Phase-aware Statistics and their Application to Storm Surge Forecasting

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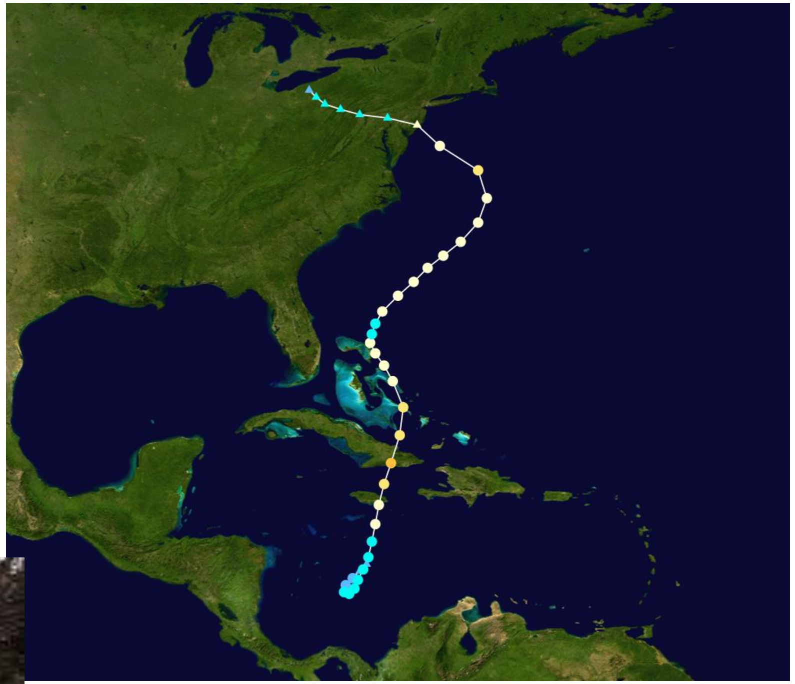
Outline

- Background material
- Phase-aware theory
- Storm surge forecasting applications

Background

Hurricane Sandy



Ensemble Forecasting

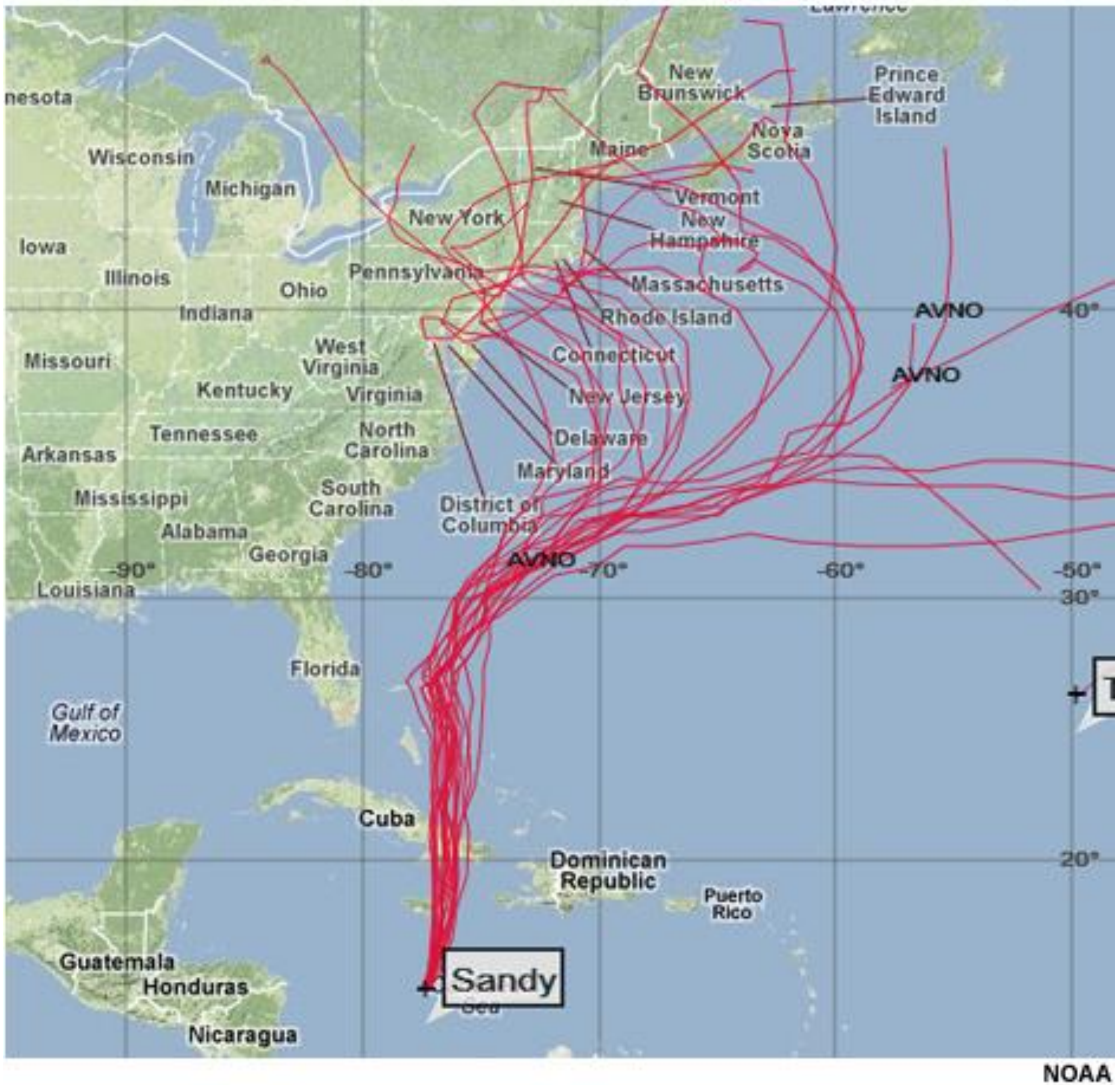
- Estimates the uncertainty of a weather forecast using multiple predictions.
- Each prediction is called an ensemble member.
- The collection of ensemble members is the sample space or ensemble system.
- The method contrasts with deterministic forecasts.
- Deterministic forecast: The forecast high is 75℉.
- Ensemble forecast: The forecast high is likely to be between 70℉ and 80℉.

Rolling a Die

- Sample Space = {1,2,3 4,5,6}
- The members of the sample space are the ensemble members.
- The ensemble members represent what could happen when the die is rolled.

Real-world Example: Hurricane Sandy

GEFS Forecast Tracks for Hurricane Sandy 00 UTC 24 Oct 2012



The Ensemble Mean

- Commonly, an ensemble mean is reported.
- The ensemble mean is the mean of all ensemble members.
- The ensemble mean suppresses the unpredictable aspects associated with the individual members.
- Forecast error is often measured relative to the ensemble mean.

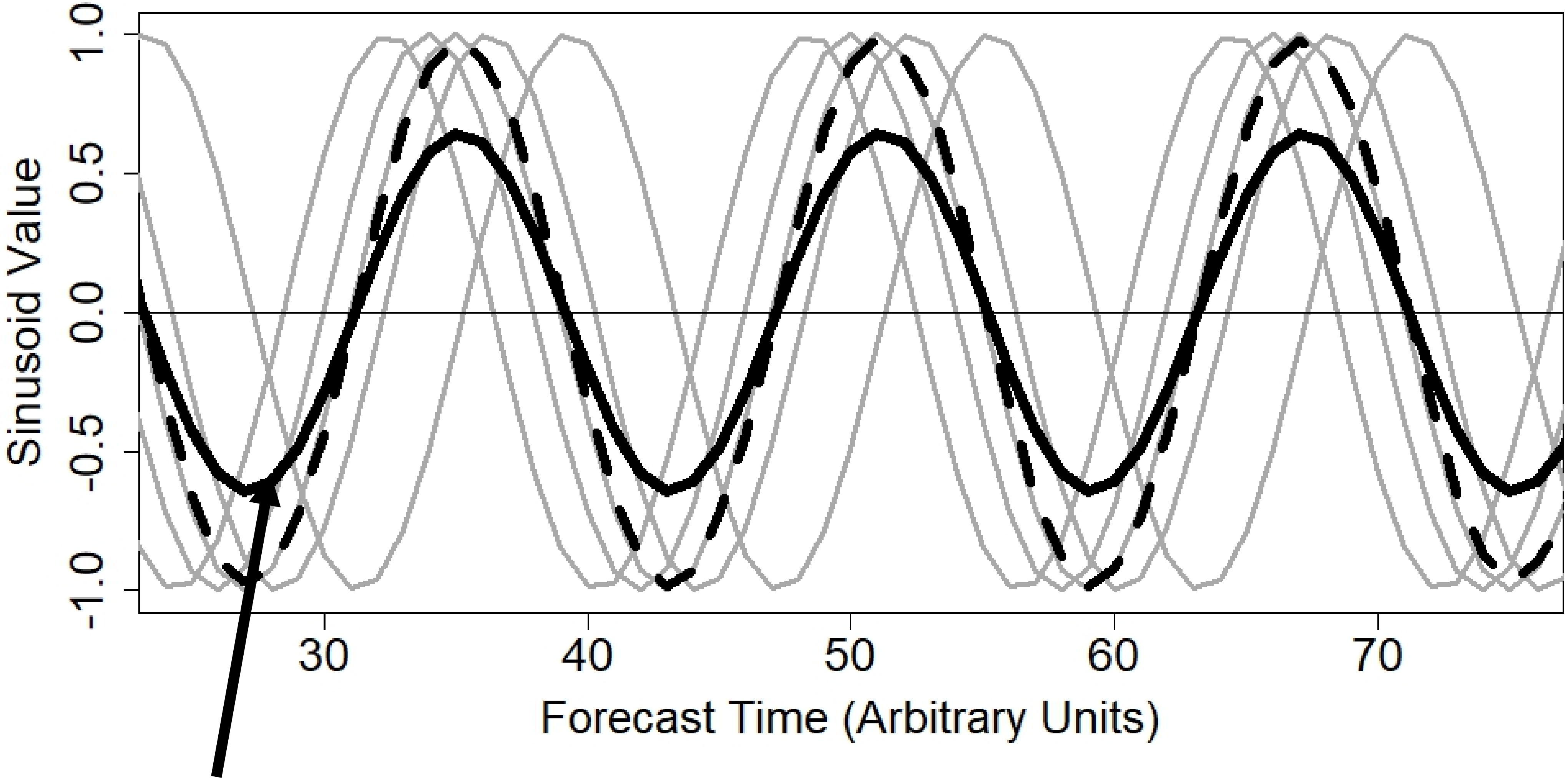
One Way of Measuring Forecast Error

- Root mean square error = $\sqrt{(ensemble\ mean\ - Observation)^2}$
- Factors contributing to forecast error:
  - Forecast uncertainty
  - Imperfect model physics
  - Initial conditions
- Research question: Is the ensemble mean the best quantity on which to base forecast error?

The sinusoid Conundrum: Experimental Set up

- Ensemble System = {sin$(\omega t + \theta_1)$, sin$(\omega t + \theta_2)$,…, sin$(\omega t + \theta_5)$}
- **Feature 1**- Each sinusoid has an amplitude equal to 1 (no intensity uncertainty).
- **Feature 2** - Phases are drawn from a normal distribution with mean 0 and standard deviation $\pi/3$ (large timing uncertainty).
- Each ensemble member is a possible outcome for the “observation.”
- The observation is an additional randomly generated sinusoid.

Sinusoidal Ensemble System



Ensemble Mean Amplitude < 1!

Key Findings

- The ensemble mean can lead to intensity error even if there is no intensity uncertainty!
- Timing differences among ensemble renders the ensemble mean unrepresentative of the ensemble system.
- Unrepresentativeness means that the ensemble mean has characteristics differing from the individual ensemble members.
- The ensemble mean flattens out as timing uncertainty increases.
- How can we remedy these drawbacks?

Phase-aware Theory

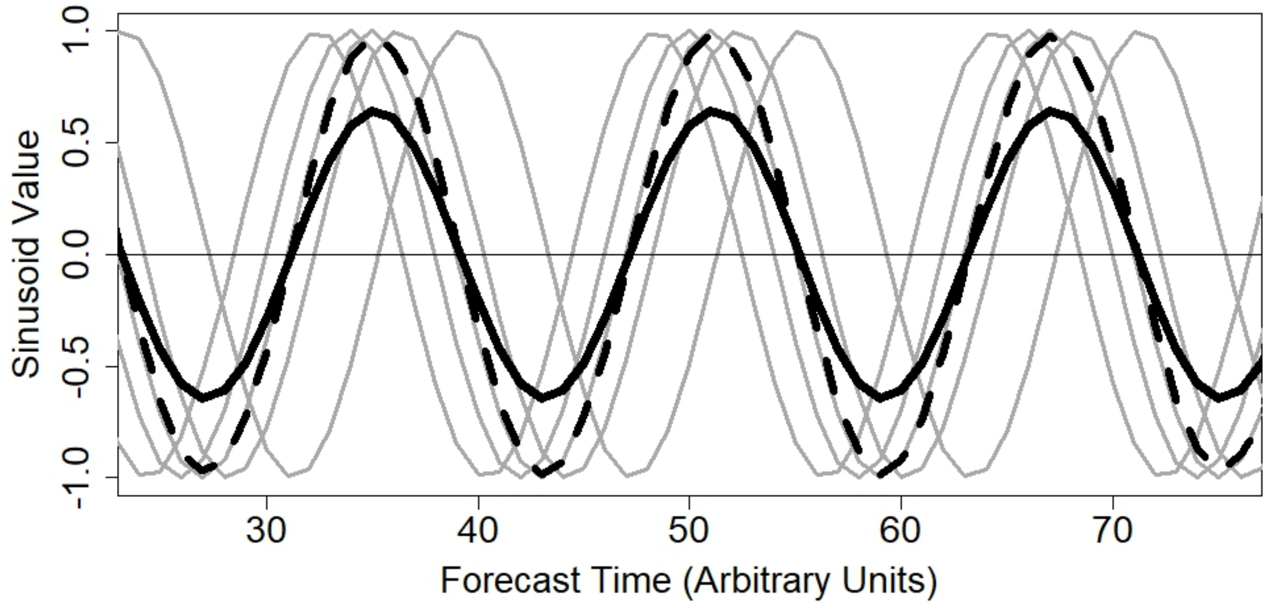
Motivation

Ensemble System = {$\sin(\omega t + \theta_1)$, $\sin(\omega t + \theta_2)$,…, $\sin(\omega t + \theta_5)$}

$$\hat{A} = \frac{A_1 + A_2 + \cdots + A_5}{5}$$

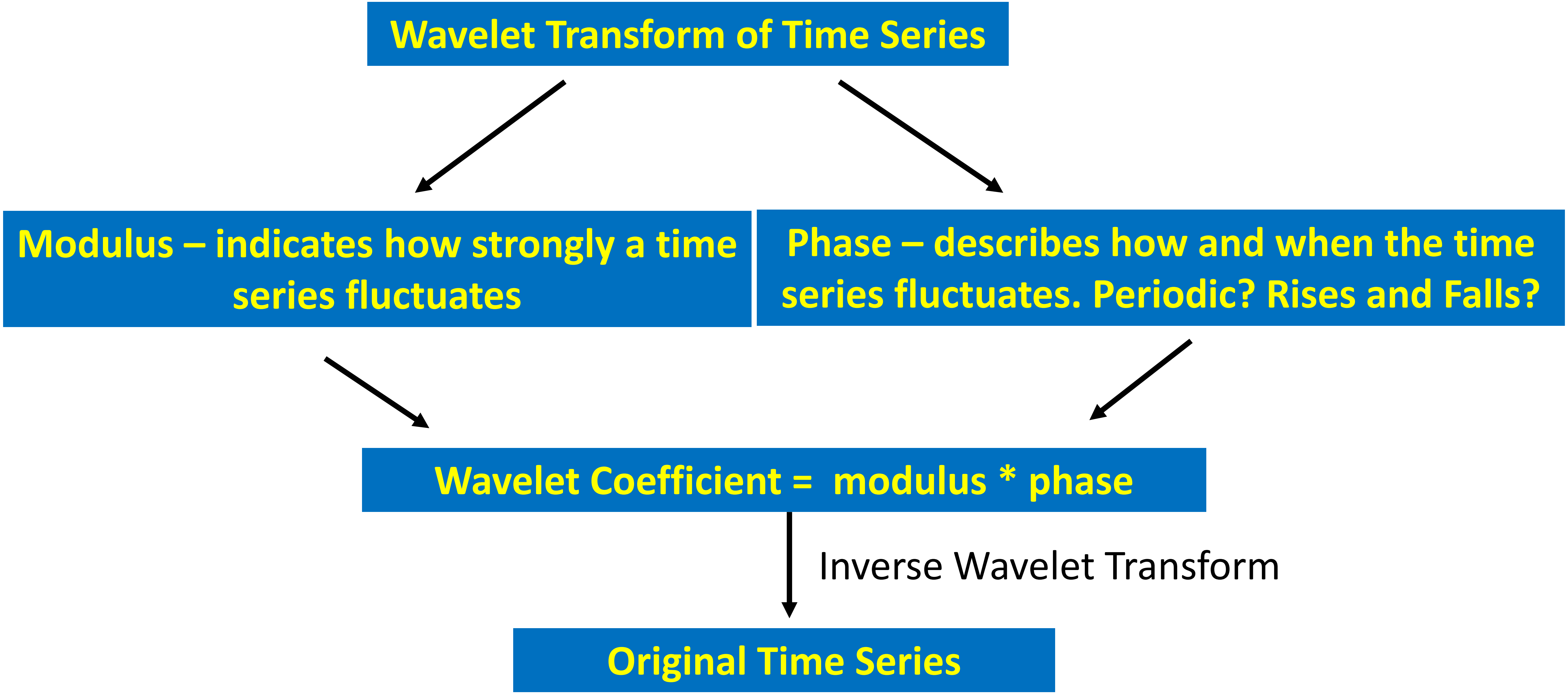
$$\hat{\theta} = \text{(circular) mean of phases}$$

$$\hat{X} = \hat{A}\sin(\omega t + \hat{\theta})$$



Research question: Can we do this procedure for arbitrary ensemble systems?

The Wavelet Transform



Phase-aware Mean: The Recipe

Step 1. Compute Wavelet Transform of each Ensemble Member

↓

Step 2. Compute Arithmetic Mean of Modulus (Intensity)

↓

Step 3. Compute Circular Mean of Phase (Timing)

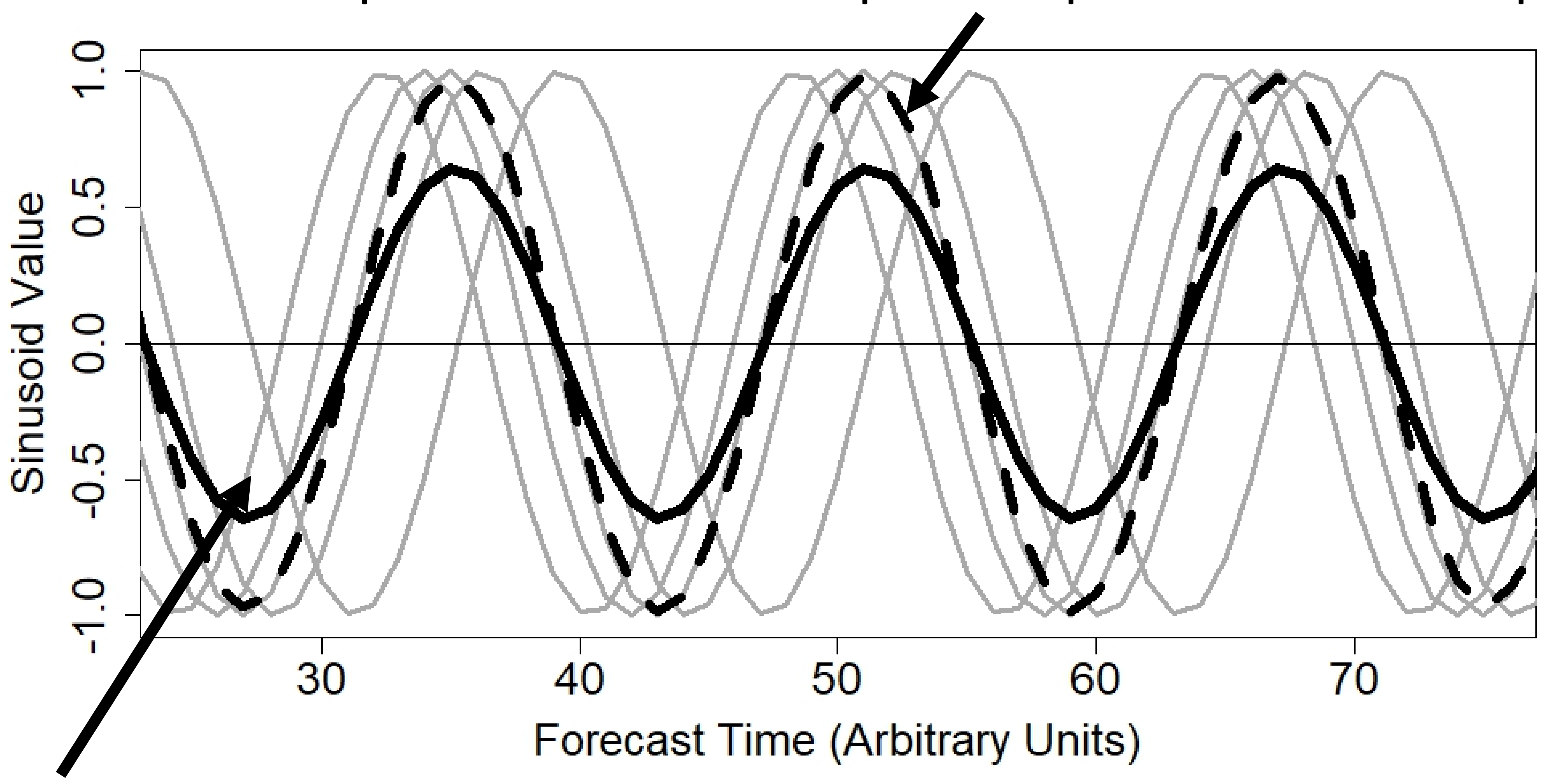
↓

Step 4. Compute Inverse Wavelet Transform of

mean wavelet coefficient = (mean modulus)*(circular mean phase)

Phase-aware mean Example

Sinusoid with amplitude = 1 and with phase equal to mean of all phases



Ensemble Mean Amplitude < 1!

Phase Aware Extensions

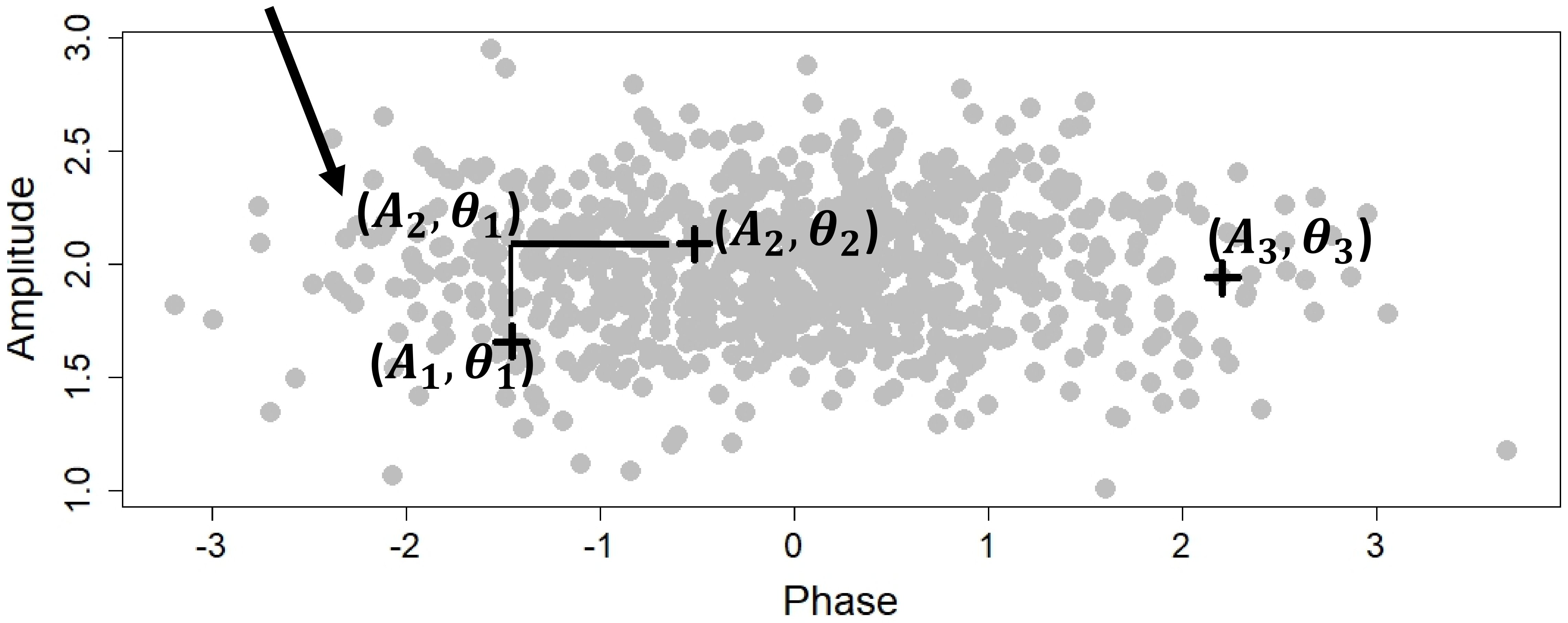
- An ensemble member can perfectly predict timing but poorly predict intensity.
- Conversely, another ensemble member can perfectly predict timing but poorly predict intensity.
- Can we create an ensemble member that perfectly predicts timing and intensity?

Phase-Aware Extensions

- Suppose our ensemble system comprises 3 sinusoids with amplitudes $A_1, A_2, \ldots, A_3$ and phases θ_1, θ_2,…, θ_3 drawn from normal distributions.
- This ensemble system assumes that one ensemble member will predict both timing (phase) and intensity (amplitude) correctly.
- Is this a good assumption?

Phase-Aware Extensions

It is possible!



Phase-Aware Extensions

$\boldsymbol{A_1 \sin(\omega t + \theta_1)}$	$A_1 \sin(\omega t + \theta_2)$	$A_1 \sin(\omega t + \theta_3)$
$A_2 \sin(\omega t + \theta_1)$	$\boldsymbol{A_2 \sin(\omega t + \theta_2)}$	$A_2 \sin(\omega t + \theta_3)$
$A_3 \sin(\omega t + \theta_1)$	$A_3 \sin(\omega t + \theta_2)$	$\boldsymbol{A_3 \sin(\omega t + \theta_3)}$

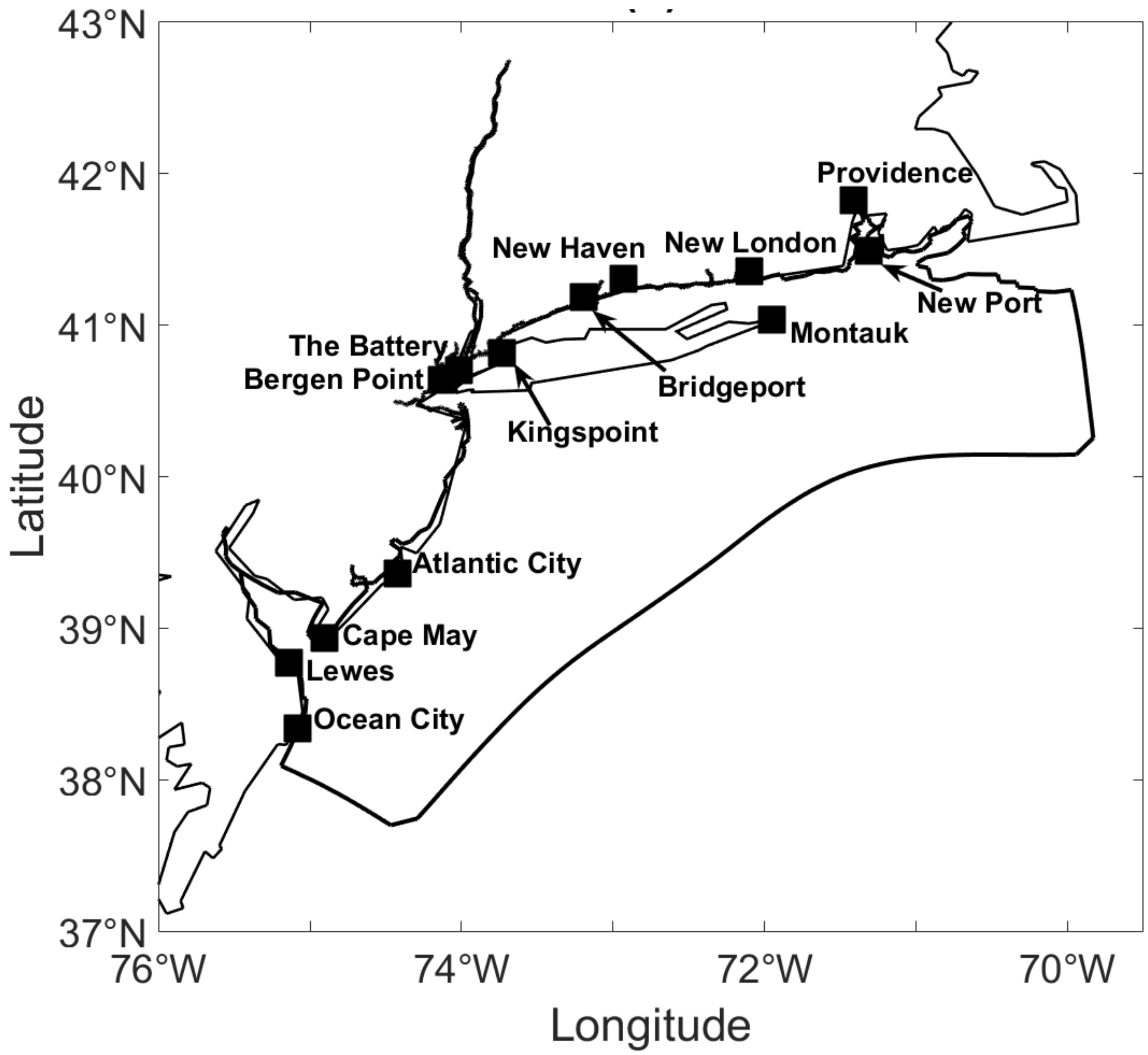
Phase-ware extension Method

1. Compute wavelet transform of each ensemble member
2. Multiply the phase spectrum of one ensemble member with the modulus spectrum of another
3. Compute the Inverse Wavelet Transform

Practical Applications to Storm Surge Forecasting

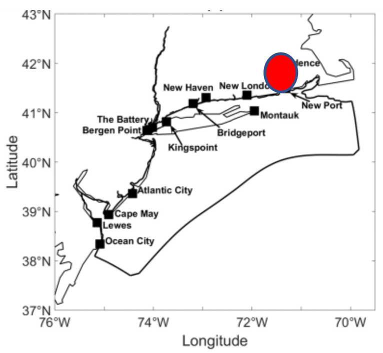
Storm Surge Forecasting Applications

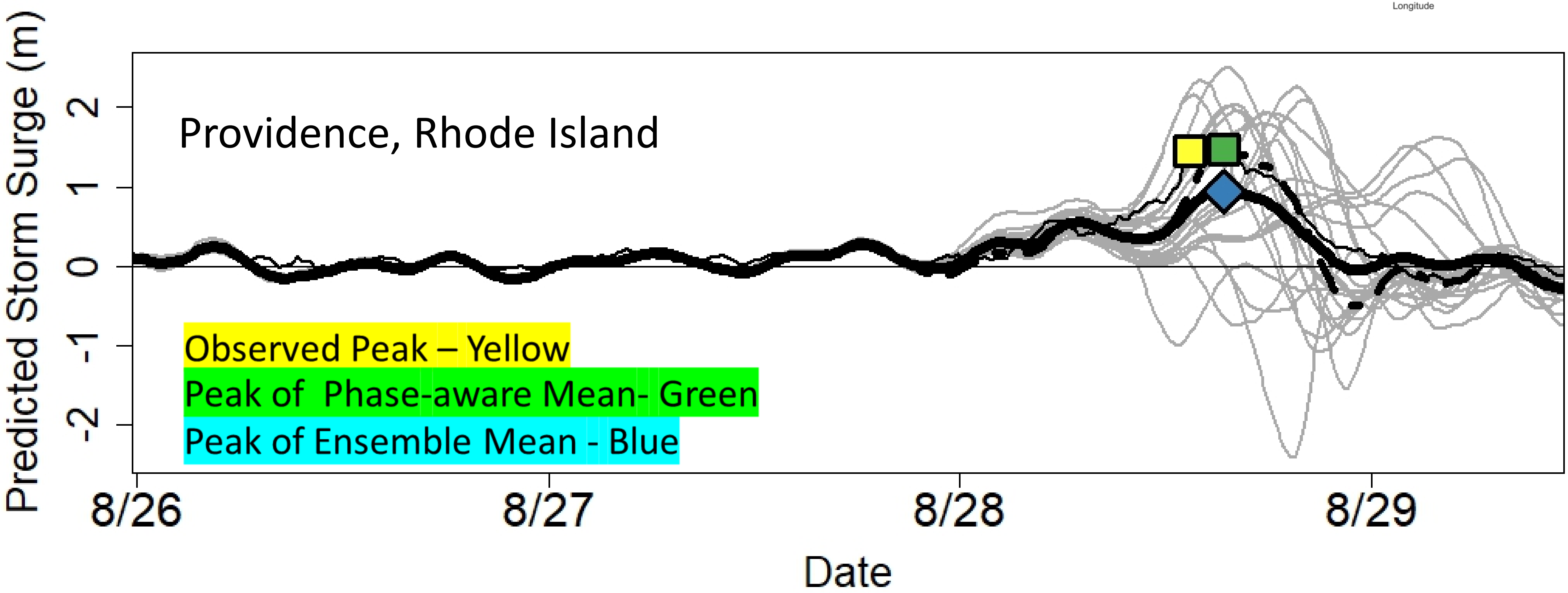
- Irene and Sandy storm surge forecasts were produced from the New York Harbor Observing and Prediction System (NYHOPS; Georgas, et al., 2016) model.
- The forecasts were issued three days out from the storm events.
- There were 21 ensemble members for each forecast.
- Meteorological forcing was provided from the GEFS Model.
- The performance of the ensemble and phase-aware means were compared across 13 stations.



43°N
42°N
41°N
40°N
39°N
38°N
37°N
Latitude
76°W
74°W
72°W
70°W
Longitude
Providence
New Haven
New London
New Port
Montauk
The Battery
Bergen Point
Bridgeport
Kingspoint
Atlantic City
Cape May
Lewes
Ocean City

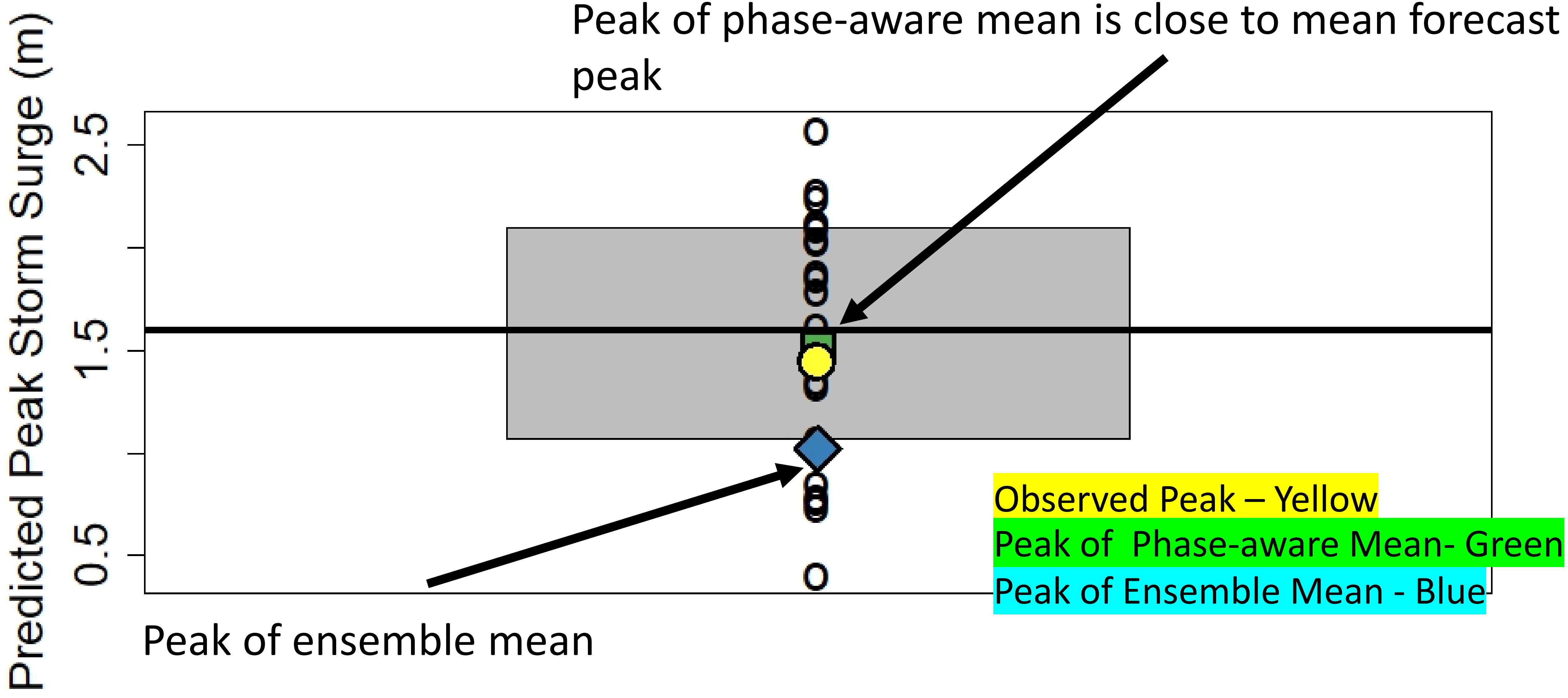
Hurricane Irene Storm Surge Forecast





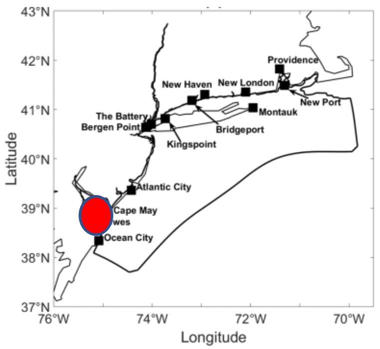
Irene Storm Surge Forecast - Providence

Peak of phase-aware mean is close to mean forecast peak



Peak of ensemble mean

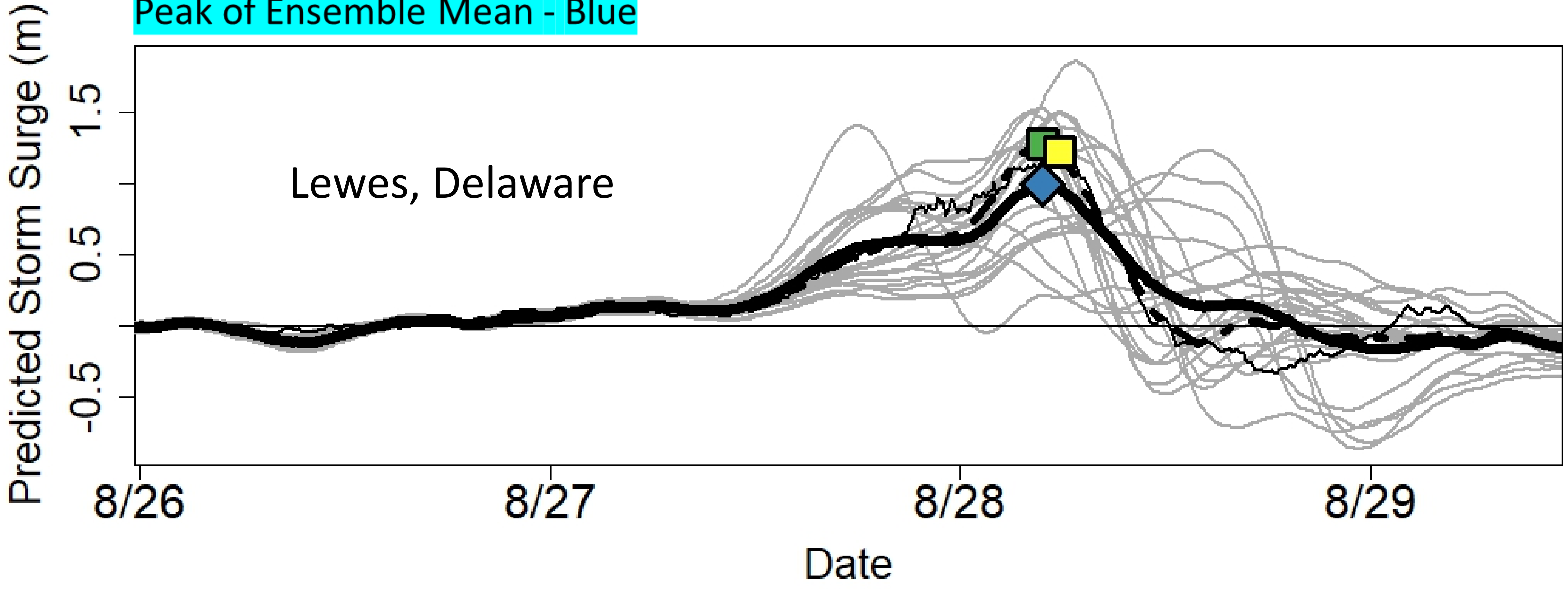
Hurricane Irene Storm Surge Forecast



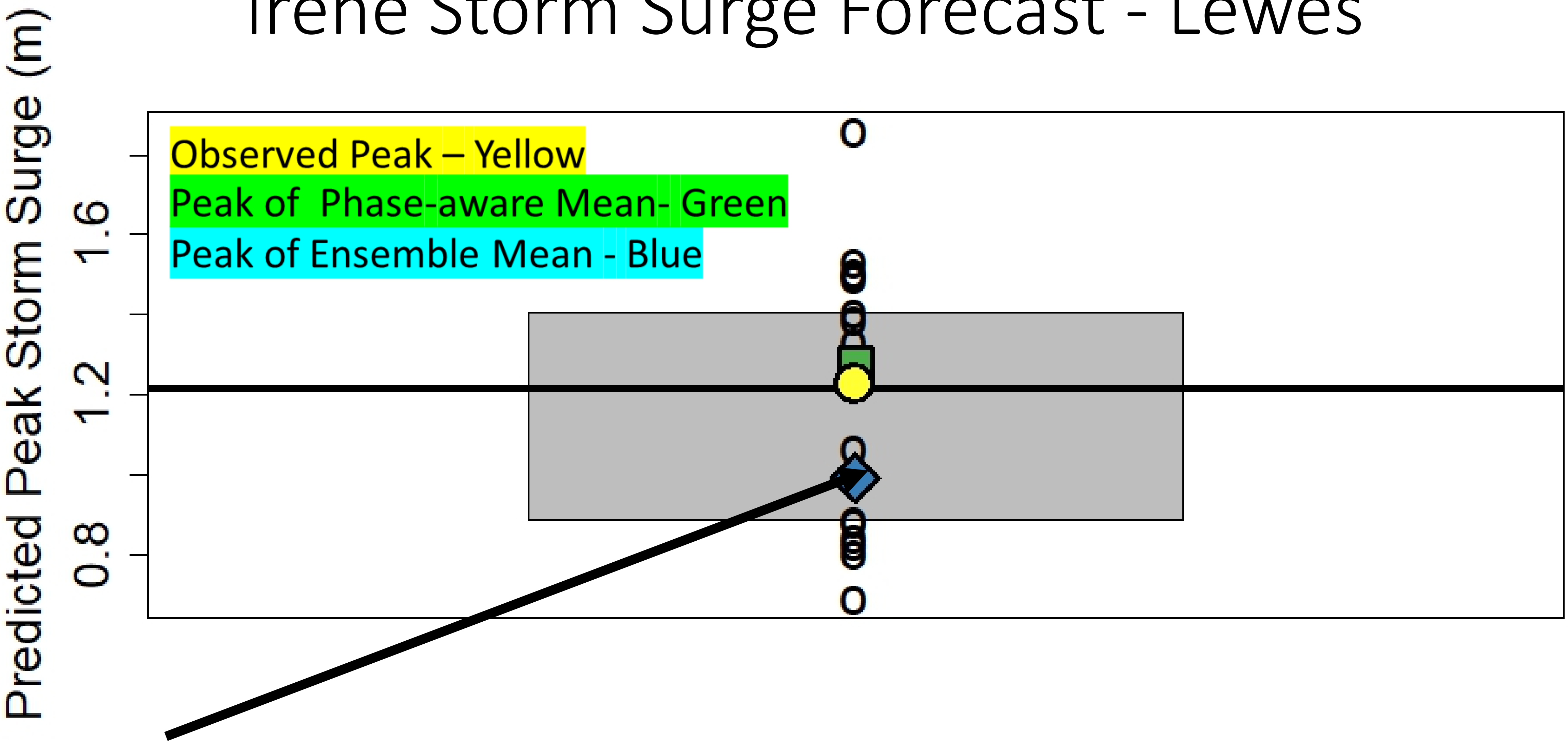
Observed Peak – Yellow

Peak of Phase-aware Mean- Green

Peak of Ensemble Mean - Blue

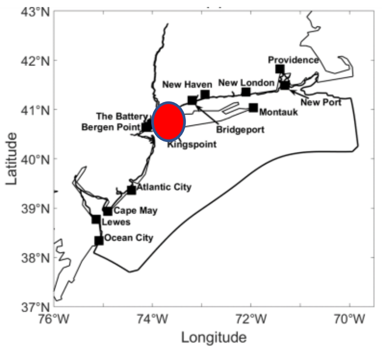


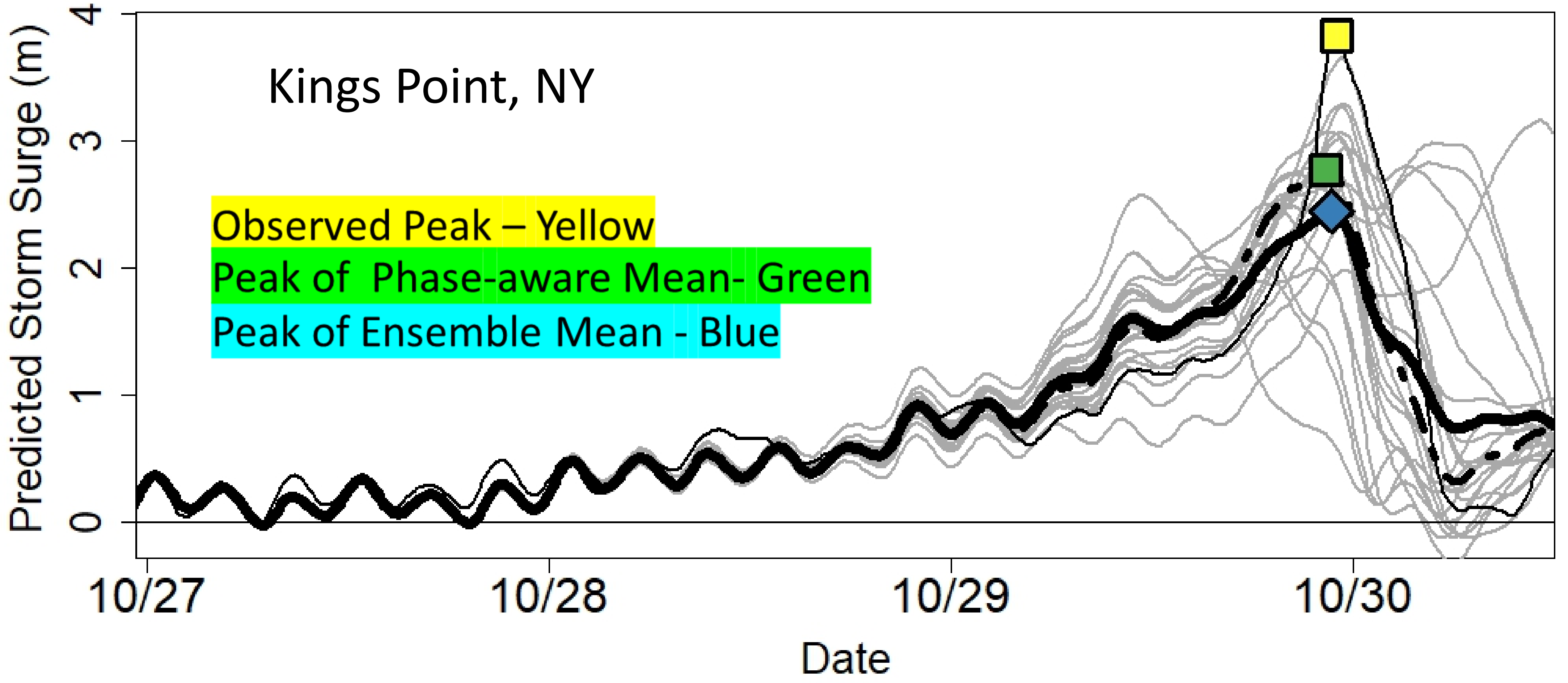
Irene Storm Surge Forecast - Lewes



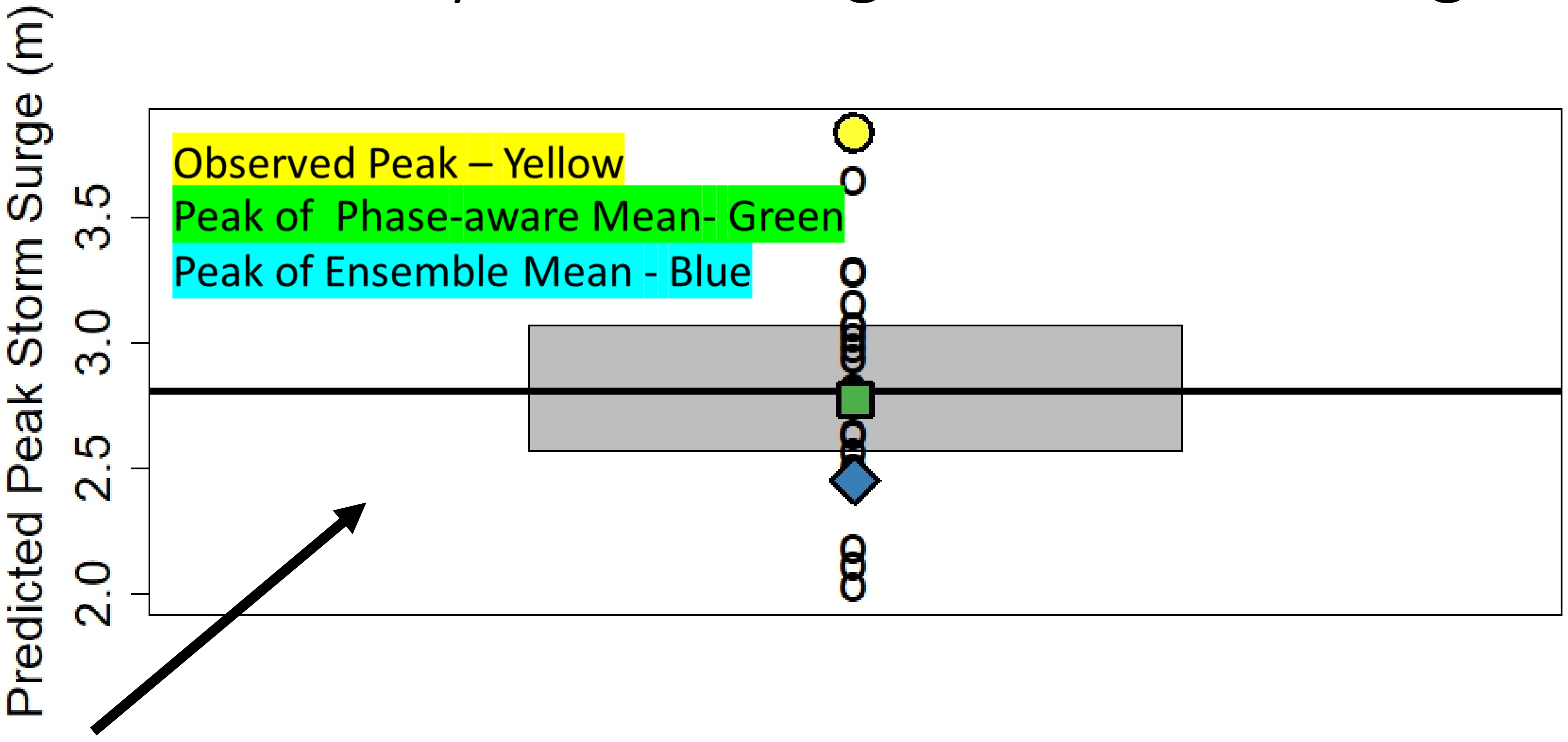
Peak of Ensemble Mean

Hurricane Sandy Storm Surge Forecast



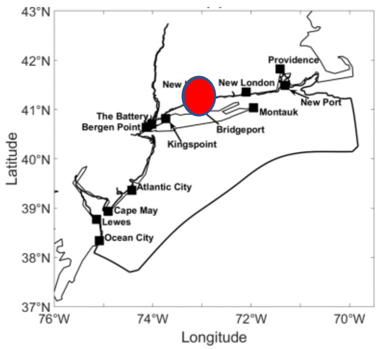


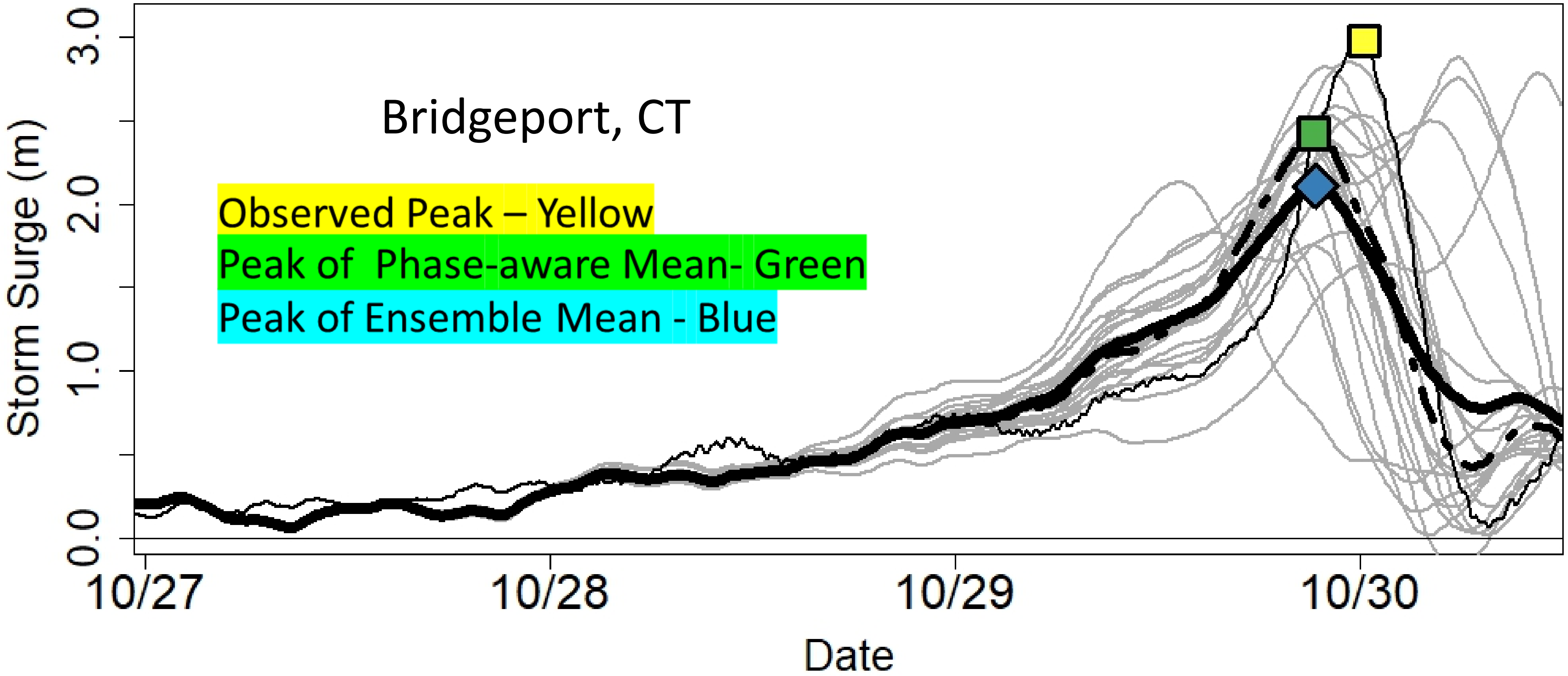
Hurricane Sandy Storm Surge Forecast – Kings Point



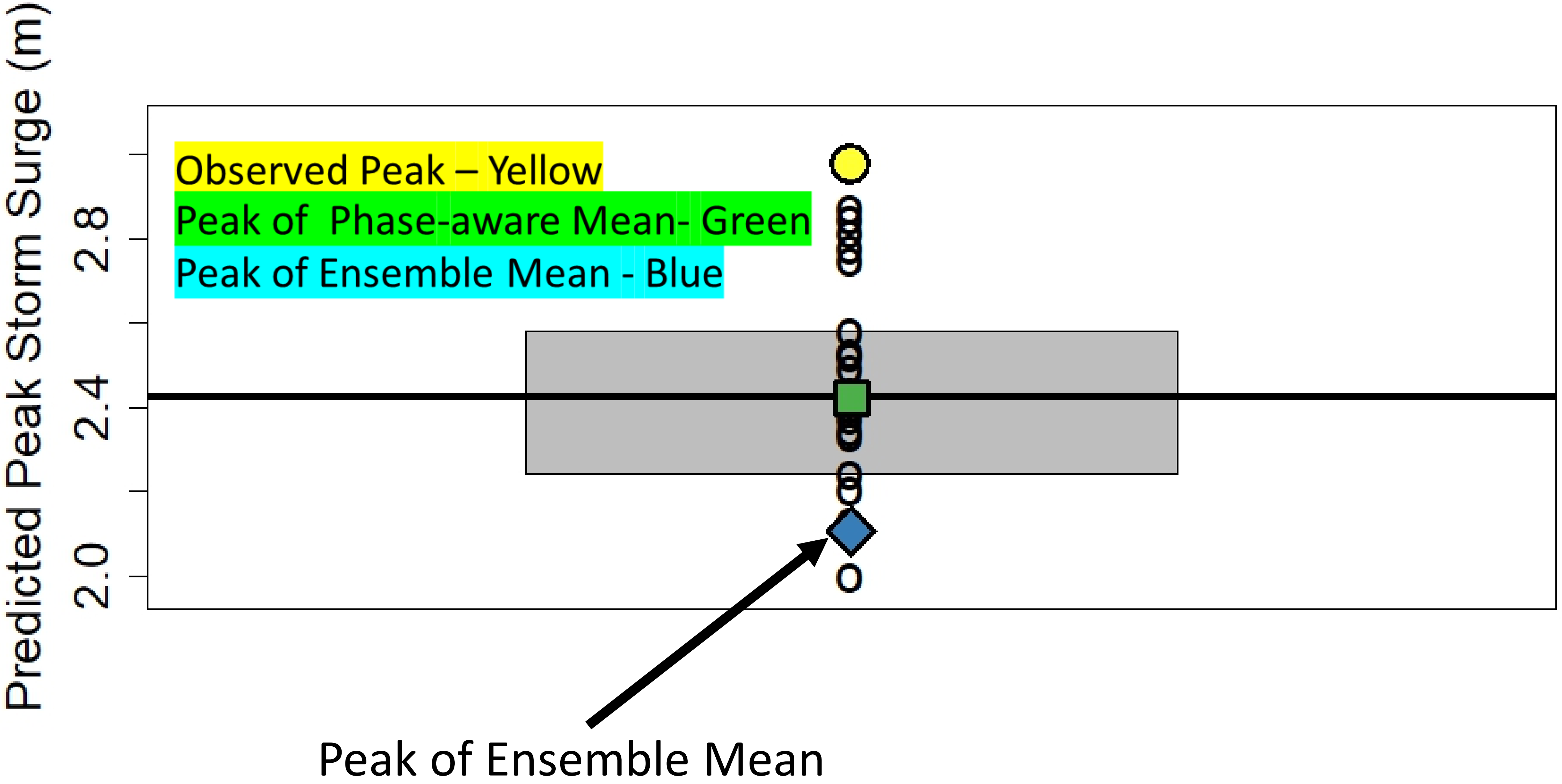
Ensemble Mean Peak

Hurricane Sandy Storm Surge Forecast

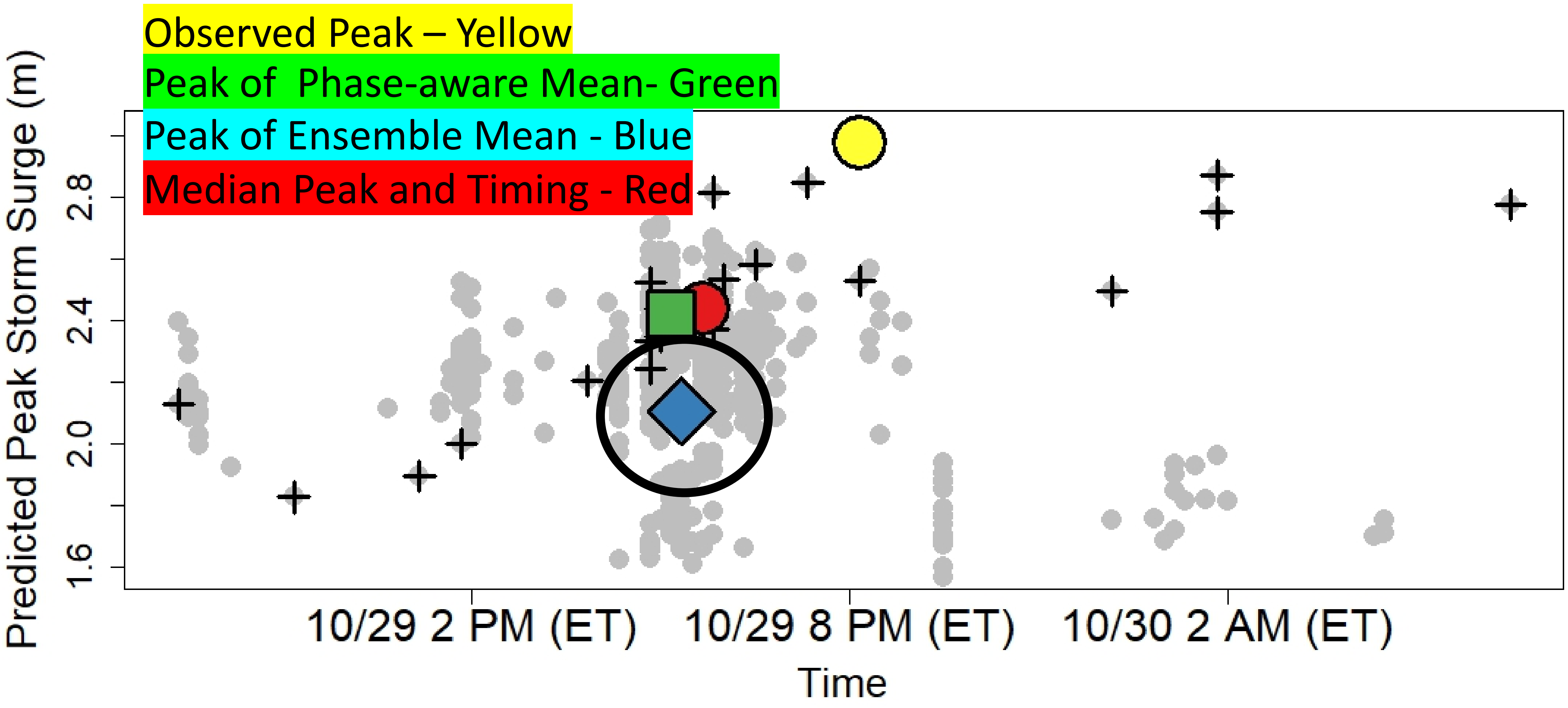




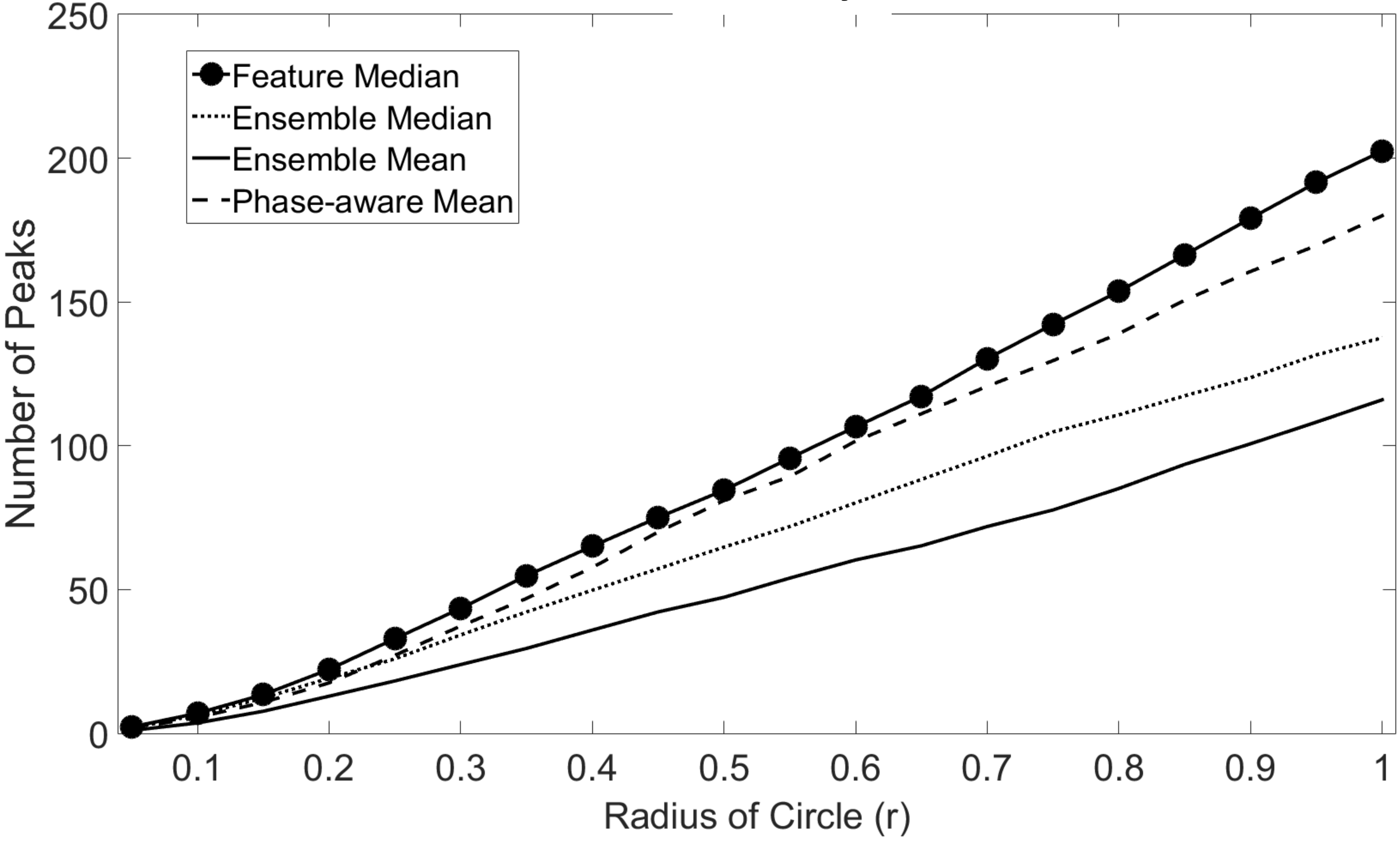
Sandy Storm Surge Forecast - Bridgeport



Sandy Storm Surge Forecast - Bridgeport

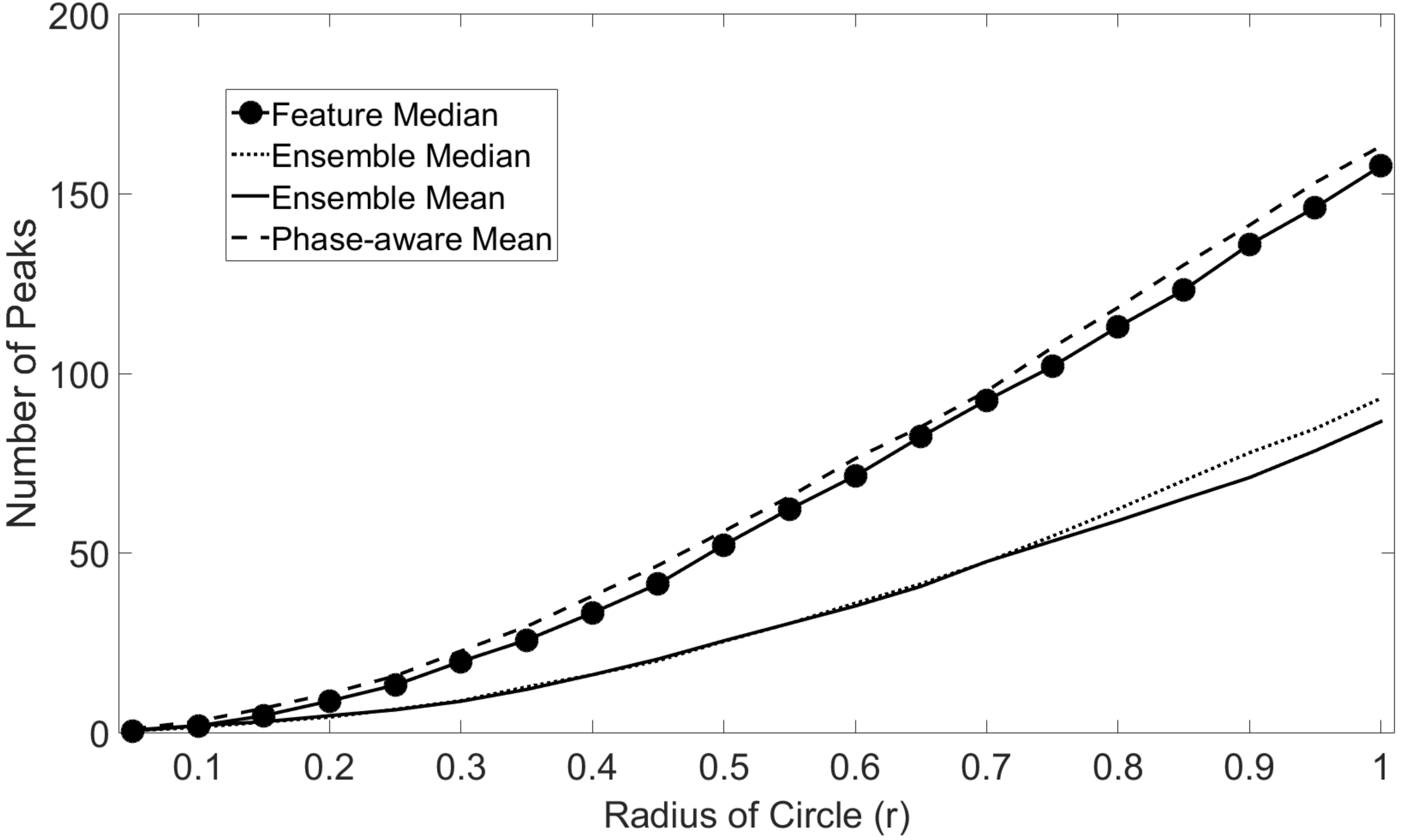


Sandy



Feature Median
Ensemble Median
Ensemble Mean
Phase-aware Mean
Number of Peaks
Radius of Circle (r)
0
50
100
150
200
250
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

Irene



Feature Median
Ensemble Median
Ensemble Mean
Phase-aware Mean
Number of Peaks
200
150
100
50
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Radius of Circle (r)

Summary

- Timing differences among ensemble members renders the ensemble mean unrepresentative of the ensemble system.
- The amplitude of the ensemble mean can be less than that of any of the individual ensemble members.
- Phase-aware mean remedies several drawbacks of the ensemble mean.
- The number of ensemble members can be increased using a phase-aware extension method.
- Storm surge applications support the results from the theoretical experiments.

Future Research Directions

- Pseudo-reanalysis data sets
- Monte Carlo methods
- Multi-model ensemble systems
- Composite analyses

References

- Schulte, J.A and Georgas, N.: Theory and Practice of Phase-aware Ensemble Forecasting, Quarterly Journal of Royal Meteorological Society,144, 2018.
- Georgas, N., Yin, L., Jiang, Y., Wang, Y., Howell, P., Saba, V., Schulte, J A., Orton, P., Wen, B. An Open-Access, Multi-Decadal, Three-Dimensional, Hydrodynamic Hindcast Dataset for the Long Island Sound and New York/New Jersey Harbor Estuaries. J. Mar. Sci. Eng., 4, 48, 2016.

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