Hydrologic Model Output Statistics (HMOS) Streamflow Ensemble Processor

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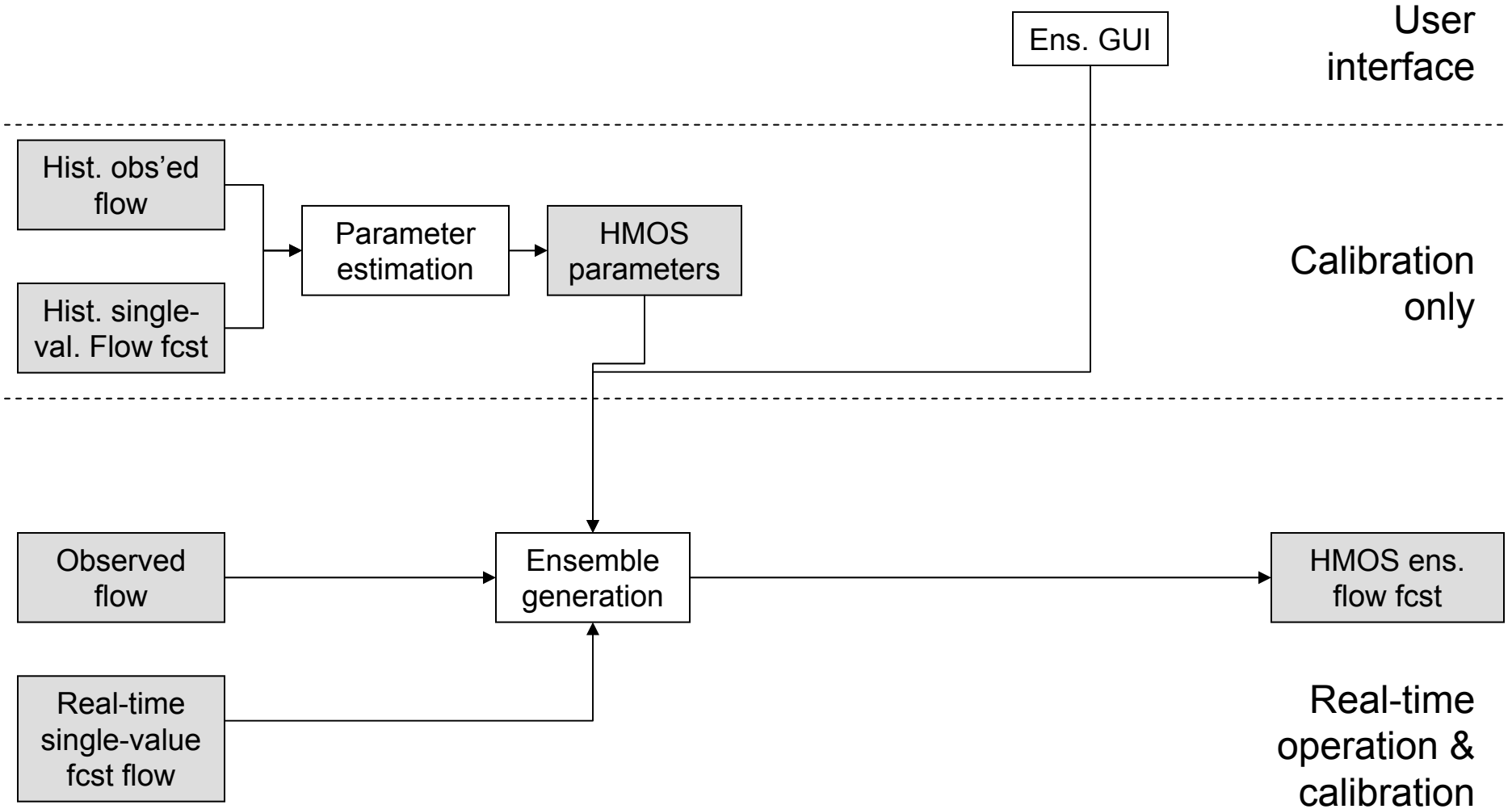
HMOS Streamflow Ensemble Processor

- Models the total (i.e. input + hydrologic) uncertainty in the operational single-value forecast
  - A simpler approach for short-term flow ensemble generation
  - Combines model output (i.e. operational single-value forecast) and recent observations statistically (cf Adjust-Q++)
  - Corrects, to the extent possible, systematic biases
  - Captures the skill in the single value operational forecast
  - Generates streamflow ensembles by propagating uncertainty in time
  - Needs multi-year archive of forecast and verifying observed stage/flow
- Key considerations
  - As parsimonious as possible
  - As much data-driven as possible

HMOS



From XEFS Design & Gap Analysis Report (NWS 2007)

HMOS: Parameter estimation

- Linear regression in normal space

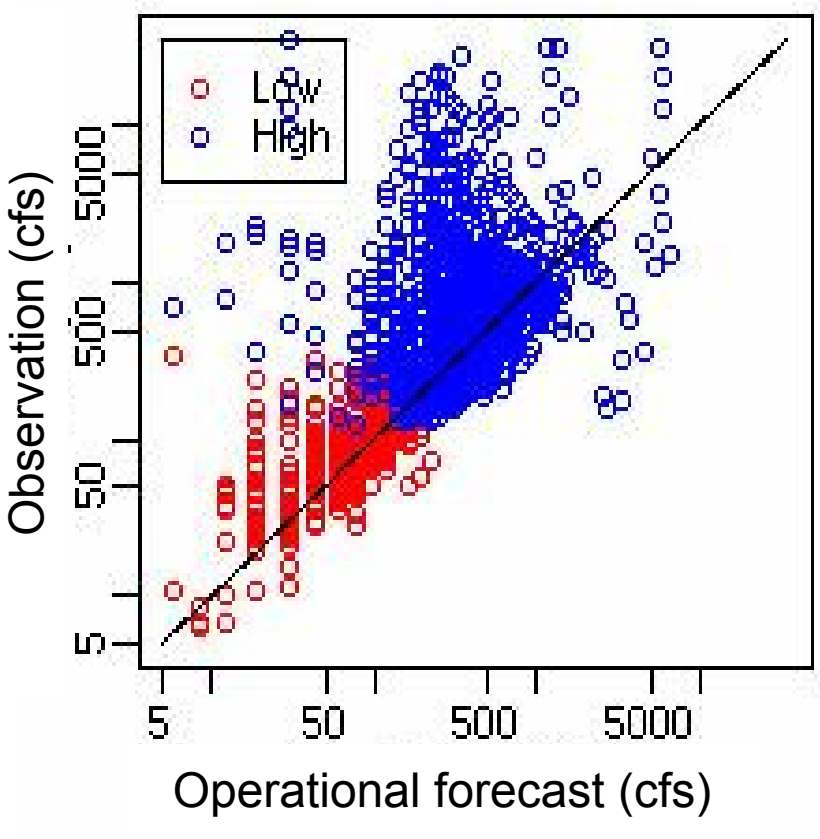
Predicted flow=(1-b) · Observed flow + b · Operational forecast

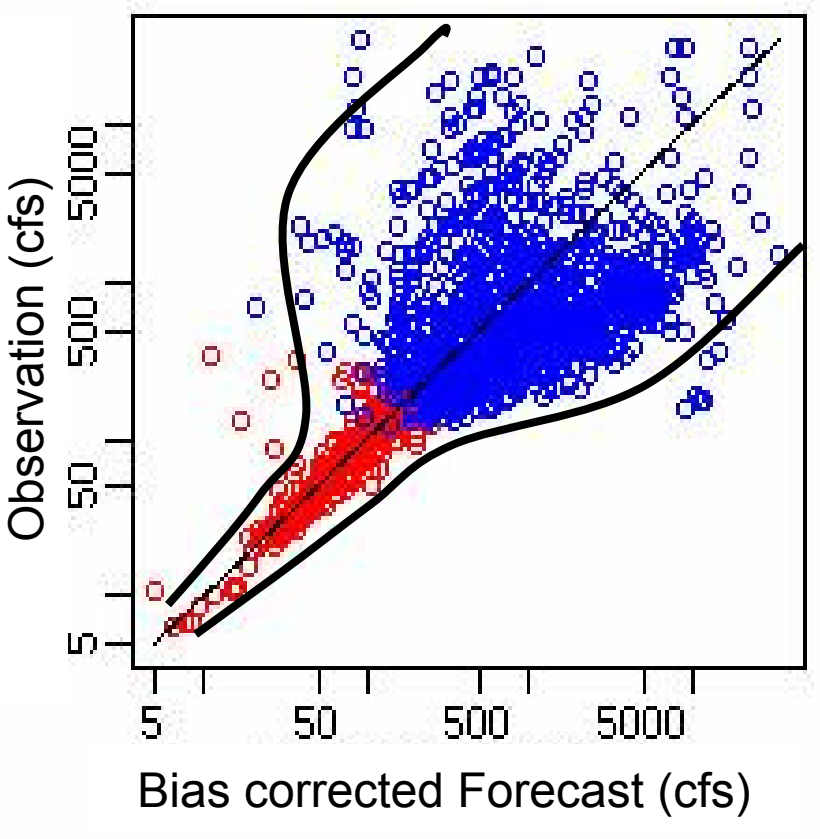
  - Estimate the optimal ‘b’ value that minimizes the objective function
  - $0 \leq b \leq 1$

- Minimization of the objective function

  - Minimize the scatter between the ensemble-mean forecast and the verifying observation
  - Probability-match the ensemble-mean forecast with the verifying observation

HMOS: Parameter Estimation (cont.)

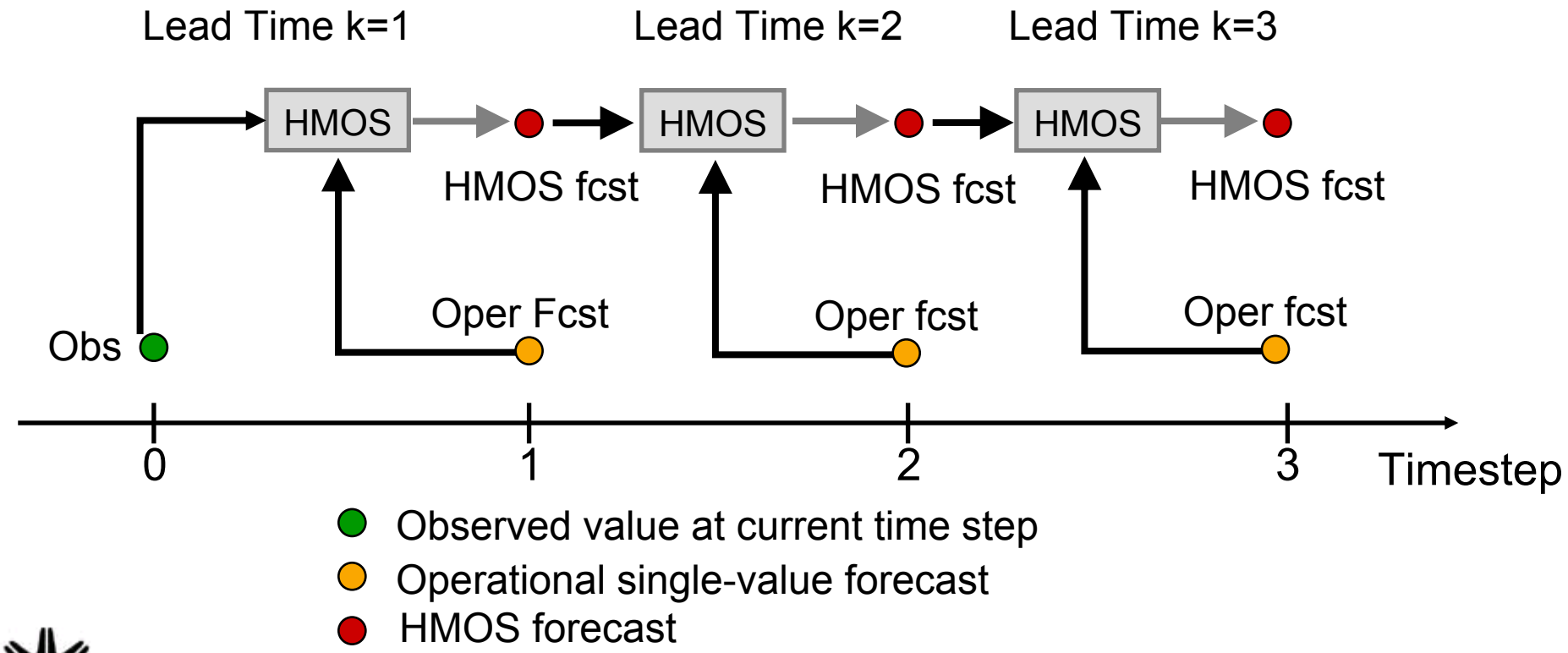




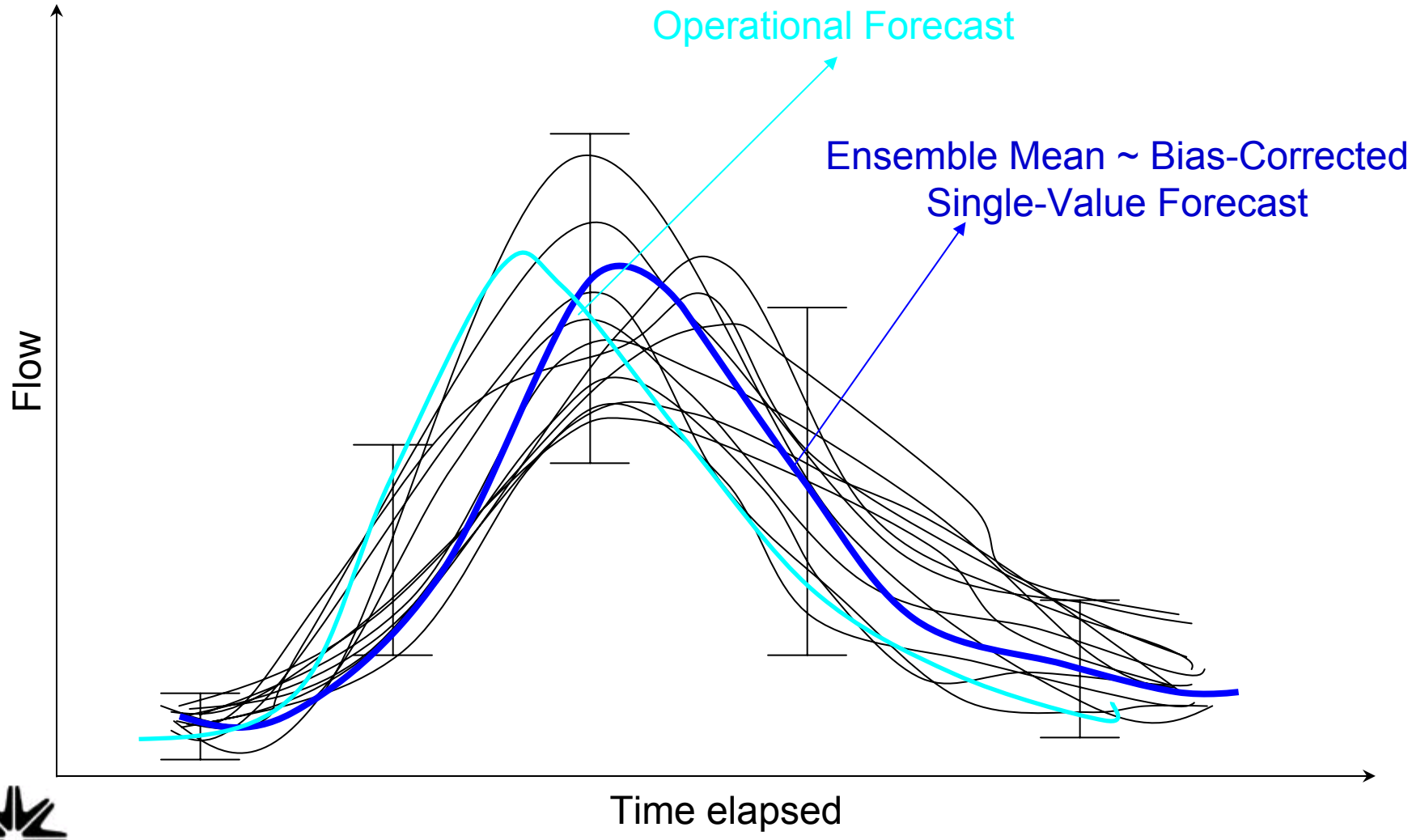
HMOS: Ensemble Generation

- Generates streamflow ensemble forecasts at a 6-hr time step

$$Z_k = (1-b_k) \bullet Z_{obs,k-1} + b_k \bullet Z_{fcst,k} + E_k$$



HMOS: Ensemble Generation (cont.)

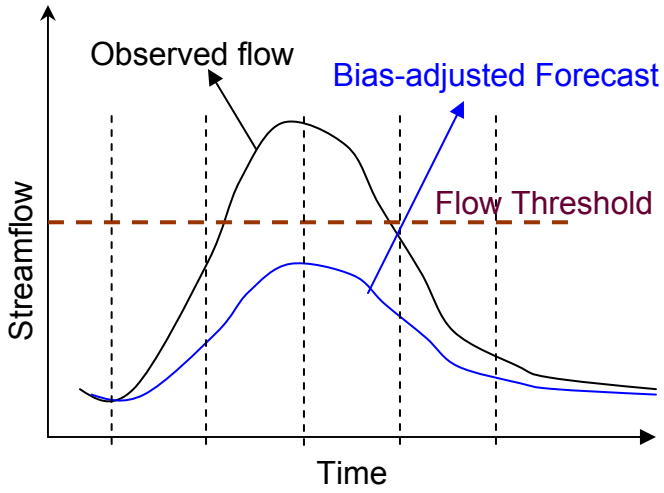


HMOS: Flow Classification

- Predictability varies greatly depending on the magnitude of flow
- HMOS classifies flow into low and high
  - Based on bias-corrected (via probability matching) operational single-value forecast

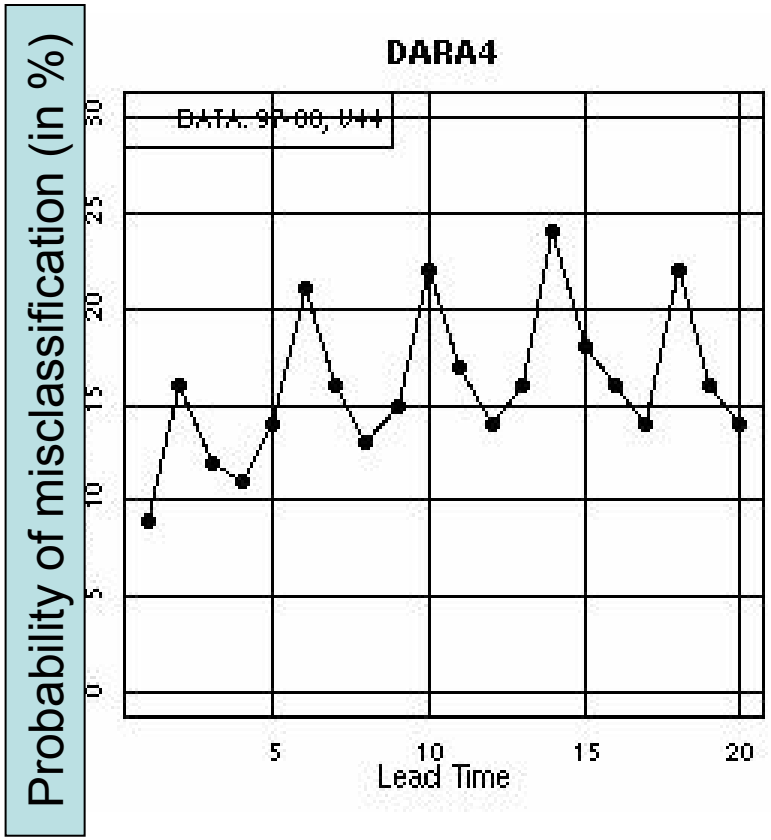
Q_{adj} =Bias-adjusted operational forecast

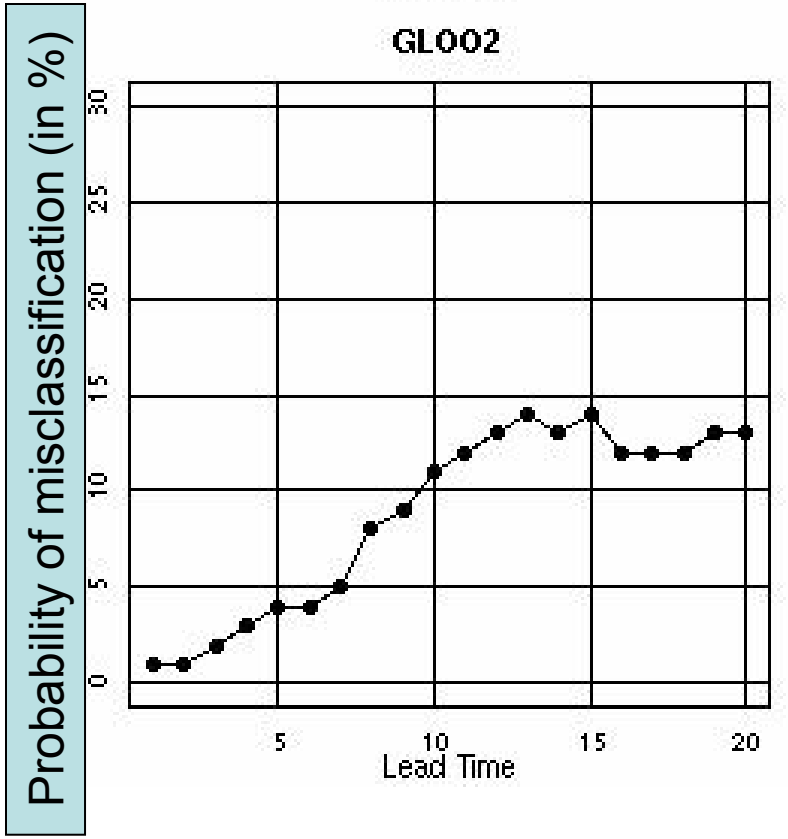
if (Q_{adj}< Threshold) then
    category=low
else
    category=high
endif



- HMOS accounts for misclassification of low and high flows in ensemble generation

Probabilities of misclassifying flow category



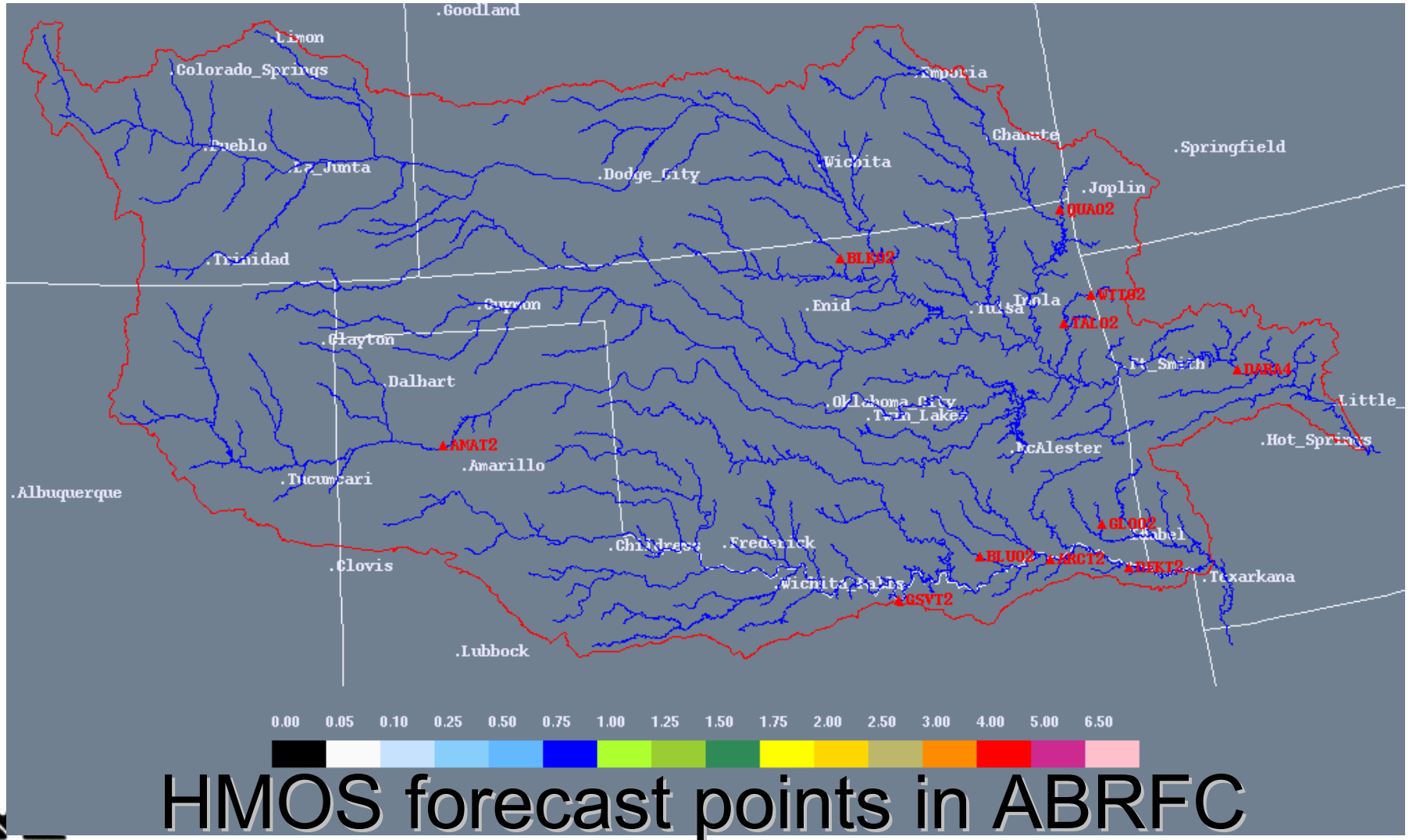


Number of ensembles correspond to High (observation) given Low (adjusted bias) **in a total of 100 ensembles**

HMOS: Limitations

- HMOS has limited “effective” lead time (QPF lead time + hydrologic memory)
  - Lack of (single-value) QPF beyond 12~24 hrs (at ABRFC)
  - No uncertainty decomposition
- Flows stratified into 2 categories only: high and low
- Seasonality not accounted for in the normal transformation
- Works well only under those conditions that are well captured in the historical archive

Large-sample verification results from multi-year hindcasting



HMOS forecast points in ABRFC

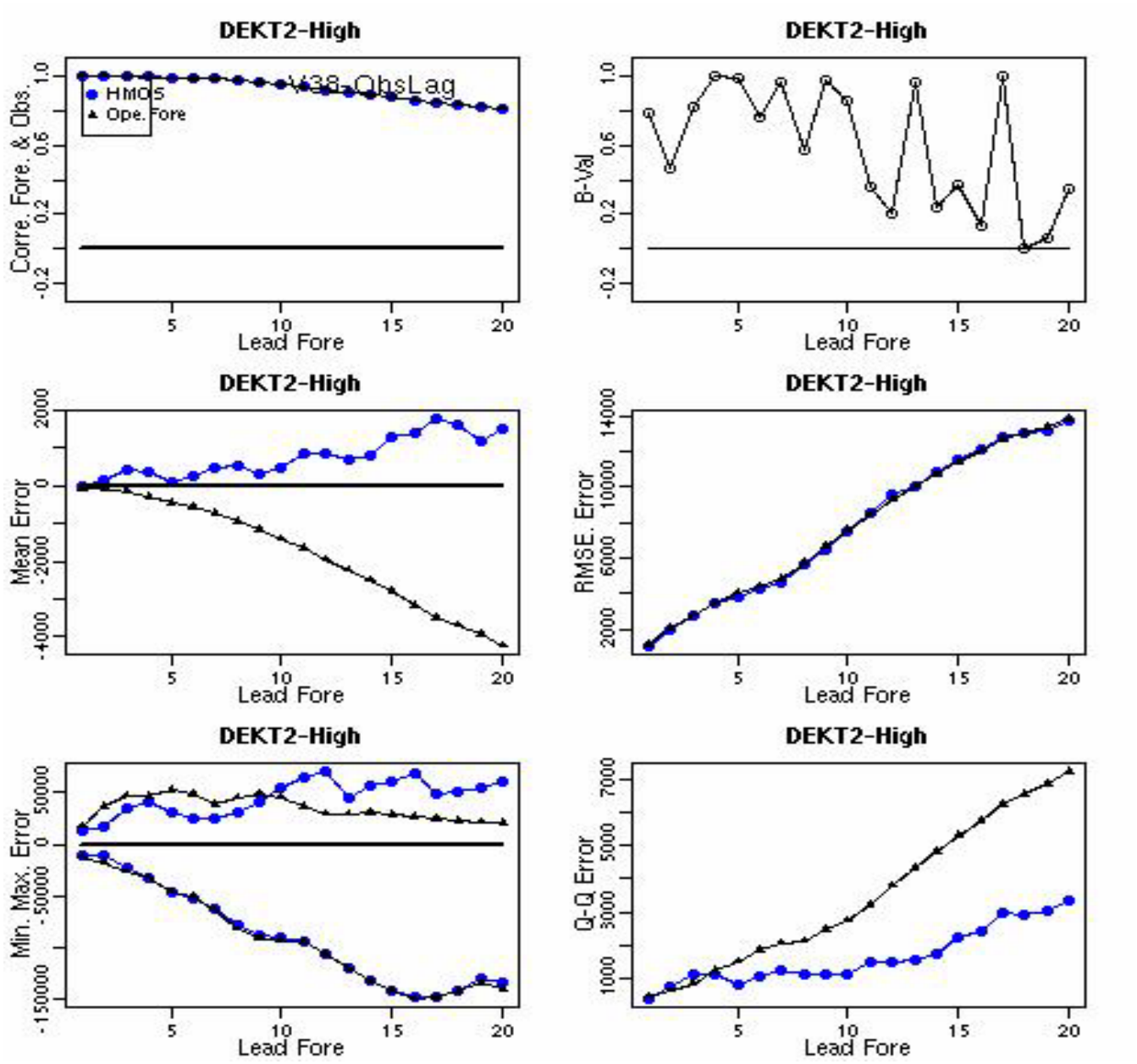
ABRFC HMOS Forecast Points (sorted by area)

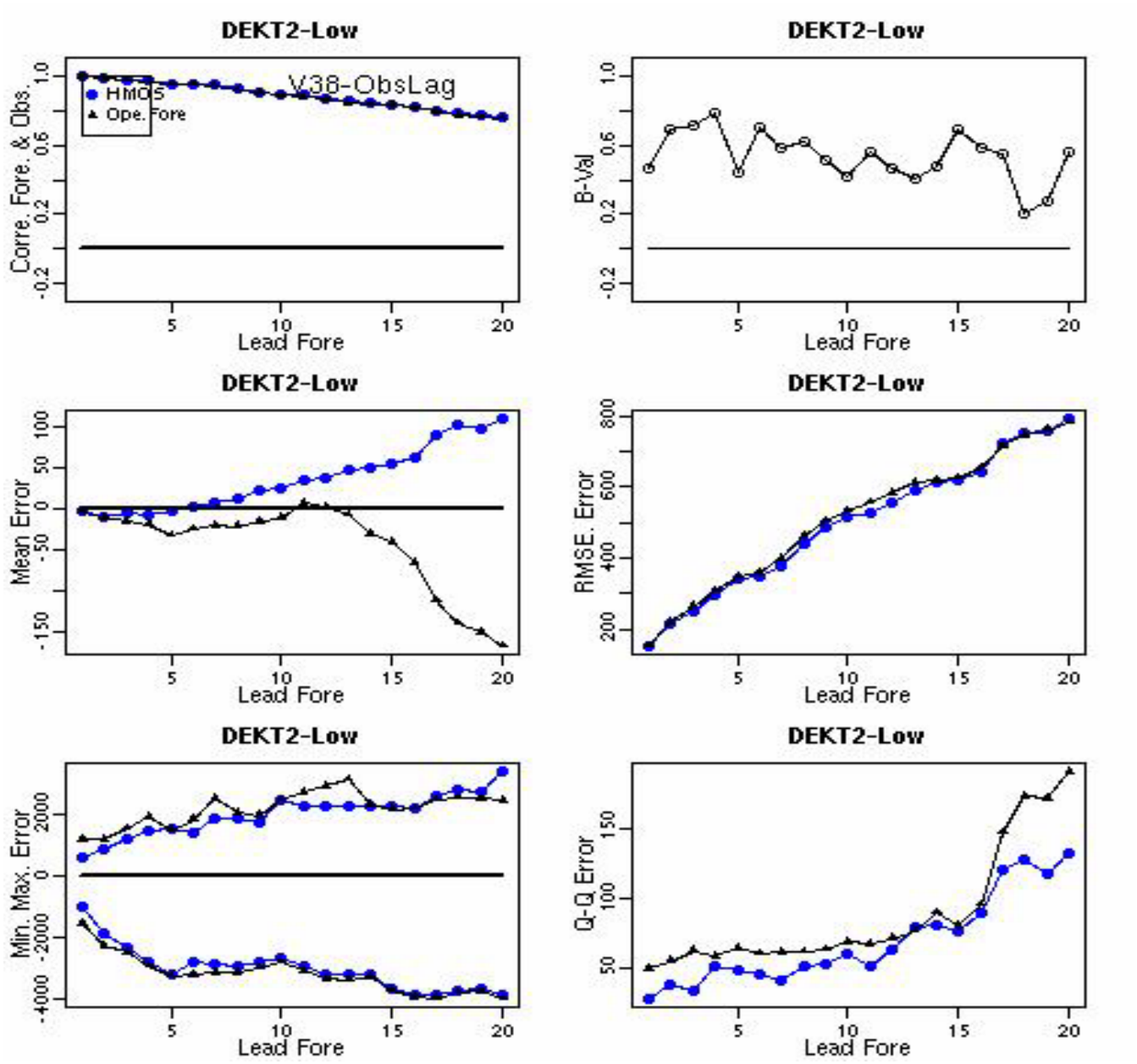
Basin	Total Drainage Area (square miles)	Rain fall (?"?)
Arkansas River near Dardanelle AR, [DARA4]	153671.75	37.5/(35.0-40.0)
Red River near Dekalb, TX [DEKT2]	47347.93	46.5/(46.0-47.0)
Red River near Arthur City, TX [ARCT2]	44530.92	46.8/(45.0-50.0)
Red River near Gainesville, TX [GSVT2]	30782.00	47.0/(45.0-50.0)
Spring River near Quapaw, OK [QUAO2]	2510.00	41.0/(40.0-45.0)
Chickaskia River near Blackwell, OK [BLKO2]	1859.00	44.1/(40.0-45.0)
Illinois River near Tahlequah, OK [TALO2]	959.00	33.0/(32.5-35.0)
Illinois River near Watts, OK [WTTO2]	635.00	46.1/(45.0-50.0)
Blue River near Blue, OK [BLUO2]	476.00	43.0/(40.0-45.0)
Glover River near Glover, OK [GLOO2]	315.00	44.6/(40.0-45.0)

Data

- Forecasts
  - Single-value operational stage forecasts issued at 6-hour interval for 5-days into the future from February 1997 to March 2008
  - Based on 12hr-ahead QPF
  - Reflect all MODs
  - Reflect input and hydrological uncertainties

Parameter Estimation Results


DEKT2-High
V38_QbsLag
HMOS
Ope. Fore
Corre. Fore. & Obs.
Lead Fore
DEKT2-High
B-Val
Lead Fore
DEKT2-High
Mean Error
Lead Fore
DEKT2-High
RMSE. Error
Lead Fore
DEKT2-High
Min. Max. Error
Lead Fore
DEKT2-High
Q-Q Error
Lead Fore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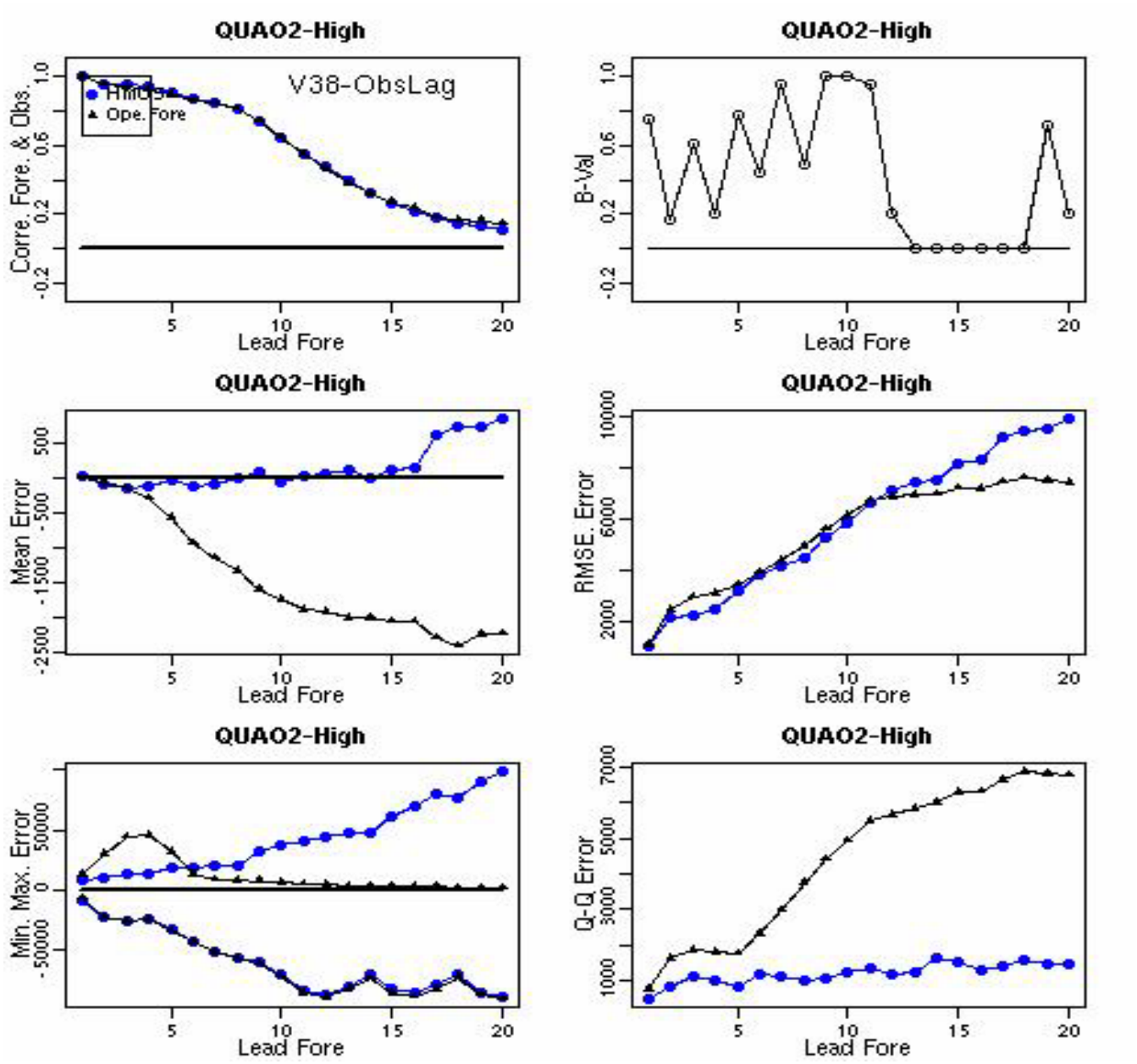
V38-ObsLag
HMOS
Ope. Fore
Corre. Fore. & Obs.
Lead Fore
DEKT2-Low
B-Val
Lead Fore
DEKT2-Low
Mean Error
Lead Fore
DEKT2-Low
RMSE. Error
Lead Fore
DEKT2-Low
Min. Max. Error
Lead Fore
DEKT2-Low
Q-Q Error
Lead Fore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Lead Fore
QUAO2-High
Mean Error
Lead Fore
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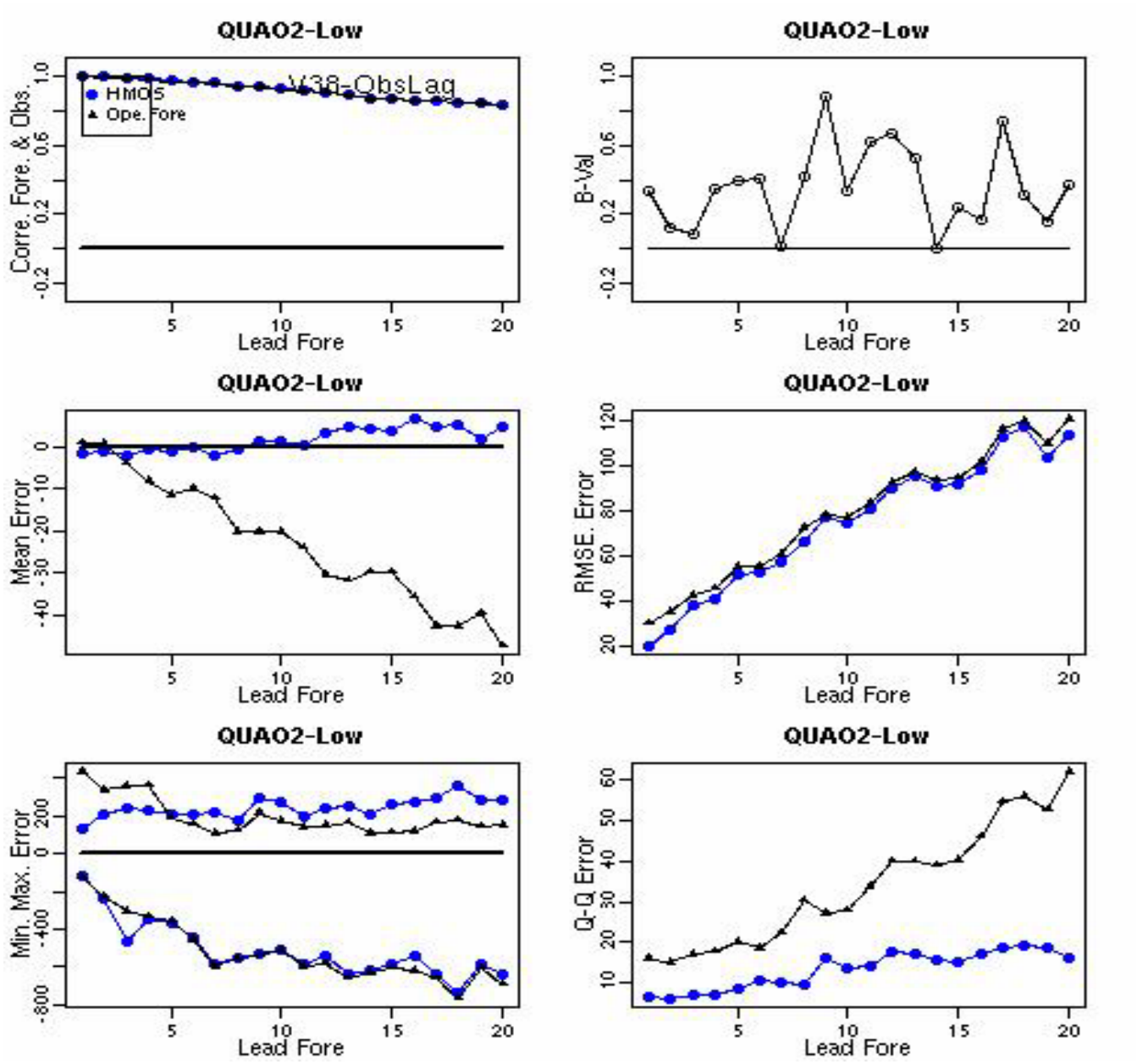
Lead Fore
QUAO2-High
Q-Q Error
Lead Fore


QUAO2-Low
V38-ObsLag
HMOS
Ope. Fore
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Lead Fore
QUAO2-Low
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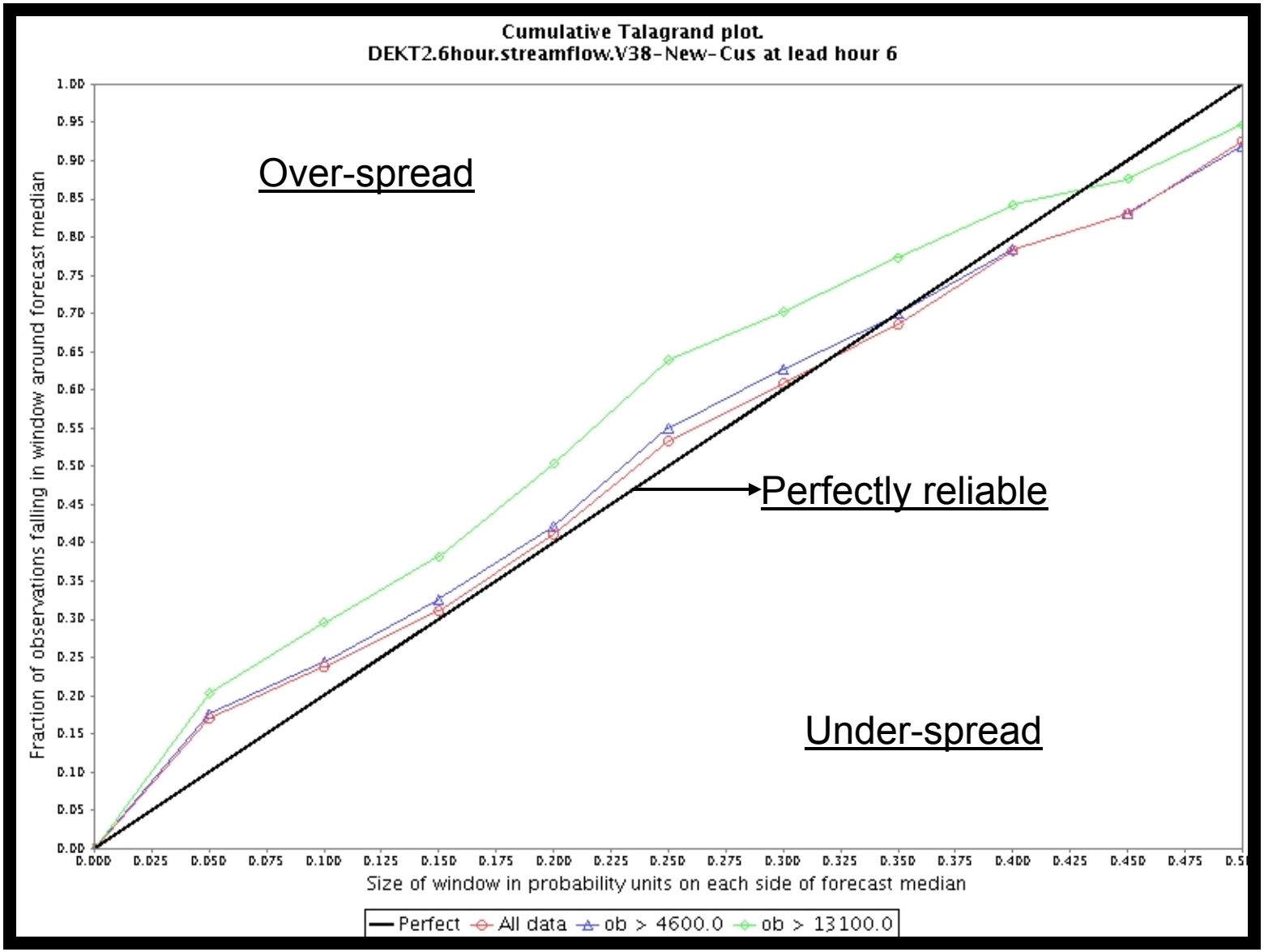
Lead Fore
QUAO2-Low
Mean Error
Lead Fore
QUAO2-Low
RMSE. Error
Lead Fore
QUAO2-Low
Min. Max. Error
Lead Fore
QUAO2-Low
Q-Q Error
Lead Fore

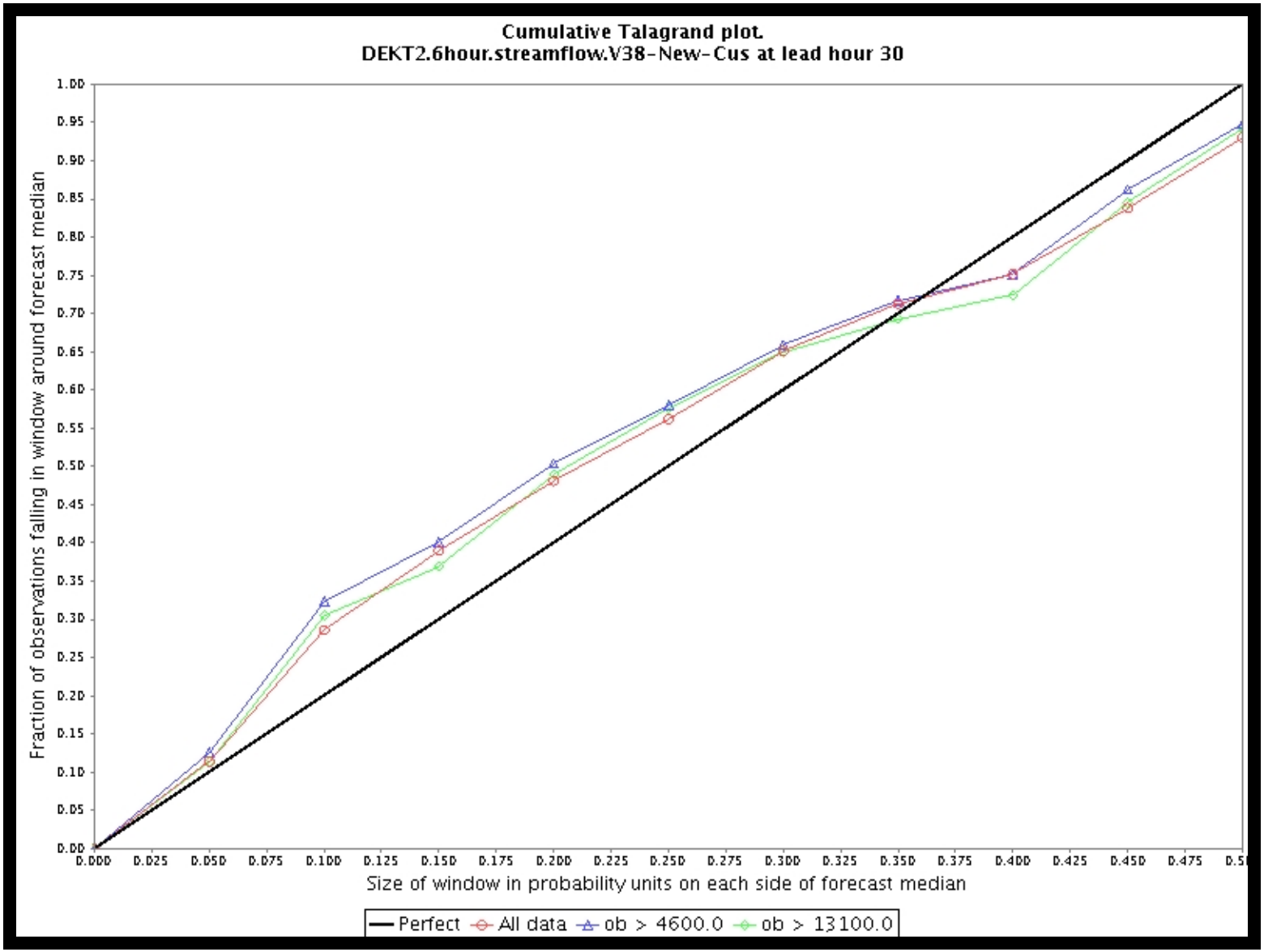
Ensemble Generation Results

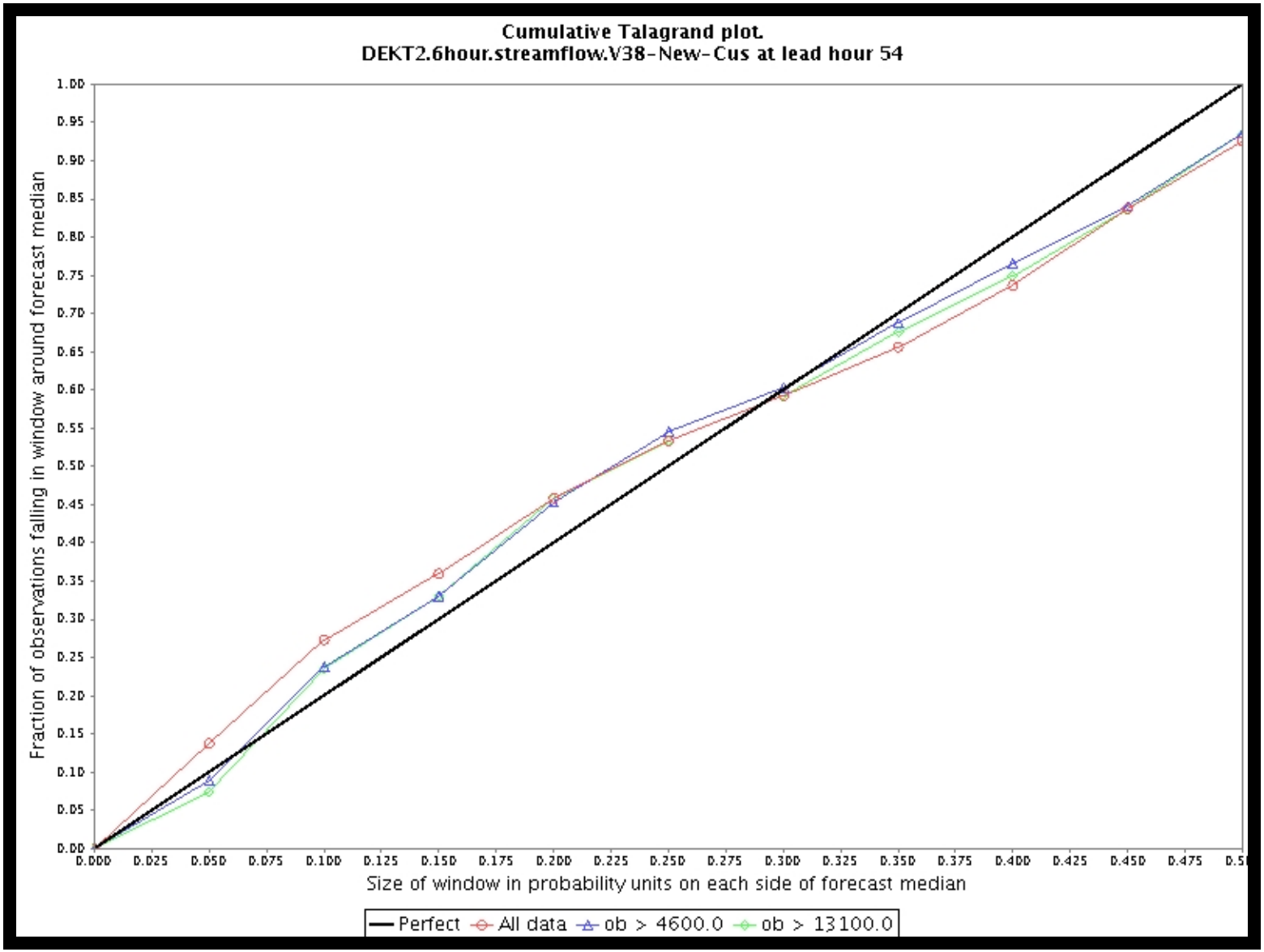
(Dependent) Verification

- Based on 10-yr hindcasts for 10 forecast points in ABRFC
- Ensemble Verification System (EVS) used

Basin	Total Drainage Area (square miles)	Precipitation (?"?)	Sample size (years)
Arkansas River near Dardanelle AR, [DARA4]	153671.75	37.5/(35.0-40.0)	2335 (6.40)
Red River near Dekalb, TX [DEKT2]	**47347.93**	**46.5/(46.0-47.0)**	**2219 (6.08)**
Red River near Arthur City, TX [ARCT2]	44530.92	46.8/(45.0-50.0)	1534 (4.20)
Red River near Gainesville, TX [GSVT2]	30782.00	47.0/(45.0-50.0)	1676 (4.59)
Spring River near Quapaw, OK [QUAO2]	**2510.00**	**41.0/(40.0-45.0)**	**1316 (3.61)**
Chickaskia River near Blackwell, OK [BLKO2]	1859.00	44.1/(40.0-45.0)	2167 (5.94)
Illinois River near Tahlequah, OK [TALO2]	959.00	33.0/(32.5-35.0)	2313 (6.34)
Illinois River near Watts, OK [WTTO2]	635.00	46.1/(45.0-50.0)	2418 (6.62)
Blue River near Blue, OK [BLUO2]	476.00	43.0/(40.0-45.0)	2046 (5.61)
Glover River near Glover, OK [GLOO2]	315.00	44.6/(40.0-45.0)	1897 (5.20)


Cumulative Talagrand plot.
DEKT2.6hour.streamflow.V38-New-Cus at lead hour 6
Over-spread
Perfectly reliable
Under-spread
Fraction of observations falling in window around forecast median
Size of window in probability units on each side of forecast median
Perfect
All data
ob > 4600.0
ob > 13100.0


Cumulative Talagrand plot.
DEKT2.6hour.streamflow.V38-New-Cus at lead hour 30
Fraction of observations falling in window around forecast median
1.00
0.95
0.90
0.85
0.80
0.75
0.70
0.65
0.60
0.55
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0.000
0.025
0.050
0.075
0.100
0.125
0.150
0.175
0.200
0.225
0.250
0.275
0.300
0.325
0.350
0.375
0.400
0.425
0.450
0.475
Size of window in probability units on each side of forecast median
Perfect
All data
ob > 4600.0
ob > 13100.0


Cumulative Talagrand plot.
DEKT2.6hour.streamflow.V38-New-Cus at lead hour 54
Fraction of observations falling in window around forecast median
1.00
0.95
0.90
0.85
0.80
0.75
0.70
0.65
0.60
0.55
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
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0.175
0.200
0.225
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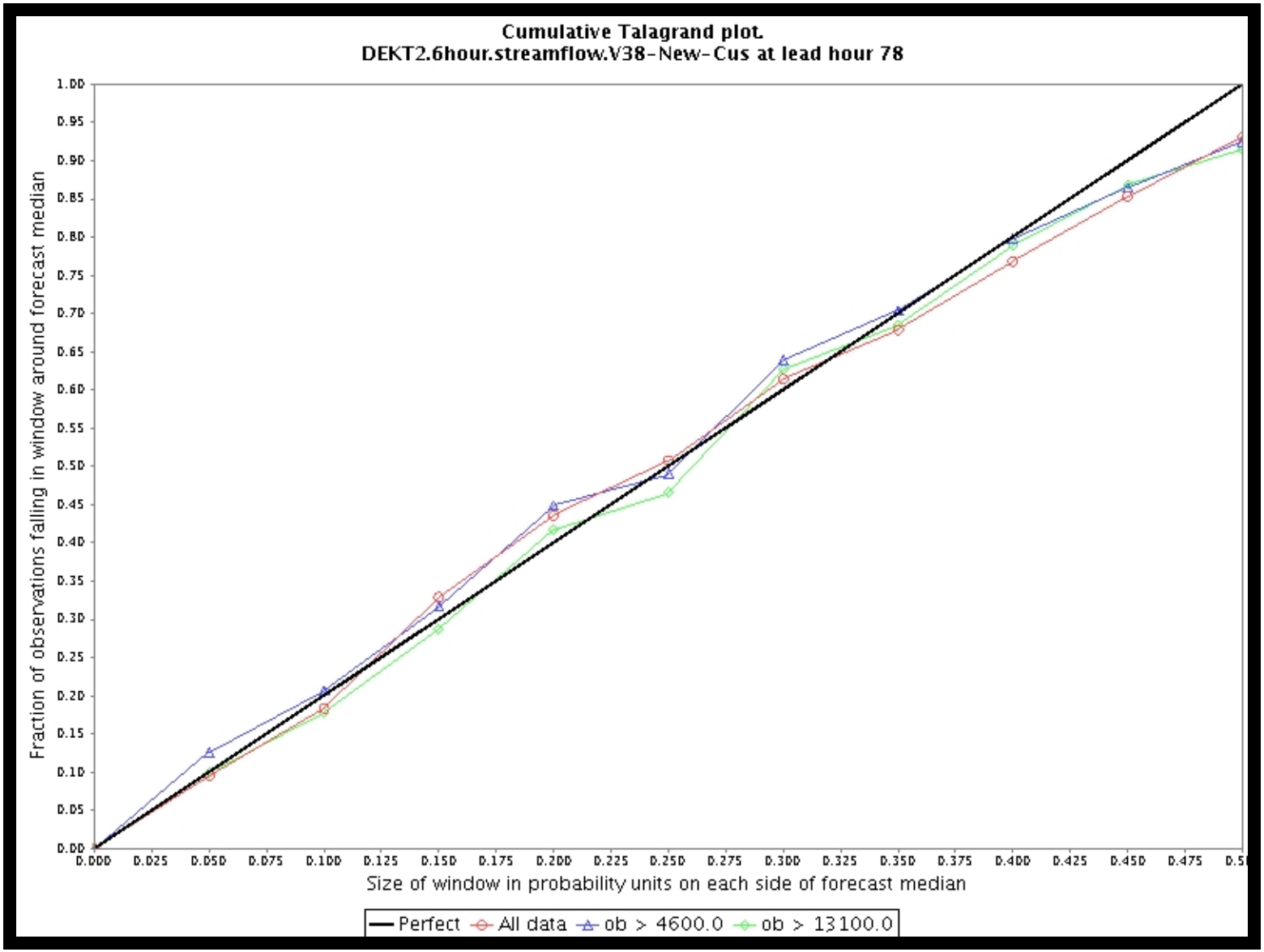
0.275
0.300
0.325
0.350
0.375
0.400
0.425
0.450
0.475
Size of window in probability units on each side of forecast median
Perfect
All data
ob > 4600.0
ob > 13100.0


Cumulative Talagrand plot.
DEKT2.6hour.streamflow.V38-New-Cus at lead hour 78
Fraction of observations falling in window around forecast median
1.00
0.95
0.90
0.85
0.80
0.75
0.70
0.65
0.60
0.55
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
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0.025
0.050
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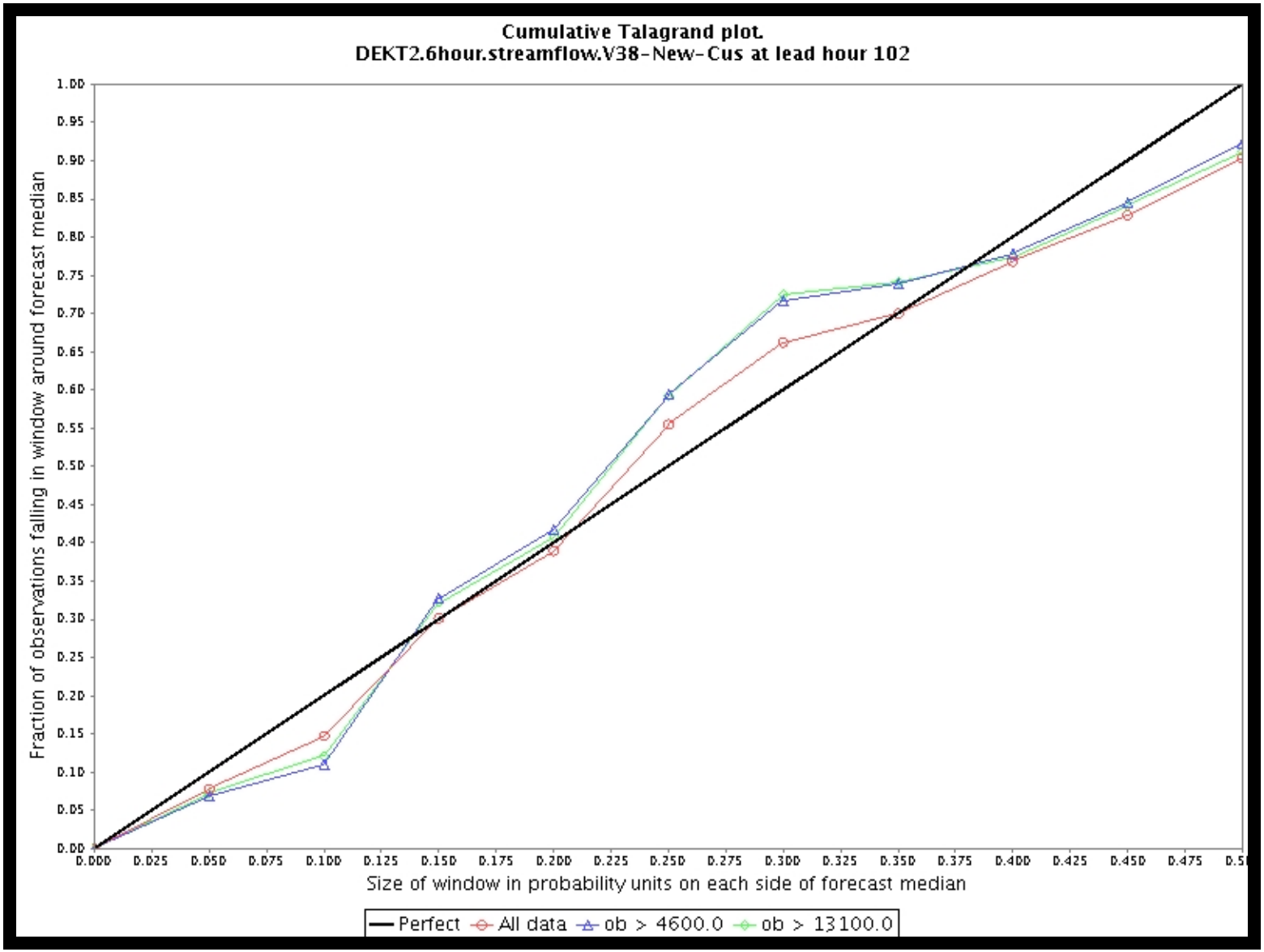
0.125
0.150
0.175
0.200
0.225
0.250
0.275
0.300
0.325
0.350
0.375
0.400
0.425
0.450
0.475
Size of window in probability units on each side of forecast median
Perfect
All data
ob > 4600.0
ob > 13100.0


Cumulative Talagrand plot.
DEKT2.6hour.streamflow.V38-New-Cus at lead hour 102
Fraction of observations falling in window around forecast median
1.00
0.95
0.90
0.85
0.80
0.75
0.70
0.65
0.60
0.55
0.50
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0.025
0.050
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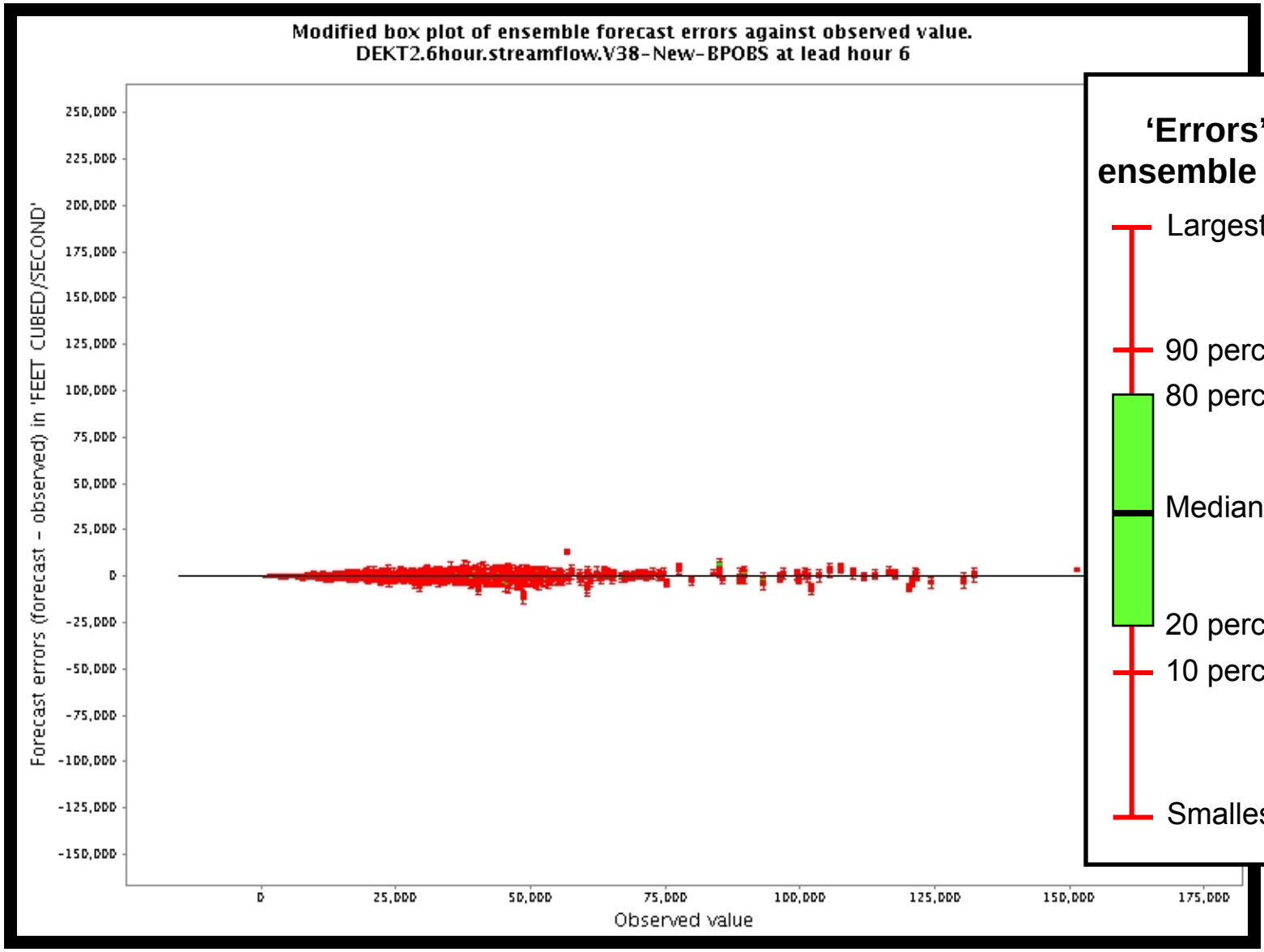
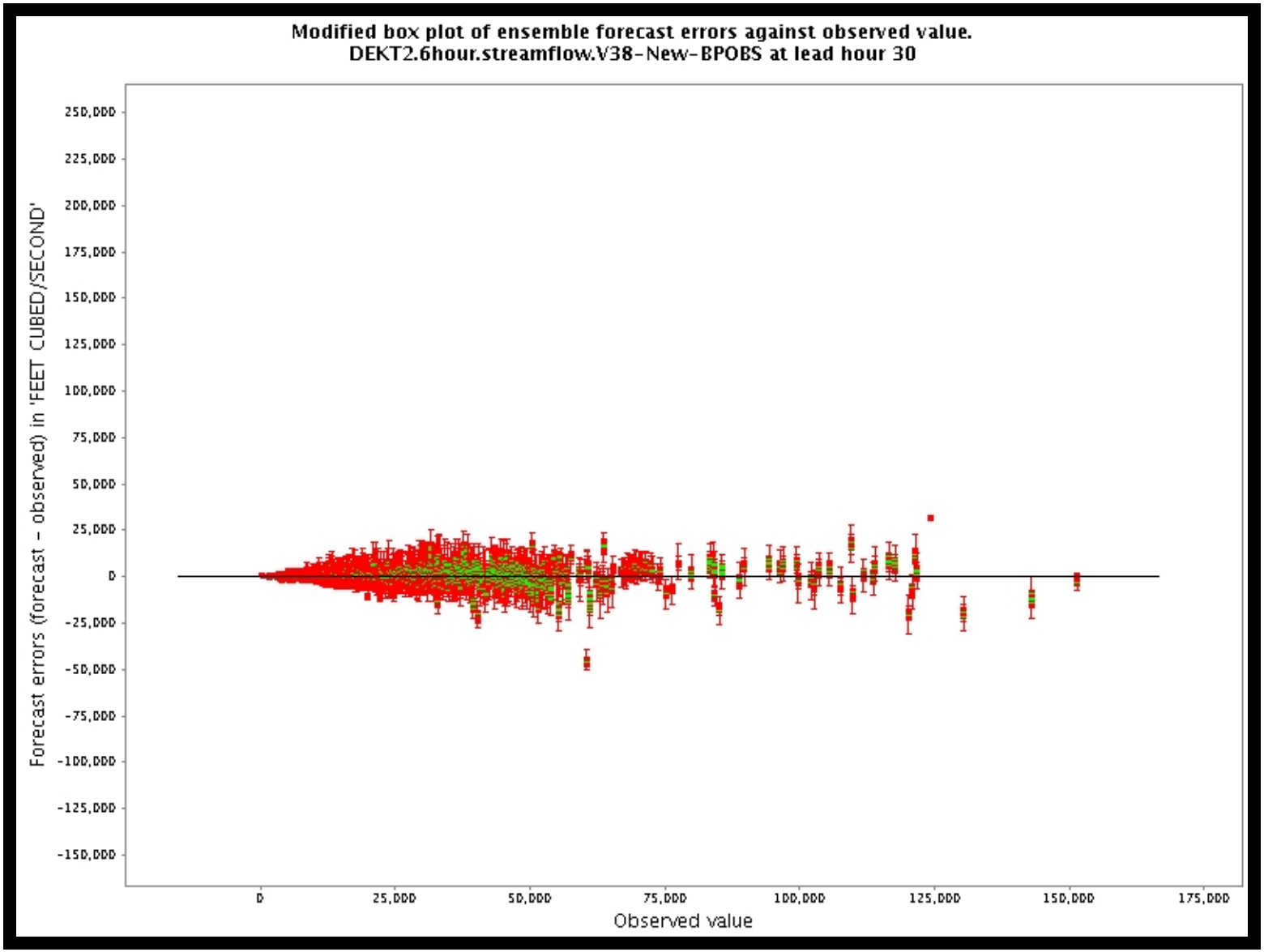
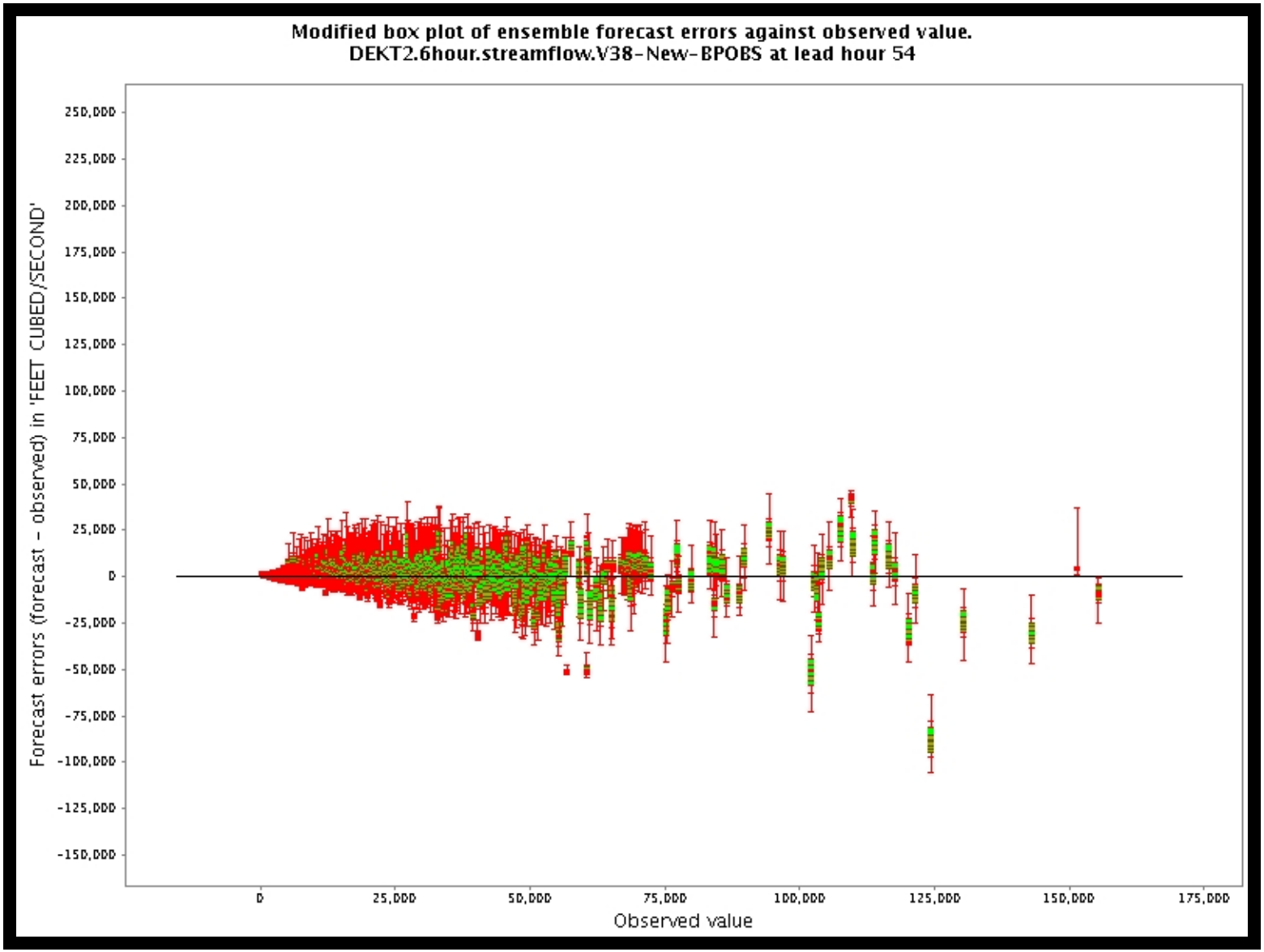
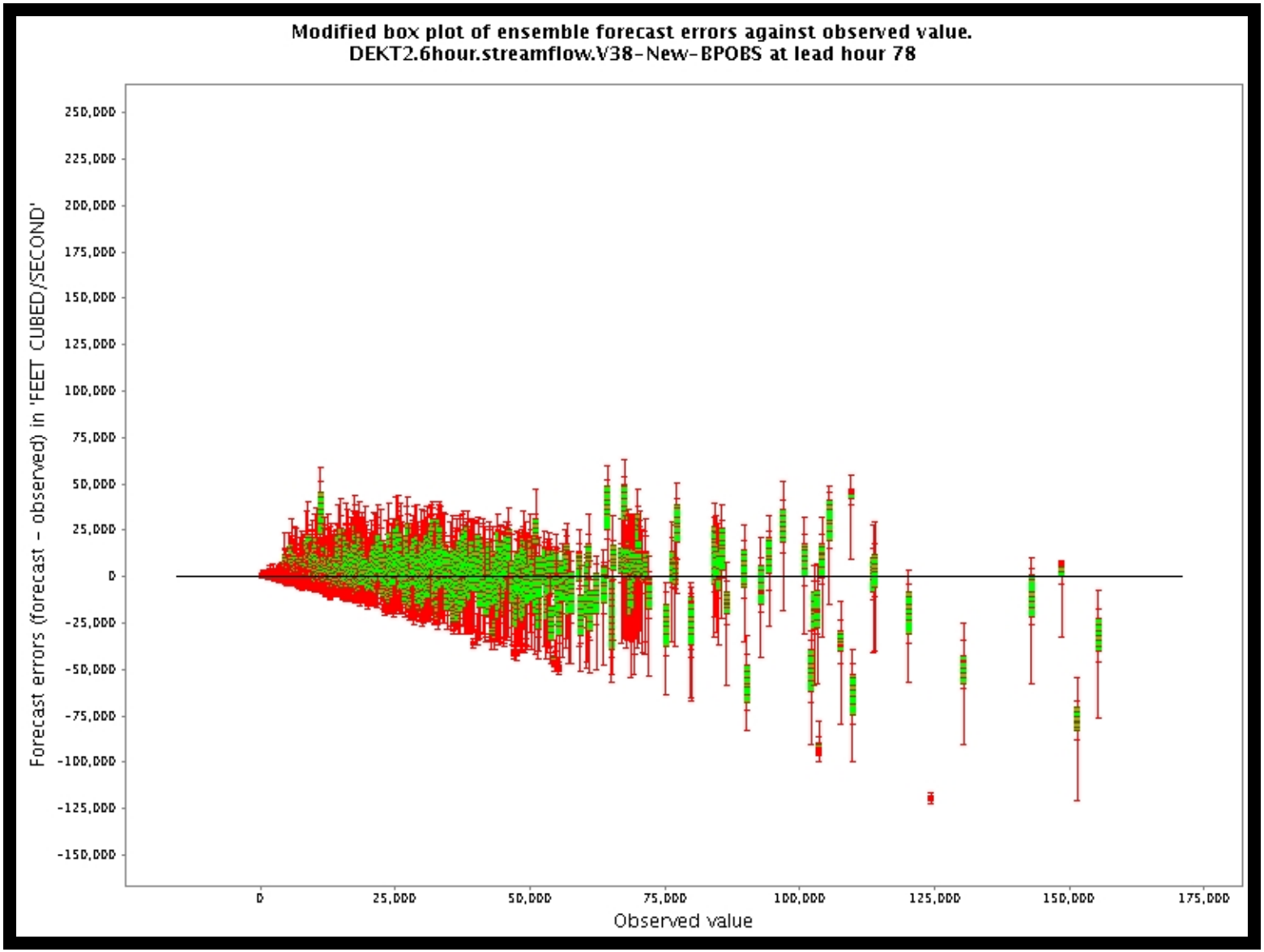
0.200
0.225
0.250
0.275
0.300
0.325
0.350
0.375
0.400
0.425
0.450
0.475
Size of window in probability units on each side of forecast median
Perfect
All data
ob > 4600.0
ob > 13100.0


Modified box plot of ensemble forecast errors against observed value.
DEKT2.6hour.streamflow.V38-New-BPOBS at lead hour 6
Forecast errors (forecast - observed) in 'FEET CUBED/SECOND'
250,000
225,000
200,000
175,000
150,000
125,000
100,000
75,000
50,000
25,000
0
-25,000
-50,000
-75,000
-100,000
-125,000
-150,000
0
25,000
50,000
75,000
100,000
125,000
150,000
175,000
Observed value
'Errors' for 1 ensemble forecast
Largest member
90 percent.
80 percent.
Median
20 percent.
10 percent.
Smallest member


Modified box plot of ensemble forecast errors against observed value.
DEKT2.6hour.streamflow.V38-New-BPOBS at lead hour 30
Forecast errors (forecast - observed) in 'FEET CUBED/SECOND'
250,000
225,000
200,000
175,000
150,000
125,000
100,000
75,000
50,000
25,000
0
-25,000
-50,000
-75,000
-100,000
-125,000
-150,000
0
25,000
50,000
75,000
100,000
125,000
150,000
175,000
Observed value


Modified box plot of ensemble forecast errors against observed value.
DEKT2.6hour.streamflow.V38-New-BPOBS at lead hour 54
Forecast errors (forecast - observed) in 'FEET CUBED/SECOND'
250,000
225,000
200,000
175,000
150,000
125,000
100,000
75,000
50,000
25,000
0
-25,000
-50,000
-75,000
-100,000
-125,000
-150,000
0
25,000
50,000
75,000
100,000
125,000
150,000
175,000
Observed value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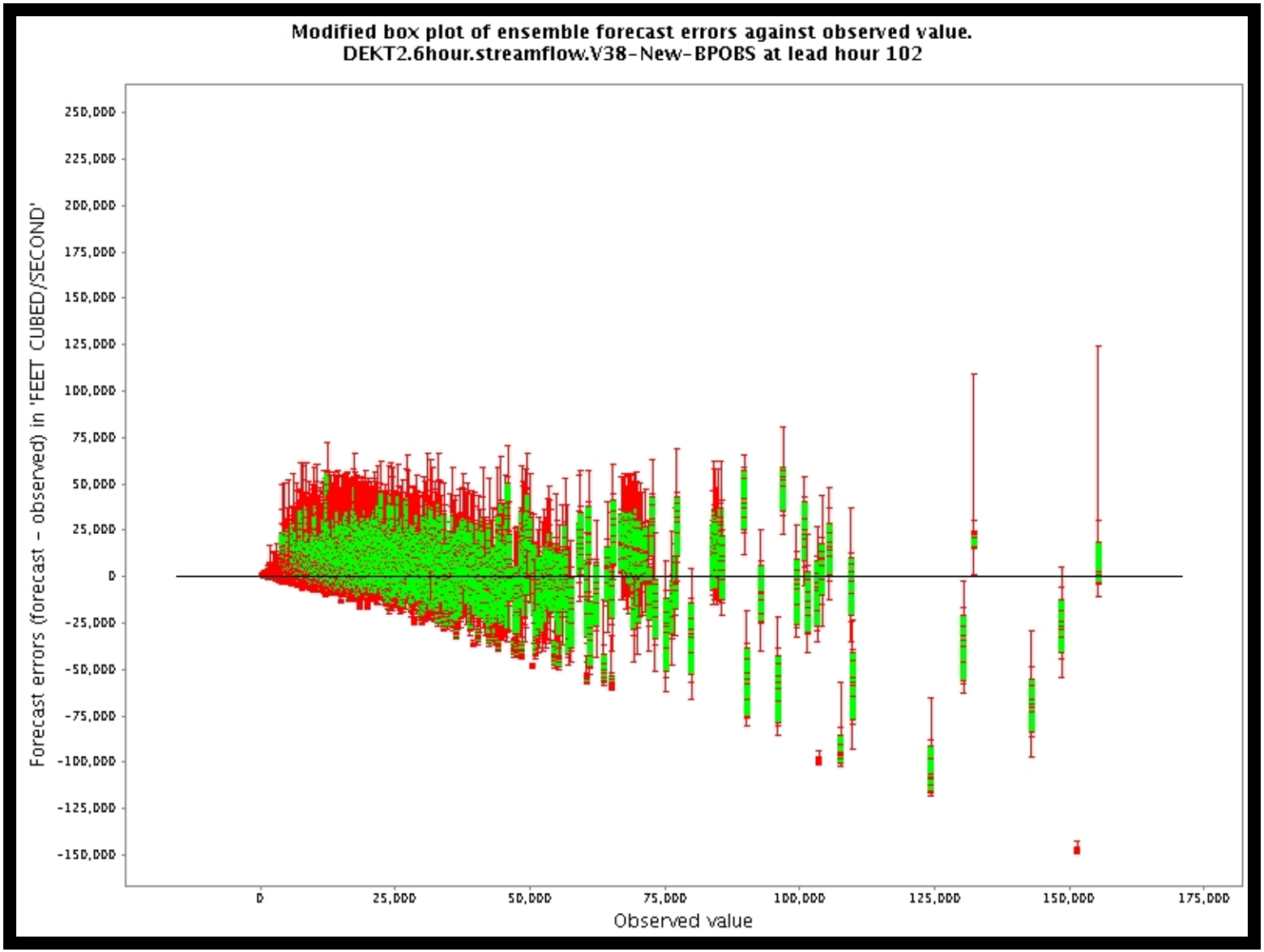
DEKT2.6hour.streamflow.V38-New-BPOBS at lead hour 78
Forecast errors (forecast - observed) in 'FEET CUBED/SECOND'
250,000
225,000
200,000
175,000
150,000
125,000
100,000
75,000
50,000
25,000
0
-25,000
-50,000
-75,000
-100,000
-125,000
-150,000
0
25,000
50,000
75,000
100,000
125,000
150,000
175,000
Observed value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DEKT2.6hour.streamflow.V38-New-BPOBS at lead hour 102
Forecast errors (forecast - observed) in 'FEET CUBED/SECOND'
250,000
225,000
200,000
175,000
150,000
125,000
100,000
75,000
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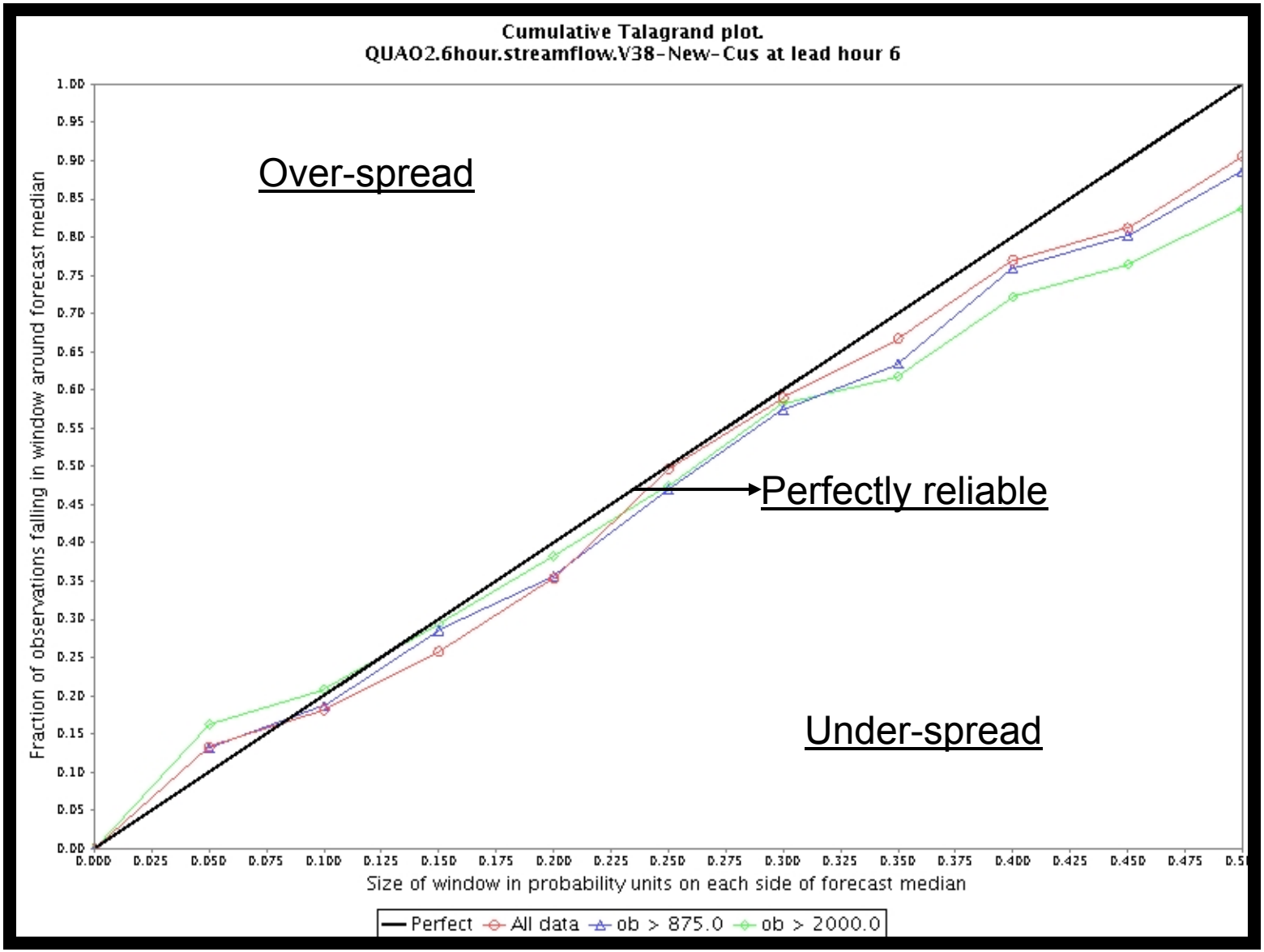
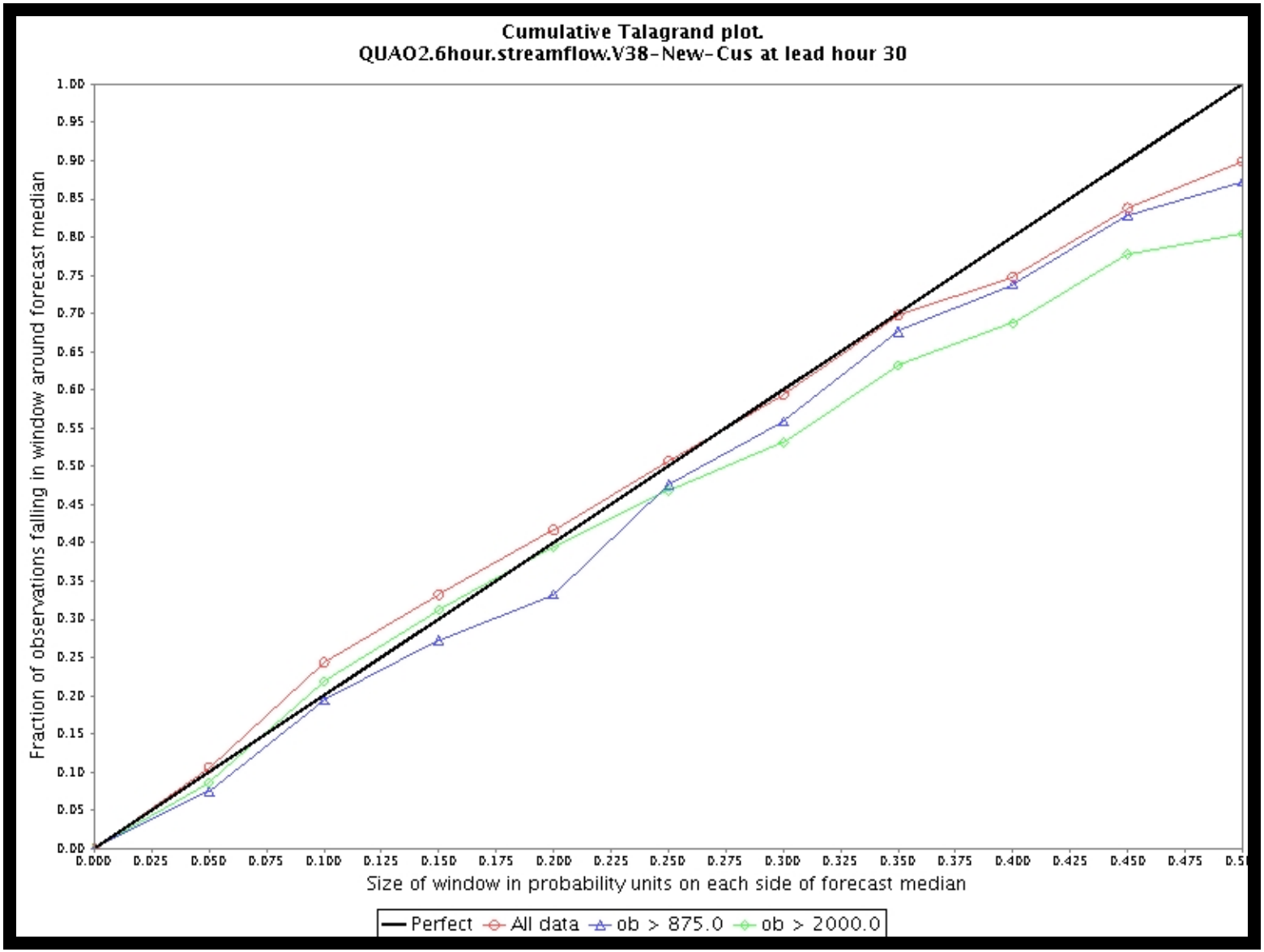
25,000
0
-25,000
-50,000
-75,000
-100,000
-125,000
-150,000
0
25,000
50,000
75,000
100,000
125,000
150,000
175,000
Observed value


Cumulative Talagrand plot.
QUAO2.6hour.streamflow.V38-New-Cus at lead hour 6
Over-spread
Perfectly reliable
Under-spread
Fraction of observations falling in window around forecast median
Size of window in probability units on each side of forecast median
Perfect
All data
ob > 875.0
ob > 2000.0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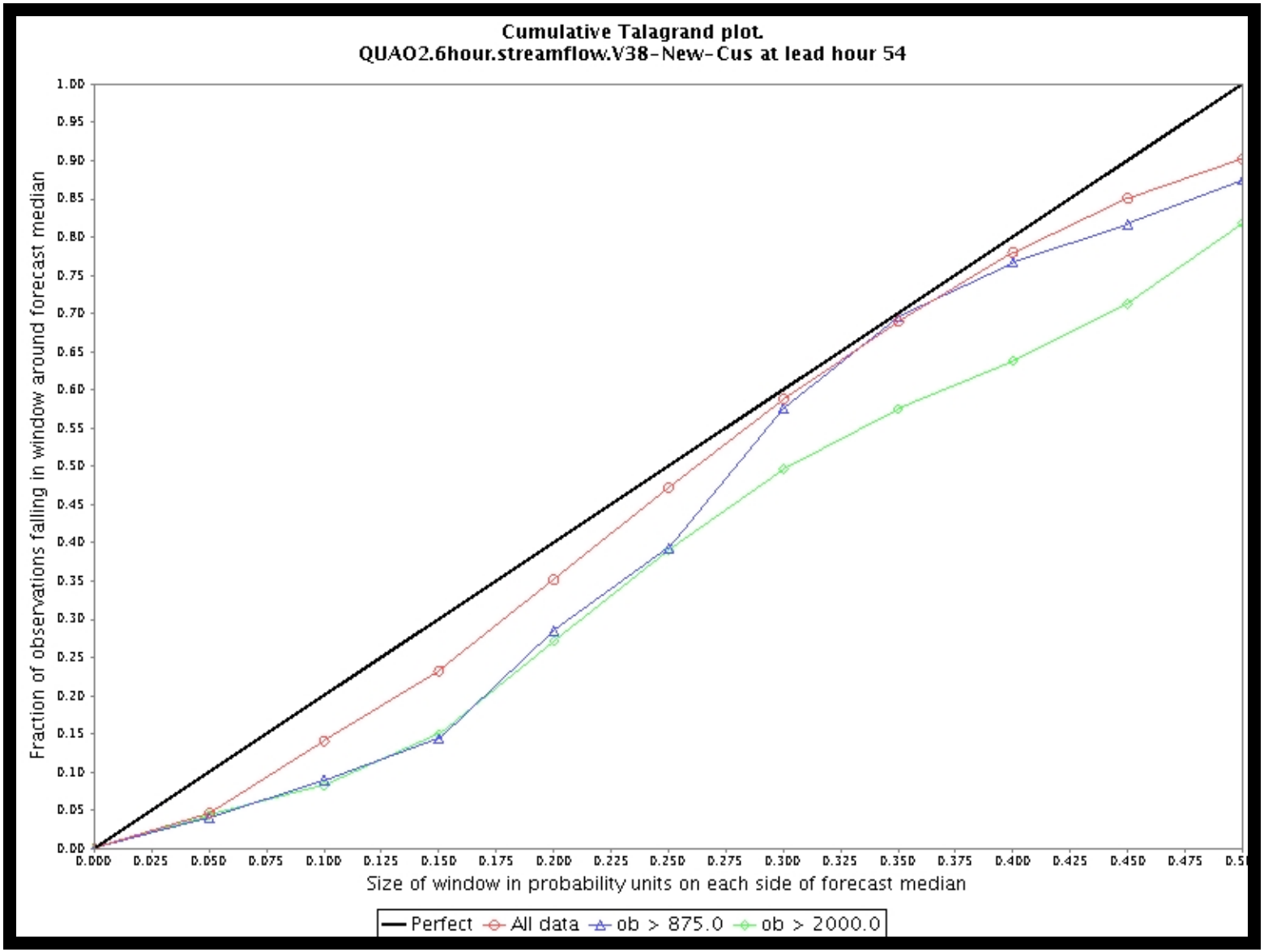
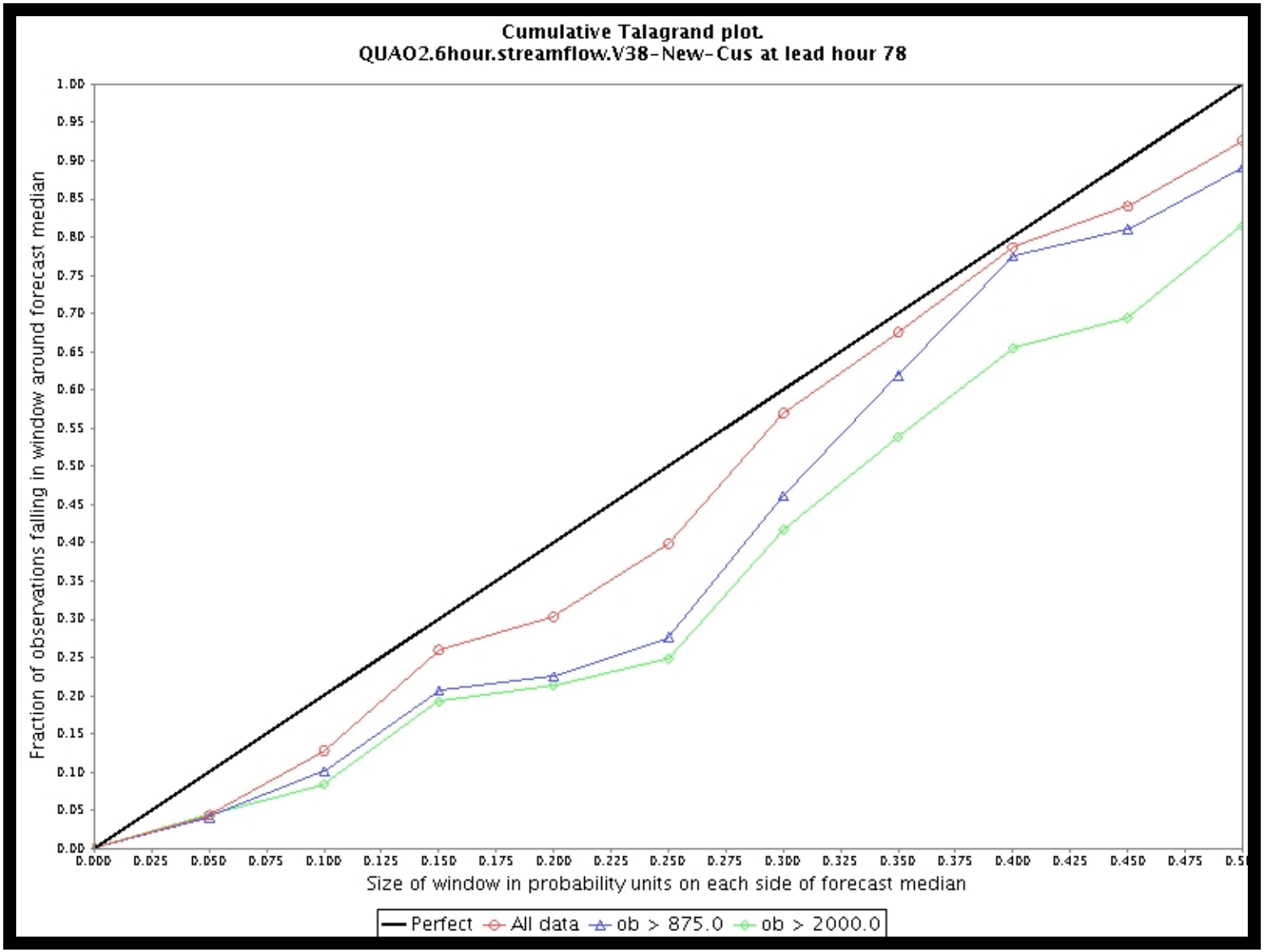
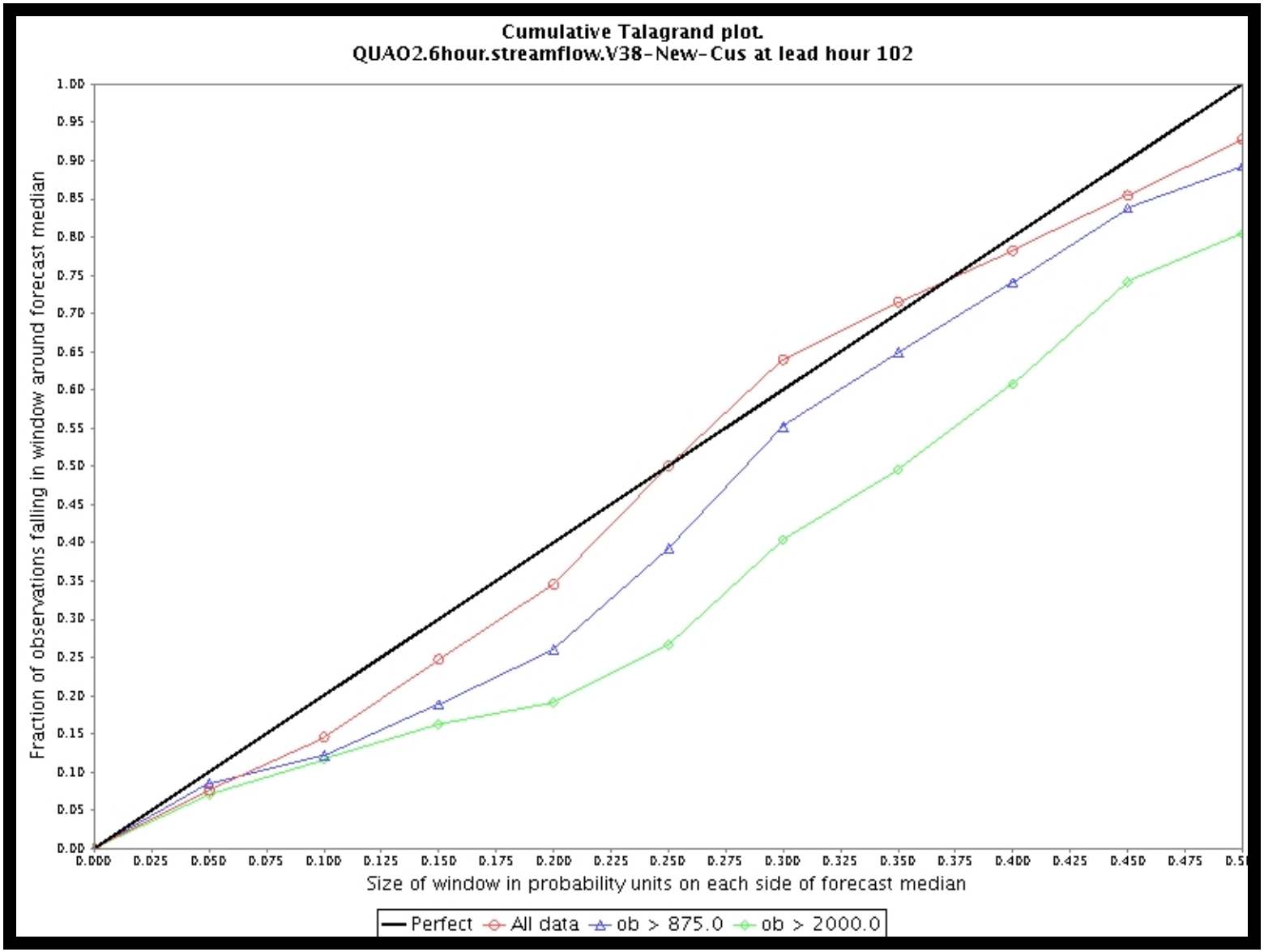
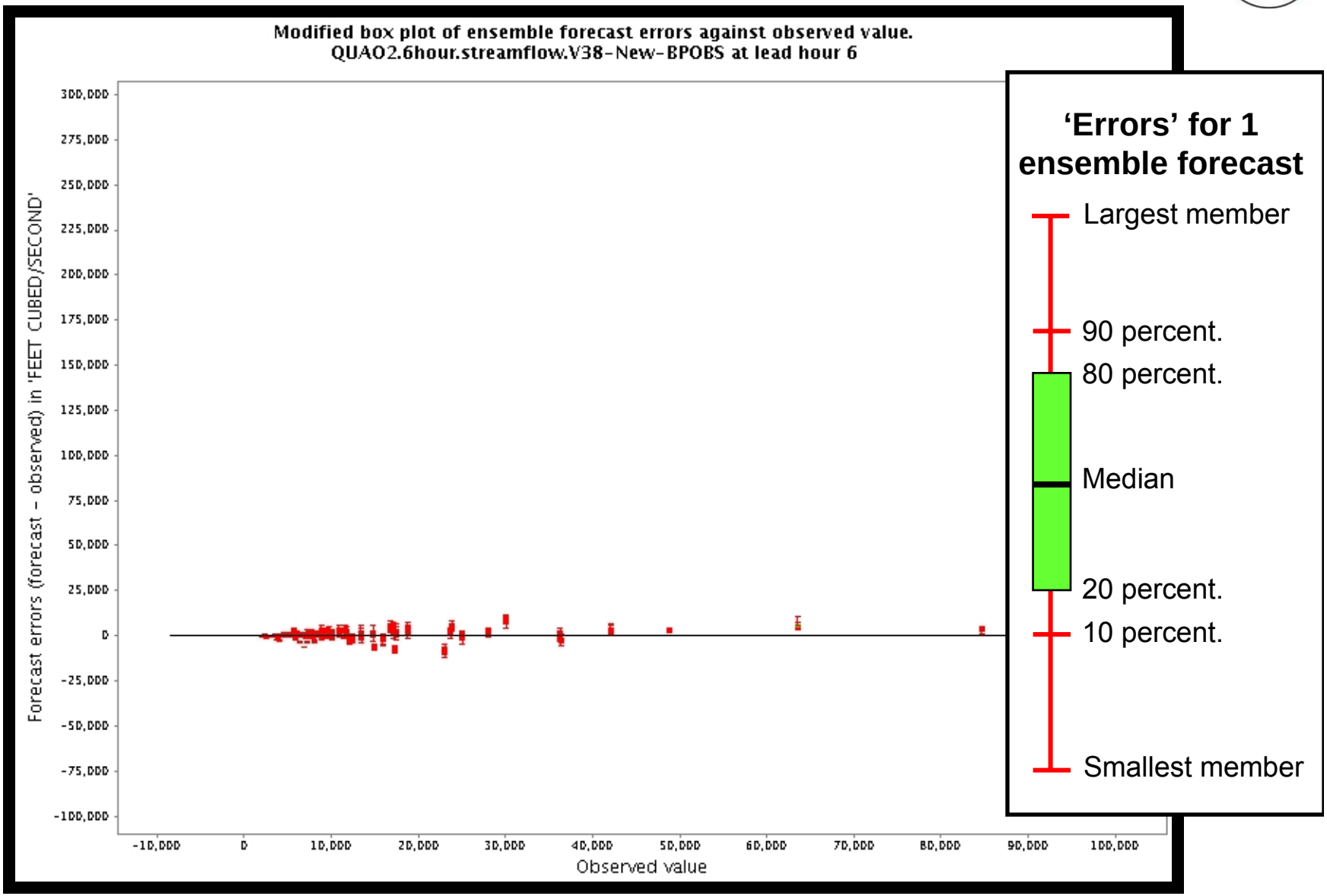
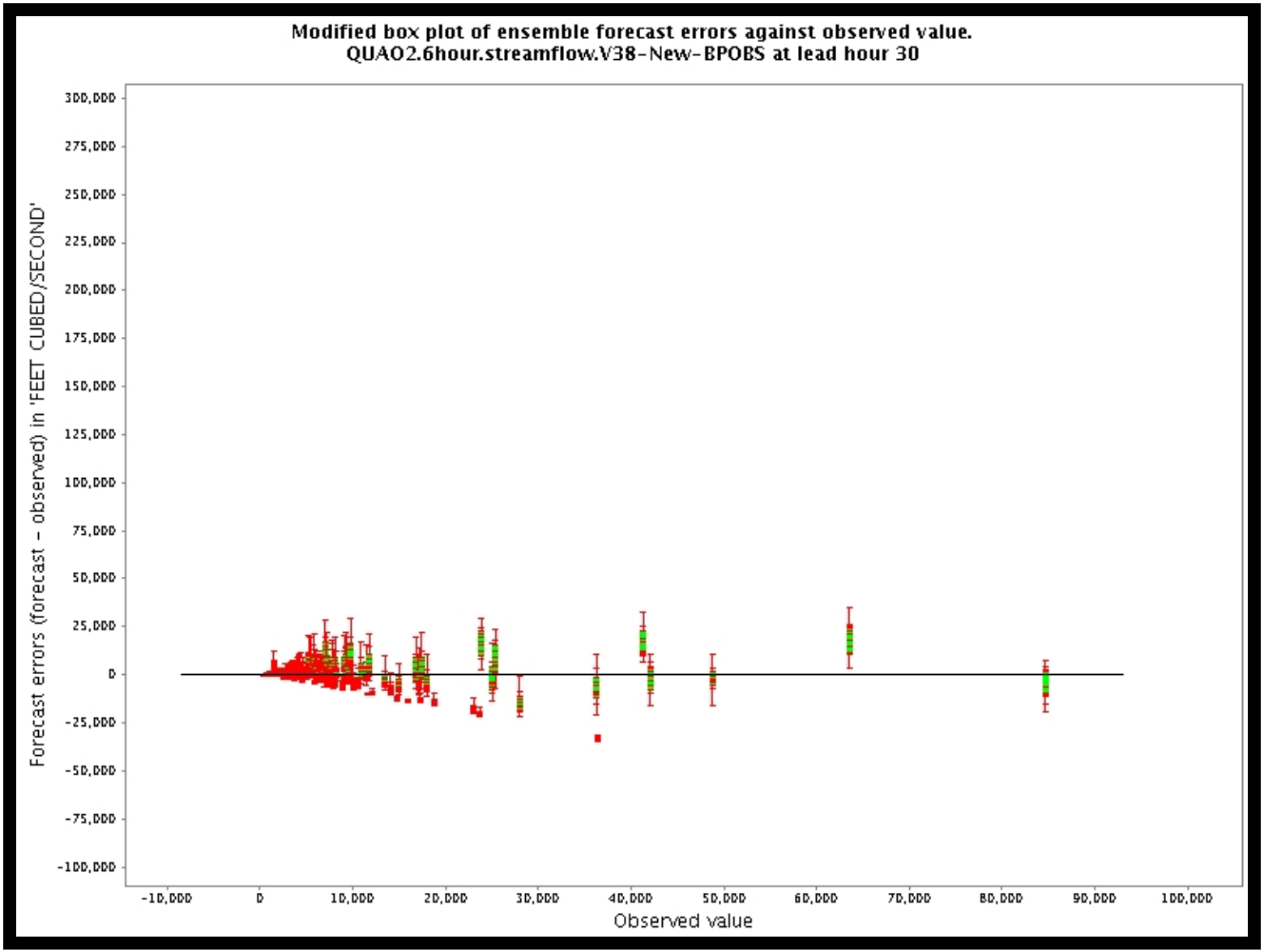
QUAO2.6hour.streamflow.V38-New-Cus at lead hour 30
Fraction of observations falling in window around forecast median
1.00
0.95
0.90
0.85
0.80
0.75
0.70
0.65
0.60
0.55
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0.000
0.025
0.050
0.075
0.100
0.125
0.150
0.175
0.200
0.225
0.250
0.275
0.300
0.325
0.350
0.375
0.400
0.425
0.450
0.475
Size of window in probability units on each side of forecast median
Perfect
All data
ob > 875.0
ob > 2000.0

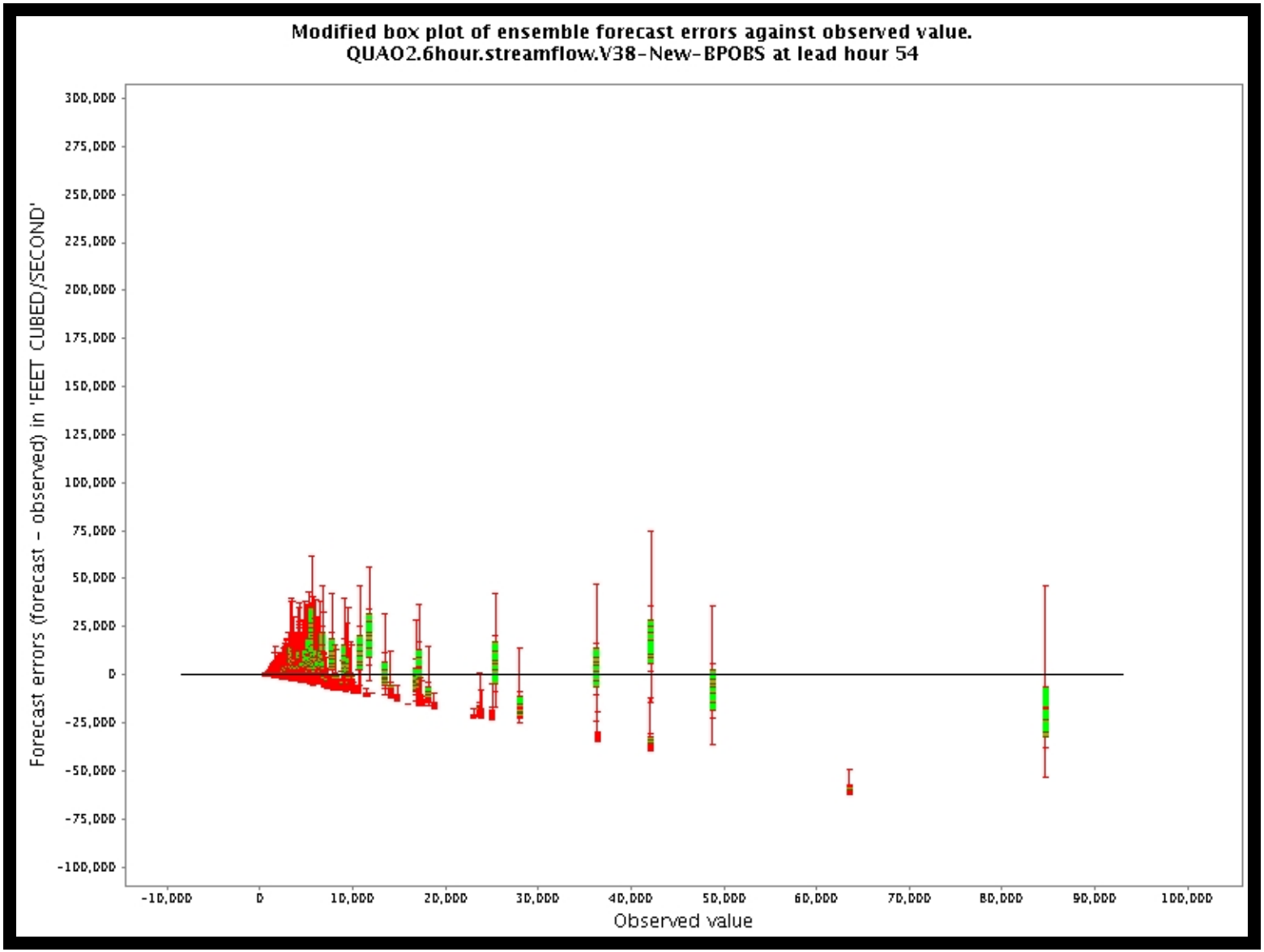

Cumulative Talagrand plot.
QUAO2.6hour.streamflow.V38-New-Cus at lead hour 54
Fraction of observations falling in window around forecast median
Size of window in probability units on each side of forecast median
Perfect
All data
ob > 875.0
ob > 2000.0

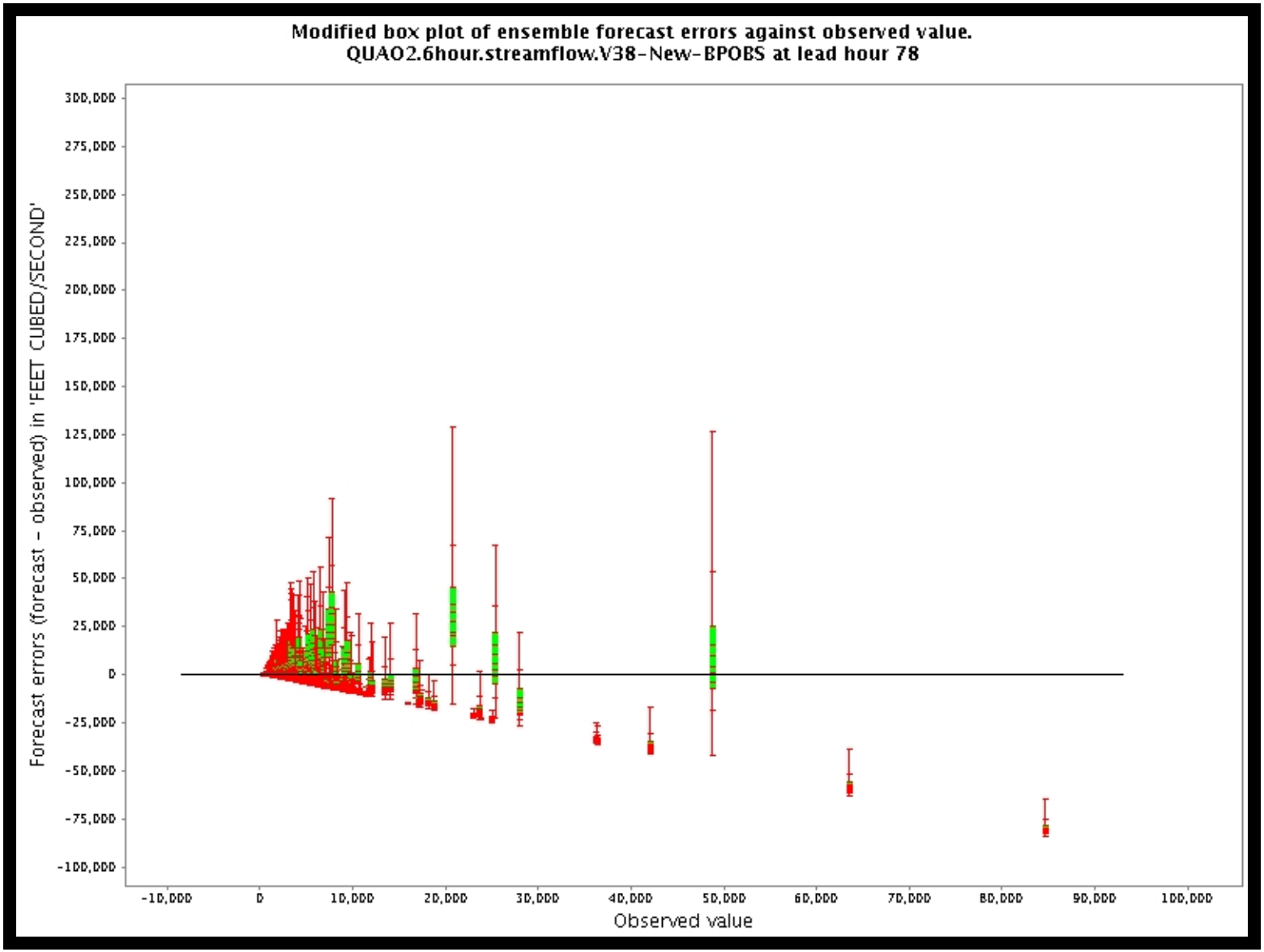

Cumulative Talagrand plot.
QUAO2.6hour.streamflow.V38-New-Cus at lead hour 78
Fraction of observations falling in window around forecast median
1.00
0.95
0.90
0.85
0.80
0.75
0.70
0.65
0.60
0.55
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0.000
0.025
0.050
0.075
0.100
0.125
0.150
0.175
0.200
0.225
0.250
0.275
0.300
0.325
0.350
0.375
0.400
0.425
0.450
0.475
Size of window in probability units on each side of forecast median
Perfect
All data
ob > 875.0
ob > 2000.0

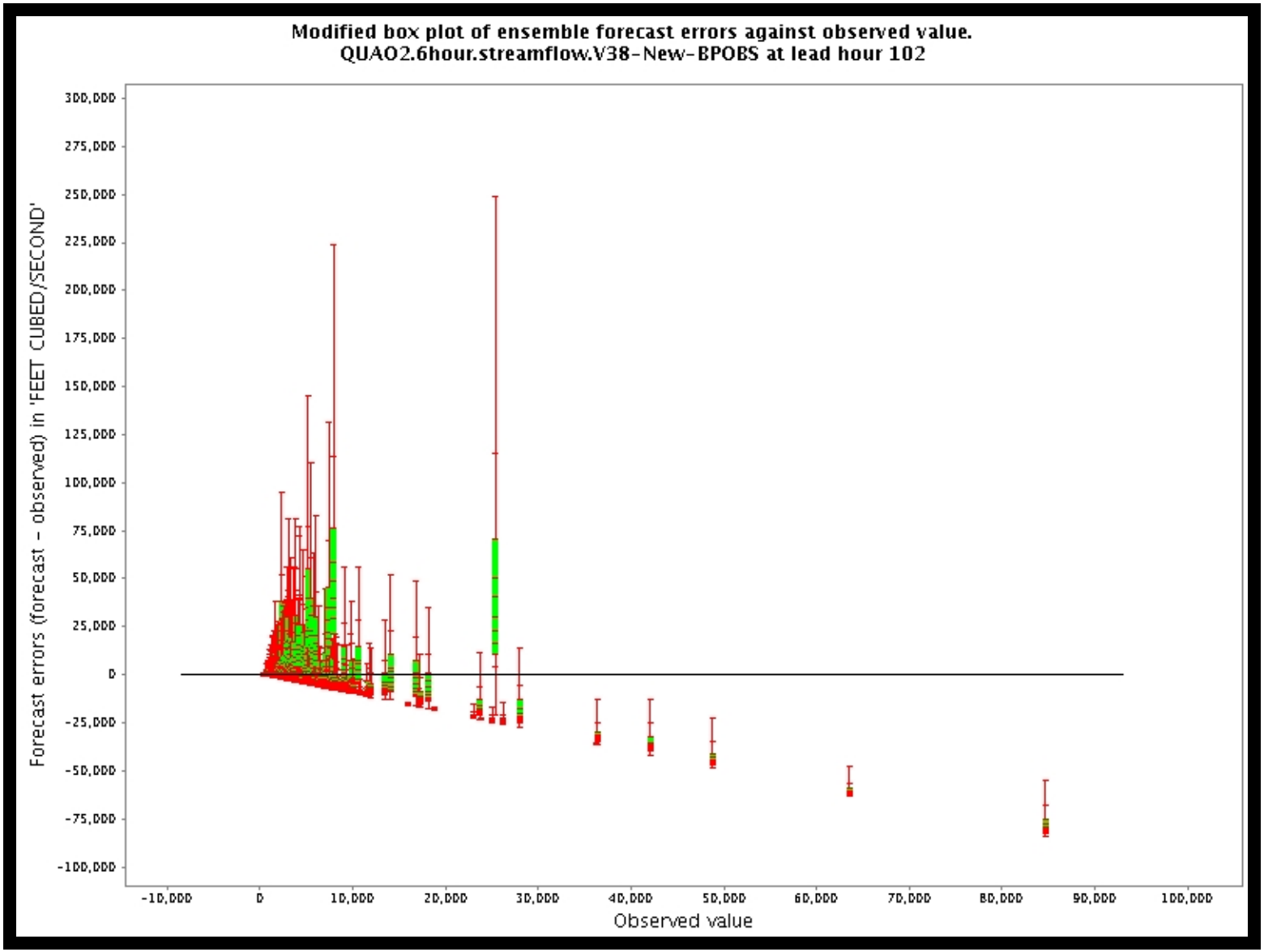

Cumulative Talagrand plot.
QUAO2.6hour.streamflow.V38-New-Cus at lead hour 102
Fraction of observations falling in window around forecast median
1.00
0.95
0.90
0.85
0.80
0.75
0.70
0.65
0.60
0.55
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0.000
0.025
0.050
0.075
0.100
0.125
0.150
0.175
0.200
0.225
0.250
0.275
0.300
0.325
0.350
0.375
0.400
0.425
0.450
0.475
Size of window in probability units on each side of forecast median
Perfect
All data
ob > 875.0
ob > 2000.0


Modified box plot of ensemble forecast errors against observed value.
QUAO2.6hour.streamflow.V38-New-BPOBS at lead hour 6
Forecast errors (forecast - observed) in 'FEET CUBED/SECOND'
300,000
275,000
250,000
225,000
200,000
175,000
150,000
125,000
100,000
75,000
50,000
25,000
0
-25,000
-50,000
-75,000
-100,000
-10,000
0
10,000
20,000
30,000
40,000
50,000
60,000
70,000
80,000
90,000
100,000
Observed value
'Errors' for 1 ensemble forecast
Largest member
90 percent.
80 percent.
Median
20 percent.
10 percent.
Smallest member


Modified box plot of ensemble forecast errors against observed value.
QUAO2.6hour.streamflow.V38-New-BPOBS at lead hour 30
Forecast errors (forecast - observed) in 'FEET CUBED/SECOND'
300,000
275,000
250,000
225,000
200,000
175,000
150,000
125,000
100,000
75,000
50,000
25,000
0
-25,000
-50,000
-75,000
-100,000
-10,000
0
10,000
20,000
30,000
40,000
50,000
60,000
70,000
80,000
90,000
100,000
Observed value


Modified box plot of ensemble forecast errors against observed value.
QUAO2.6hour.streamflow.V38-New-BPOBS at lead hour 54
Forecast errors (forecast - observed) in 'FEET CUBED/SECOND'
300,000
275,000
250,000
225,000
200,000
175,000
150,000
125,000
100,000
75,000
50,000
25,000
0
-25,000
-50,000
-75,000
-100,000
-10,000
0
10,000
20,000
30,000
40,000
50,000
60,000
70,000
80,000
90,000
100,000
Observed value


Modified box plot of ensemble forecast errors against observed value.
QUAO2.6hour.streamflow.V38-New-BPOBS at lead hour 78
Forecast errors (forecast - observed) in 'FEET CUBED/SECOND'
300,000
275,000
250,000
225,000
200,000
175,000
150,000
125,000
100,000
75,000
50,000
25,000
0
-25,000
-50,000
-75,000
-100,000
-10,000
0
10,000
20,000
30,000
40,000
50,000
60,000
70,000
80,000
90,000
100,000
Observed value


Modified box plot of ensemble forecast errors against observed value.
QUAO2.6hour.streamflow.V38-New-BPOBS at lead hour 102
Forecast errors (forecast - observed) in 'FEET CUBED/SECOND'
300,000
275,000
250,000
225,000
200,000
175,000
150,000
125,000
100,000
75,000
50,000
25,000
0
-25,000
-50,000
-75,000
-100,000
-10,000
0
10,000
20,000
30,000
40,000
50,000
60,000
70,000
80,000
90,000
100,000
Observed value

Findings

- HMOS streamflow ensembles are generally reliable for all 10 test basins for all lead times out to Day 5
- HMOS ensembles fully capture, in the mean sense, skill in the single-value forecast
  - Removes/reduces systematic biases
  - Often improves skill in low-flow conditions
- Parameter estimation is sensitive, to a varying degree, to both quantity and quality of data
  - The process is otherwise robust and straightforward, but CPU-intensive (depending on the period of record)
- The quality of ensembles is susceptible, to a varying degree, to sampling uncertainties in the statistical parameters
  - Robust estimation is employed to reduce sensitivity to outlying data points

Next steps

- Independent validation (w/ ABRFC)
  - Verification of HMOS Hindcasts at ABRFC
  - Over different time scales (6-hourly, daily, 5-daily)
  - Assessment of data requirement
  - Assessment of sensitivity to ensemble size
- Consider additional conditioning, predictors
  - Seasonality (in normal transformation)
  - QPF
  - Hydrograph response (e.g., rising vs. falling limbs)
- Accounting of uncertainties in rating curves, observations
- Improve error modeling

Thank you

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Additional Slides

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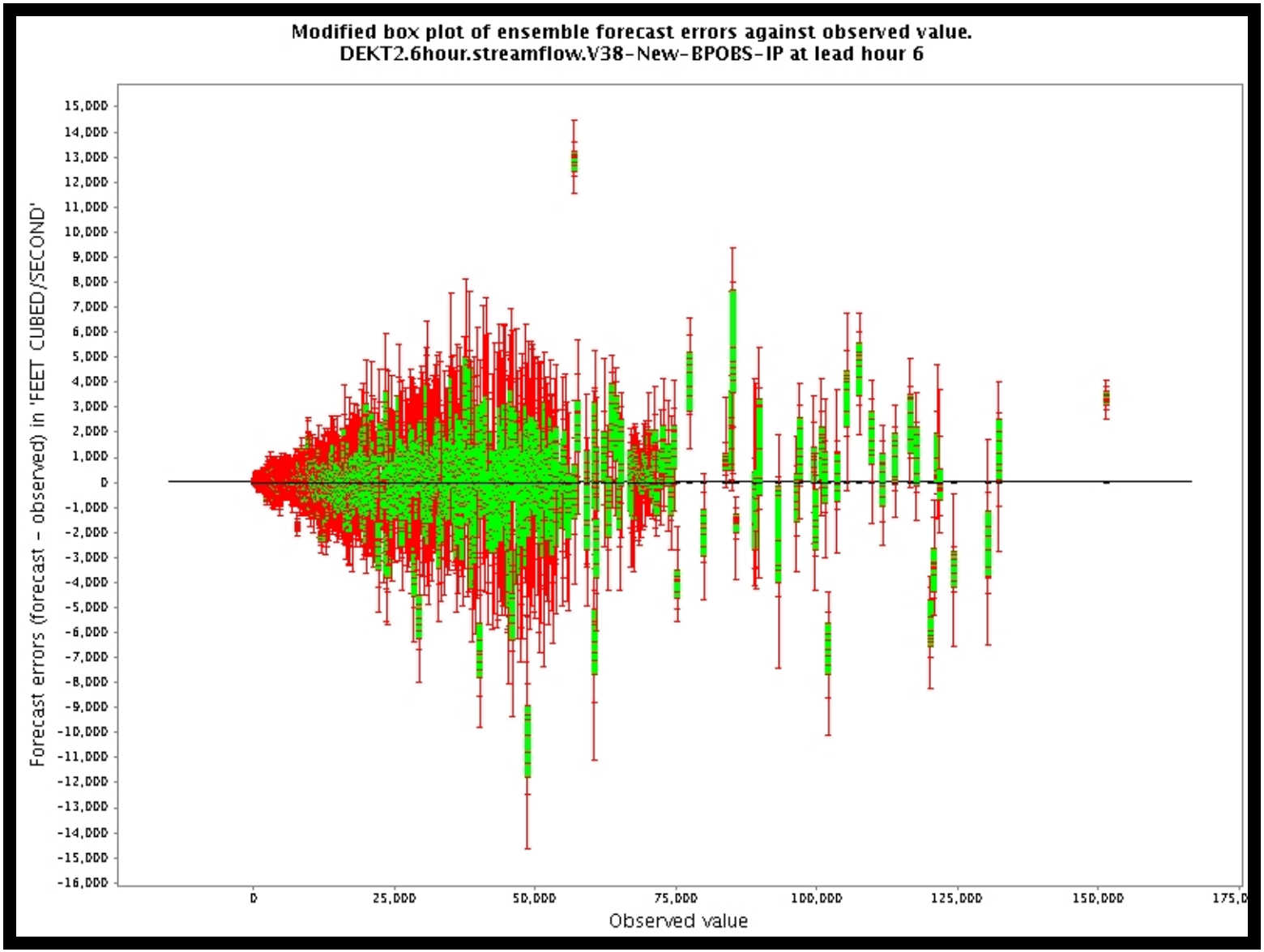

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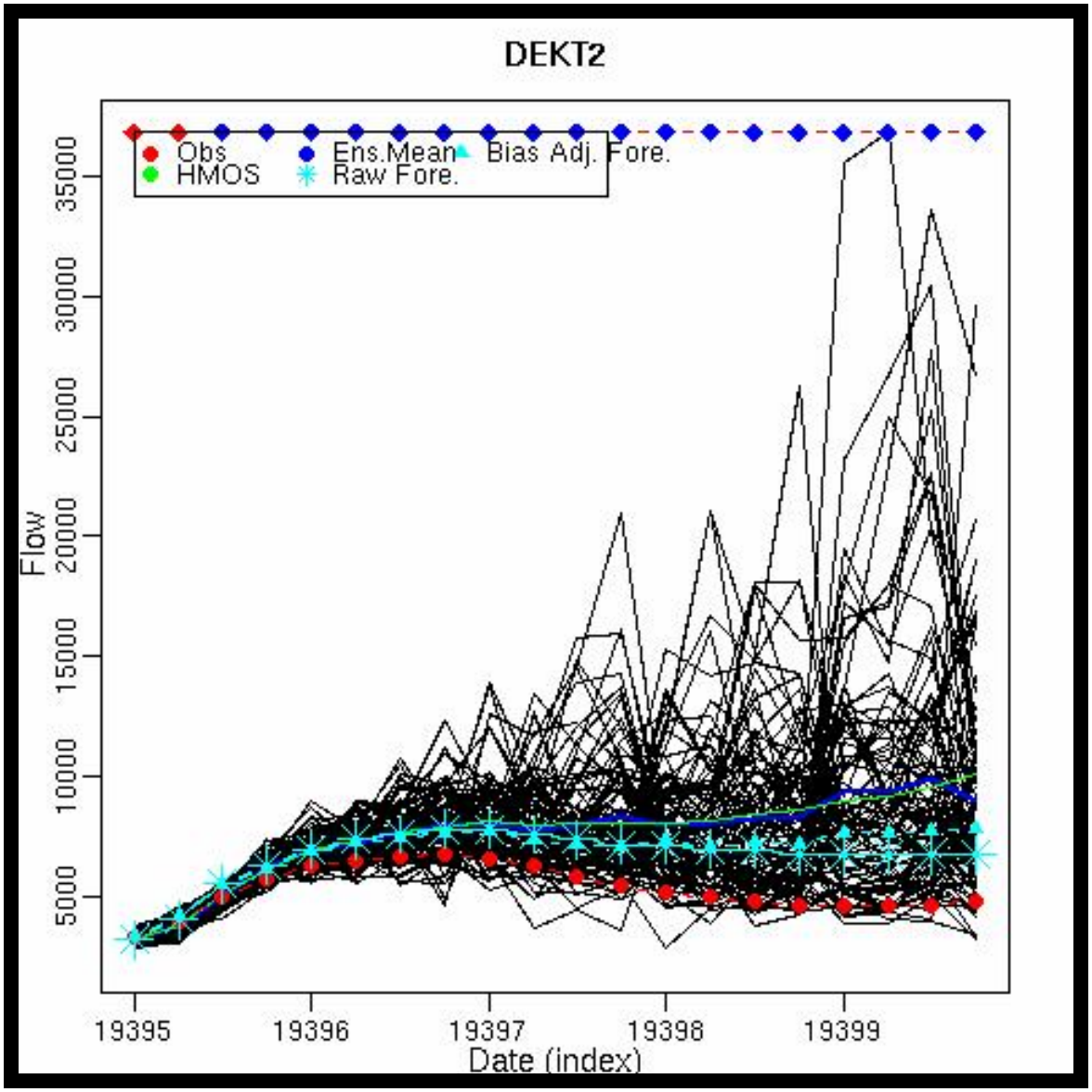

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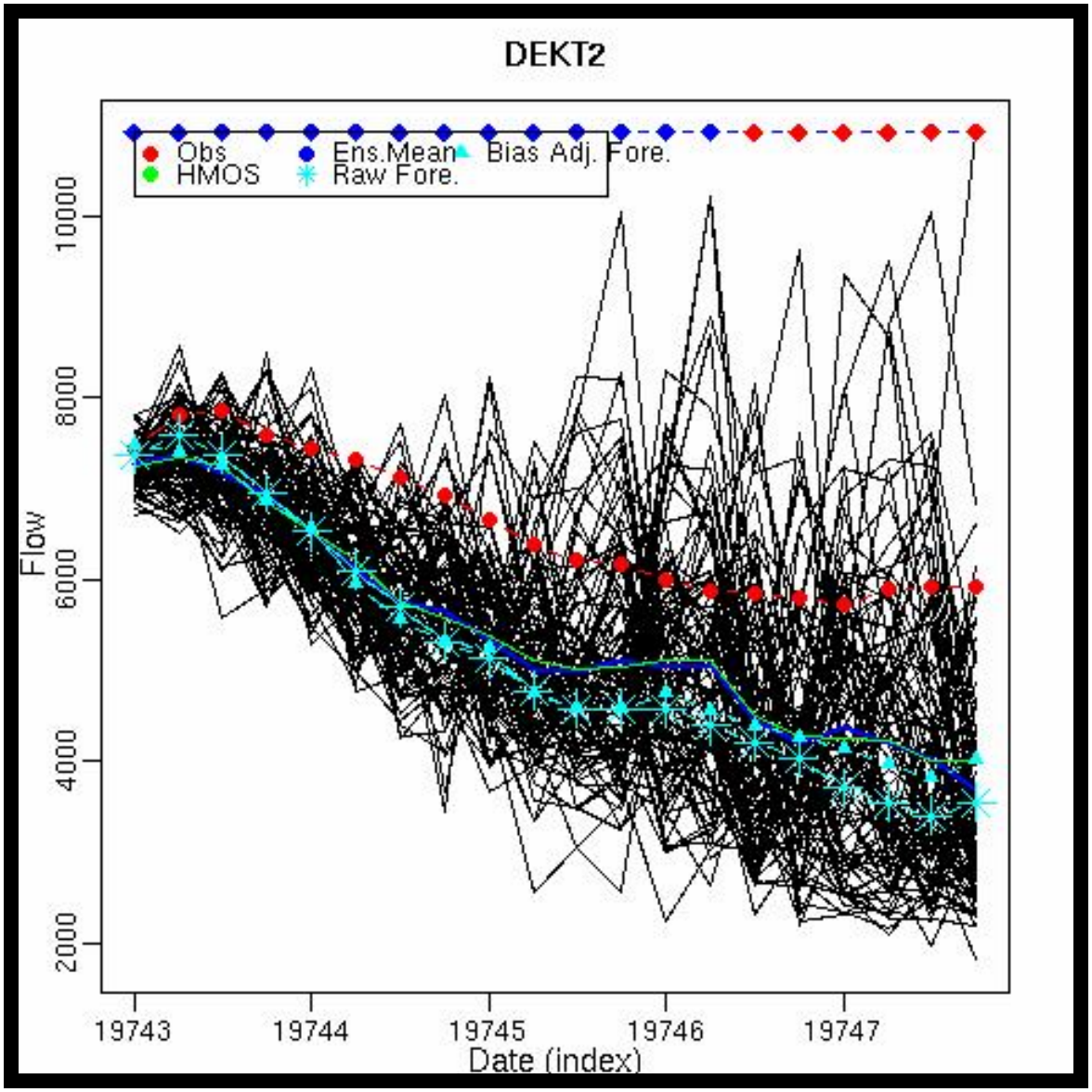

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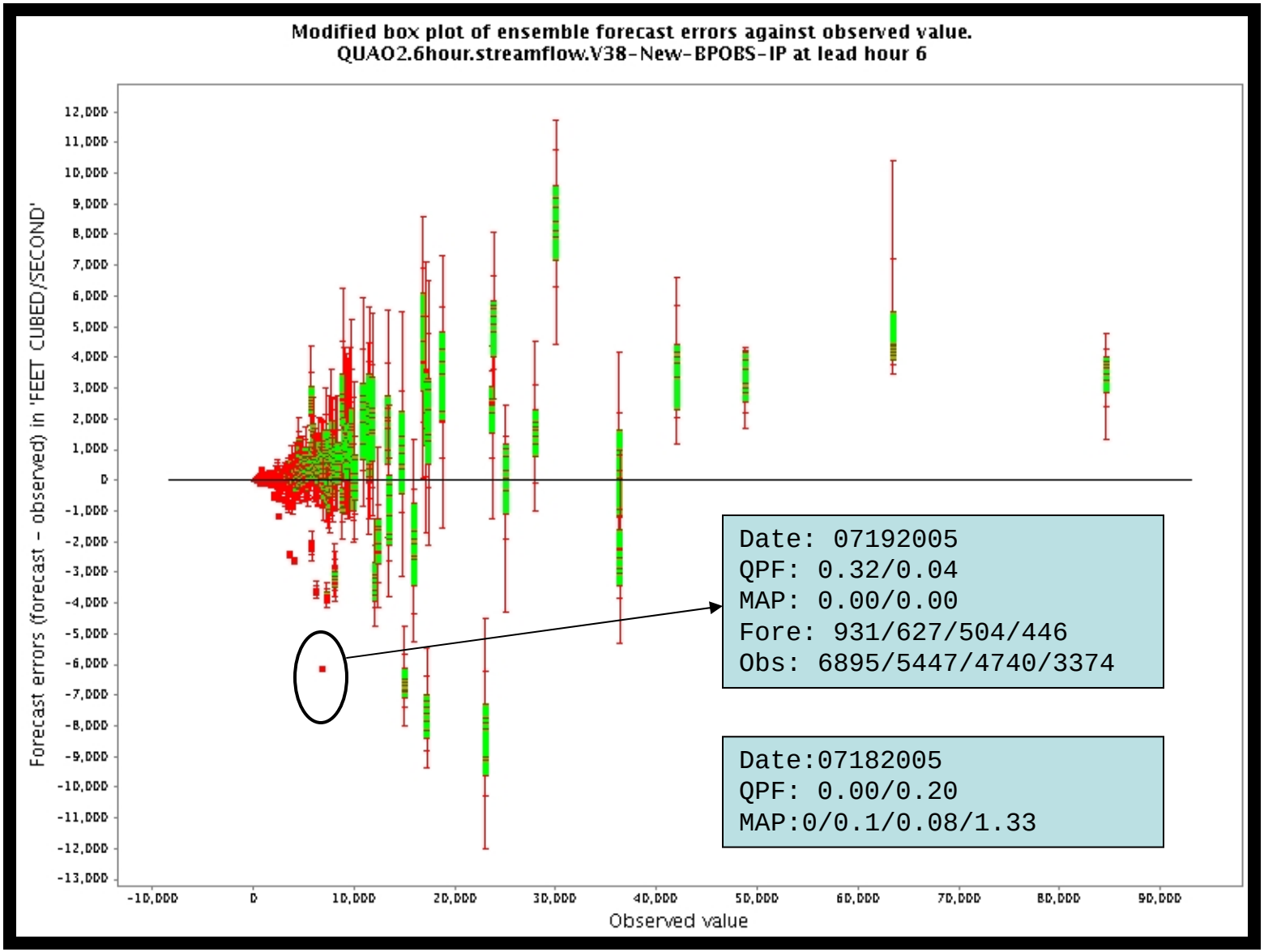

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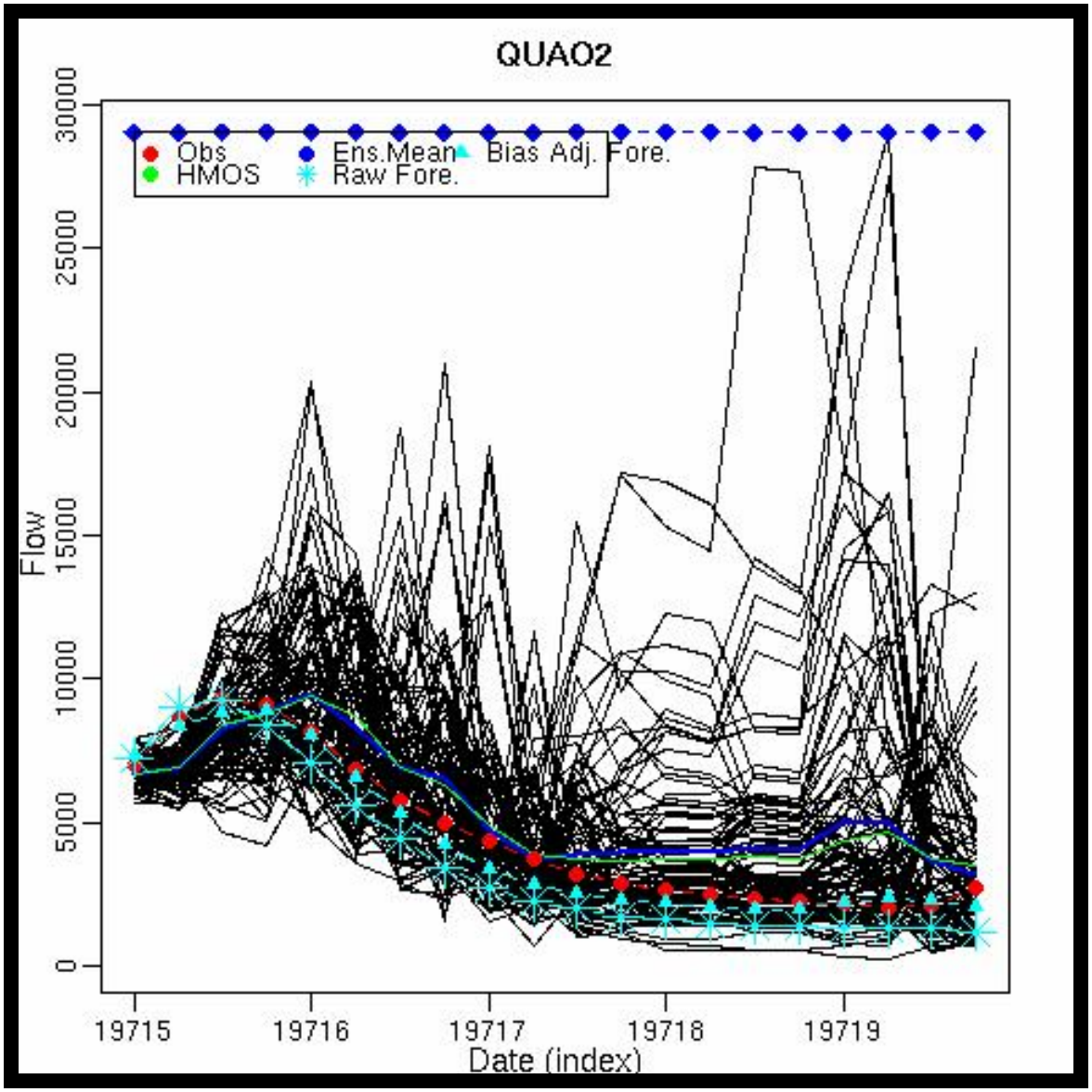

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