Ensemble prediction – The new paradigm in operational hydrologic forecasting

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- NOAA/ESRL/Zoltan Toth
- And many more
In this presentation

• Operational hydrologic ensemble forecasting – background
• Why hydrologic ensemble prediction?
• Theoretical framework
• Hydrologic Ensemble Forecast System (HEFS)
• Short-range ensemble precipitation forecasts
• Closing comments
• Q/A, discussion
Hydrologic Ensemble Uses

- **Short-range** (hours to days)
  - Watch and warning program
  - Local emergency management activities
  - Reservoir and flood control system management

- **Medium-range** (days to weeks)
  - Reservoir management
  - Local emergency management preparedness
  - Snowmelt runoff management

- **Long-range** (weeks to months)
  - Water supply planning
  - Reservoir management

From Hartman (2007)
Why hydrologic ensemble forecasting?

1) **Provide an estimate of the forecast (i.e. predictive) uncertainty**
   - Confidence information (for the forecasters)
   - For user-specific risk-based decision-making (for the customers)

2) **Improve forecast accuracy**
   - An (optimally weighted) average of two good (or bad) forecasts is better than either of the two

3) **Extend forecast lead time**
   - Weather and climate forecasts are highly uncertain and noisy; they cannot practically be conveyed as single-valued

4) **Cost-effective improvement of forecast systems, science and process**
Need for ensemble forecasting and verification

In 2006, the National Research Council recommended that NWS produce uncertainty-quantified products, expand verification and make information easily available to all users in near real time.

- Forecasts get objective guidance for level of confidence in forecasts
- End users decide whether to take action based on their risk tolerance
Theoretical framework

\[ f_1(q_f \mid q_o) = \int f_2(q_f \mid q_o, s_f) \, f_3(s_f \mid q_o) \, ds_f \]

**Predictive uncertainty in streamflow**  
**Residual hydrologic uncertainty**  
**Uncertainty in model-predicted streamflow**

where  
- \( q_f \): Streamflow at some future times  
- \( q_o \): Observed flow up to and including the current time  
- \( s_f \): Model-predicted streamflow at the future times

Krzysztofowicz (1999)

\[ f_3(s_f \mid q_o) = \int \int \int f_4(s_f \mid b_f, i, p, q_o) \, f_5(b_f \mid i, p, q_o) \, f_6(p \mid i, q_o) \, f_7(i \mid q_o) \, db_f \, di \, dp \]

**Uncertainty in model-predicted streamflow**  
**Conditional hydrologic model simulation**  
**Future forcing uncertainty**  
**Parametric uncertainty**  
**Initial condition uncertainty**

where  
- \( b_f \): Future boundary conditions (precipitation, temperature)  
- \( i \): Initial conditions  
- \( p \): Model parameters

Seo et al. (2006)
Elements of a Hydrologic Ensemble Prediction System

QPE, QTE, Soil Moisture

Data Assimilator

Streamflow

QPF, QTF

Ensemble Pre-Processor

Hydrology & Water Resources Models

Ensemble Post-Processor

Hydrology & Water Resources Models

Hydrology & Water Resources Models

QPF, QTF

Input Uncertainty Processor

Parametric Uncertainty Processor

Hydrologic Uncertainty Processor

Hydrology & Water Resources Ensemble Product Generator

Aug 10, 2011

HRFCO seminar
Hydrologic Ensemble Forecast System (HEFS)

From NWS (2007)

Forecasters add value

HEFS will enable seamless hydrologic ensemble prediction from weather to climate scales and translate weather and climate prediction into uncertainty-quantified water information

Aug 10, 2011

HRFCO seminar
In general, the post-processed ensemble members consistently encompass the verifying observation, and the ensemble mean closely resembles the single-valued forecast.
Verification of post-processed streamflow ensembles – daily flow

Reliability Diagram

Relative Operating Characteristics (ROC)
HEFS Testing

- Ensemble Pre-Processor
- Hydrologic Model Output Statistics (HMOS)
- Ensemble Processor
- Ensemble Post-Processor
- Ensemble Verification System
- Ensemble Pre-Processor
- Hydrologic Model Output Statistics (HMOS)
- Ensemble Processor
- Hydrologic Ensemble Hindcast
- Ensemble Verification

http://www.erh.noaa.gov/mmefs/
Verification of streamflow ensembles

American River at North Fork (inflow forecast for the Folsom Dam above Sacramento, CA)

From Demargne et al. (2010)
Continuous Ranked Probability Score (CRPS)

\[ CRPS = \int_{-\infty}^{+\infty} (F - O)^2 \, dx \]

- mean CRPS: average across multiple forecasts
- small scores = better

Observed (O) CDF
Forecast (F) PDF
Forecast (F) CDF

Cumulative probability
Precipitation amount (inches)
HEFS/Ensemble Pre-Processor (EPP)

**Short-Range**
- Hist. RFC s.-v. fcst
  - Parameter estimation
- Hist. obs
  - Parameter estimation
  - GFS ens. mean refcst

**Medium-Range**
- Hist. ens.
  - GFS stat. parameters
  - Real-time GFS fcst
  - Strat. Cond. Simulation
- Hist. ens.
  - GFS stat. parameters
  - Real-time GFS fcst
  - Strat. Cond. simulation

**Long-Range**
- CFS ens. refcst
  - Parameter estimation
  - Hist. obs
- Hist. ens.
  - CFS stat. parameters
  - Real-time CFS fcst
  - Strat. Cond. simulation
  - Prob. M. & S. Shuffle
  - Day 1-to-5 ens.

- CPC outlook fcst
  - Probability shifting
  - Hist. ens.
  - Climate indices
  - Samp. from Hist. ens.
  - Day 15~ ens.

**Real-time operation & calibration**
- Merging of RFC & GFS Day 1-5 ens.
  - Merged Day 1-5 ens.
  - Joining & Blending
  - Ens. fcsts

**Joining & blending**
- Merged Day 15~ fcsts
  - Day 15~ ens.
  - Merging Day 15~ fcsts

**From NWS (2007)**

- HEFS/Ensemble Pre-Processor (EPP)
  - From NWS (2007)
  - HEFS/Ensemble Pre-Processor (EPP)
NCEP ensemble forecasts – precipitation

- **SREF** (Short-Range Ensemble Forecast)
  - ~ Day 4
  - [http://www.nco.ncep.noaa.gov/pmb/nwprod/analysis/namer/sref/21/model_s.shtml](http://www.nco.ncep.noaa.gov/pmb/nwprod/analysis/namer/sref/21/model_s.shtml)
  - Du et al. (2009)

- **GEFS** (Global Ensemble Forecast System)
  - ~ Day 15
  - [http://www.emc.ncep.noaa.gov/gmb/ens/](http://www.emc.ncep.noaa.gov/gmb/ens/)
  - Toth et al. (1997)

- **CFS** (Climate Forecast System)
  - ~ 9 months
  - Saha et al. (2006)
SREF

- Implemented in May 2001 with 10 members from the Eta and RSM models (Du and Tracton 2001)
- Subsequently added members from the Weather Research and Forecasting (WRF) models (NMM and ARW cores) resulting in 20+1 members
- Ensemble spread comes from:
  - I.C. perturbations based on a mixture of:
    - The Global Forecast System (GFS) Ensemble Transform perturbations (Wei et al., 2008)
    - Regionally-bred vectors
  - Lateral B.C. (from GEFS) perturbations
  - Structural uncertainty from:
    - The four model cores of Eta, RSM, NMM and ARW
    - Various microphysics packages (Du et al. 2009)
- The models are initialized daily at 3Z, 9Z, 15Z, and 21Z
- Forecasts are issued on a ~32 km grid at hourly time step from 1-39 hours and at 3-hourly time step from 40-87 hours (Du et al. 2009)
Verification of SREF precipitation forecasts

- Brown, J. D., D.-J. Seo, and J. Du, 2011. Verification of precipitation forecasts from NCEP’s Short Range Ensemble Forecast system (SREF) with reference to hydrologic forecasting in lumped basins, to be submitted to JHM.
  - Evaluates the quality of the SREF precipitation forecasts from April 2006 to August 2010 with an emphasis on their use in ensemble streamflow prediction
  - For observed precipitation, the gridded Climatology Calibrated Precipitation Analysis (CCPA) from NCEP (http://www.emc.ncep.noaa.gov/gmb/yzhu/imp/i201007/CCPA.pdf) was used
From Brown et al. (2011)
From Brown et al. (2011)
From Brown et al. (2011)
At lead times 28-51 hours

From Brown et al. (2011)
b. ABRFC

6-hour precipitation

- All data
- 0.1
- 0.01
- 0.001

From Brown et al. (2011)
In closing

- Hydrologic ensemble forecasting is a natural progression from single-value forecasting
  - Allows risk-based decision making
  - Improves absolute accuracy
  - Increases lead time
  - Provides an integrated forecasting framework that draws from advances in hydrologic sciences and computing power
- Utilization of short- to medium-range ensemble forecasts of forcing variables provides lower-hanging fruits if they are/can be rendered reliable
- A number of challenges to produce reliable and skillful hydrologic ensemble forecasts
  - The management practice must be risk-based and consistent with the ensemble paradigm
References

- Brown, J. D., D.-J. Seo, and J. Du, 2011. Verification of precipitation forecasts from NCEP’s Short Range Ensemble Forecast system (SREF) with reference to hydrologic forecasting in lumped basins, to be submitted to JHM.
References (cont.)

- Hagedorn, R., 2005. EPS diagnostic tools, ECMWF, Reading, UK.
Thank you
Q/A, discussion
For more information, contact:
djseo@uta.edu
Hyperlinked slides
COLUMBIA - THE DALLES DAM (TDAO3)
Forecasts for Water Year 2011

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Move the mouse over the desired "Forecast Period" to display a graph.
Red River Flood

- April 1997
- 100-year flood overall
- 500-year peak flows in some places
- 95% of residents evacuated
- Downtown fire
- $4 billion damages total – $3.6 billion in GF/EGF

Pictures taken from the Grand Forks Herald

From Sorenson (2002)
The Flood Devastation

From Sorenson (2002)

A river takes two cities

The Red rises to a new record

Areas flooded by midnight Friday, April 18 [these areas generally correspond to flood damage above the first level]

Areas flooded by midnight Saturday, April 19 [these areas generally correspond to flood damage in the basement and possibly the first level]

Areas flooded by midnight Sunday, April 20 [these areas generally correspond to flood damage in the basement]

Pictures from “Come Hell and High Water”, produced by the Grand Forks Herald
Ensemble Challenges - Flood of 2008

> 1000 year average recurrence interval

From Carter (2008)
Ensemble Challenges - Flood of 2008

Mississippi River at Keokuk, IA
Rising, forecast to exceed flood of record

Cedar River at Cedar Rapids, IA
Falling from approx. 11 ft above flood of record

From Carter (2008)
Short-Term Ensemble Streamflow Prediction: Application

6-hour mean areal precipitation ensembles for lead days 1-5

6-hour streamflow ensembles for lead days 1-5

Flood mapping

6-hour chances of exceeding river flows for lead days 1-5
California-Nevada RFC
Prototype Hydrologic Ensemble Forecasting Operation

30-day Temperature Ensembles

Smith River
Salmon River
Van Duzen River
Navarro River
American River
(9 basins)

30-day Precipitation Ensembles

Smith River – February 7, 2007

http://www.cnrfc.noaa.gov/ahps.php
Provide an actionable estimate of the forecast (i.e. predictive) uncertainty

With ensemble forecasting

Current product
Hydrologic ensemble prediction for risk-based management of water hazards & resources

Adapted from Hagedorn (2005)
Why ensemble prediction?

Results based on simple cost/loss models have indicated that probabilistic forecasts have a higher value than single deterministic forecasts.

From Hagedorn (2005)
Distributed Model Intercomparison Project I (DMIP1)  
(Smith et al. 2004)

Cross-hair = best single-model  
Arrow = weighted 5-member ensemble

From Georgakakos et al. (2004)
In single-valued forecast process, “hydrologic error-tolerable” lead time for QPF is very limited

**QUAO2 – High flow**

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<th>Mean Error (cfs)</th>
<th>Lead Time (hrs)</th>
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- Ensemble mean streamflow forecast
- RFC single-valued streamflow fcst
Uncertainties in hydrologic forecast

- Quantify meteorological/Input uncertainty
- Quantify parametric uncertainty
- Quantify uncertainty in initial conditions
- Reduced uncertainty due to pre-processing
- Reduced uncertainty due to calibration
- Reduced uncertainty due to data assimilation

Lead Time

- Structural uncertainty, residual uncertainty
- Ensemble pre-processor
- Parametric uncertainty processor
- Data assimilator
- Ensemble post-processor, multimodel ensemble

Flow regulations - A large challenge
End of slides