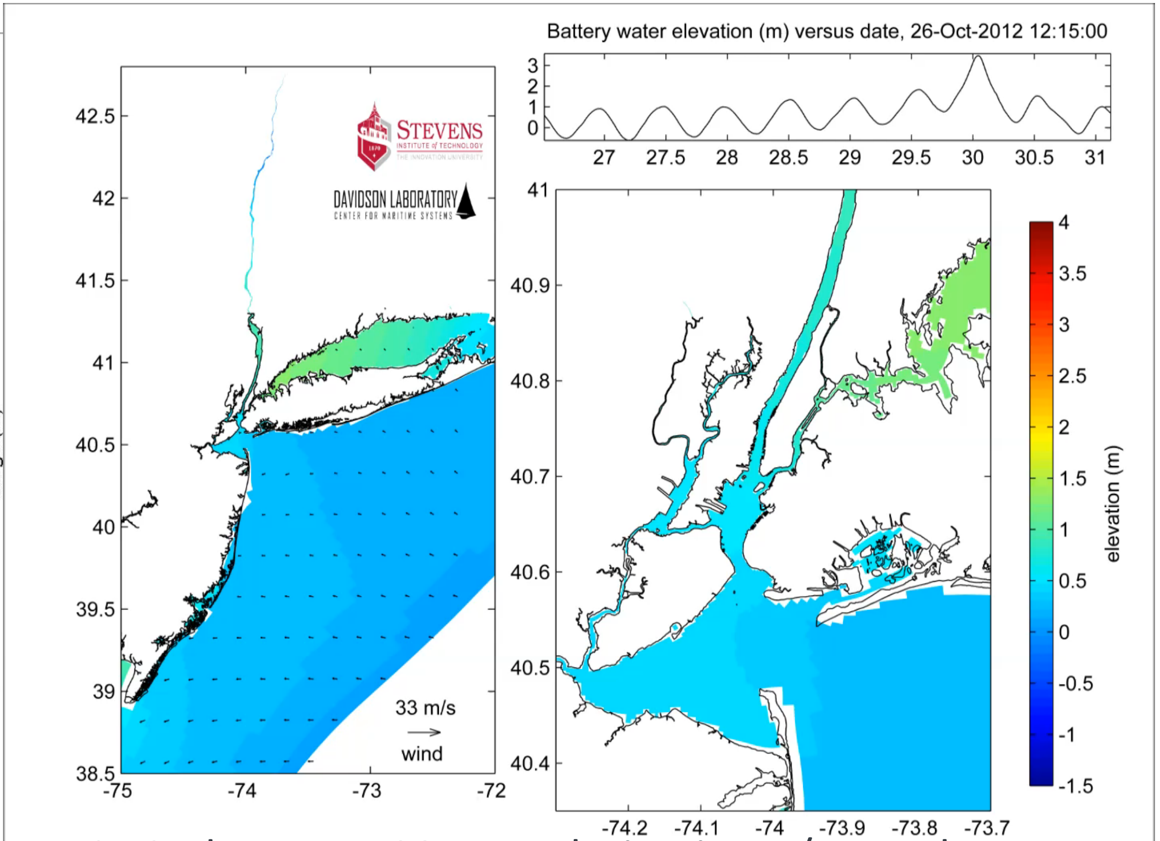
- Evaluate forecast accuracy and spread of SFAS (vs NOAA-PETSS)
  - Recent two-year period with 96-member “Super-ensemble” of met forcing (US, Canadian and European)
  - Spans a wide range of conditions from negative to positive surge events
- Compare the forecast performance using the super-ensemble, various sub-ensembles and NOAA P-ETSS
- Understand the key factors contributing to error or bias, and
- Gain a broader understanding of the future potential of mid-latitude water level and flood forecasting.

Methods – forecasts and assessment

Forecast Methods: 3D Regional Nested Modeling, Ensemble Forcing



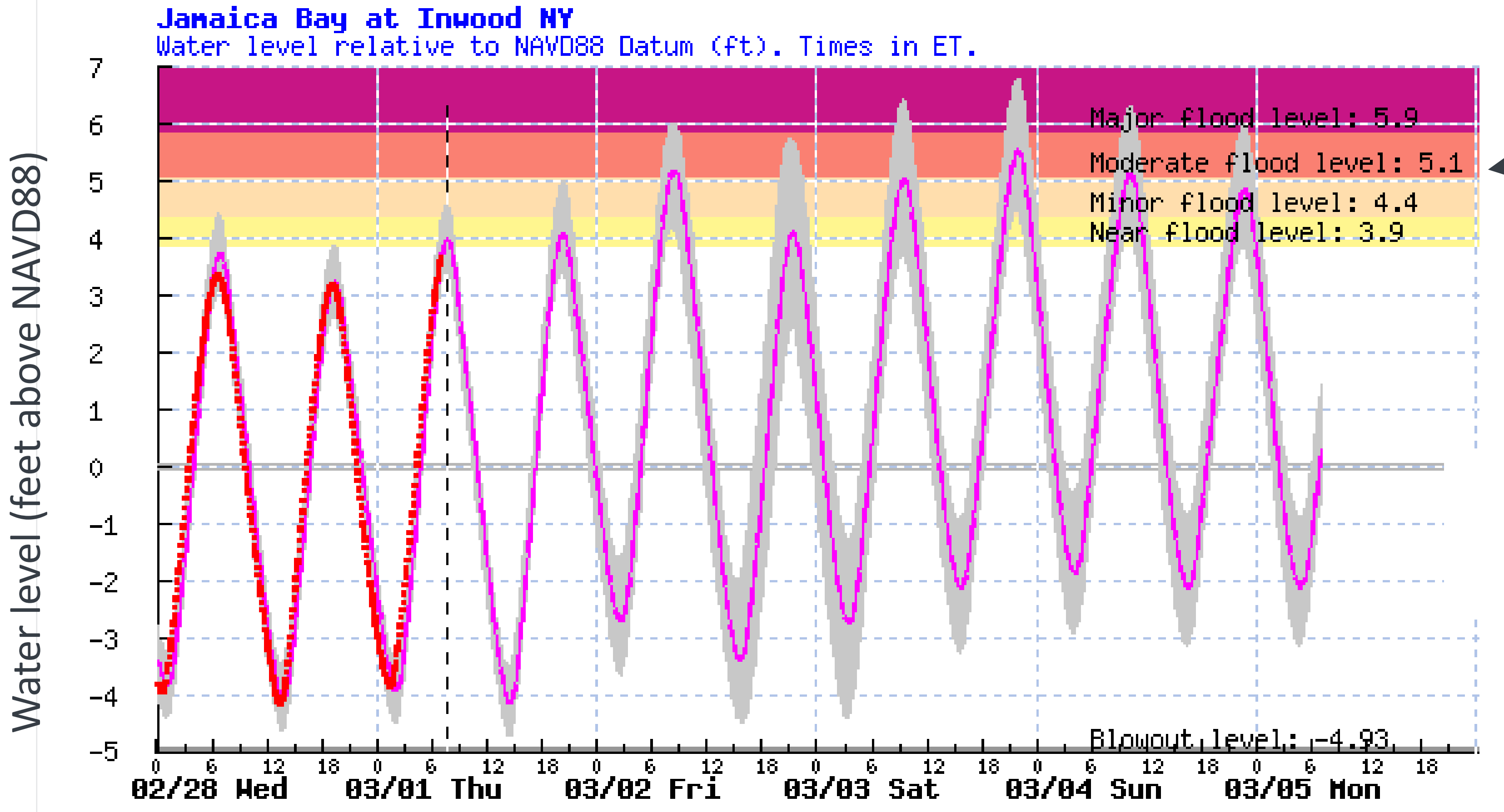
NEST 1: 5km resolution



NEST 2: down to 100m resolution in NY/NJ Harbor

- Water level model – Stevens ECOM (Blumberg et al. 1999; Georgas et al. 2010) coupled with GLERL wave model (Donelan, 1977; Schwab et al.,1984)
- Meteorological forcing from a Super-Ensemble – US forecast products (GFS, NAM, GEFS ensemble), European products (ECMWF-Hi Rez, ensemble) and Canadian ensemble (GEPS; “CMC”)
- Hydrology: HEC-HMS simulations for NY/NJ Metro and Hudson River watersheds (Saleh et al. 2016; 2017)
- “Dressing”: + forecast dressing is a key – two types of bias corrections

Assessment Methods



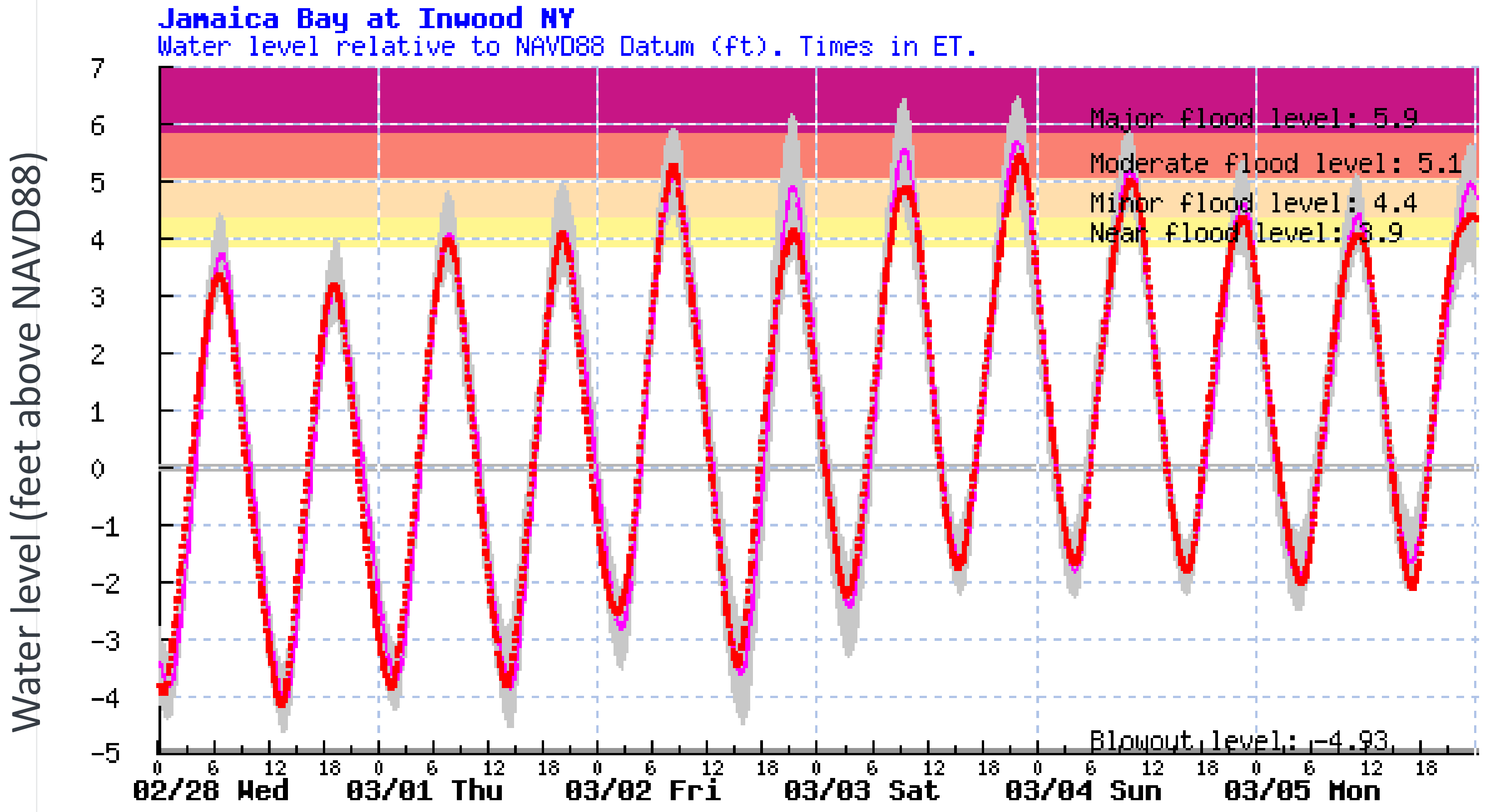
National Weather Service flood thresholds

The forecast: water level

The "spread": 90% confidence of prediction

Observed water levels

Assessment Methods

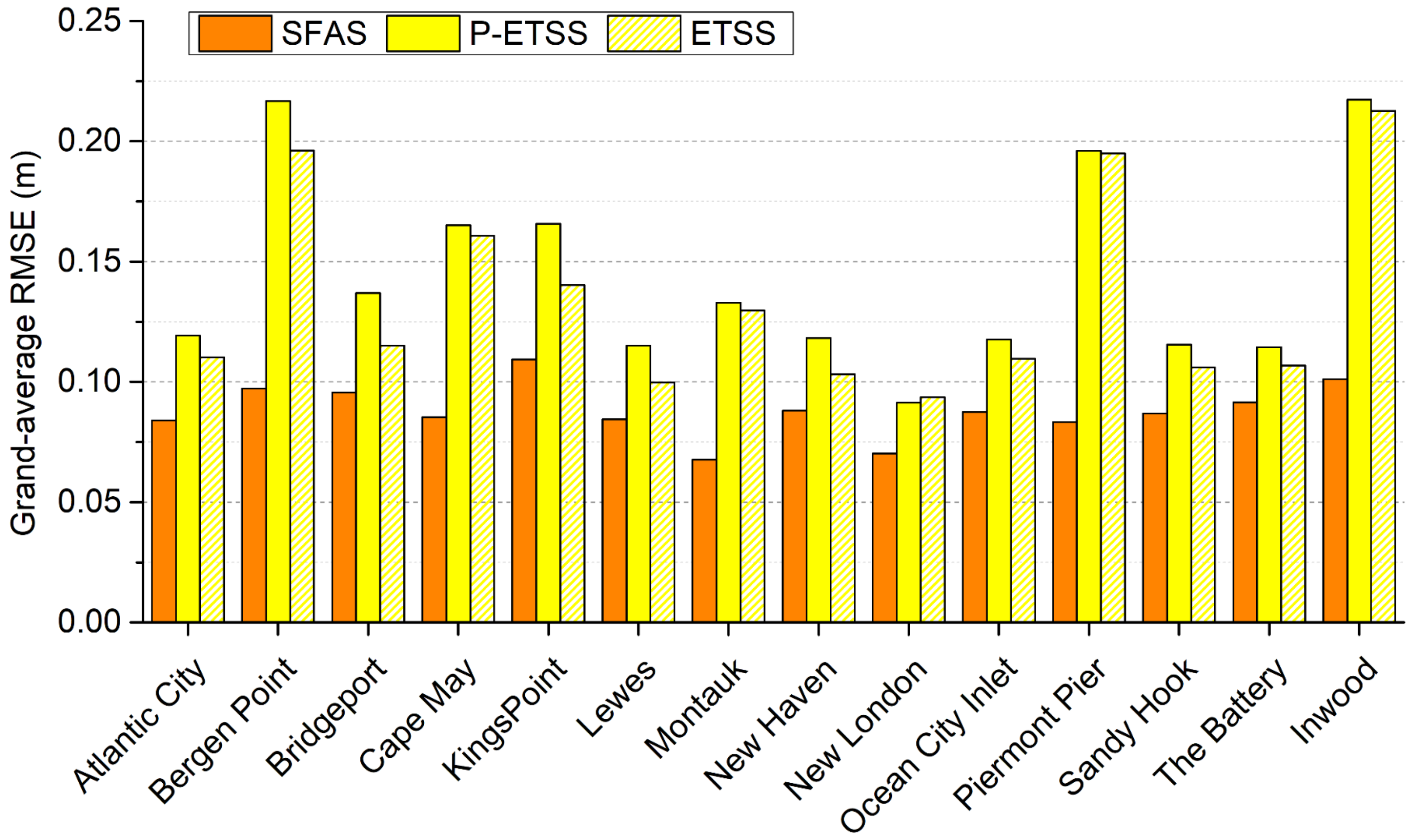


Forecast Error is quantified as RMSE

Spread is Quantified with Coverage of Uncertainty by observations (COU; optimal value of 90%)

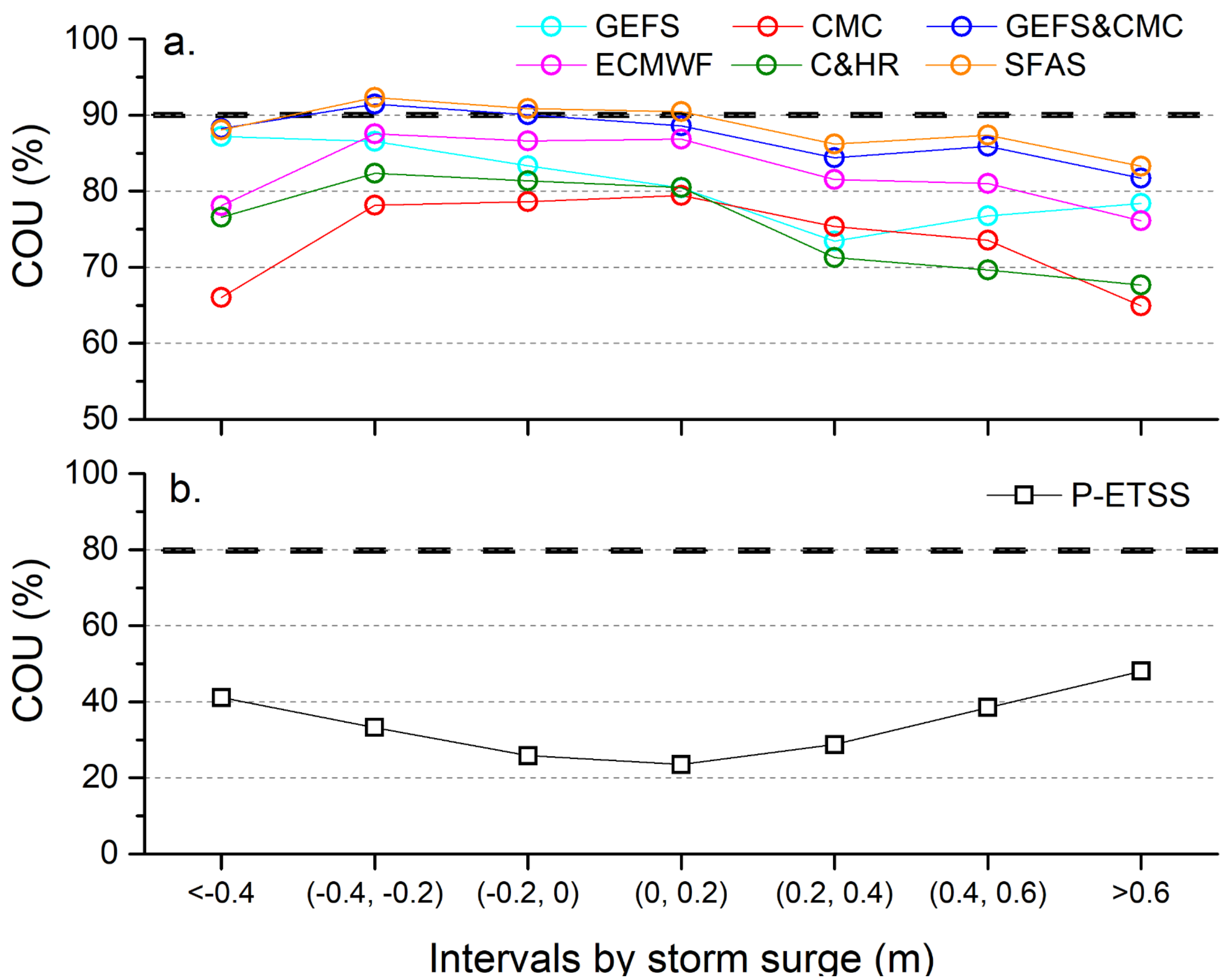
Results – accuracy, spread and biases

Time Series Assessment: Accuracy



The SFAS stations have a 0.06 m to 0.11m RMSE across the 14 stations, while NOAA forecasts (P-ETSS, ETSS) have higher RMSE (worse accuracy).

Time Series Assessment: Spread (Uncertainty)



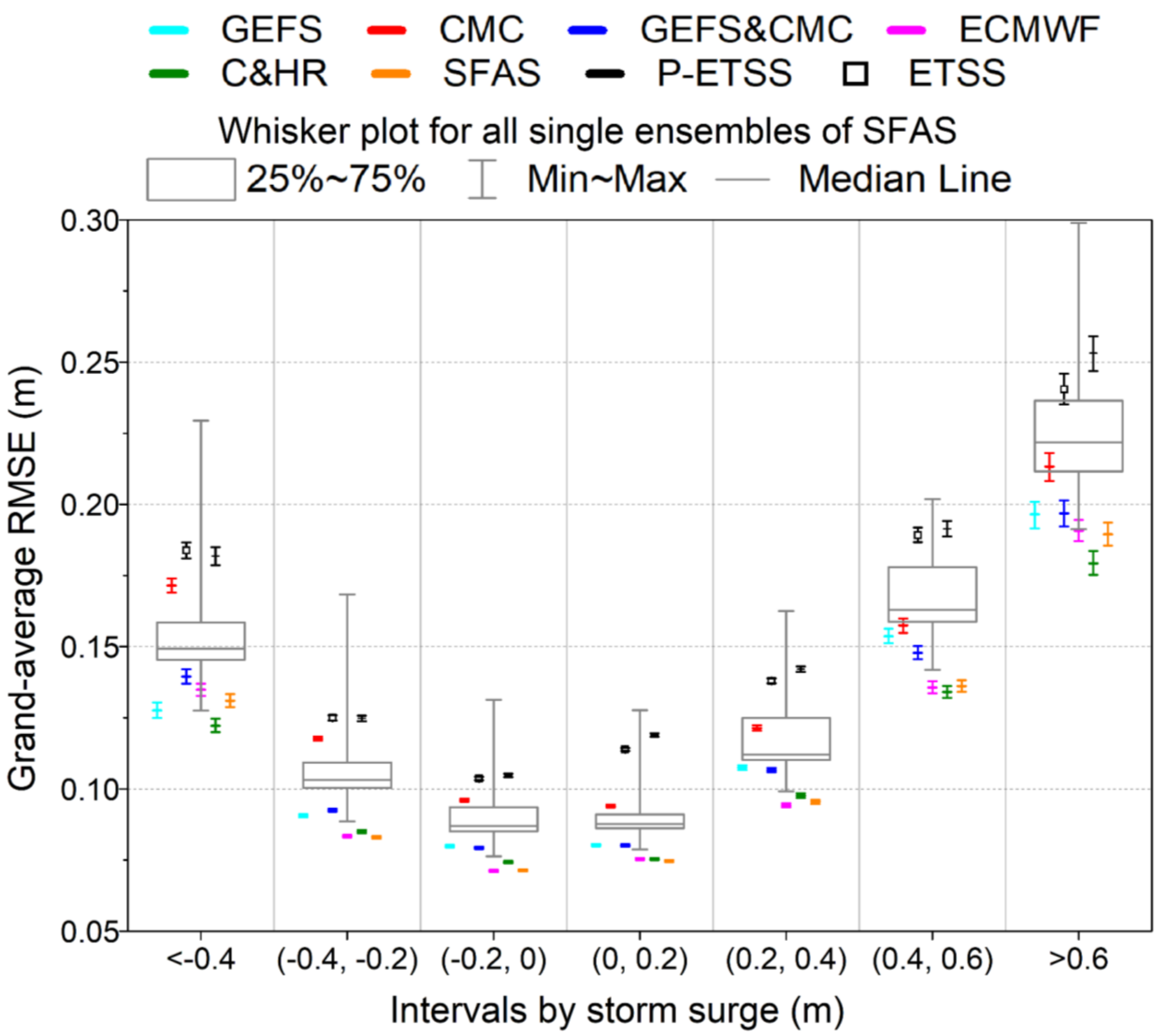
The COU variation with surge threshold is shown for Stevens forecasts (panel a), and for the NOAA forecast (panel b).

Panel a includes the full SFAS ensemble and several smaller sub-ensembles for comparison.

The COU optimal value for P-ETSS is 80% but data are far lower

→ Super-ensemble (SFAS) spread is as good or better than all sub-ensembles and NOAA P-ETSS

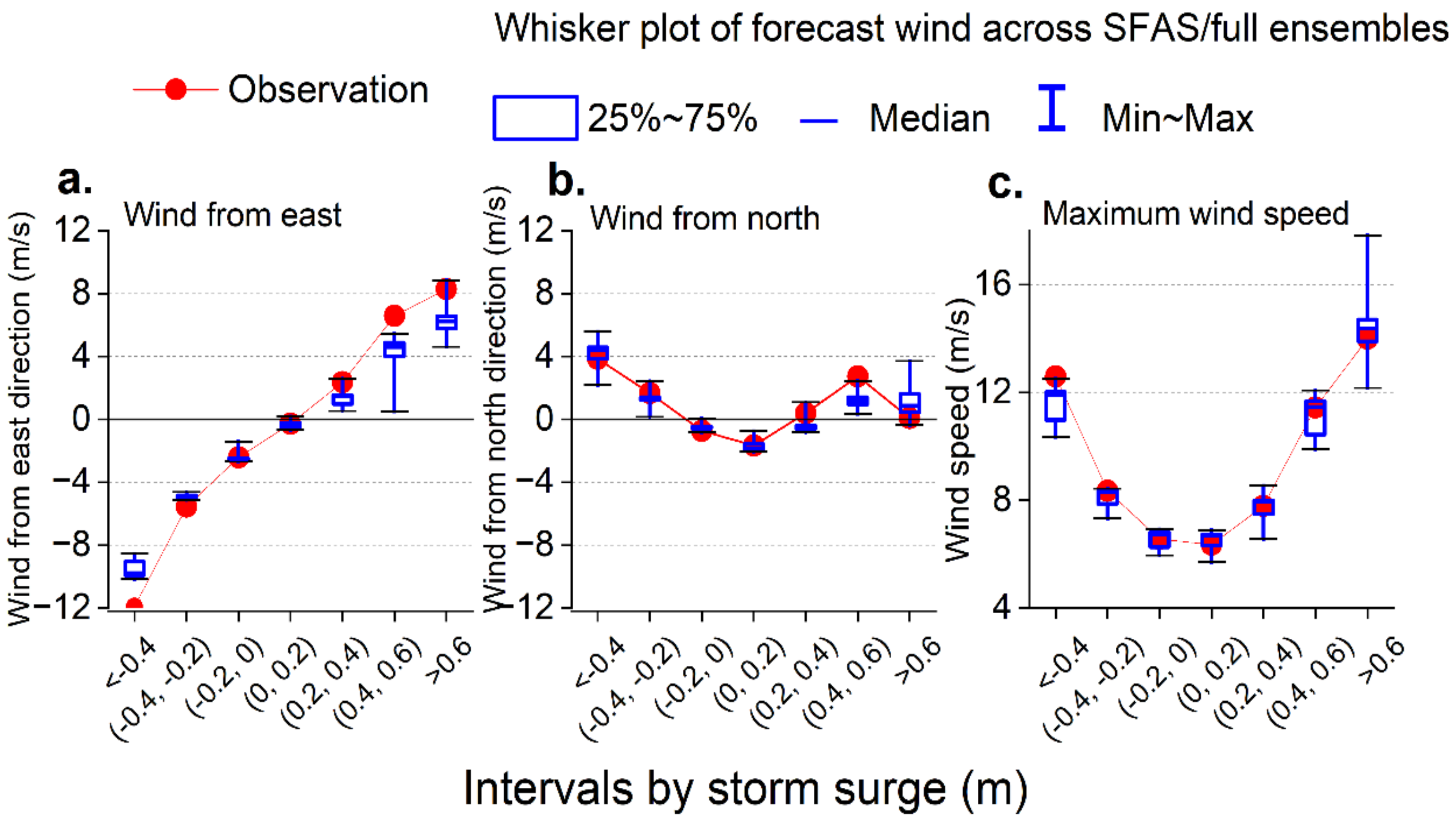
Peaks Accuracy Assessment



- **Super-ensemble (SFAS) as good or better than all sub-ensembles and NOAA**
- Control & High Resolution member (C&HR) ensemble is best
- Similar story for negative and positive surge
- **However, for both positive and negative surges, there is a (not shown) low bias in water level magnitude**

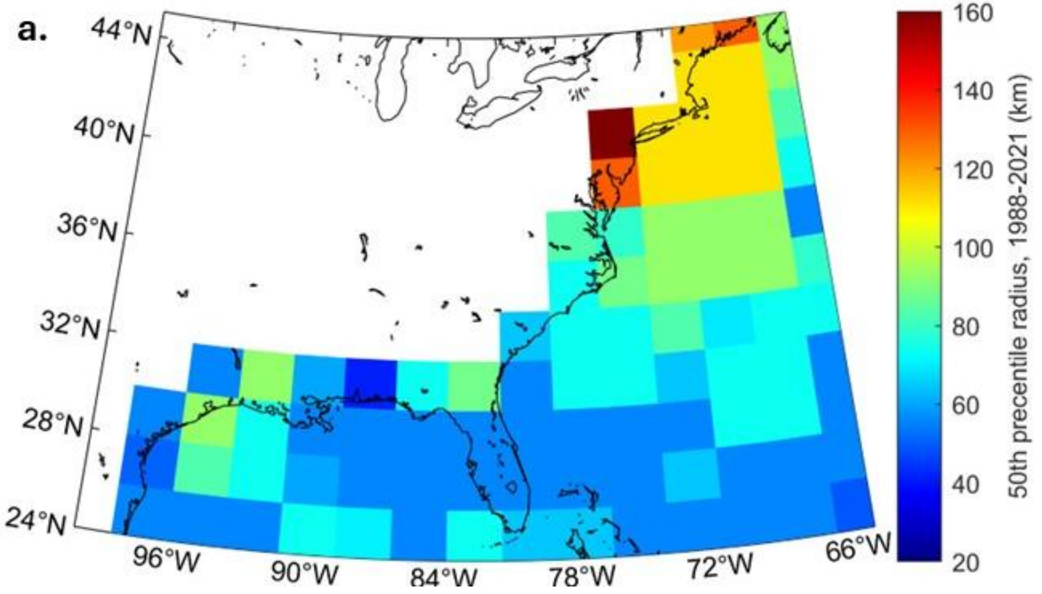
Wind Forcing: Accuracy Assessment

- Wind predictions in NY Bight showed no bias in peak wind speed (mostly 0.25-0.50° wind products)
- They had a counter-clockwise (CCW) rotation bias, which could be blurring of land friction effects across coastal grid cells



Discussion: Advantages of Mid-Latitude Ensemble Forecast Systems

- Year-round consistent flood forecast products
- … for events ranging from tidal to extreme
- Accurate time-dependent high-tide flood forecasting
- Forecasting for all storms, including extratropical
- A different forecast approach for tropical cyclones, at times better in mid-latitude areas
  - TCs become larger (**see Figure**) and elongated in shape
  - Transition to extratropical status



The 50th percentile observed storm radii based on the radius of maximum wind data from the Extended HURDAT database.

Conclusions

- Accuracy: Higher accuracy for SFAS central forecasts than NOAA P-ETSS and ETSS, across events from high-tide floods to severe storm events
- Spread: The COU of the SFAS 5th-to-95th percentile is close to the 90% optimal value, better than the spreads of P-ETSS or any of the individual ensemble products
- Ensembles: The super-ensemble gave a better spread and accuracy than sub-ensembles; An ensemble of high-rez and control members improved accuracy but only slightly reduced bias
- Challenge: Low bias grew with increasing storm surge, with directional biases of wind forcing one apparent reason – however, meteorological models are improving
- Advantages: Year-round consistent flood forecast products for ALL flood events, including extratropical and tropical and tidal floods; and a different approach for tropical cyclones, at times better in mid-latitude areas

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References for Capabilities, Assessments

Survey –

Orton, P. M., Kerr, L., Eisler Burnett, H., & Kuonen, J. (2024). *User Survey for the Stevens Flood Advisory System. Retrieved from: https://data.mendeley.com/datasets/x6rtf59w4c/1*

Forecast assessment –

Chen et al., Advantages and Challenges of Mid-latitude Ensemble Coastal Water Level Forecast Systems, manuscript submitted to AMS *Weather and Forecasting*

Ayyad, M., Orton, P.M., El Safty, H., Chen, Z. and Hajj, M.R. (2022). Ensemble forecast for storm tide and resurgence from Tropical Cyclone Isaias. *Weather and Climate Extremes*, 38, p.100504.

Jordi, A., et al., (2019). A next-generation coastal ocean operational system: Probabilistic flood forecasting at street scale. *Bulletin of the American Meteorological Society*, 100(1), pp.41-54.

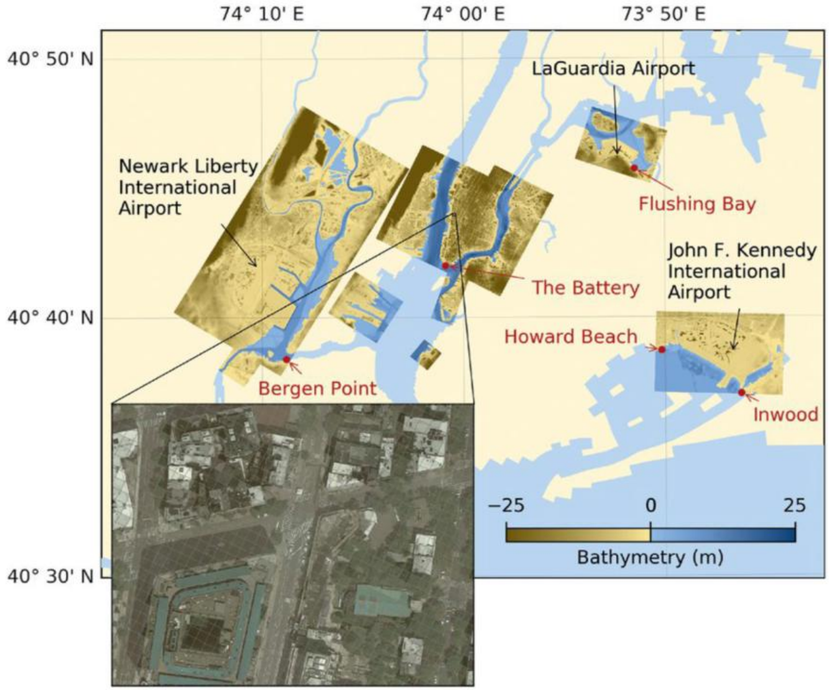
Orton, P. M., Z. Chen, H. El Safty, M. Ayyad, R. Datla, J. Miller, and M. R. Hajj (2021), Stevens Flood Advisory System 2020 Ensemble Forecast Assessment: NY/NJ Harbor Area, p. 21, Hoboken, New Jersey, USA.

Orton, P. M., Z. Chen, H. El Safty, M. Ayyad, R. Datla, J. Miller, and M. R. Hajj (2022), Stevens Flood Advisory System 2021 Ensemble Forecast Assessment: NY/NJ Harbor Area,, p. 23, Hoboken, New Jersey, USA.

Georgas, N., et al., (2016). The Stevens Flood Advisory System: Operational H3E flood forecasts for the greater New York/New Jersey Metropolitan Region. *International Journal of Safety and Security Engineering*.

Local Street-Scale Flood Forecast Mapping

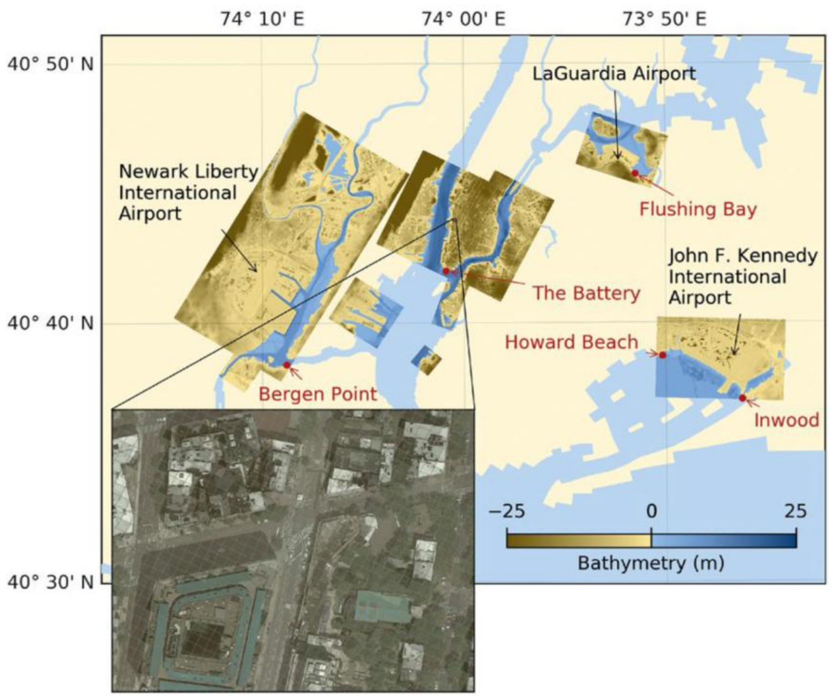
Retrospective Example: Hurricane Sandy

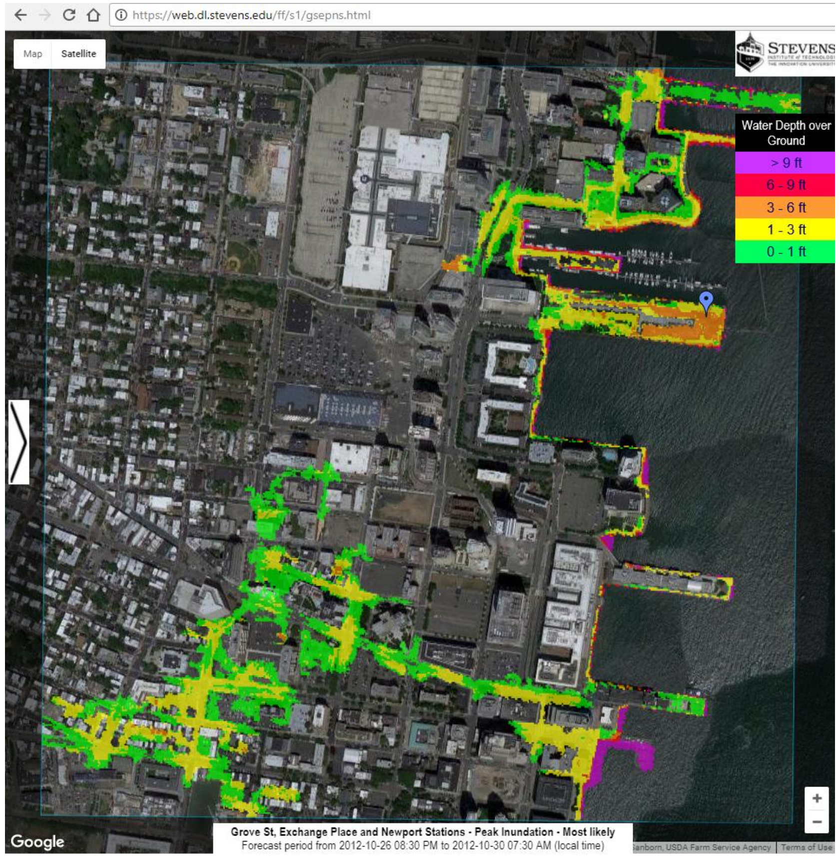


"Expect at least this much water over ground" (5^{th} percentile)

Local Street-Scale Flood Forecast Mapping

Retrospective Example: Hurricane Sandy

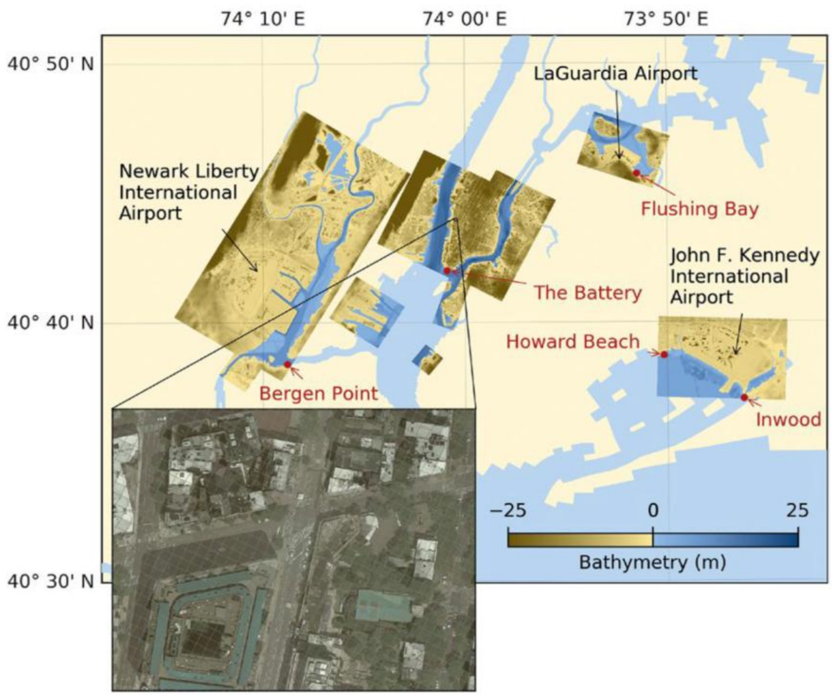


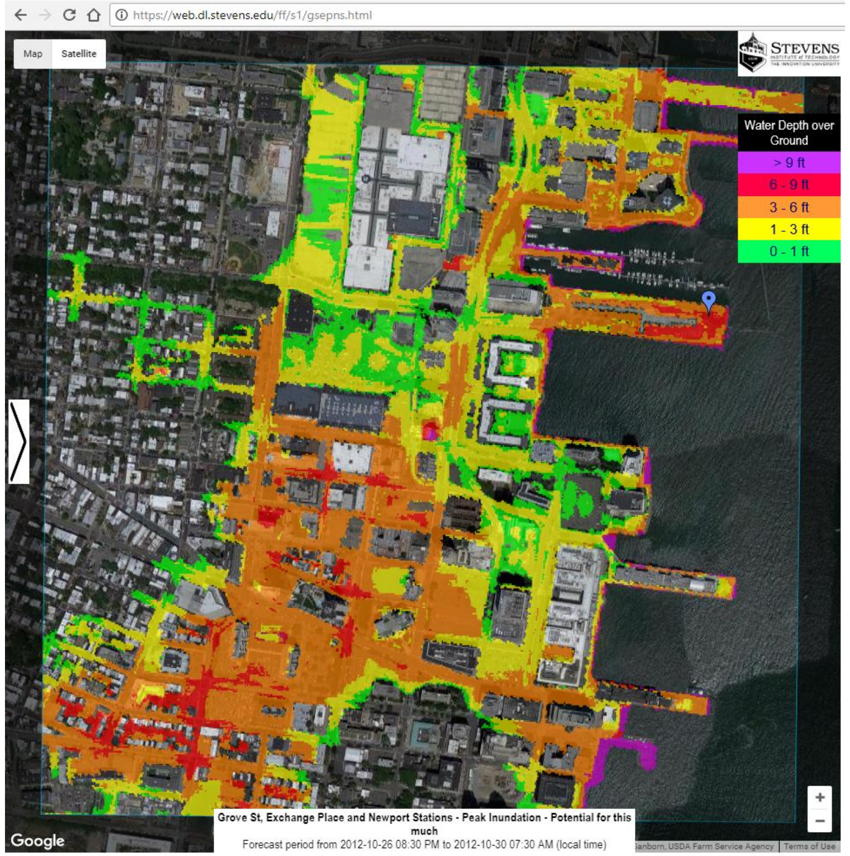


"Most likely flood depth above ground" (50th percentile)

Local Street-Scale Flood Forecast Mapping

Retrospective Example: Hurricane Sandy





"Potential for this much water over ground" (95th percentile)

Stevens Shares its Data for NWS Forecasts

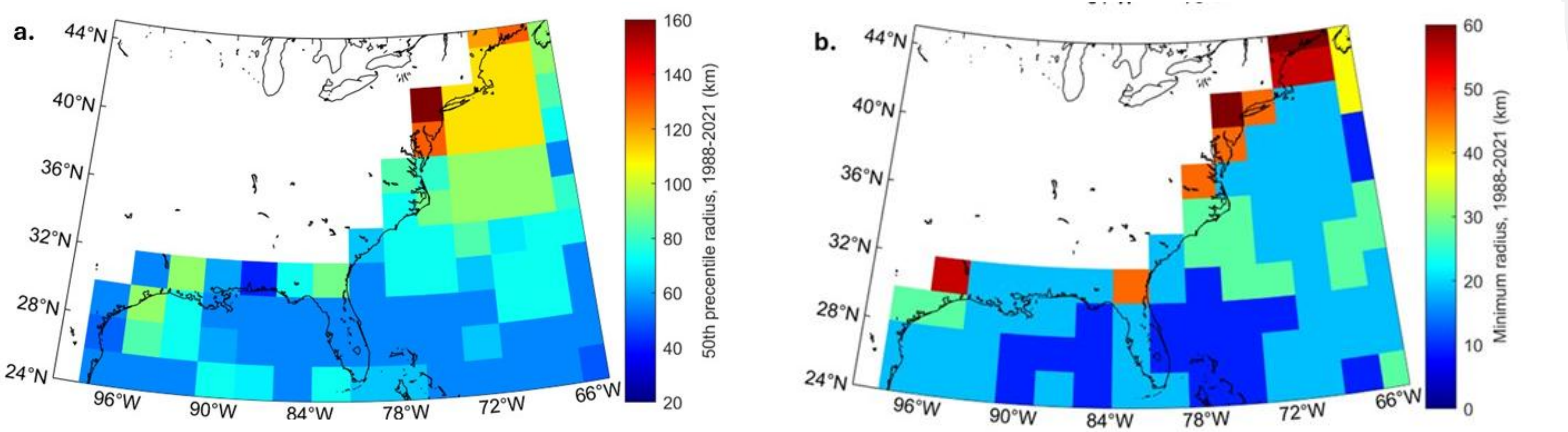
Stevens shares our SFAS data with National Weather Service Weather Forecast Offices (WFOs) from Maryland to Maine, where five different WFOs use the data to help develop their forecast guidance.

"[Stevens forecasts] have been tremendously helpful during our forecast and warning operations. Not only has this guidance helped forecasters make routine day-to-day tidal forecasts, but it also increased their confidence during [storms]." - Robert Deal, NWS WFO Mt. Holly (NJ/PA)

"The NWS New York, NY office has a rich and productive history of collaboration with Stevens Institute … SFAS is used by NWS New York, NY in real time for coastal flood forecasting and watch/warning decision making." - A. Ross Dickman, NWS WFO New York/Upton

"We rely heavily on storm surge and water level guidance produced by Stevens Institute in order to provide timely Watches and Warnings for coastal flooding events that impact the coastlines of Massachusetts and Rhode Island and provide email briefings to federal, state, and local emergency managers to provide specific flood impacts." - Joseph Dellicarpini, NWS WFO Boston

Discussion: Benefits and Challenges of Mid-Latitude Ensemble Forecast Systems



Map showing 50th percentile (panel a) and minimum (panel b) observed storm radii on a 222 km grid (2 degrees latitude). The map was created using a radius of maximum wind data from the Extended HURDAT database that began in 1988 (Demuth et al., 2006) and only includes data from when a storm center was over the ocean.