National Weather Service (NWS) Hydrologic Ensemble Forecast Service

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National River Forecast Services Leader

NWS Partners Meeting July 2016

Outline

- Impetus for Hydrologic Ensemble Forecasts
- Concept and Design
- Implementation Status
- New Products and Services
- Future Efforts

Why use hydrologic ensemble forecasts?

National Research Council, 2006

"All prediction is inherently uncertain and effective communication of uncertainty information in weather, seasonal climate, and hydrological forecasts benefits users' decisions. These uncertainties generally increase with forecast lead time and vary with weather situation and location. *Uncertainty is thus a fundamental characteristic of weather, seasonal climate, and hydrological prediction, and no forecast is complete without a description of its uncertainty.*" [emphasis added]

COMPLETING THE FORECAST

Characterizing and communicating Uncertainty for Better Decisions Using Weather and Climate Forecasts

Committee on Estimating and Communicating Uncertainty in Weather and Climate Forecasts

Board on Atmospheric Sciences and Climate

Division on Earth and Life Studies

NATIONAL RESEARCH COUNCIL OF THE NATIONAL ACADEMIES

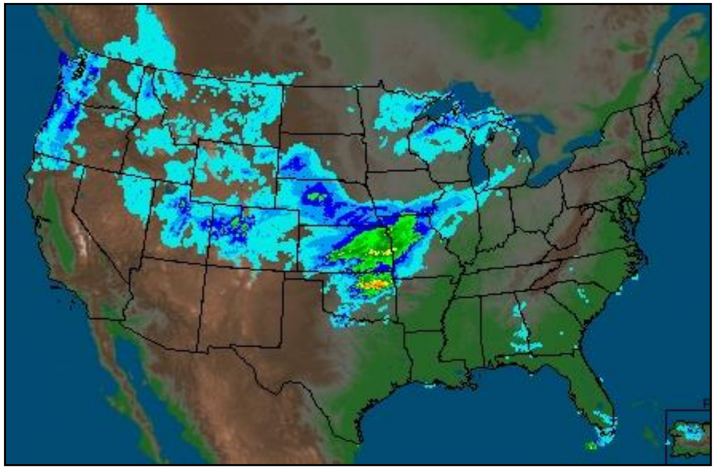
THE NATIONAL ACADEMIES PRESS
Washington, D.C.
www.nap.edu

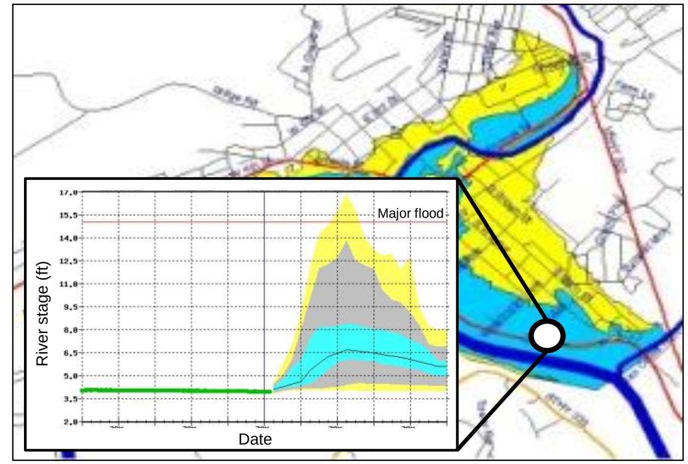
Why use hydrologic ensemble forecasts?

- Consistent feedback from customers and research community
    - 2006 National Research Counsel (NRC) report
    - 2008 Customer Feedback Insights (CFI) survey
    - River Basin Commission Stakeholder Engagements and Regional Water Conversations
- Aptima study (human centered engineering) validated need for water managers
- Multiple Internal NWS Service Assessments
    - Red River Floods in 1997 and 2009
    - Central U.S. Floods in 2008
    - Nashville Flooding in 2010

Why use hydrologic ensemble forecasts?

Goal: capture skill in weather ensembles

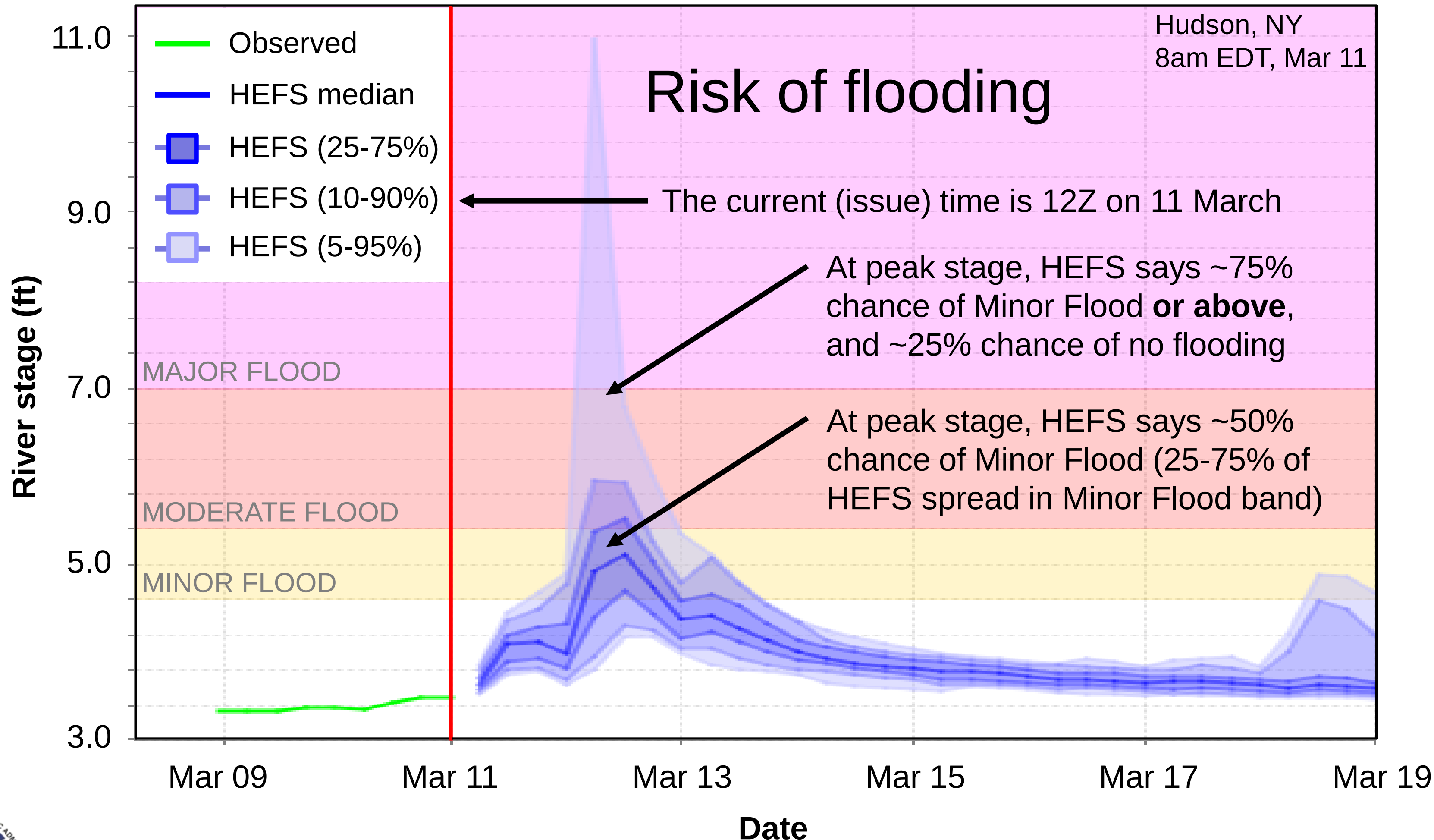




- Ensembles are standard in weather forecasting
- Include single models and "multi-model" ensembles
- Essential that water forecasts capture this information
- <u>But</u>, problematic to use them directly: wrong scale, biases

Why use hydrologic ensemble forecasts?

Goal: better-informed water decisions



Why use hydrologic ensemble forecasts?

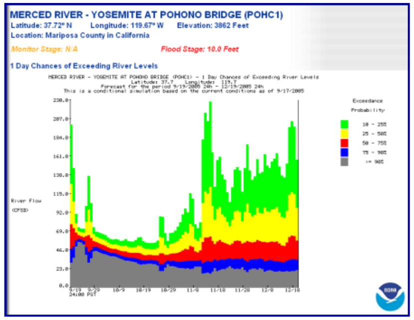
Goal: improve NWS hydrologic services

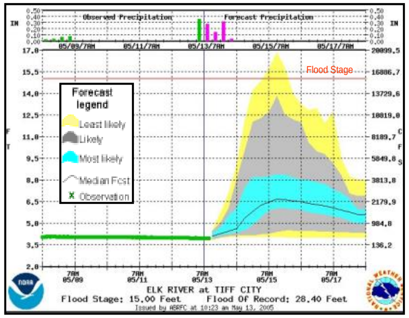
Feature	ESP (old service)	HEFS (new service)
Forecast time horizon	Weeks to seasons	Hours to years, depending on the input forecasts
Input forecasts ("forcing")	Historical climate data (i.e. weather observations) with some variations between RFCs	Short-, medium- and long-range weather forecasts
Uncertainty modeling	Climate-based. No accounting for hydrologic uncertainty or bias. Suitable for long-range forecasting only	Captures total uncertainty and corrects for biases in forcing and flow at all forecast lead times
Products	Limited number of graphical products (focused on long-range) and verification	A wide array of data and user-tailored products are planned, including standard verification

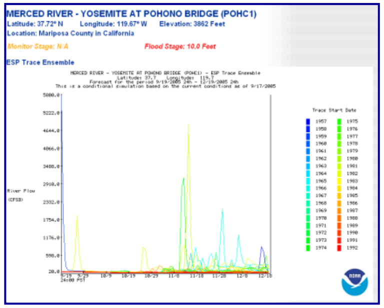
HEFS Service Level Objectives

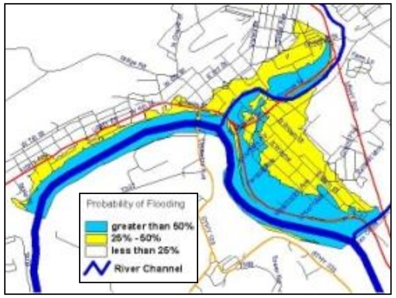
Produce ensemble streamflow forecasts that:

- seamlessly span lead times from one hour to one year
- statistically calibrated (unbiased with reliable spread)
- consistent across time and space
- effectively capture information in NWS weather/climate models
- dependable (consistent with retrospective forecasts)
- adequately verified
- aid user's decisions (compatible with Decision Support Systems)



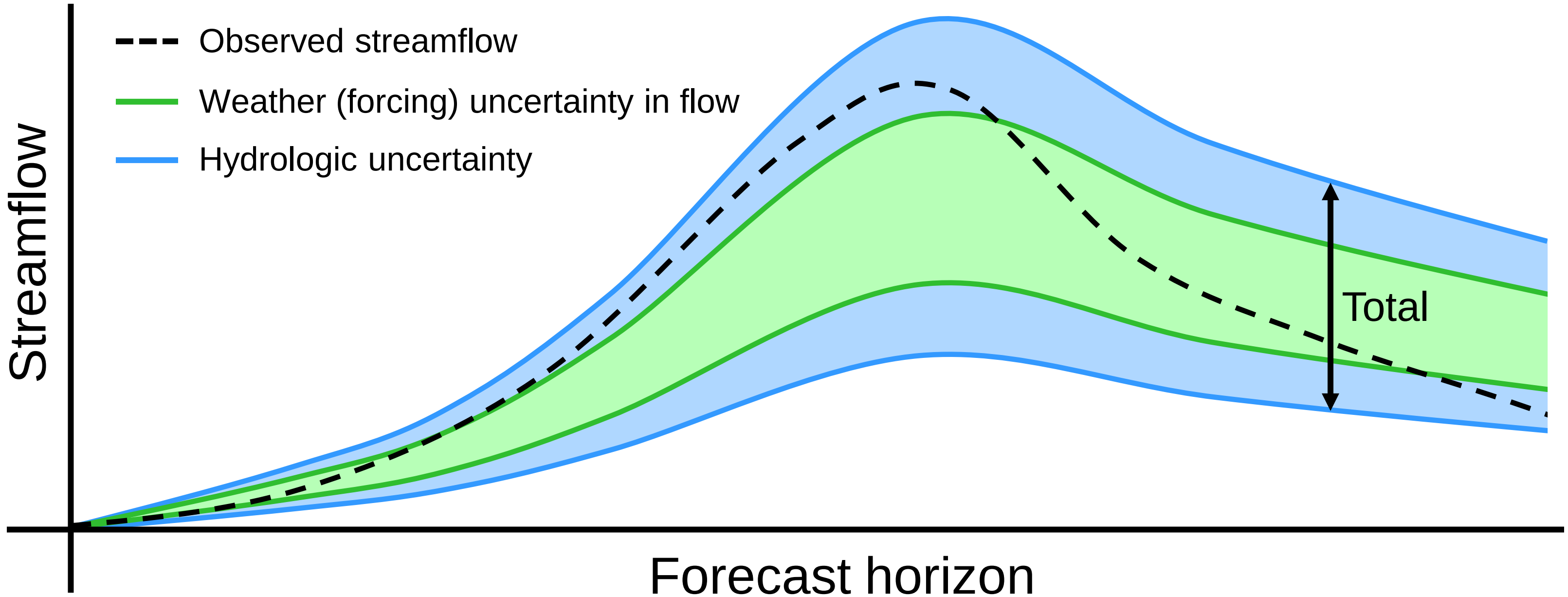






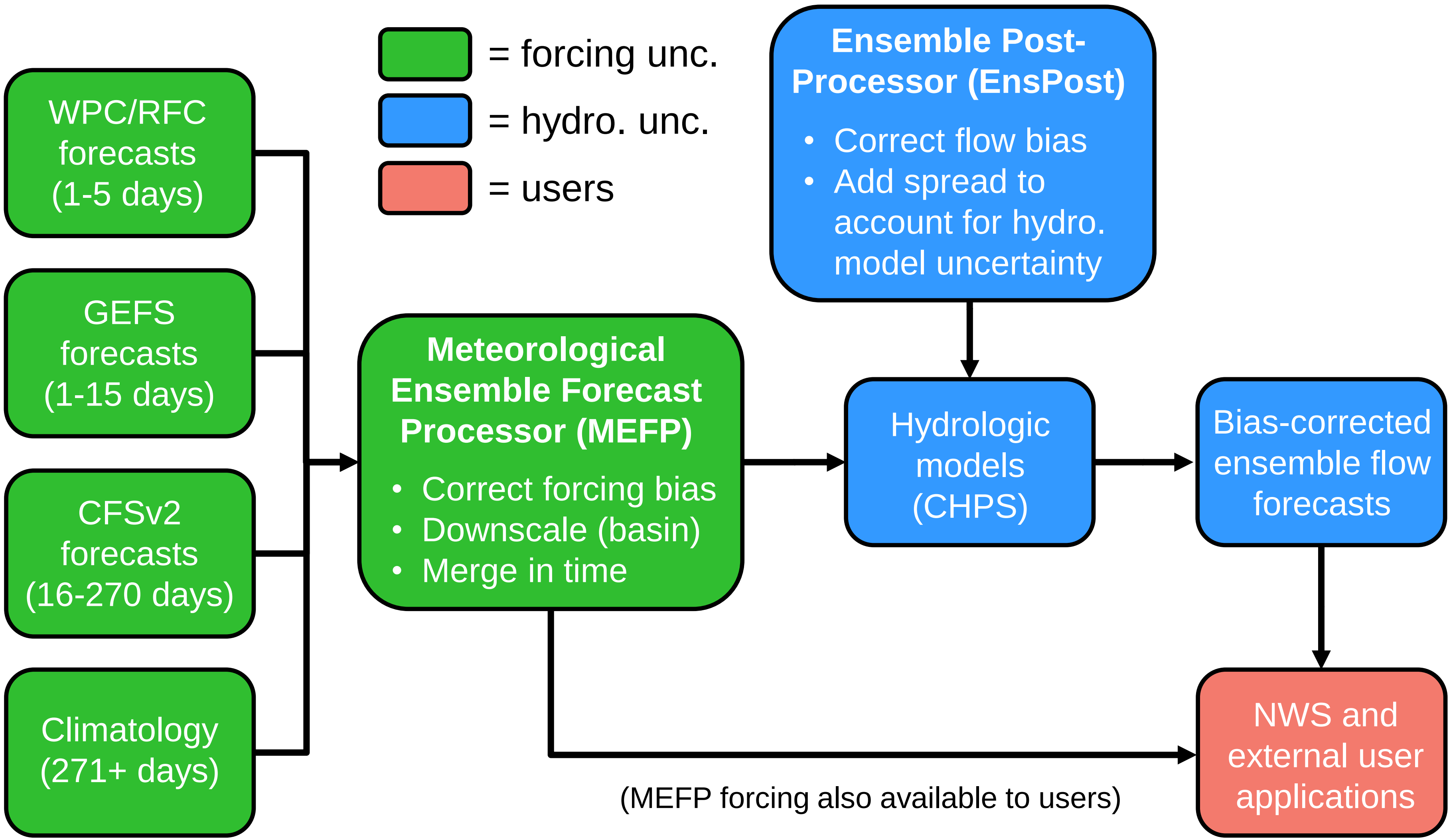
What is the HEFS?

Goal: quantify total uncertainty in flow



- HEFS aims to “capture” observed flow consistently
- So, must account for total uncertainty & remove bias
- Total = forcing uncertainty + hydrologic uncertainty

What is the HEFS?

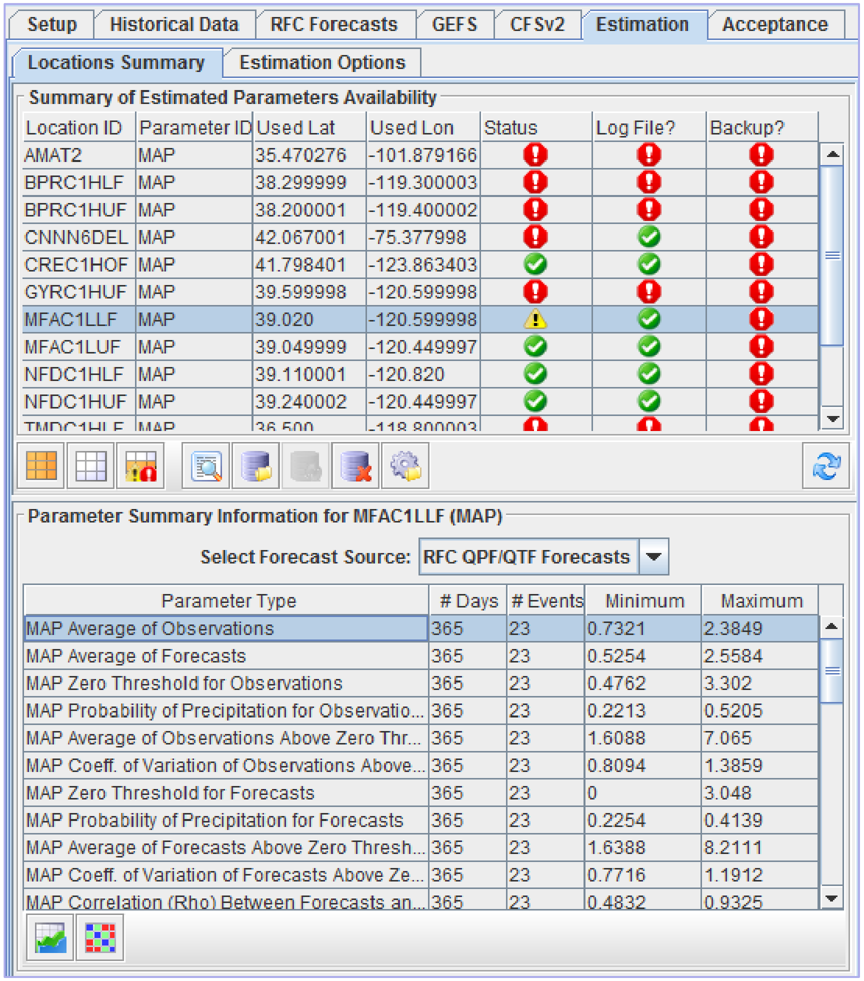


What is the HEFS?

MEFP (“forcing processor”)

- Does three things to raw forcing
    1. Adds sufficient spread to account for forecast errors
    2. Corrects systematic biases
    3. Downscales to basin
- The MEFP uses separate statistical models for temperature and precipitation
- The MEFP parameters are estimated using historical data (forecast archive or hindcasts)
- The outputs from the MEFP are FMAP and FMAT for a basin

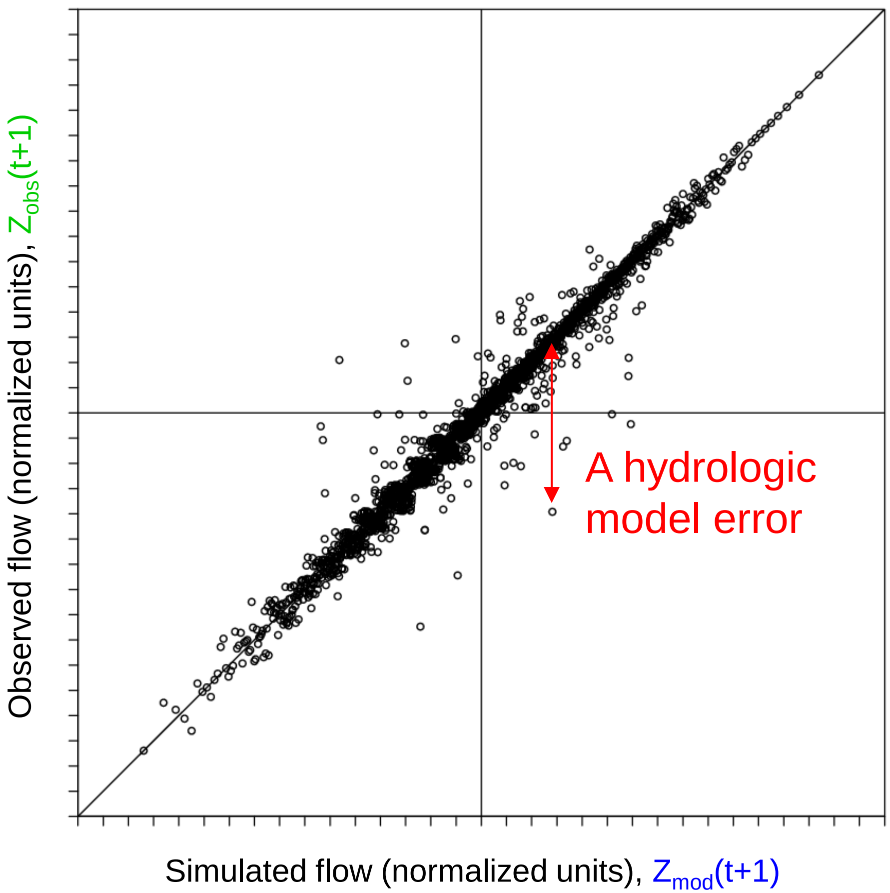
MEFP Parameter Estimation Subpanel



What is the HEFS?

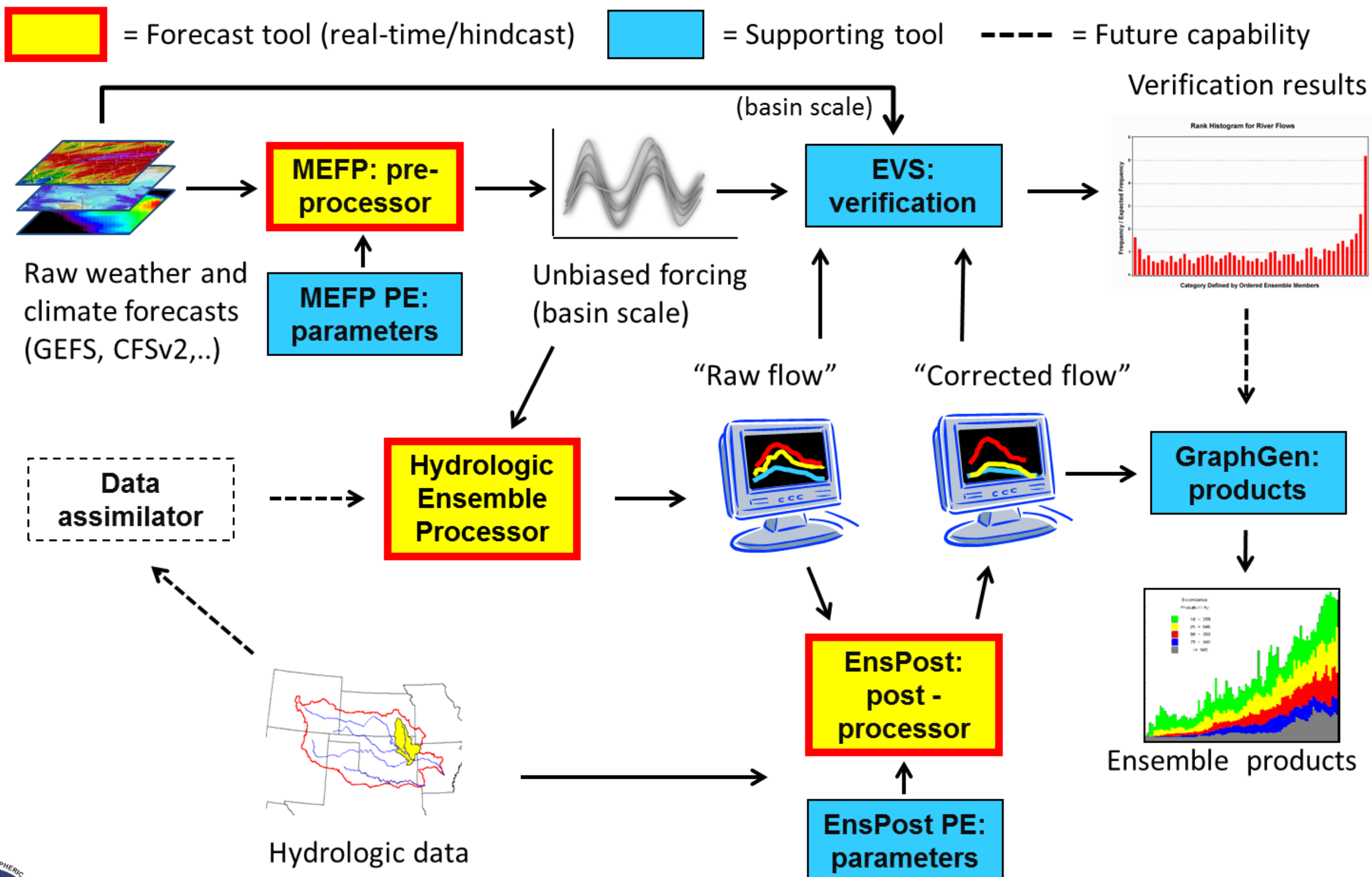
EnsPost ("flow processor")

- Does two things to flow forecast
  1. Adds spread to account for hydrologic model errors
  2. Corrects systematic biases
- Uses linear regression between observed flow and historical simulated flow (observed forcing)
- Scatter around line of best fit represents the hydrologic error (i.e. no forcing uncertainty)
- Prior observation ("persistence") also included in regression (not shown here)



$$\hat{Z}_{obs}(t+1) = bZ_{mod}(t+1) + E(t+1)$$

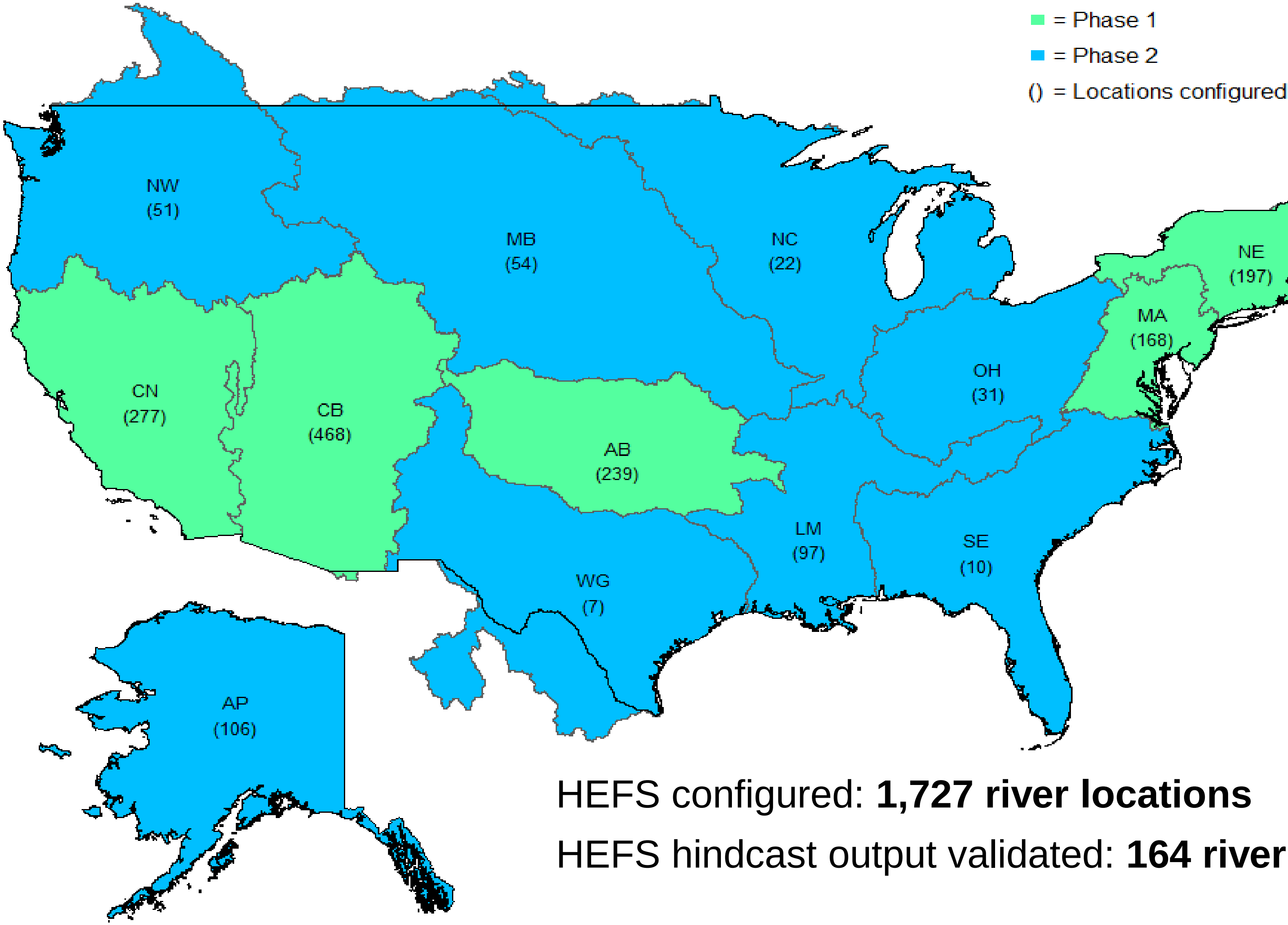
What is the HEFS?



HEFS Development Timeline

- 2011: Definition of initial version (1.0)
- 2012 - 2013: Develop prototype versions and training to five (Phase 1) RFCs
- 2014: Release version 1.0 to all RFCs and provide training to remaining RFCs
  - Includes tools and training for retrospective forecasts, i.e. validation
- 2015-16: RFCs begin implementation and validating at initial locations
- 2017-2018: RFCs expand implementation; OWP/RFCs address limitations of HEFS version 1

HEFS Implementation Status



HEFS configured: **1,727 river locations**

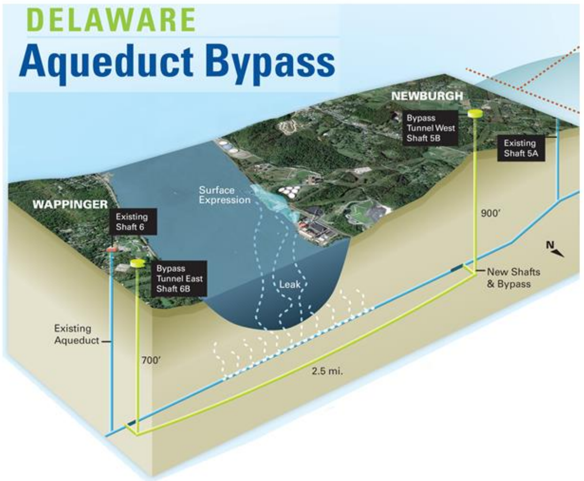
HEFS hindcast output validated: **164 river locations**

Example of early application of HEFS

Managing NYC water supply

- Croton; Catskill; and Delaware
- Includes 19 reservoirs, 3 lakes; 2000 square miles
- Serves 9 million people (50% of NY State population)
- Delivers 1.1 billion gallons/day
- Operational Support Tool (OST) to optimize infrastructure, and avoid unnecessary (**$10B**+) water filtration costs
- HEFS forecasts are central to OST. The OST program has cost NYC under **$10M**

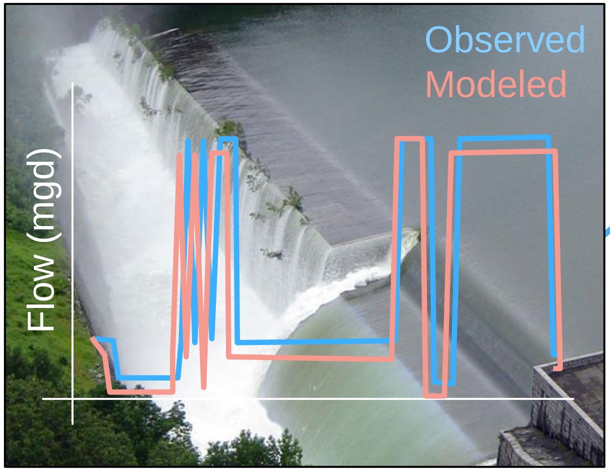
Example of early application of HEFS



"Mission critical decision to manage shutdown of RBWT Tunnel based on HEFS forecasts"

"HEFS forecasts critical to protecting NYC drinking water quality during high turbidity events"

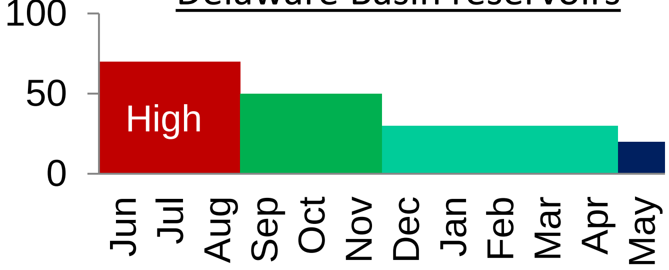
HEFS streamflow forecasts are used to optimize and validate the NYC OST for million/billion dollar applications



(Cannonsville Reservoir Spillway)

"HEFS forecasts help optimize rule curves for seasonal storage objectives in NYC reservoirs"

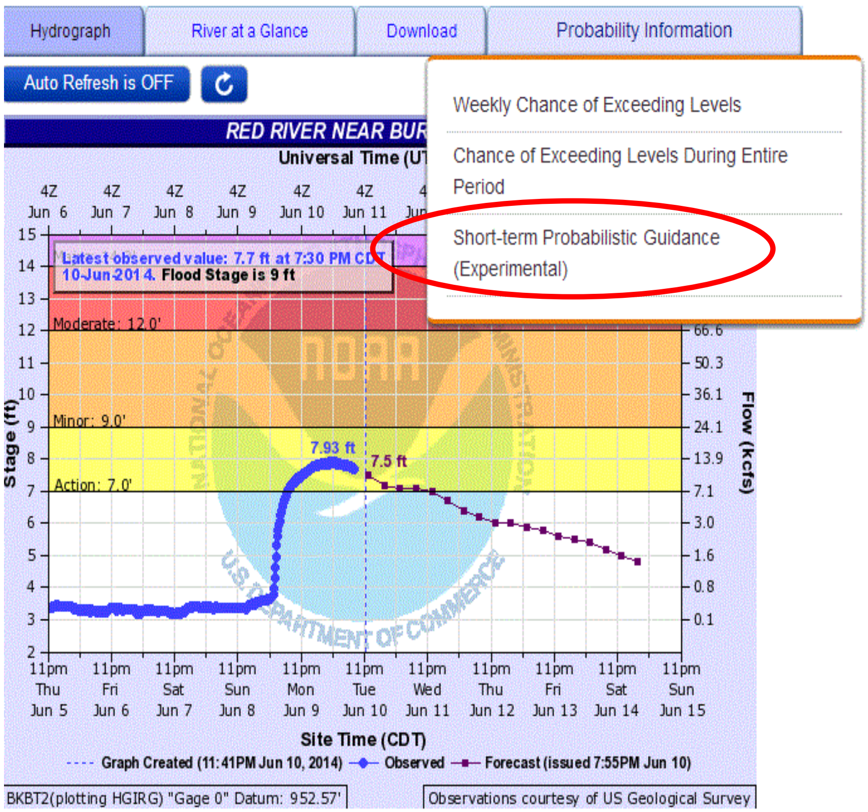
Risk to water availability from Delaware Basin reservoirs

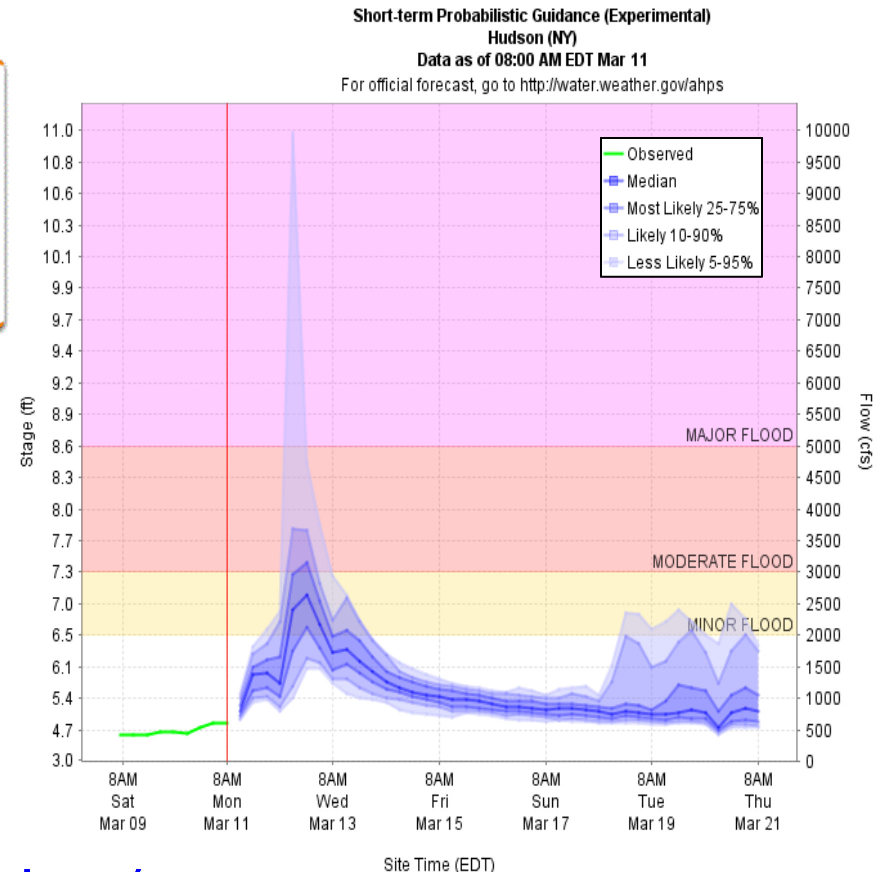


"HEFS forecasts used to determine risks to conservation releases"

Example of national HEFS product

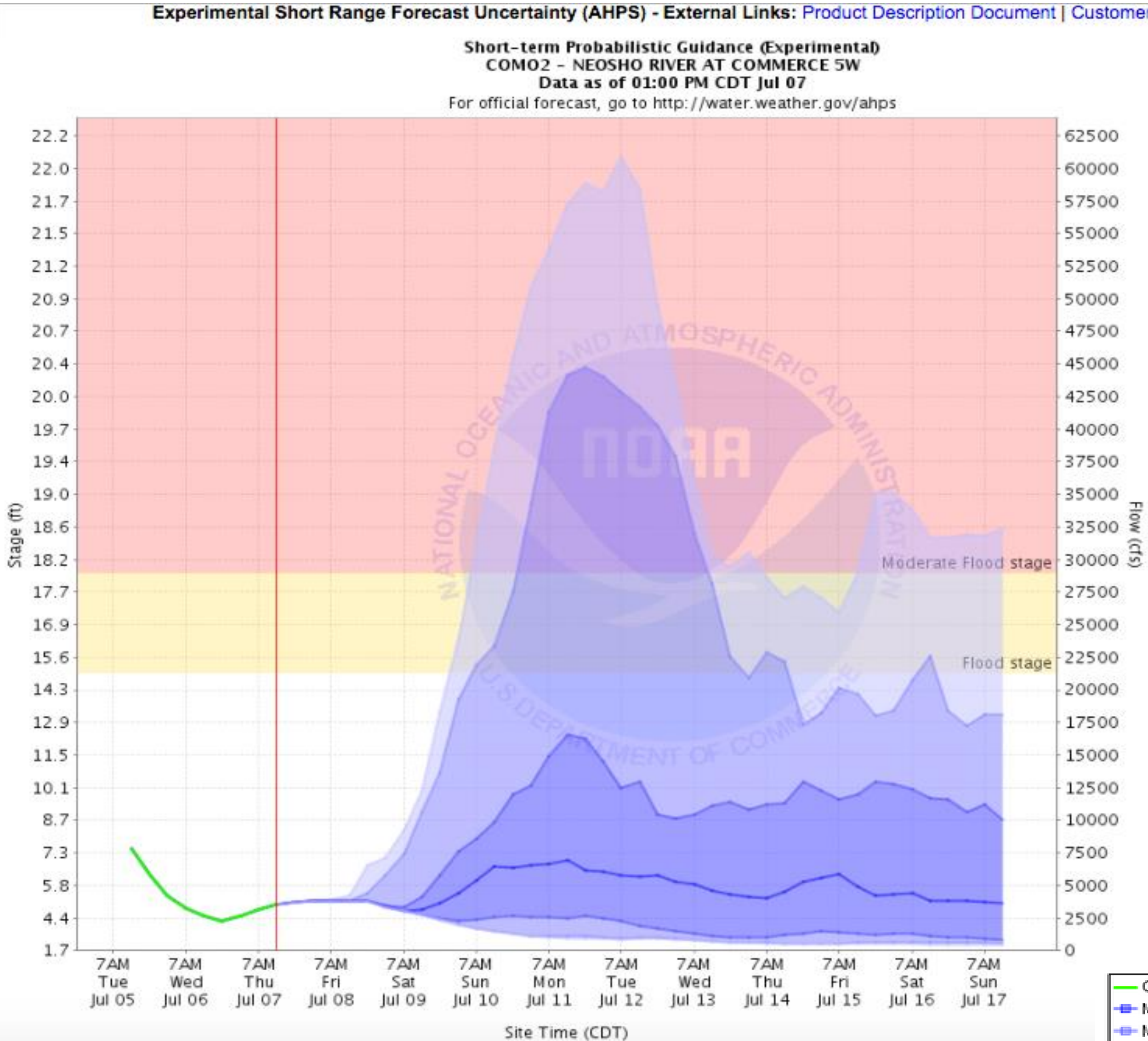
AHPS short-range probabilistic product



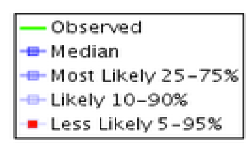


See: http://water.weather.gov/ahps/

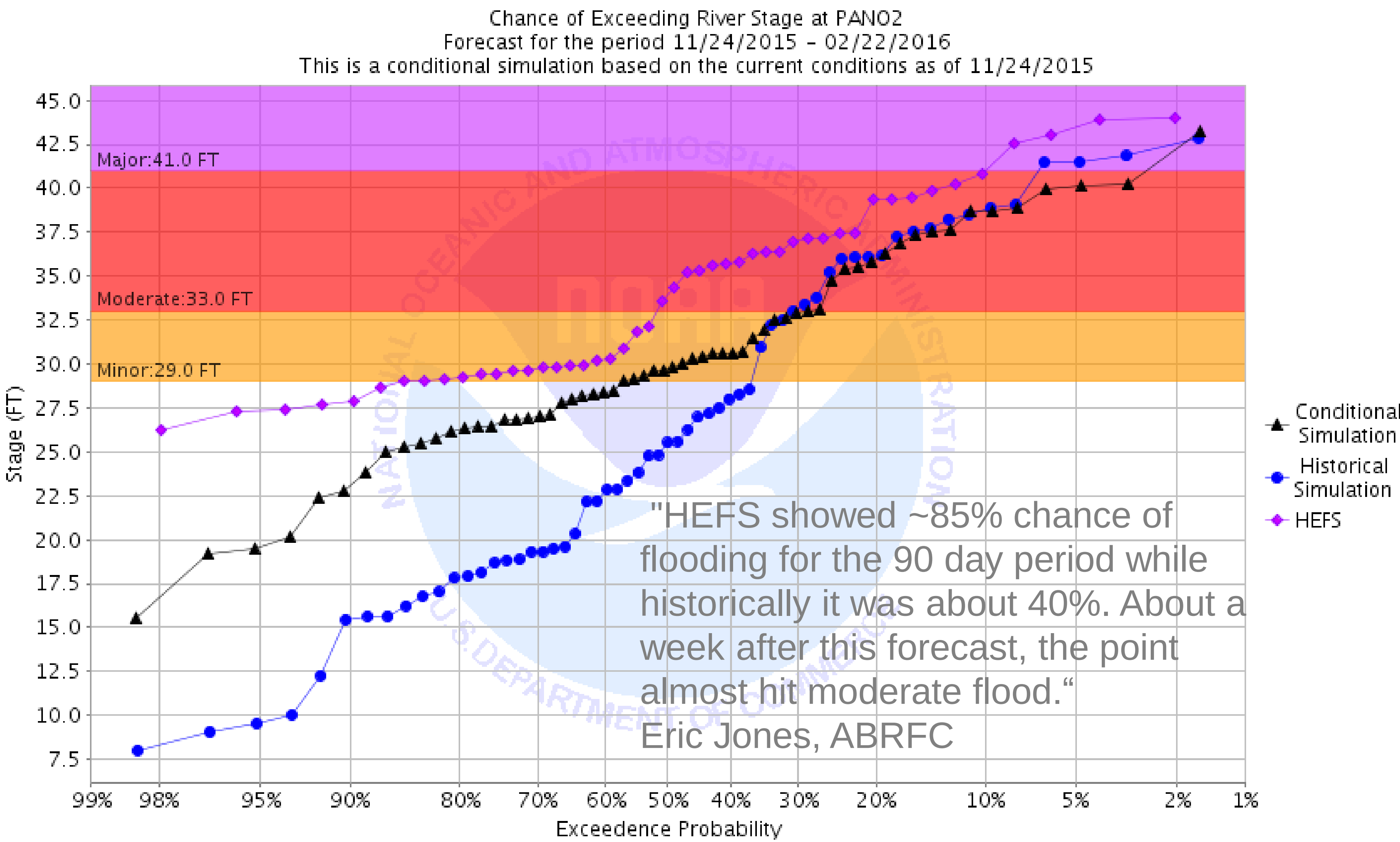
Example: short-range AHPS product



- Initial Experimental HEFS product depicts the uncertainty in short-range river forecasts
- Probability bands
  - Median (50%)
  - 25-75%
  - 10-90%
  - 5-95%
- 130 locations have experimental product on AHPS
- New river service locations will expand throughout 2016-17
- Feedback via survey



Example: Exceedance Probability Plot



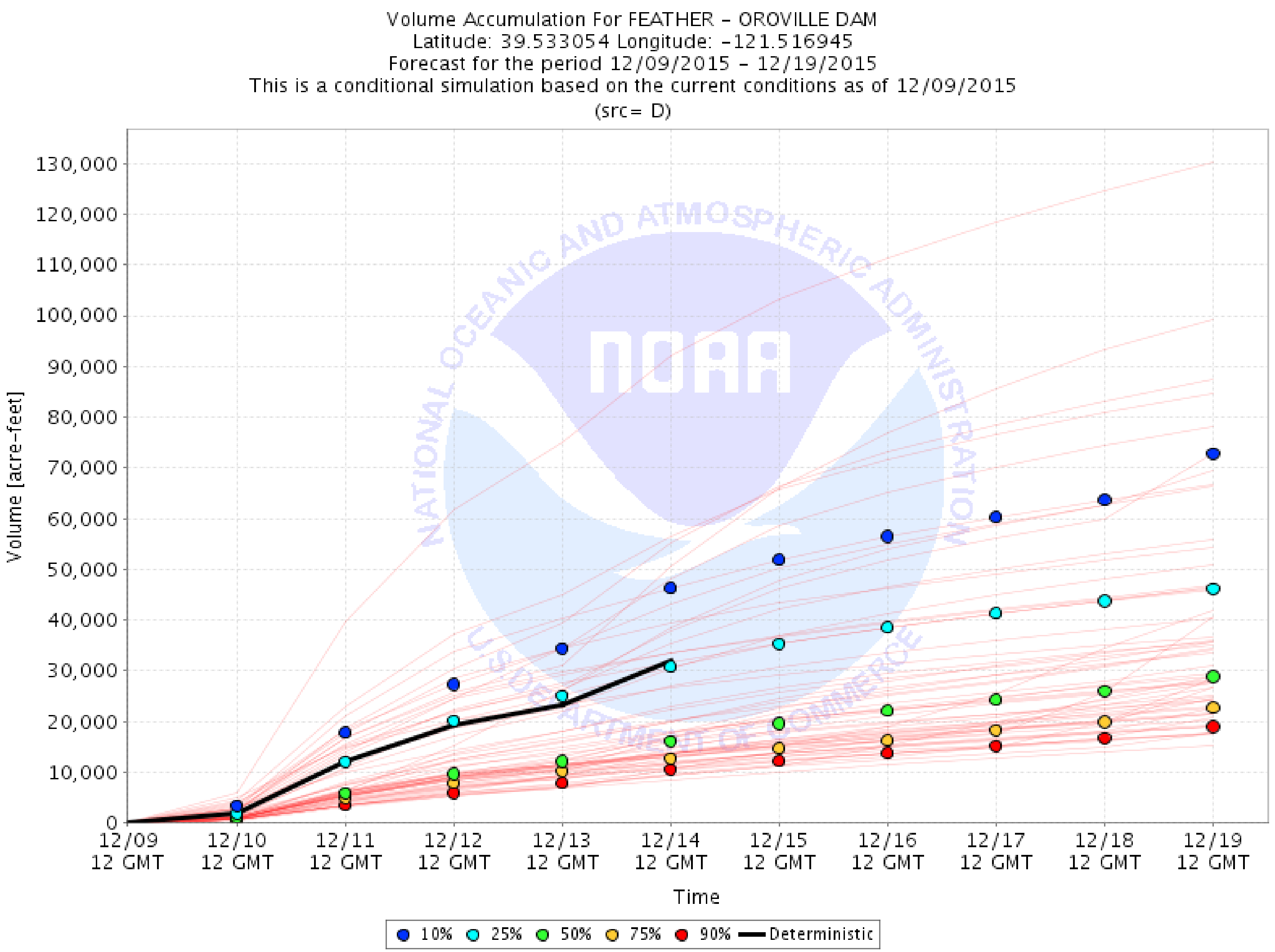
"HEFS showed ~85% chance of flooding for the 90 day period while historically it was about 40%. About a week after this forecast, the point almost hit moderate flood."
Eric Jones, ABRFC

Example: 10-Day Accumulated Reservoir Inflow

Accumulated Reservoir Inflow over next 10 days

- 1 day
- 2 day, etc.

Includes single value forecast



HEFS Challenges/Future Development

- Address performance in extreme events
- Effectively include the effects of reservoir regulation and other water management activities
- Improved hydrologic uncertainty estimation
- Automated Data Assimilation techniques
- Expand probabilistic product suite and leverage emerging NWS and NWC Data Services

Ensemble Forecast Challenge of a different kind

- Effectively communicate uncertainty information in a form and context that is useful to our customers
  - Education and training
  - Context, validation and verification
  - Compatibility with decision support tools

- Realize the full utility of this probabilistic information for optimized decisions
  - Internal NWS (WFO warning/hazard operations)
  - External partners and customers (Forecast Informed Reservoir Operations, EM response, etc.)

Summary

- As HEFS is rolled out over the next few years, applications for decision support are expected to expand dramatically
  - Warning Operations
  - Emergency Services
  - Resource Management (water supply, fisheries, ecosystems, recreation, navigation)
  - Hydropower production
- The future of NWS water intelligence resides in our ability to support optimized risk-based decisions
  - Ensemble-based (probabilistic) forecasting is foundational
  - Utilizing NCEP model reforecasts in HEFS dramatically expands the utility of output for decisions, **but** creates a requirement for NOAA/NWS to continue to produce robust reforecasts

Questions

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Backup slides

Phased science validation

Three phases completed & documented

Phase I: medium-range (1-14 days), frozen GFS (discont.)

- Selected basins in four RFCs (AB, CB, CN, MA)

Phase II: long-range (1-330 days), GEFS+CFSv2+CLIM

- Selected basins in MA and NE (in support of NYCDEP)

Phase III: medium-range, latest GEFS

- Same design as Phase I to establish gain from GEFS

See: http://www.nws.noaa.gov/oh/hrl/general/indexdoc.htm

Two papers forthcoming in JoH special issue (Brown et al.)

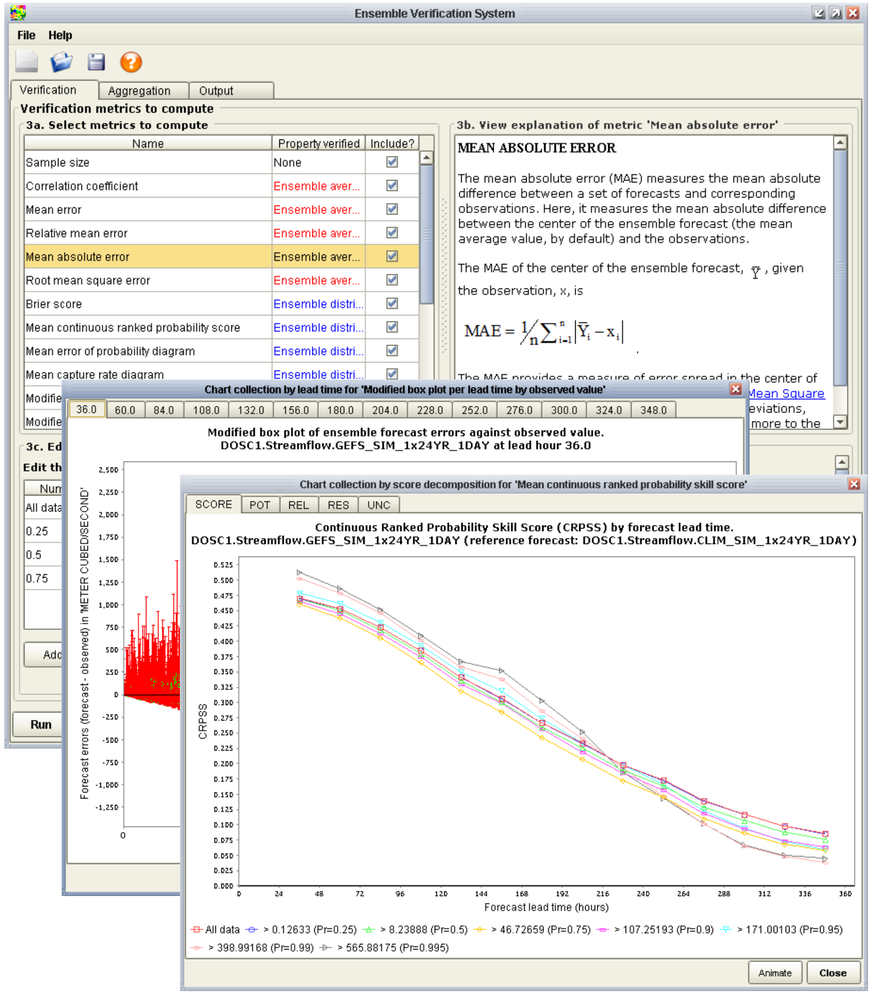
Evaluation - *Strengths*

- Supports implementation of HEFS by identifying problems, optimizing calibration, and providing info for risk-based decision support
- The HEFS broadly performs as anticipated
  - Captures skill in forcing inputs (weather and climate), including skill from multiple temporal scales. Corrects for biases.
  - Produces streamflow forecasts that are skillful and reliable (includes hydrologic uncertainty and corrects for hydrologic biases)
  - For short/medium-range forecasts, the **GEFS adds meaningful extra lead time** compared to the frozen GFS (1-2 days for precipitation, 2-4 days for temperature, 1-2+ days for streamflow)
  - At most locations, EnsPost is critically important for reliable streamflow forecasting. Improvements have been made to address "noisy" time-series, but HEFS improvements are an ongoing process

What is the HEFS?

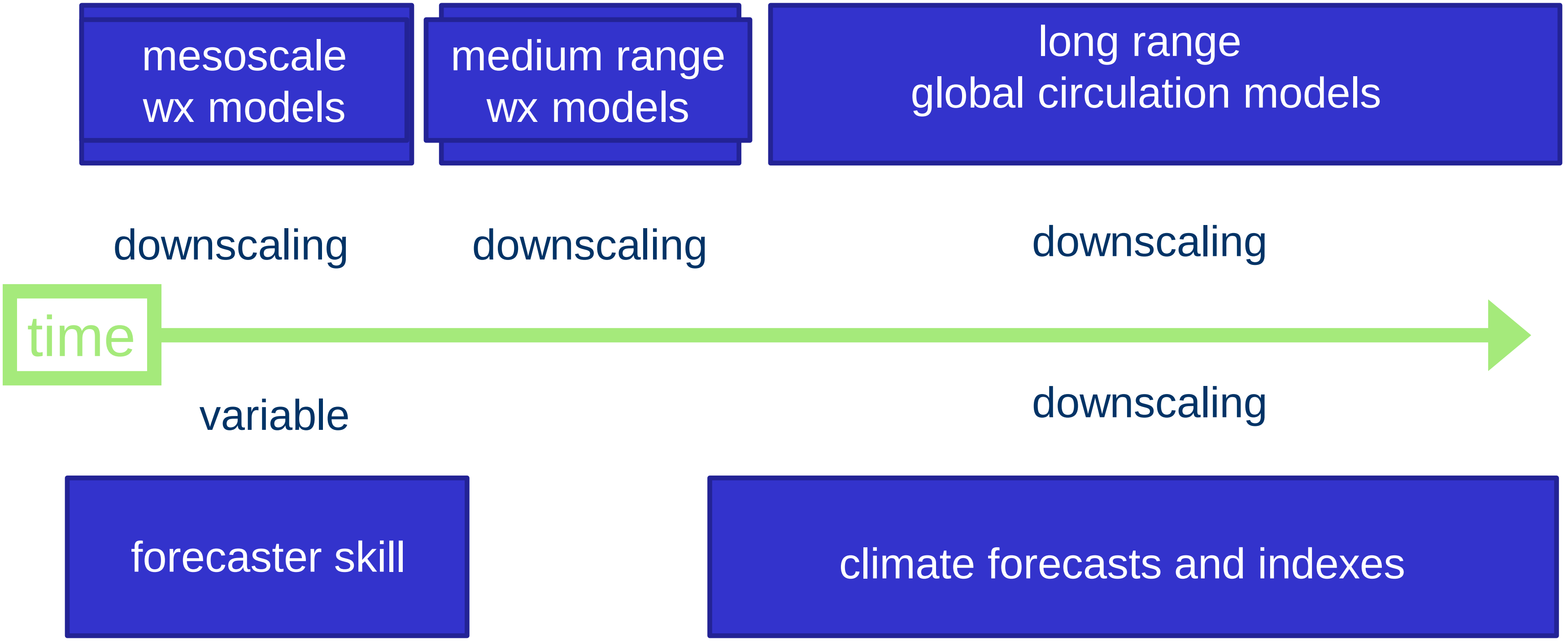
Ensemble Verification Service

- Supports verification of HEFS including for precipitation, temperature and streamflow
- Verification of all forecasts or subsets based on prescribed conditions (e.g. seasons, thresholds, aggregations)
- Provides a wide range of verification metrics, including measures of bias and skill
- Requires a long archive of forecasts or hindcasts
- GUI or command-line operation



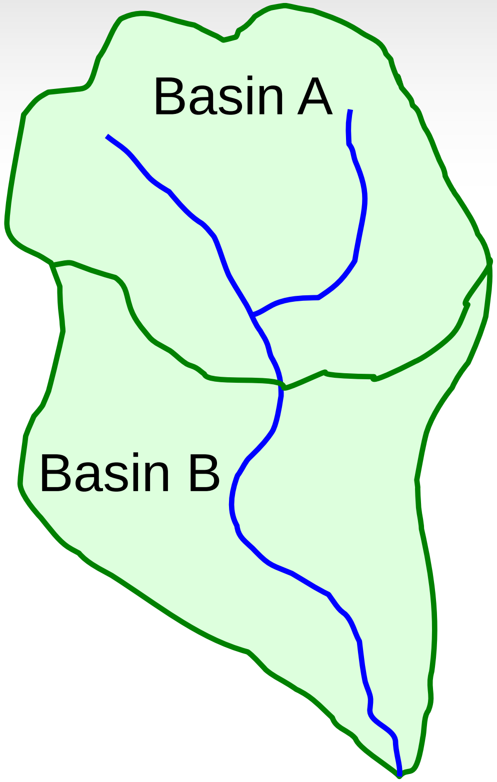
Ensemble Forecasting Challenge

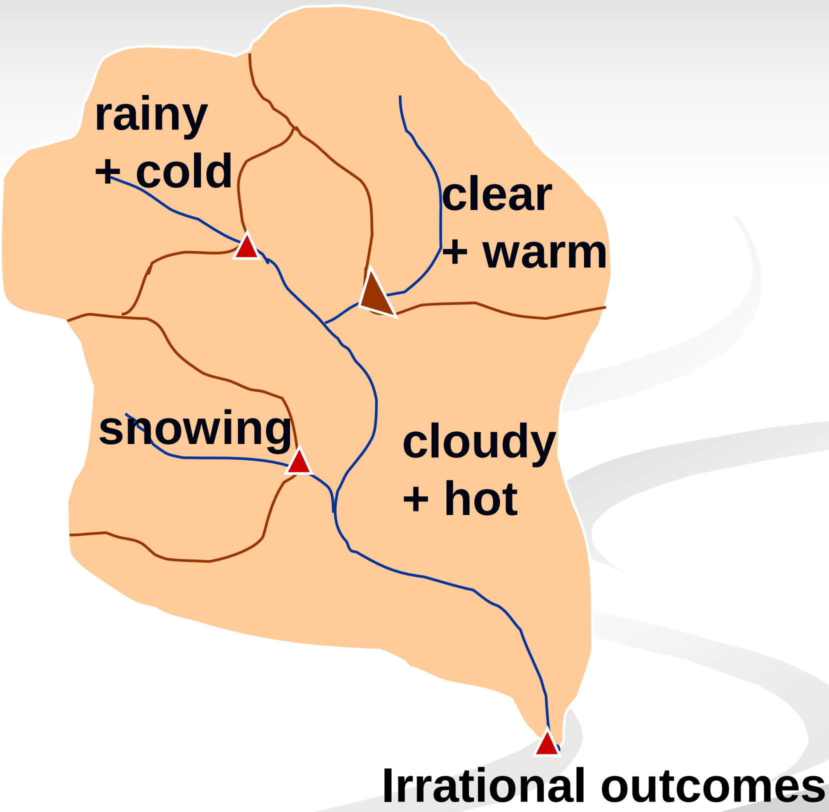
- Mesh ensemble forcings from short, medium, and long range techniques.



Ensemble Forecasting Challenge

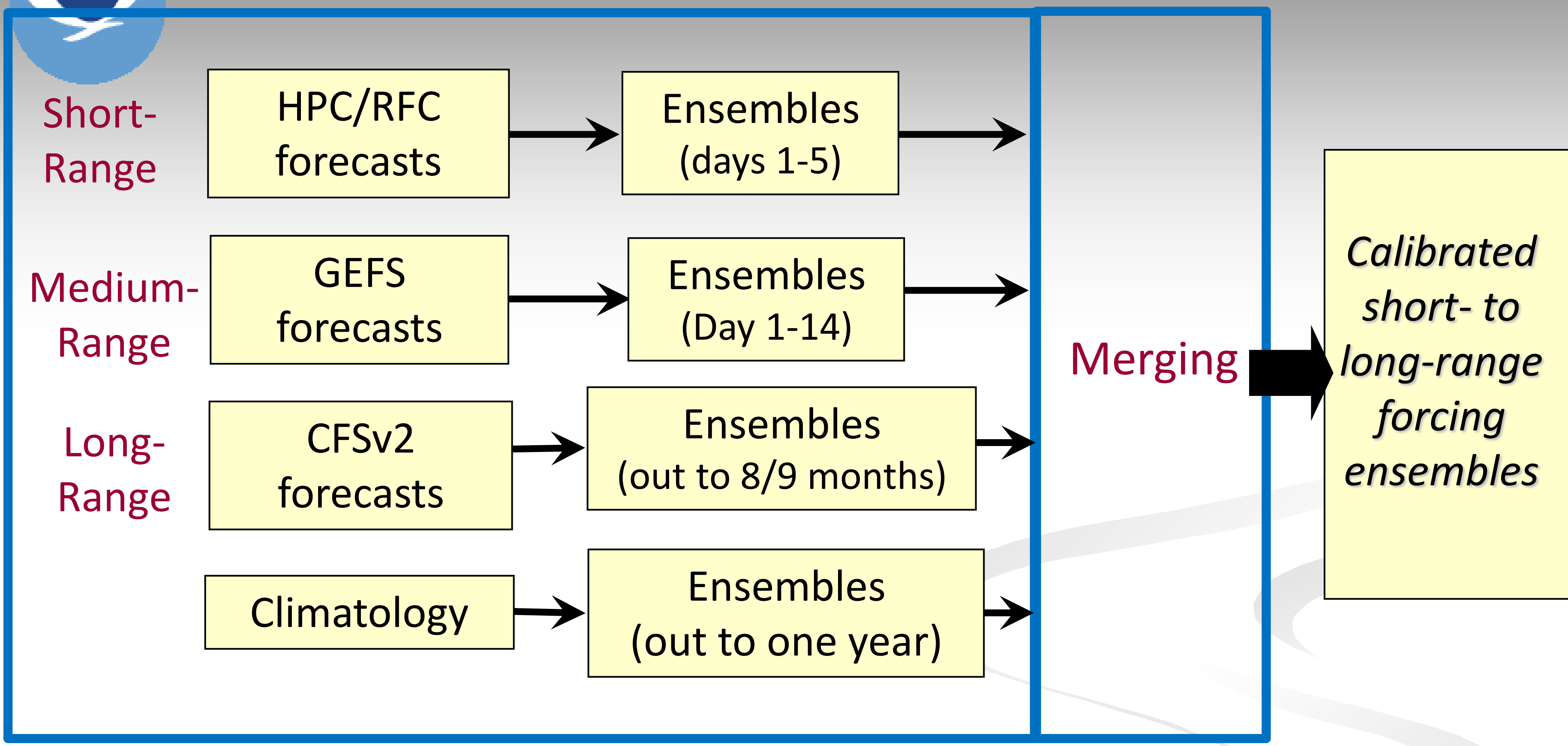
- Ensure forecast ensembles maintain spatial and temporal relationships across many scales





- Similarly, ensure consistency between precipitation and temperature is preserved in the forecast ensembles.

Meteorological Ensemble Forecast Processor



MEFP Methodology

Goal: Produce reliable ensemble forcings that capture the skill and quantify the uncertainty in the source forecasts.

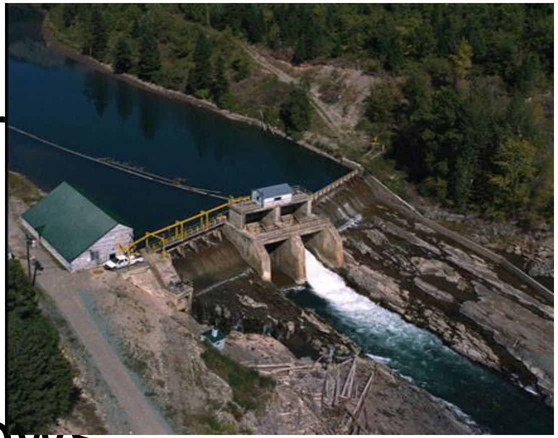
Key Idea: Condition the joint distribution of single-valued forecasts and the corresponding observations using the forecast.

- Use forecasts from multiple models to cover short- to long-range.
- Model the joint probability distribution between the single-valued forecast and the corresponding observation from historical records.
- Sample the conditional probability distribution of the joint distribution given the single-valued forecast.
- Rank ensembles based on the magnitude of the correlation coefficients between forecast and observation for the time scales and associated forecast sources.
- Generate blended ensembles (using Schaake Shuffle) iteratively for all time scales from low correlation to high correlation.

Ensemble Forecast Challenge

- Accurately incorporate the impacts of reservoirs and diversions

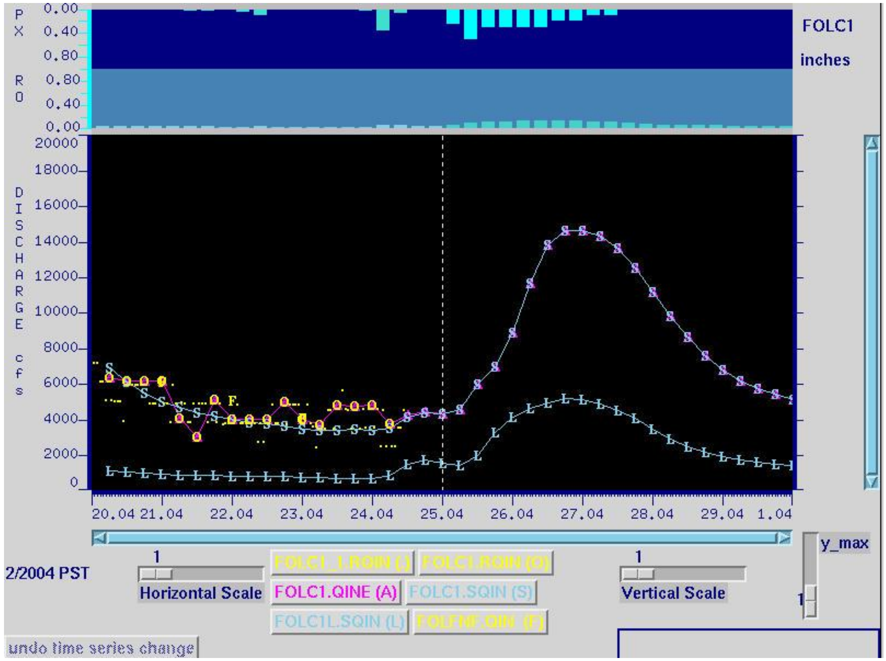
  - Reservoir models only approximate the actual operator decisions
  - Reliable information about diver available

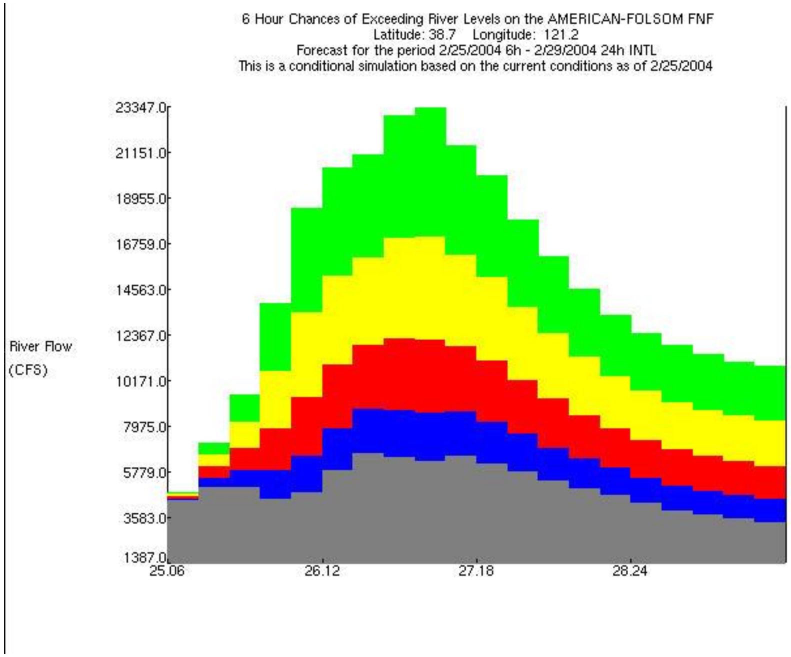


  - Significant impact on “actual” flows
  - Very important to many user groups

Ensemble Forecasting Challenge

- Maintain coherence between deterministic and ensemble forecasts





What is needed for partners?

- Demonstrating the skill/value in these forecasts
  - Verification Information
  - Event specific
- Communicating effectively
  - Understandable
  - Enhanced formats
  - Data Services
- Commitment to overcoming hurdles
  - Policy
  - Legislative mandates
  - Bureaucracy
  - Entrenched process

Summary

- NWS has an established practice of probabilistic forecasting at the long range, but there is much more potential in that information to be exploited
- At the short range, NWS is just beginning to really determine how best to use streamflow ensemble output
- The communication and process challenges may be as difficult as the technical challenges of producing reliable/skillful ensemble forecasts.

Evaluation - *Weaknesses*

- For long-range forecasting, HEFS value is more modest
  - The CFSv2 generally adds little or no skill when compared to climatology
  - But MEFP should be able to capture skill with improved climate information
- Current Ensemble Post-Processor is limited
  - Lumps all hydrologic uncertainties and biases, which reduces ability to model the total uncertainty effectively
  - Primarily benefits short-range ensembles (lead time 1-5 days)
  - Issues with temporal consistency (discontinuities): needs science solution
  - Automated data assimilation needed as a long-term investment (reduces lumping together of uncertainties, hence reduces pressure on EnsPost)
  - Not designed for correcting regulated flows. Should leverage HRC work on this
- Some issues with the MEFP forcings
  - "Canonical events", which try to capture skill at different temporal scales. Causing problems with lack of smoothness/discontinuities in P and T.
  - Biases in Probability of Precipitation (PoP). Currently under investigation.

Forecast quality: validation results

Phased validation of the HEFS

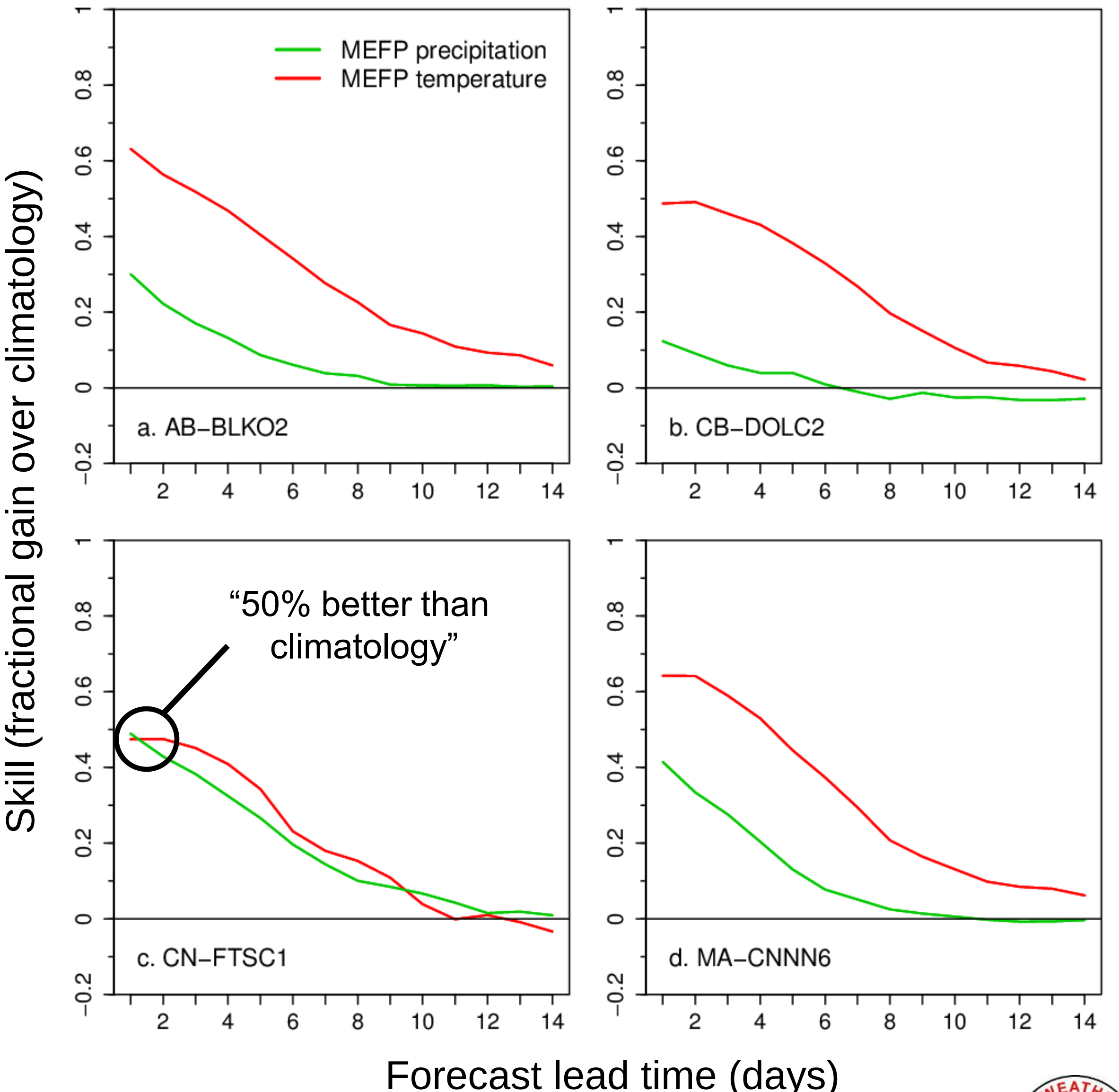
- Temperature, precipitation and streamflow validated
- See: www.nws.noaa.gov/oh/hrl/general/indexdoc.htm

1. **First phase:** short- to medium-range (1-15 days)
   - GEFS forcing used in the MEFP
   - Selected basins in four RFCs (AB, CB, CN, MA)
2. **Second phase:** long-range (1-330 days)
   - GEFS (15 days) and CFSv2 (16-270 days)
   - Climatology (≈ESP) after 270 days
   - Selected basins in MARFC and NERFC

Forecast quality: validation results

MEFP forcing

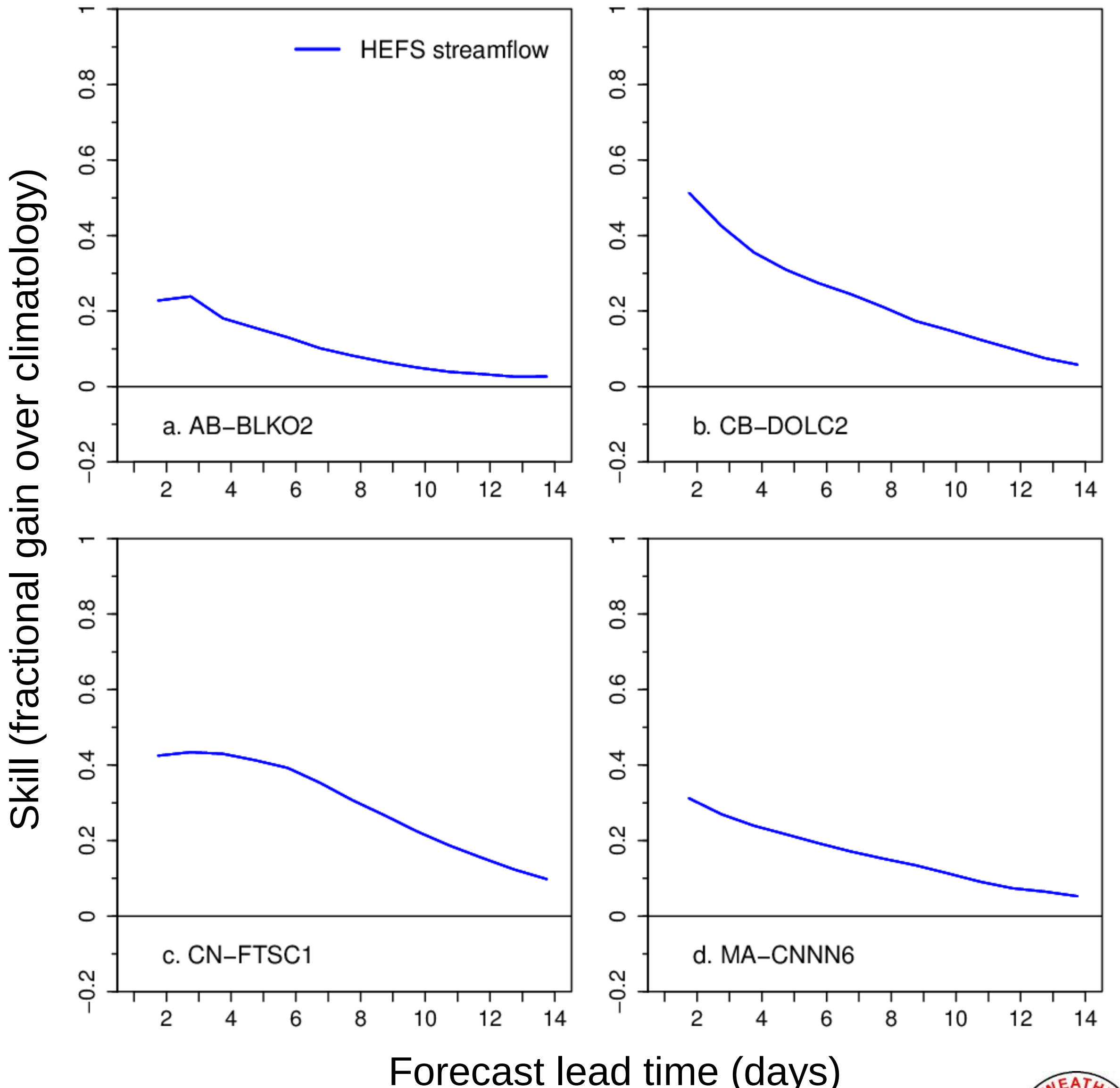
- Skill of the MEFP with GEFS forcing inputs
- Positive values mean fractional gain vs. climatology (e.g. 50% better on day 1 at FTSC1)
- MEFP temperature generally skillful, even after 14 days
- MEFP precipitation skillful during first week, but skill varies between basins



Forecast quality: validation results

HEFS streamflow

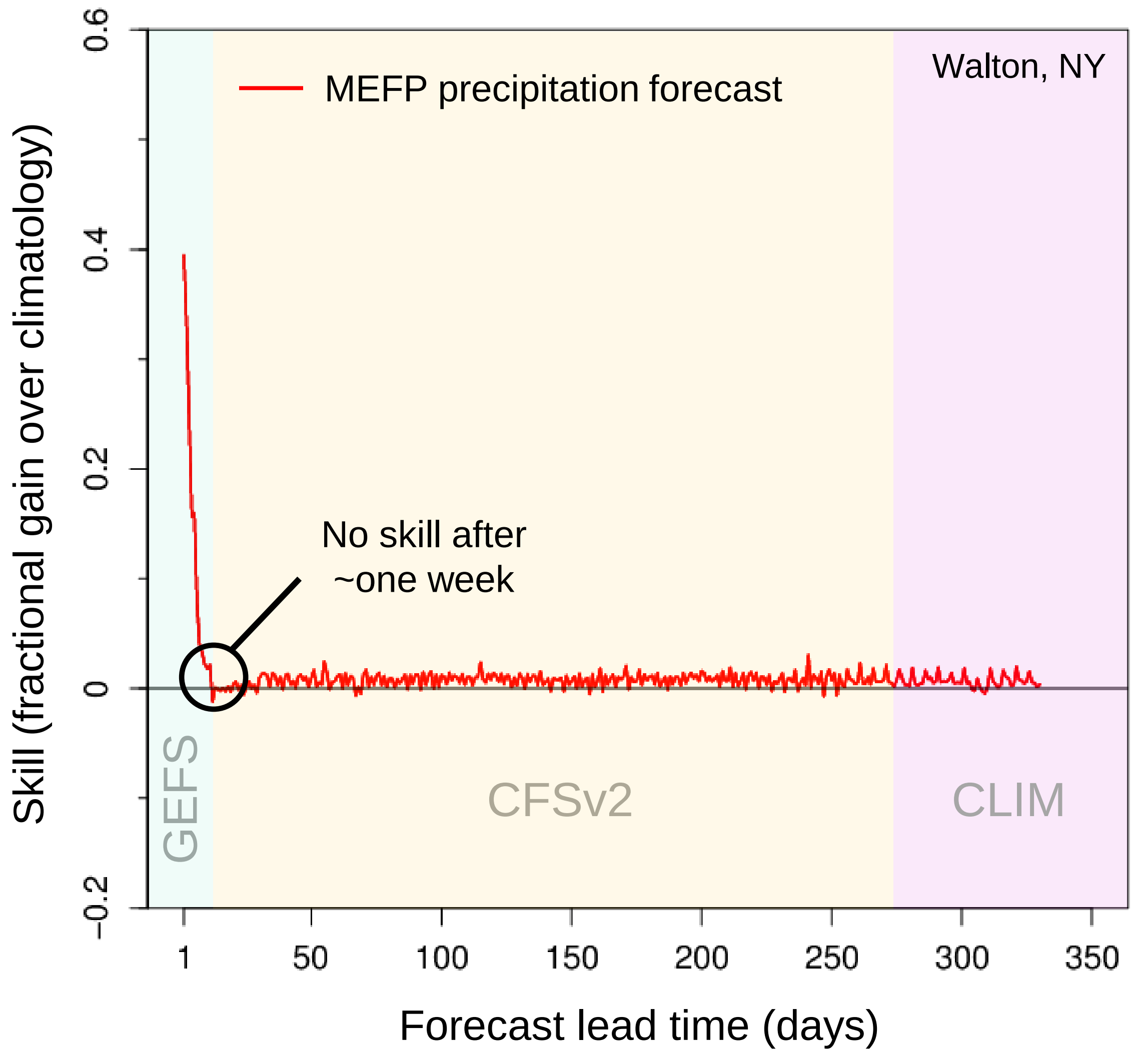
- Skill of HEFS streamflow forecasts (including EnsPost)
- Positive values mean fractional gain vs. climatology (≈ESP)
- HEFS forecasts consistently beat climatology (by up to 50% for short-range)
- Both MEFP and EnsPost contribute to total skill (separate contribution not shown)



Forecast quality: validation results

Long-range forecasts

- Example of MEFP precipitation forecasts from Walton, NY
- Beyond one week of GEFS, there is little skill vs. climatology
- In other words, the CFSv2 adds little skill for the long-range (but forcing skill may last >2 weeks in flow)
- If climate models improve in future, HEFS can be updated



Summary and conclusions

Ensemble forecasts are the future

- Forecasts incomplete unless uncertainty captured
- Ensemble forecasts are becoming standard practice
- HEFS implementation, products, and validation is ongoing and expanding
- Initial validation results are promising

HEFS will evolve and improve

- Science and software will improve through feedback
- Guidance will improve through experience
- We are looking forward to supporting end users!

Additional resources

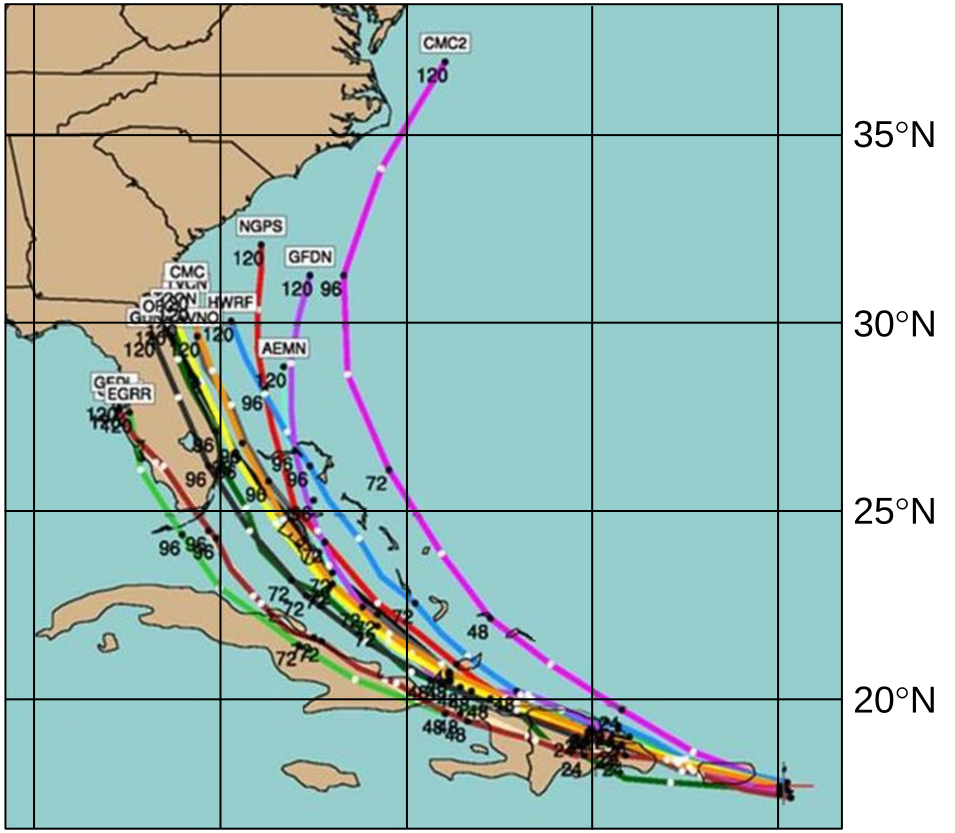
- Demargne, J., Wu, L., Regonda, S.K., Brown, J.D., Lee, H., He, M., Seo, D.-J., Hartman, R., Herr, H.D., Fresch, M., Schaake, J. and Zhu, Y. (2014) The Science of NOAA's Operational Hydrologic Ensemble Forecast Service. *Bulletin of the American Meteorological Society*, 95, 79–98.
- Brown, J.D. (2014) Verification of temperature, precipitation and streamflow forecasts from the Hydrologic Ensemble Forecast Service (HEFS) of the U.S. National Weather Service: an evaluation of the medium-range forecasts with forcing inputs from NCEP's Global Ensemble Forecast System (GEFS) and a comparison to the frozen version of NCEP's Global Forecast System (GFS). Technical Report prepared by Hydrologic Solutions Limited for the U.S. National Weather Service, Office of Hydrologic Development, 139pp.
- Brown, J.D. (2013) Verification of long-range temperature, precipitation and streamflow forecasts from the Hydrologic Ensemble Forecast Service (HEFS) of the U.S. National Weather Service. Technical Report prepared by Hydrologic Solutions Limited for the U.S. National Weather Service, Office of Hydrologic Development, 128pp.
- HEFS documentation: http://www.nws.noaa.gov/oh/hrl/general/indexdoc.htm

What are ensemble forecasts?

A collection of forecasts to capture uncertainty

- Single-valued forecasts are known to be imperfect (data and models contain errors)
- For example, multiple weather models predict multiple hurricane tracks →
- Ensemble forecasts capture these uncertainties by producing an "ensemble" of weather (or water) forecasts
- Each ensemble member represents one possible outcome (e.g. one track)

Hurricane Irene track forecasts, 08/22/11



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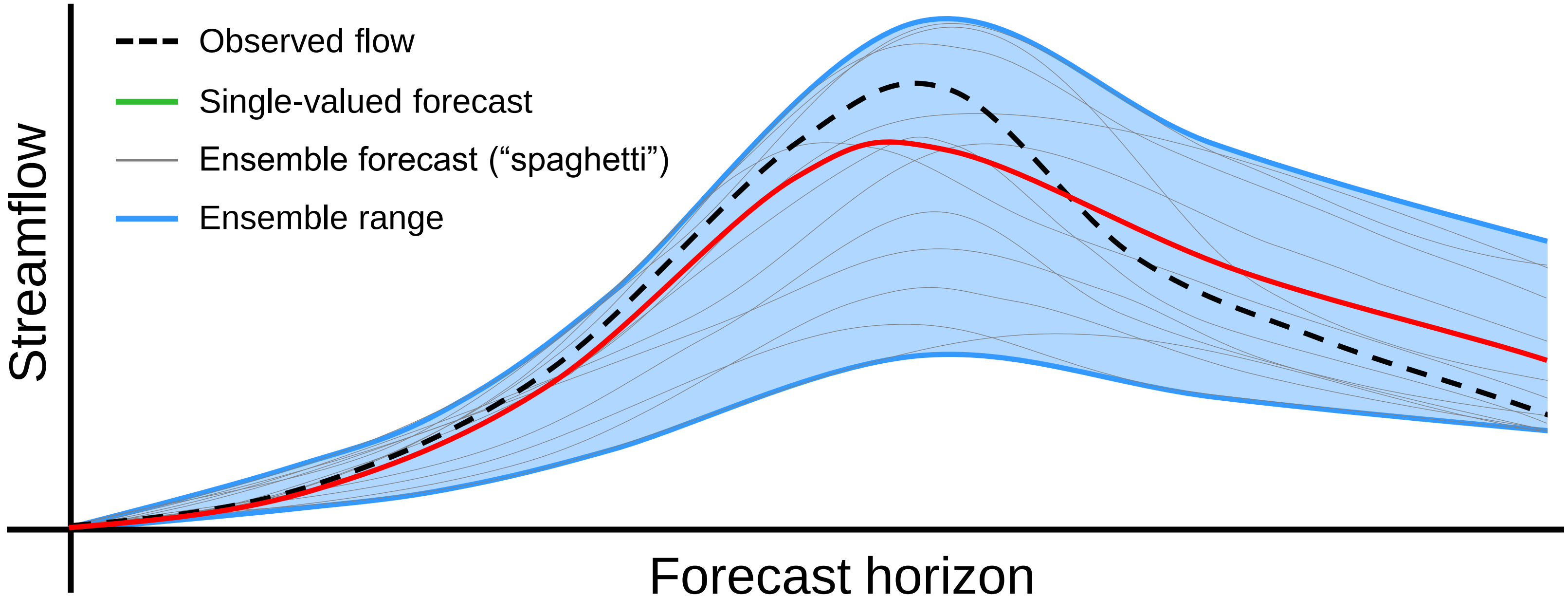

- Single-valued forecasts are known to be imperfect
- An ensemble provides a collection of forecasts
- Each ensemble member is one possible outcome

Why use hydrologic ensemble forecasts?

Demand from the science community

- Single-valued forecasts are primitive and can mislead
- Ensemble techniques are rapidly becoming standard

Demand from operational forecasters

- For **simple** and **objective** ways to assess uncertainty
- For clear products to communicate uncertainty

Demand from users of water forecasts

- Increasingly, water decisions seek to evaluate **risks**
- Range of possible outcomes needed to assess risk