Short- to Long-Term Hydrologic Ensemble Forecasting at the NWS River Forecast Centers

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OHRFC

NCEP Ensemble User Workshop - May 10, 2011
Uncertainty sources

OBSERVATIONS
- precipitation
- air temperature
- streamflow

MODEL STATES
- soil moisture
- snow
- basin routing

MODELING SYSTEM
- simplifications
- temporal issues
- scale issues

FORECASTS
- precipitation
- air temperature
- regulation

MODEL PARAMETERS
- soil moisture
- snow
- basin routing

HUMAN INPUT
- education
- training
- experience

Quantification of uncertainty

NWS Hydrologic Ensemble Forecast Service
to provide seamless probabilistic hydrologic forecasts from short to long range
User and Product Requirements

- **High Priority**
  - 6-hr ensemble streamflow forecasts out to 1 year w/ daily updates
  - *Reforecasts for several decades*

  *Requires atmospheric reforecasts*

- **Wide range of products**
  - Probabilistic products and ensemble traces
  - Forcing inputs and hydrologic outputs
  - Real-time forecasts and reforecasts
  - Verification information

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**Example of sophisticated users**

- **Turbidity issues**
- **Water supply issues**

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**Probabilistic Forecast**

**Ensemble Traces**

**Ensemble Forecast Error**

**Forecast Skill Score Map**

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- NYC Environmental Protection
- New York City's Water Supply System
- Various maps and graphics illustrating water supply systems and forecast error metrics.
Hydrologic Ensemble Forecast System

Atmospheric Uncertainty

Weather and Climate Forecasts

GFS, CFS, NAEFS, SREF

Hydrologic Ensemble Pre-Processor

Ensemble Verification System

Hydrologic Uncertainty

Land Data Assimilator

Hydrologic, Hydraulic, Water Resources Models

To be implemented at all RFCs by 2013

Observations (forcing, flow)

Hydrologic Ensemble Post-Processor

Hydrology & Water Resources Product Generator

Water Products & Services
Uncertainty Integration in HEFS

Uncertainty in hydrologic forecast = Uncertainty in future forcings + Uncertainty in everything else

Atmospheric Ensemble Pre-Processor: 2 approaches
- Use single-valued input forecasts from multiple sources to generate unbiased ensembles
- Use downscaled ensemble input forecasts from multiple models (no bias correction currently)

Hydrologic Ensemble Post-Processor:
- lump all hydrologic uncertainties into one and model it via Gaussian linear regressions
# Atmospheric Ensemble Pre-Processor: multiple forecast sources and approaches

## Approach 1

<table>
<thead>
<tr>
<th>Source</th>
<th>Days</th>
</tr>
</thead>
<tbody>
<tr>
<td>HPC/RFC single-valued forecast</td>
<td>Day 1-5</td>
</tr>
<tr>
<td>GFS/GEFS ens. mean</td>
<td>Day 1-14</td>
</tr>
<tr>
<td>CFS/CFSv2 forecast</td>
<td>Day 15~</td>
</tr>
</tbody>
</table>

## Approach 2

- Other ensembles (SREF, NAEFS...)

## Planned

- Other info (climate indices...)

## Blending

Calibrated and seamless short- to long-term forcing input ensembles
Atmospheric Ensemble Pre-Processor: strategy for approach 1

- Bias?
- Skill?

Archive of observed-forecast pairs

Bias-corrected ensemble mean
Spread based on forecast skill
Atmospheric Ensemble Pre-Processor: multiple temporal scales for approach 1

- Capturing skill at multiple scales:
  - Temporal aggregation of weather/climate forecasts to form multiple forecast events
  - Correlation with observations for each forecast event
  - Generation of ensembles iteratively for all forecast events from low correlation to high correlation

**Example of events**

<table>
<thead>
<tr>
<th>6-hr events for Lead Days 1-5</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-day events for Lead Days 6-8</td>
</tr>
<tr>
<td>2-day events for Lead Days 9-16</td>
</tr>
<tr>
<td>4-day events for Lead Days 17-24</td>
</tr>
<tr>
<td>6-day event for Lead Days 25-30</td>
</tr>
<tr>
<td>1-month events for Lead Months 2-9</td>
</tr>
</tbody>
</table>

**GFS-based precipitation forecast skill**

*CREC1, California Forecast date of Apr. 1*

*Adjustment*
Example of Experimental Ensembles from approach 1

GFS and CFS based ensembles: experimental products updated daily at Colorado RFC (CBRFC) & California-Nevada RFC (CNRFC)

www.cbrfc.noaa.gov/devel/hefs/
Atmospheric Ensemble Pre-Processor: strategy for approach 2

- Meteorological Model-based Ensemble Forecast System (MMEFS)
  - Utilizes 3- & 6-hr precipitation & temperature grids from NAEFS & SREF ensembles as input to hydrologic/hydraulic models
  - No bias correction or blending

- Current implementation
  - Multiple (automatic) runs daily soon after data becomes available
    - SREF (21 members) — 03Z, 09Z, 15Z, 21Z
    - NAEFS (GEFS & CMC) (42 members) — 00Z & 12Z
    - GEFS (21 members) — 06Z & 18Z
  - Graphics generation updated soon
  - GoogleMaps interface under construction

Tested at 4 ER RFCs
- SERFC
- MARFC
- NERFC
- OHRFC

Example of input: 1 NAEFS member gefs.2011050112.conus15
Example of Experimental Ensembles from Approach 2


**NAEFS ensembles for OHRFC**

**NAEFS GEFS ensembles**

**NAEFS CMC ensembles**

**NAEFS-based hydrologic ensembles for one basin at MARFC**

NAEFS-based Stage Simulations Traces
Susquehanna River at Wilkes Barre, PA (WSRP)
Analysis for the period 05/03/2011 18 UTC - 05/11/2011 12 UTC
Example of Evaluation Results for Approach 2

- MMEFS results are very promising
  - WFO and external users are very positive and pleased with hydrologic forecast uncertainty information
  - Hydrologic modeling uncertainty and calibration of NWP ensembles to be added in future

- Systematic hydrologic reforecasting and verification underway
  - Requires archive of real-time forecasts or reforecasts
Assessment of hydrologic value of SREF

Precipitation skill/bias by:
1. Location (see right)
2. Forecast lead time
3. Amount of precip.
4. Temporal aggregation
5. Basin size
6. Season
7. Relative to GEFS

- Multiple verification metrics (e.g. Type-I/Type-II conditional biases)
- Will consider other variables later
- Paper submitted (Brown et al., JHM)
One way to look at the Type-II biases in SREF precipitation ensembles

RFCs want a good forecast of heavy precip. when heavy precip. actually occurs
Requirements: length of reforecasts

For Water Sector:

- Pronounced decadal variability in western US
- Reforecasts support analysis of:
  - many ‘types of years’
  - training of DSS
  - comparison with past critical events
  - analog selection

Needs reforecasting for ~30 years

Requirements for Hydrologic Services

• Generate **reforecasts of calibrated forcing input ensembles and hydrologic ensembles for several decades** to support
  - forecast calibration and verification
  - user decision making (e.g., calibration of downstream applications, DSS)

• OHD and RFCs need to
  - select forcing input forecasts with long enough archive of reforecasts
  - coordinate with NCEP and partners (NCDC, NCAR...) for new model implementation and reforecast availability
Immediate Needs for Hydrologic Services

• NCEP to continue CFSv1 runs at 0 UTC to support current experimental hydrologic ensemble forecasts - Until?

• NCEP to deliver NAEFS and SREF ensembles reliably

• NCEP and partners to provide access to reforecasts and forecasts
  ▪ CFSv2 reforecasts out to 10/11 months (cover 29 years+)
  ▪ GEFS reforecasts out to 16 days (available late 2011)
  ▪ In future: expand 45-day and 1-season CFSv2 reforecasts to cover all 29 years (instead of 12 years)?

• OHD-RFC to enhance Atmospheric Ensemble Pre-Processor
  ▪ Upgrading prototype 1 to use CFSv2 (~Fall 11) and GEFS
  ▪ Expanding prototype 2 w/ other bias correction techniques and new ensemble products
Thank you!

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Experimental Ensemble Prototypes:  www.weather.gov/oh/XEFS/
CBRFC Experimental Ensemble Products:  www.cbrfc.noaa.gov/devel/hefs/
OHRFC Experimental Ensemble Products:
          www.erh.noaa.gov/mmefs/index.php

References on Atmospheric Ensemble Pre-Processor:
Wu et al, 2011. Generation of ensemble precipitation forecast from single-valued quantitative precipitation forecast for hydrologic ensemble prediction, JoH.
Schaake et al, 2006. Precipitation and temperature short-term ensemble forecasts from existing operational single-value forecasts, HESSD.
Brown et al. Verification of precipitation forecasts from NCEP’s SREF system with reference to hydrologic forecasting in lumped basins, submitted to JHM.
Adams & Ostrowski, 2010. Short lead-time hydrologic ensemble forecasts from numerical weather prediction ensemble models, ASCE.
Extra Slides
Assess hydrologic value of SREF

Quality of ensemble mean:

- Correlation of ensemble mean and observation
- Subset pairs by observation exceeding climatological probability threshold
- For example, 0.001 represents a 1-in-1000 accumulation
- Shown for 6, 12, 24-hr accumulations
- Shaded areas are 5th-95th bounds
- Skill depends very strongly on RFC and amount
Assess hydrologic value of SREF

Scope for post-processing:

• Depends on: 1) inherent skill of SREF (e.g. correlation); 2) magnitude of bias; and 3) type of bias (e.g. Type-I/Type-II conditional biases)

• Type-II conditional biases are tougher to remove (i.e. post-processors focus on Calibration-Refinement factorization or Type-I bias)

• All locations have large Type-II conditional biases for zero and large precipitation amounts

• NWRFC: correlations good and Type-I biases are moderate = good scope for post-processing

• MARFC: correlations weak and Type-II biases high = more difficult to post-process

• No single post-processing technique will be best! Need to decide based on RFC/basin group
Critical Efforts & Challenges

• Primary efforts
  - Ensemble bias-correction: additional info (ens. spread, atm. indices), other techniques (DA), and forecaster guidance of hydrologic model operation
  - Long-term ensemble reforecasting (~30 years) and verification
    ➢ Collaboration between atmospheric and hydrologic communities and users

• Challenges
  - Provide uncertainty information useful to users
    ➢ Testing/training and outreach w/ forecasters and users
  - Reduce cone of uncertainty for improved decision support
  - Improve uncertainty modeling of rare events
**Atmospheric Ensemble Pre-Processor: calibration**

Off line, model joint distribution between single-valued forecast and verifying observation for each lead time

Archive of observed-forecast pairs

- **Joint distribution**
  - Sample Space
  - PDF of Observed
  - PDF of Obs. STD Normal
  - Correlation (X,Y)
  - NQT

- **Joint distribution**
  - Model Space
  - PDF of Observed
  - PDF of Fcst STD Normal
  - NQT

- Archive of observed-forecast pairs

NQT: Normal Quantile Transform

Schaake et al. (2007), Wu et al. (2011)
Atmospheric Ensemble Pre-Processor: ensemble generation (1)

In real-time, given single-valued forecast, generate ensemble traces from the conditional distribution for each lead time

Joint distribution

Model Space

Observed

Forecast

Conditional distribution given $x_{fcst}$

Ensemble members for that particular time step

Given single-valued forecast, obtain conditional distribution

Schaake et al. (2007), Wu et al. (2011)
Atmospheric Ensemble Pre-Processor: ensemble generation (2)

For each time step, arrange the ensemble members such that they have the same ordering as historical observations.

Illustration of Schaake Shuffle (Clark et al. 2004)
Atmospheric Ensemble Pre-Processor: ensemble generation (2)

In real-time, string together lead-time specific ensemble values across lead times to generate traces using ranks of historical values

*Based on ranks of historical values (from climatology time series)*

Different illustration of Schaake Shuffle (Clark et al. 2004)
Atmospheric Ensemble Pre-Processor: ensemble generation (2)

In real-time, string together lead-time specific ensemble values across lead times to generate traces using ranks of historical values

Using new conditional ensemble values instead of historical values

Different illustration of Schaake Shuffle (Clark et al. 2004)
Hydrologic Ensemble Post-Processor: strategy

- Current prototypes for short range (days 1-5)
  - Probability matching combined w/ auto-regression (Seo et al. 2006) to process each ensemble trace
  - Hydrologic Model Output Statistics approach to process single-valued flow forecasts

- Future approach
  - Other statistical post-processing techniques
    - HEPEX post-processing testbed and workshop (June 2011)
  - Data assimilation (DA) techniques to improve initial condition uncertainty modeling
  - Parametric uncertainty processor, multi-model hydrologic ensembles
Hydrologic Ensemble Post-Processor: strategy

Precipitation ensemble forecast

Hydrologic, hydraulic models

Raw flow ensemble forecast

Observed streamflow (cms)

Simulated streamflow (cms)

Archive of obs-simulated pairs

Bias? Skill?

Uncertainty-integrated flow ensemble forecast

Repeat for all individual raw flow ensemble members

Post-processed flow ensemble member
HEFS Prototype Testing

- Prototype testing at 8 River Forecast Centers (RFC)

- Verification case study:
  - 2 test basins at CNRFC and 2 test basins at ABRFC
  - Daily flow ensembles out to 14 lead days from 1979-1999 using GFS reforecasts
  - GFS-based flow ens. from Ens. Pre-Processor (EPP) and Ens. Post-Processor (EnsPost) compared w/clim-based flow ens.
Case Study: verification results

- EPP-EnsPost GFS-based flow ens. vs. Clim-based flow ens.

**Skill Score for Mean Continuous Ranked Probability Score (CRPSS) in reference to clim-flow ens.**

- Significant gain in skill from EPP-EnsPost at all lead times from 3 basins, more especially for larger flows
- Bias correction of ens. median but still under-forecasting bias for larger flows and over-forecasting of low-medium flows
Example of Experimental Ensembles from approach 1

GFS and CFS based ensembles: experimental products updated daily at Colorado RFC (CBRFC) & California-Nevada RFC (CNRFC)
Example of Experimental Ensembles from approach 2


2 types of products