Theory and Practice of Phase-aware Ensemble Forecasting

Justin Schulte (jschulte@stevens.edu) and Nickitas Georgas (ngeorgas@stevens.edu)
Davidson Laboratory, Stevens Institute of Technology, Hoboken, New Jersey

Introduction

- The Ensemble Mean is often adopted as the best available estimate of the future behavior of some physical quantity.
- The spread around the ensemble mean indicates the uncertainty around the ensemble mean.
- In storm surge forecasts there are two uncertainty sources of interest: timing and intensity of events.
- Even if the intensity of an event were to be perfectly forecast, timing uncertainty can lead to large root-mean-square errors for the ensemble mean around storm surge peaks, as the mean filters out the peaks.
- It is therefore important to develop statistics that operate on the timing statistics separately from the intensity statistics.

Data

- Stevens Institute of Technology has developed a regional storm surge ensemble forecasting system (www.stevens.edu/SFAS) that is based on the evaluated and operational New York Harbor Observation Prediction System (NYHOPS).
- The model is a three-dimensional hydrodynamic model covering the Mid-Atlantic Bight and its estuaries.
- 21 NYHOPS retrospective storm surge ensemble members for TC Irene were forced with meteorological inputs derived from 21 ensemble members of the Global Ensemble Forecast System (GEFS/R).

Definitions

- Let $X_1(t), X_2(t) \ldots, X_N(t)$ be N ensemble members.
- One can compute the wavelet transform of each $X_k(t)$.
- The wavelet transform of each $X_k(t)$ is given by

$$W_k(s,t) = R_k(s,t)e^{i\varphi_k(s,t)}$$

- The $\varphi_k(s,t)$ describe the phase of the ensemble members at each wavelet scale (similar to Fourier period) and are related to the timing of the ensemble members.
- The $R_k(s,t) = |W_k(s,t)|$ are related to the intensity of the fluctuations at each Fourier period. Larger $R_k(s,t)$ means larger fluctuations.
- The *phase-aware mean* is defined by

$$\widehat{W}(s,t) \equiv \hat{R}e^{i\hat{\varphi}}$$

Arithmetic mean modulus at each time and wavelet scale (mean intensity of event)

Circular mean phase at each time and wavelet scale (mean timing of event)

Inverse wavelet transform is then used to convert the spectral mean to a physical time series

$$\widehat{X(t)} = phase-aware\ mean\ time\ series$$

- *Phase-aware uncertainty bounds* can be obtained by replacing the mean modulus by, say, the 95th and 2.5th percentiles of the N modulus spectra and then computing the inverse wavelet transform.
- Further, one can create a new (extended) ensemble member representing an additional possible outcome using the following:

$$W_{ij}(s,t) = R_i(s,t)e^{i\varphi_j(s,t)}$$

- Intuitively, the above equation mixes the intensity of one ensemble member with the phase of another ensemble member.
- The extended N^2ensemble members are obtained by taking the inverse wavelet transform of the $W_{ij}(s,t)$
- This statistical extension allows for extended physical solutions, as one original ensemble member can predict the intensity well but the timing poorly, while another ensemble member can poorly predict the intensity but perfectly predict the timing.

Phase-aware Mean Results

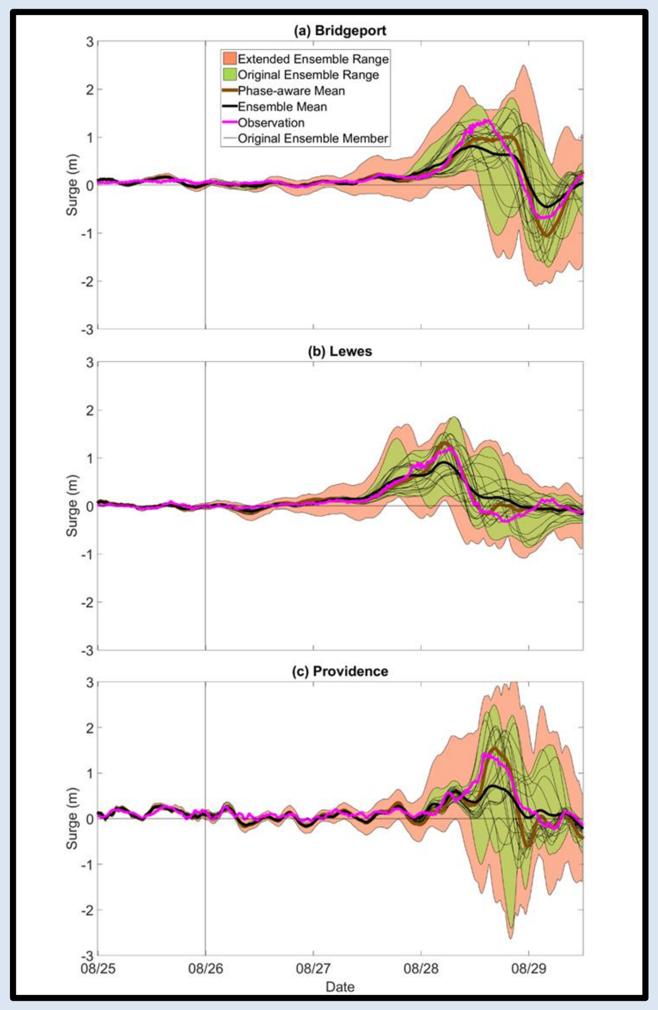

Figure 1. TC Irene storm surge reforecasts for (a) Bridgeport, Connecticut, (b) Lewes, Delaware, and (c) Providence, Rhode Island initialized on August, 26 2011 0 UTC. Thin black curves represent the original 21 NYHOPS ensemble member predictions generated with the 21 GEFS/R meteorological forcings. Green shading represents the original ensemble range (across-member max and min at any given time) and orange shading is the extended ensemble range. The phase-aware mean (brown), ensemble mean (black), and the verifying observation (magenta) are also shown.

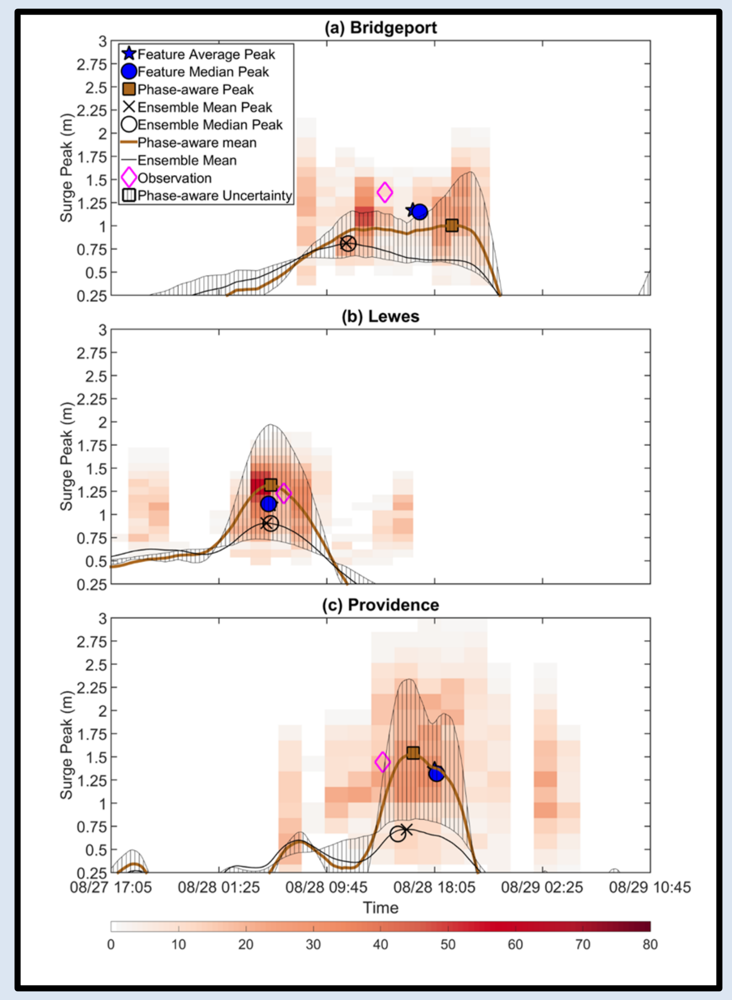

Figure 2. Bivariate histograms of storm surge peaks corresponding to the TC Irene storm surge reforecasts for (a) Bridgeport, (b) Lewes, and (c) Providence shown in Figure 1. The histograms were obtained by computing the global maxima and timing of global maxima for each (extended) ensemble member and then binning the data. Markers denote locations of the peaks for various ensemble metrics and the verifying observation. The Feature Median is defined as the median of the global maxima and the timing of the global maxima. The Feature Average is defined similarly. Hatched regions denote the 95% phase-aware uncertainty intervals.

Key Findings

- The ensemble mean and median are underestimates of the most probable peak in the presence of timing uncertainty.
- The underestimation can be large. For example, for Providence it was 0.75m (see Figure 2c).
- The phase-aware mean often falls on the center of masses of the bivariate peak distributions (Figure 2).
- The (peak) feature median and means are sensitive to distributional bimodality (see Figure 2a).
- Phase-aware uncertainty intervals better represent the uncertainty in peak intensity than traditional 95% uncertainty intervals that are based on percentiles.
- The method's performance was evaluated for 4 other storms: TC Sandy, Hermine, Joaquin, and ETC Jonas. Similar results were identified.

Extended Ensemble Results

- Differences between the original and extended ensemble ranges have been included in Figure 1 above. An example of the outcome of the ensemble extension procedure for the Bridgeport reforecast (Figure 1a) is shown in Figure 3.

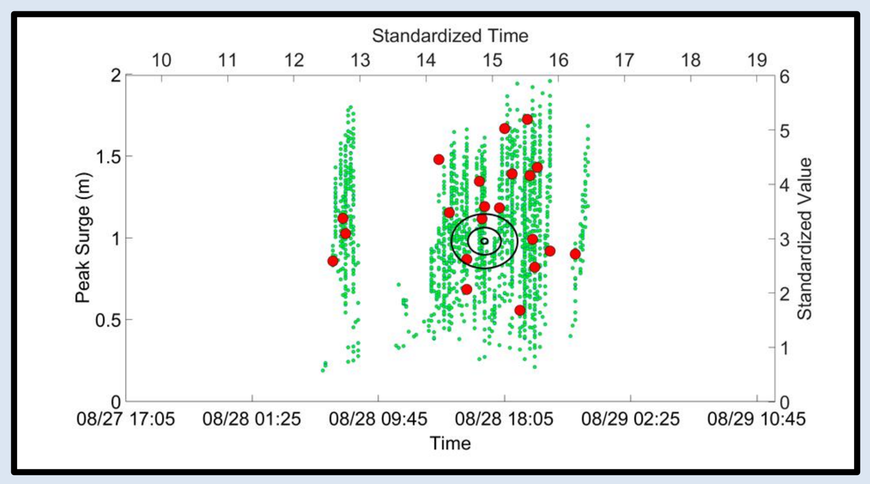

Figure 3. Example of an extended forecast. Green dots are the timing and values of peak storm surge after creating the extended ensemble. Red dots indicate locations of original ensemble members peaks.

Key Findings

- The extended ensemble is better dispersed than the original ensemble.
- The better dispersion was verified using rank histograms (not shown).
- The ensemble range after the generation of extended ensemble members is larger than that of the original ensemble during the forecast event period (see Figure 1).

Conclusions

- A phase-aware ensemble mean was introduced to remedy the problem that the traditional ensemble mean is an underestimation of the most probable peak surge from a numerical model-derived ensemble.
- Practical applications of the phase-aware methodology showed that the phase-aware mean falls more closely to the center of masses of joint distributions representing peak surge intensity and timing than the ensemble mean and median.
- Using wavelet analysis, one can create at least N^2 statistical ensemble members from an original set of N numerical model-derived ones, extending the ensemble range.
- The result of creating N^2 ensemble members is a better-dispersed ensemble obtained without having to run more computationally expensive numerical models.

Acknowledgments and Invitation to Next Meeting

This work was partially funded by a research task agreement entered between the Trustees of the Stevens Institute of Technology and the Port Authority of New York and New Jersey.

Join us in Seattle at AMS 2017, for a presentation and more on the Phase-Aware method. Talk J3.6, Tuesday, 24 January 2017.