NEXRAD/MPE Precipitation Estimation Bias within the Ohio River Forecast Center Area of Operations — TAC Meeting Oct. 2004

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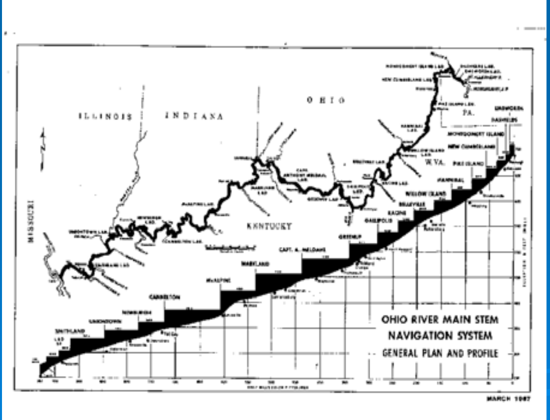
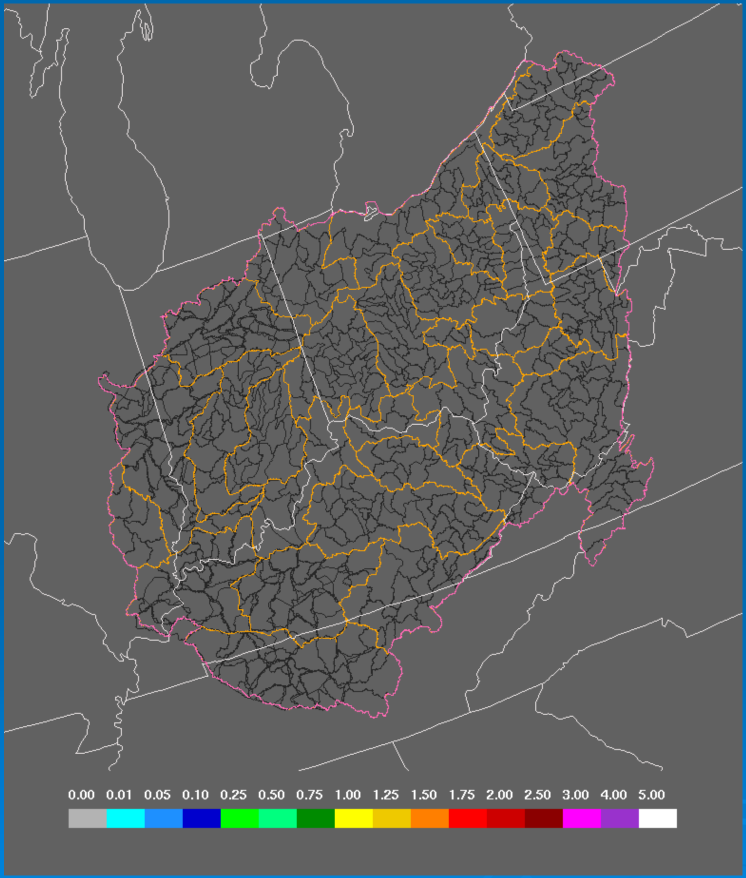
OHRFC Facts



- Staff of 16 hydrologists & meteorologists, 1 Administrative Support Assistant
- Ohio River drainage area = 453250 km^2
- 29 major subbasins, subdivided into ~700 smaller subbasins
- Ohio River Mainstem highly regulated for navigation
- Also responsible for Lake Erie drainage

Topics

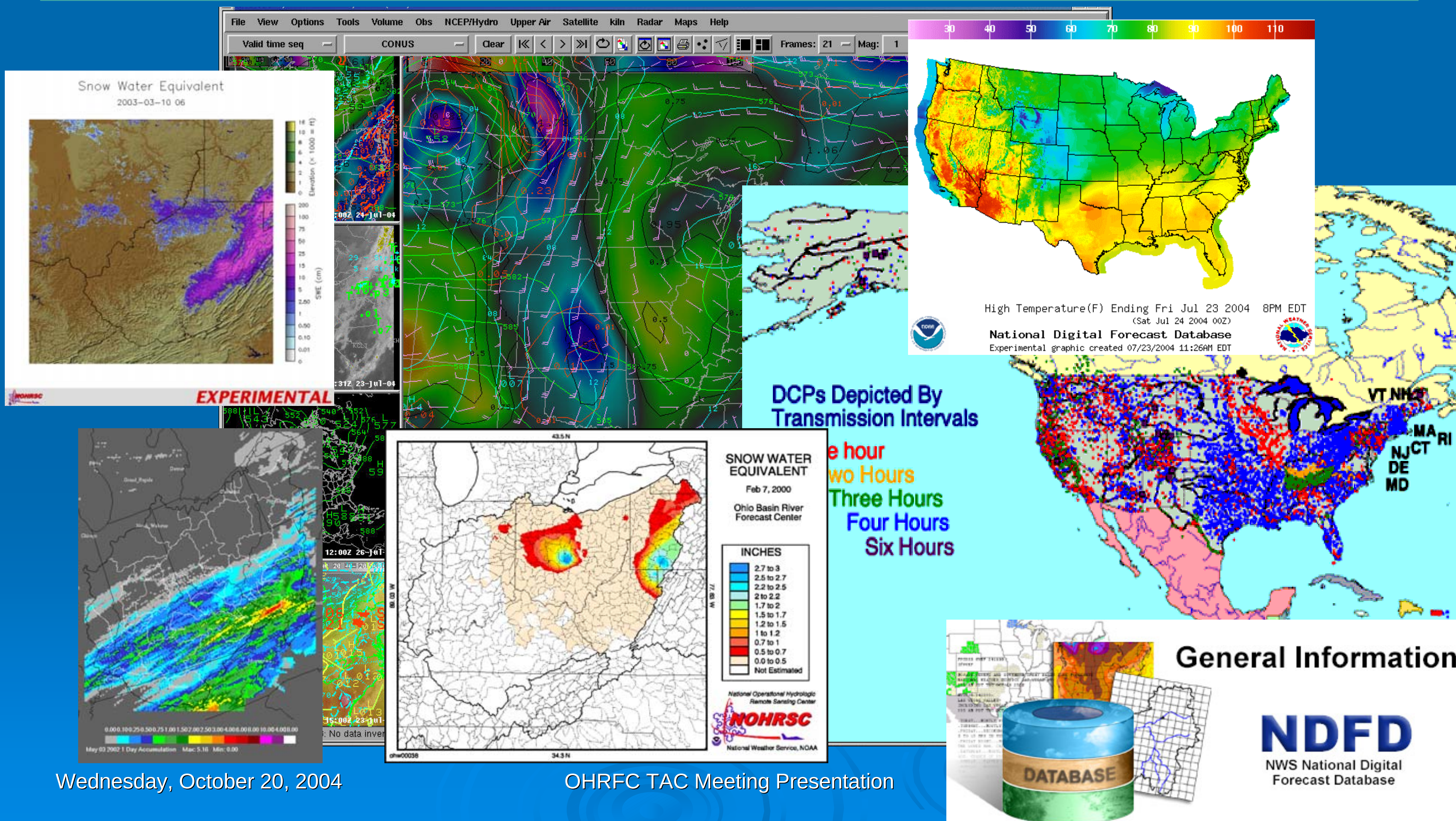


- Current OHRFC operations
- Sacramento Soil Moisture Accounting (SAC-SMA) model
- MPE Precipitation Estimation Bias
- Hydrologic Implications of Biased Precipitation Estimation
- OHD Proposed Range Correction Algorithm (RCA) & Convective-Stratiform Separation Algorithm (CSSA)
- Conclusions

Current OHRFC operations

- Deterministic operations
  - River flow & flood forecasting
  - 1 daily interactive forecast, partial evening update, & updates during flooding
  - 16 hours/day operations, 365 days/year — 24 hours/day during flooding
  - NWS River Forecast System (NWSRFS)
    - Operational Forecast System (OFS)
    - Calibration System
    - Ensemble Streamflow Prediction (ESP) System
    - Flash Flood Guidance System
  - 5-day forecasts
  - NEXRAD radar based precipitation estimation (MPE) with raingage correction
  - Forecasted precipitation & temperature
  - FFG (1-, 3-, 6-, 12-, 24-hr)
  - RRM/ESS product generation
- AHPS/Probabilistic forecasts
  - Provides estimates of forecast uncertainty
    - Model error
    - Uncertainty in initial model states
    - Hydrometeorological uncertainty
  - Long-term probabilistic forecasts using ESP

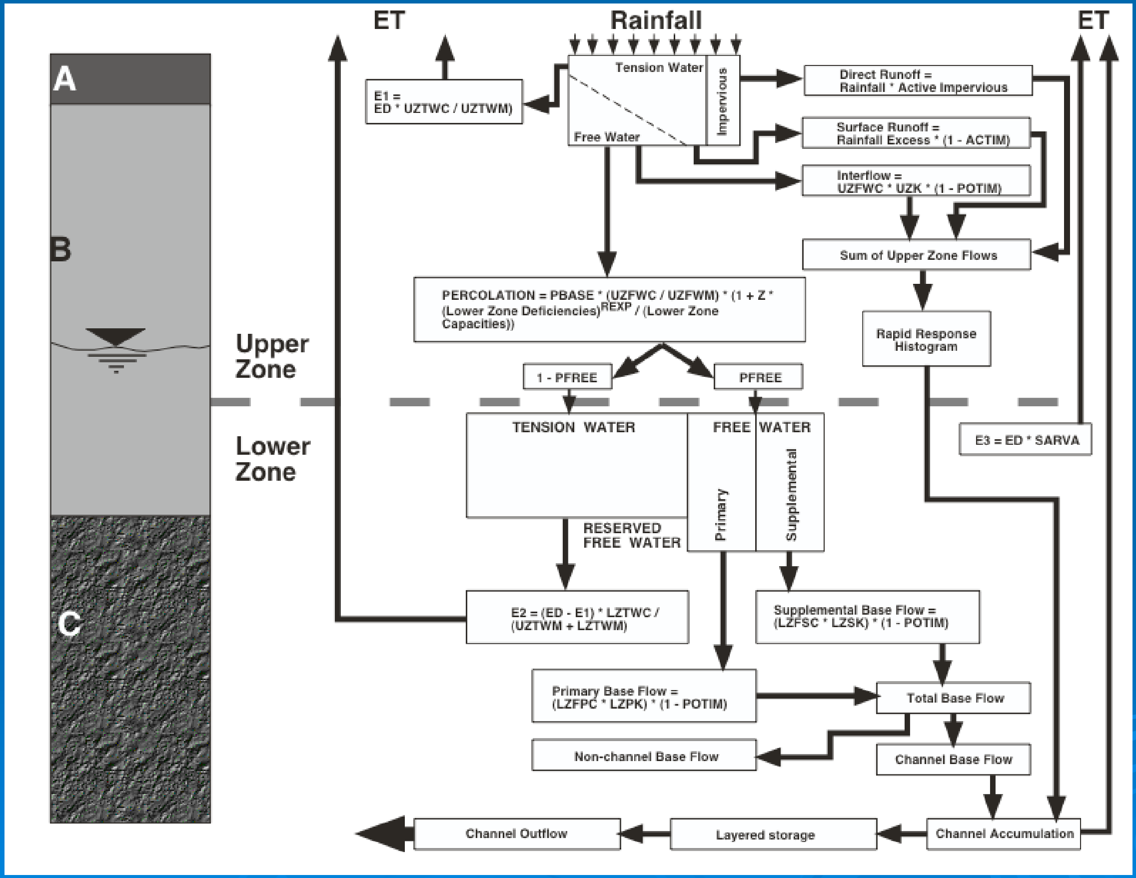
Hydrometeorological Data



The SAC-SMA model

- Conceptual hydrologic model derived from the *Stanford Watershed Model* (*circa* 1960)
- Lumped parameterization as opposed to distributed (e.g., a regular grid)
- 17 model parameters
  - Initial physically based estimates from NRCS STATSGO soil properties
- Requires calibration against observed streamflows
- Other models
  - Statistical (regression relationship, stochastic)
  - Physical (*TOPMODEL*, *DHSVM*, *SHE*)
  - Parametric (e.g., API)
- Lumped & distributed versions of the SAC-SMA out-performed all other participating *Distributed Modeling Intercomparison Project* (DMIP) models — results forthcoming in the *Journal of Hydrology*

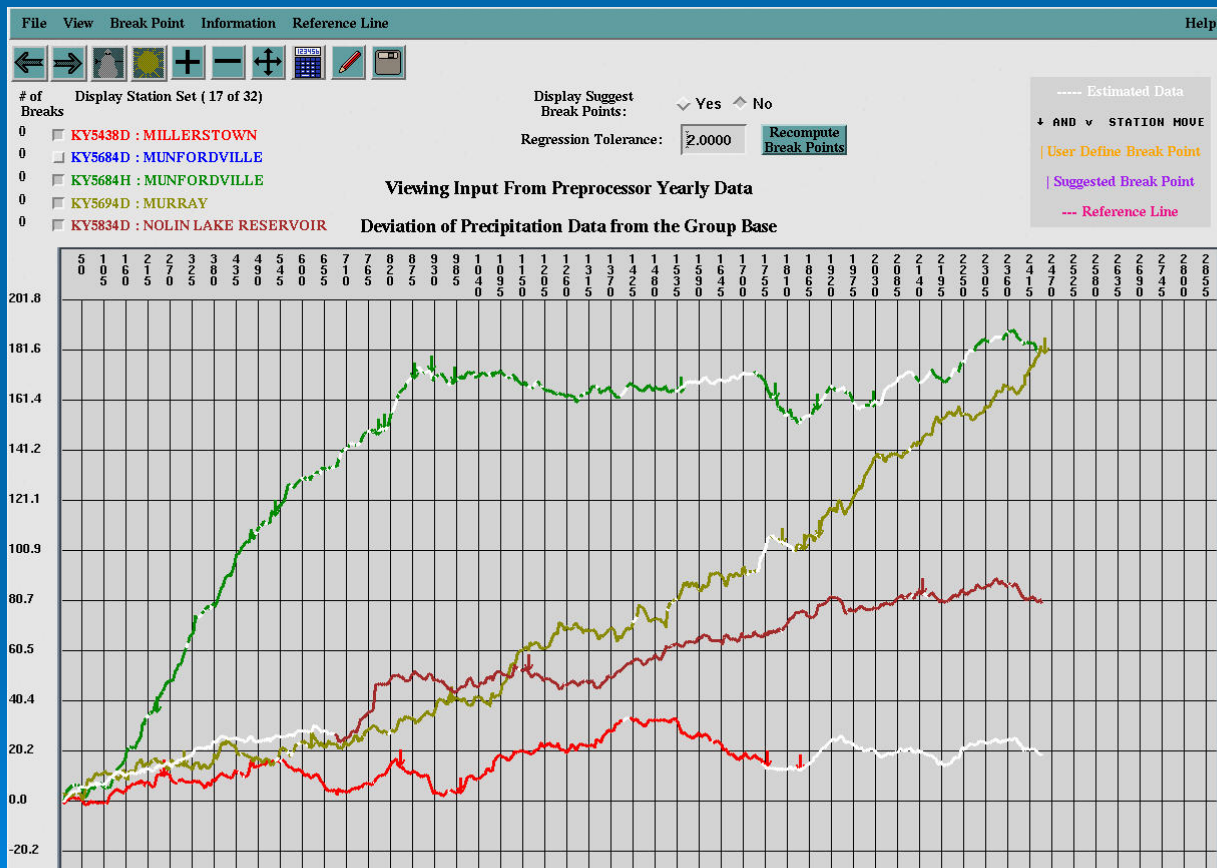
SAC-SMA model Conceptualization



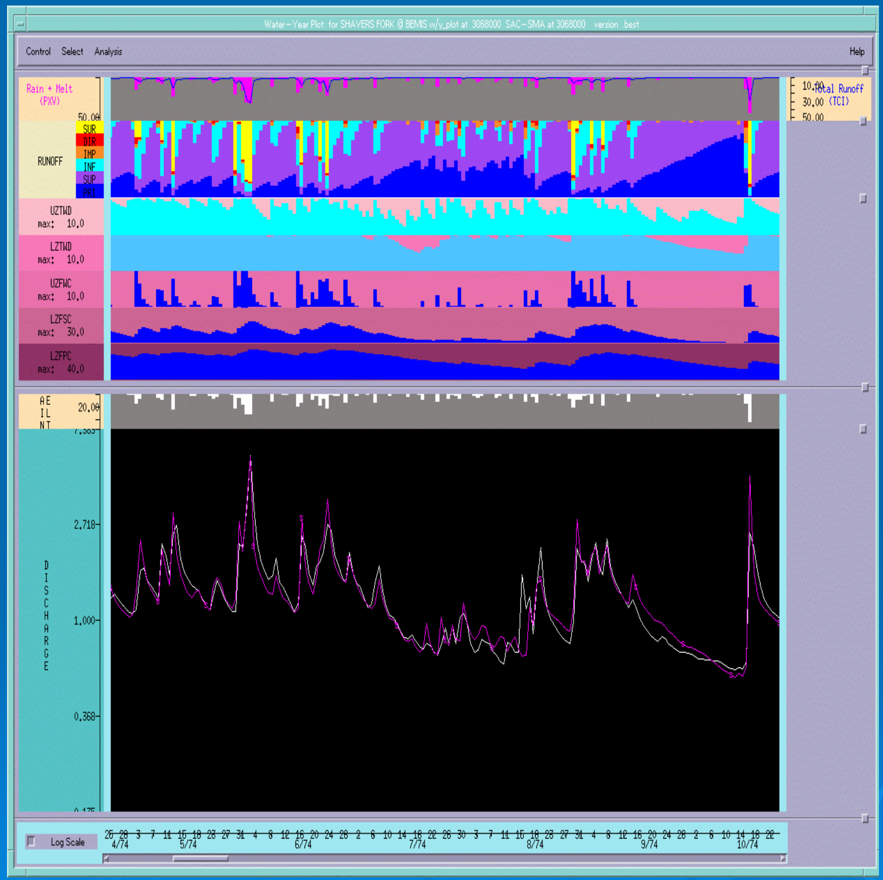
Model Calibrations

- Process by which model parameter values are adjusted to get *optimal* agreement between observations & simulation
- Many sources of error
  - Model is an inexact representation of reality, e.g., lumped vs spatially distributed models
  - Data biases, data inconsistency (e.g., station location changes, MAP vs MAPX), poor observational coverage, etc.
- Calibration periods normally exceed 20 years and span wet & dry climatic periods
- Significant effort is made to keep model parameter values regionally consistent
- Every effort made to not adjust physically estimated parameter values
- Not possible to calibrate downstream subbasins
- Some automatic model optimizations have been attempted, but generally a tedious manual process

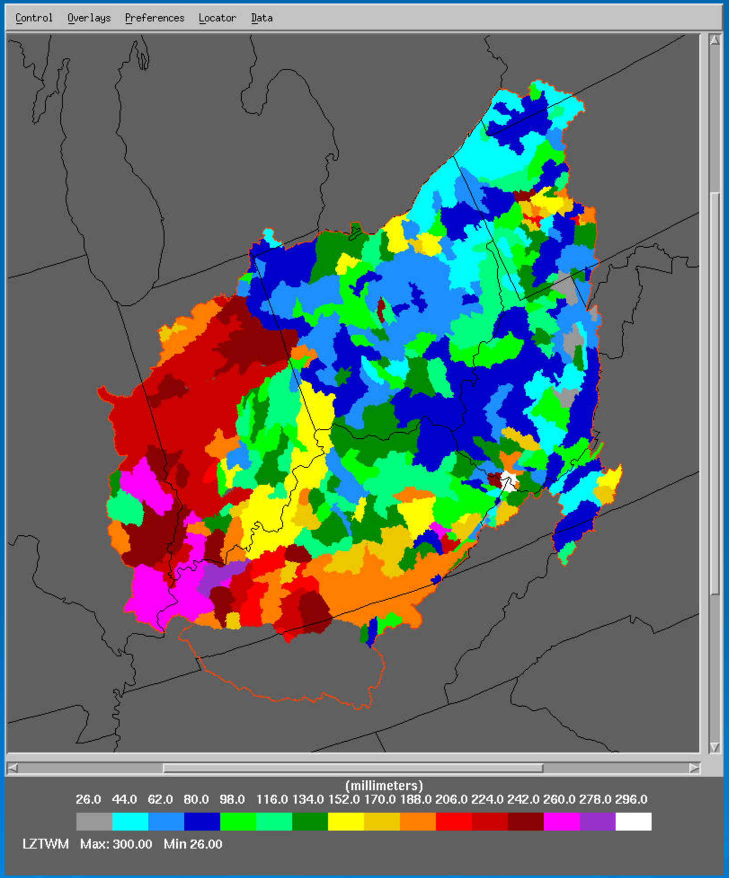
Analysis of Precipitation & Temperature data



SAC-SMA Model Calibration



Lower Zone Tension Water Maximum (LZTWM)



MPE Precipitation Estimation Bias in the OHRFC Region

- *Multisensor Precipitation Estimator* (MPE) (and Stage-3) precipitation processing essential to OHRFC operations
- One of only 4 or 5 RFCs using either MPE or Stage-3 operationally
- NEXRAD radar derived precipitation used operationally for hydrologic model input since ~1997
- Significant biases apparent since early in ~1998
- Questions concerning sources of the biases
  - *Random* or systematic errors?
  - What adjustments are possible?
  - How much do these biases influence hydrologic forecast uncertainty?

Motivation for Radar Precipitation Study

- OHRFC operational commitment to Stage-3/MPE precipitation estimation
  - Operational use since 1997 using MAPX as sole precipitation input to NWSRFS hydrologic models
  - Inadequate raingauge support
    - Uneven spatial coverage
    - Reporting times too late to meet operational start
    - Complex terrain
- Operational biases apparent (known problem)
  - OHRFC operational experience
  - Other RFCs
  - NEXRAD radar precipitation estimation studies by Smith et al (Princeton Univ.) & others
    - Beam blockage
    - Beam over shooting
    - Range effect (spreading of the radar beam)
    - Non unique Z-R relationship
    - Hail contamination
    - Poor snow estimation
    - Orographic enhancement
    - Radar calibration
    - Truncation error (most apparent with stratiform precipitation)
    - Brightbanding
- Identify & understand all sources of biases and attempt to make corrections
- Use of nationally supported operational technology/software

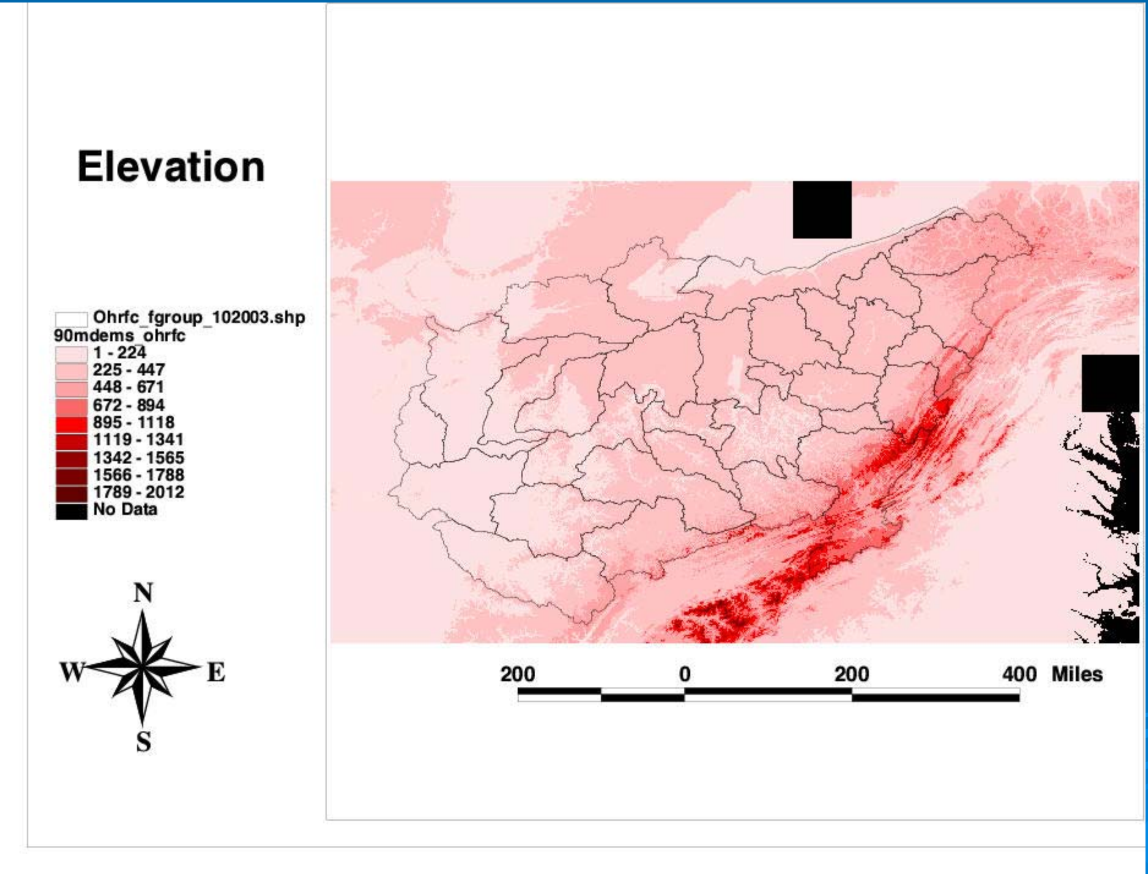
Study Methodology

- Estimate MPE bias relative to raingauge-only estimate over the OHRFC area
  - *bias* = XMRG/raingauge
  - Uniform gridded field: ~ 5 x 5 km^2
- Re-gridding of cell-centered (in lat-long coordinates) HRAP XMRG daily values
- IDW (inverse distance weighting) spatial interpolation to a new grid bounding the OHRFC area
- Spatial interpolation using *Ordinary Kriging* (spherical model) of daily Co-op station reports (independent of hourly raingauge network used in MPE corrections)
- Summation of the new gridded fields
  - Annual total for 2002 & 2003
  - Seasonal DJF & JJA for 2002 & 2003
- Statistical analyses using R
- Tools — *GRASS GIS* 5.3, *R* 1.7, & *GSTAT*

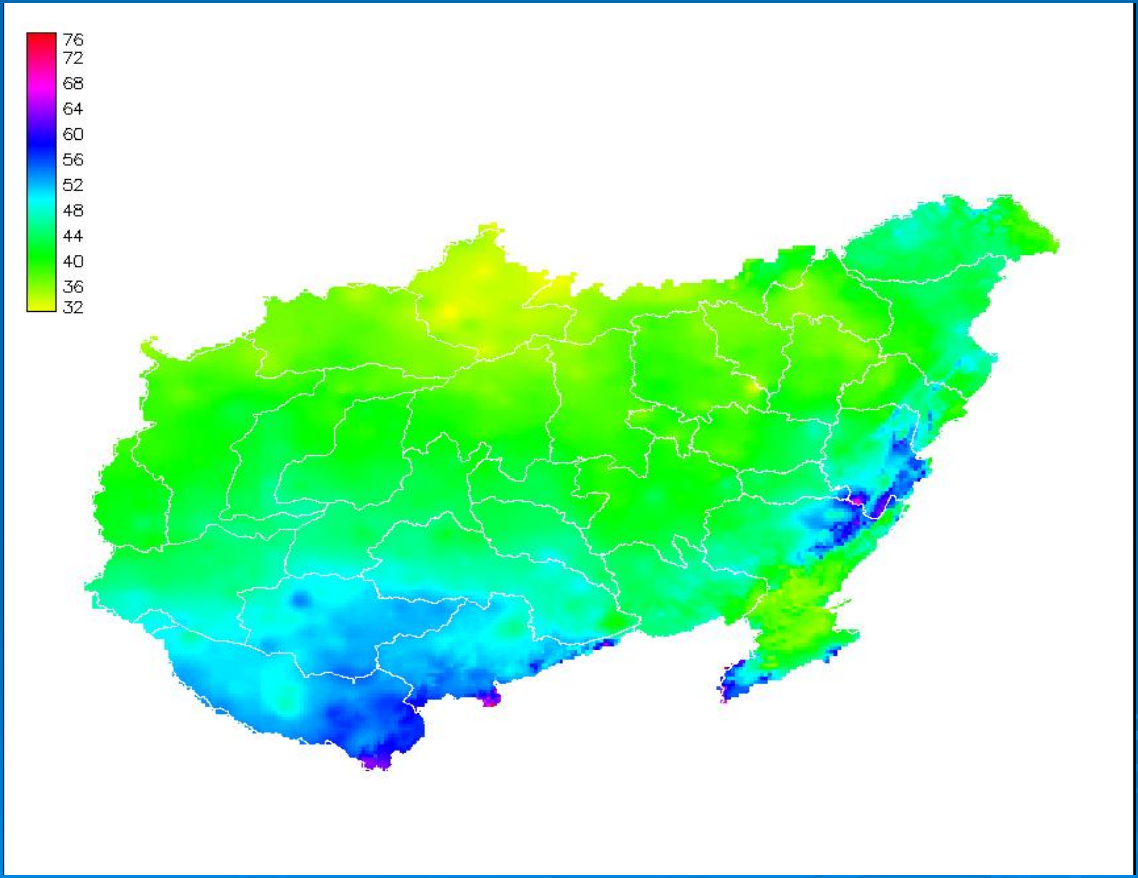
Methodological Assumptions & Issues

- Not true independence of MPE XMRG precipitation estimates and raingauge precipitation estimates — the Co-op station reports also used in MPE estimation
- Inconsistent set of raingauges used in raingauge fields — only 147 consistent for all 12 months out of ~600
- Terrain effects (orographic enhancement) not included in raingauge field precipitation estimation — *some* underestimation?
- Raingauge density inadequate to capture convective precipitation variability
- Grid comparisons based on geographic rather than HRAP grid basis
- HRAP grid missing a *small* portion of Lower Wabash River basin
- The criteria for using raingauges may be to restrictive with respect to intolerance for missing data

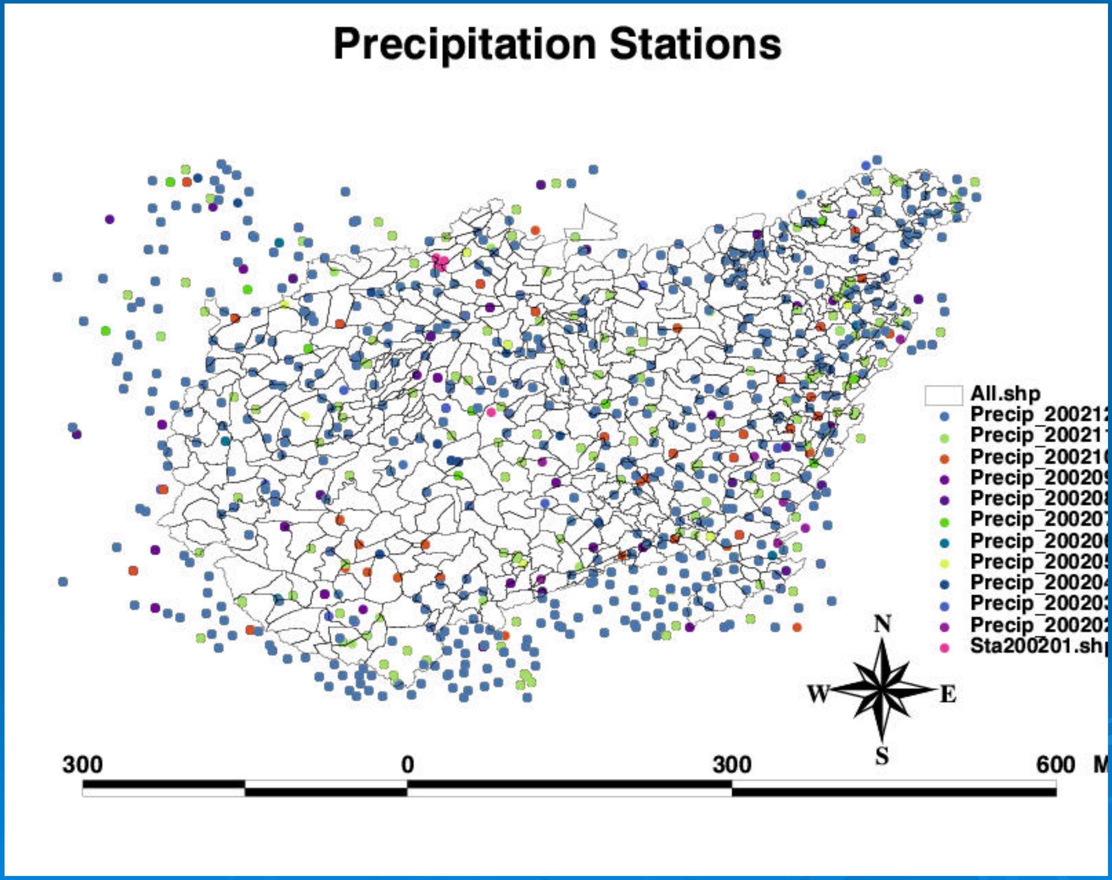
OHRFC Terrain



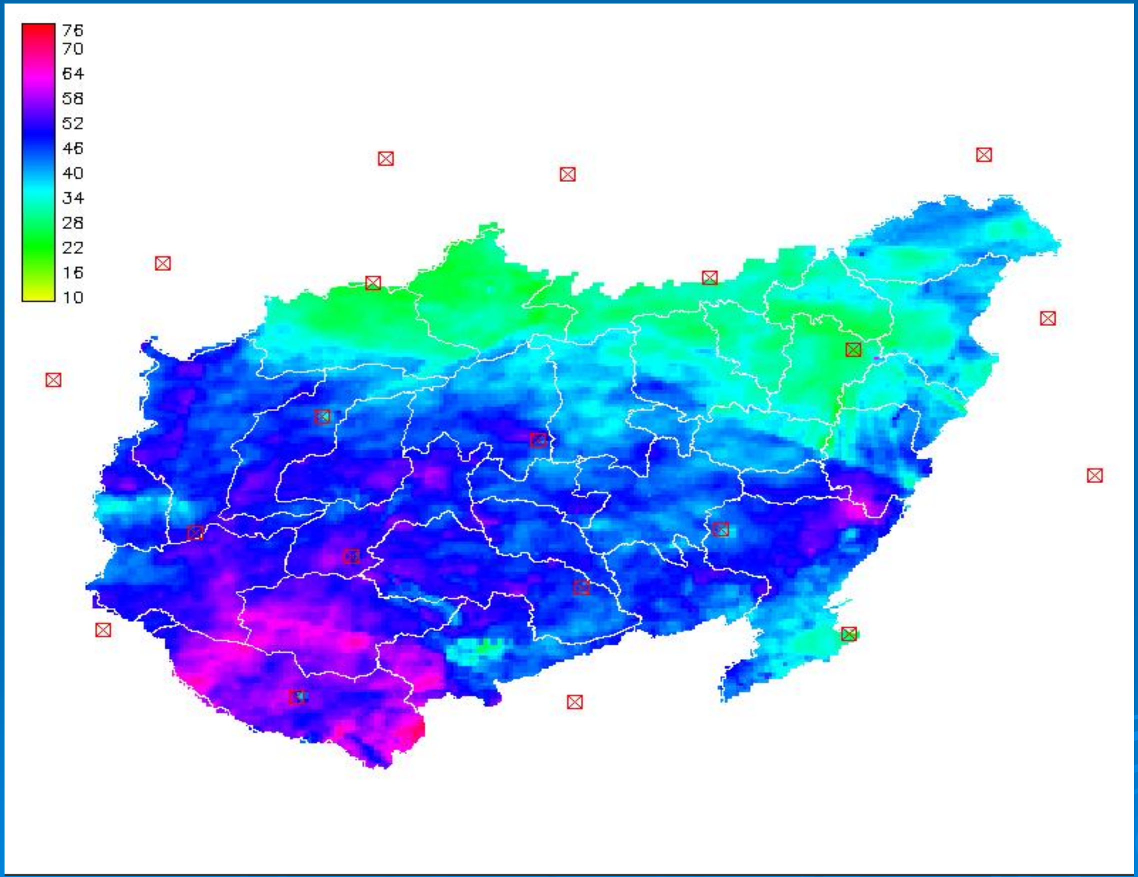
OHRFC PRISM Mean Annual Precipitation, 1961-90



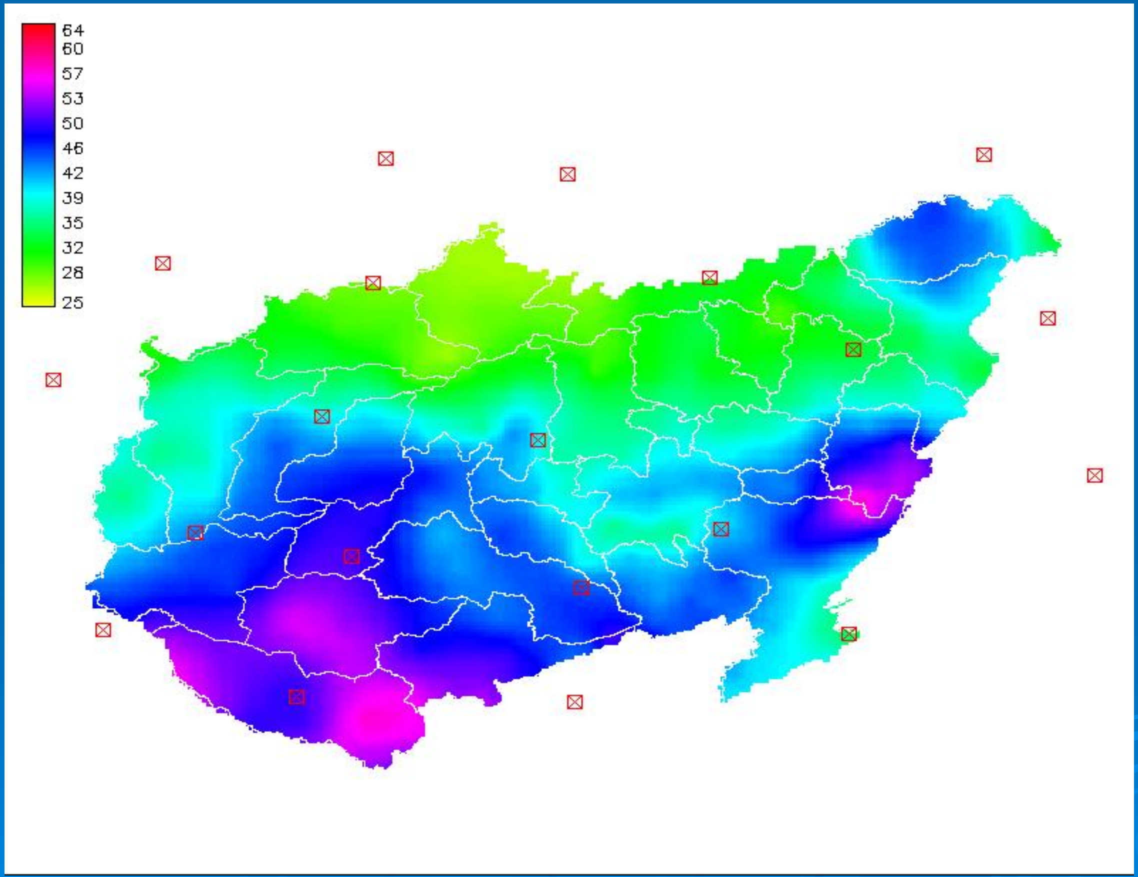
Raingauge Stations



2002 MPE xmrg Precipitation Estimate

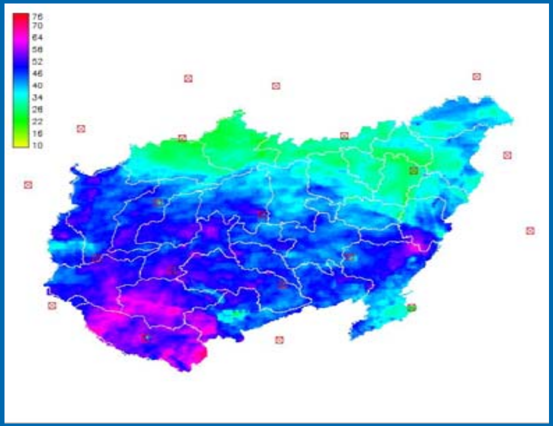


Co-op Raingauge Network 2002 Precipitation Estimate

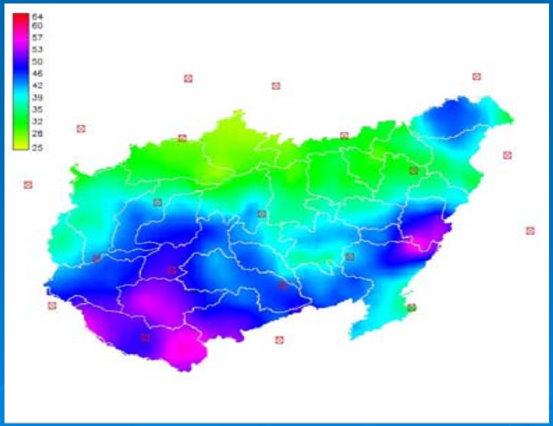


Bias Calculation

MPE xmrg precipitation

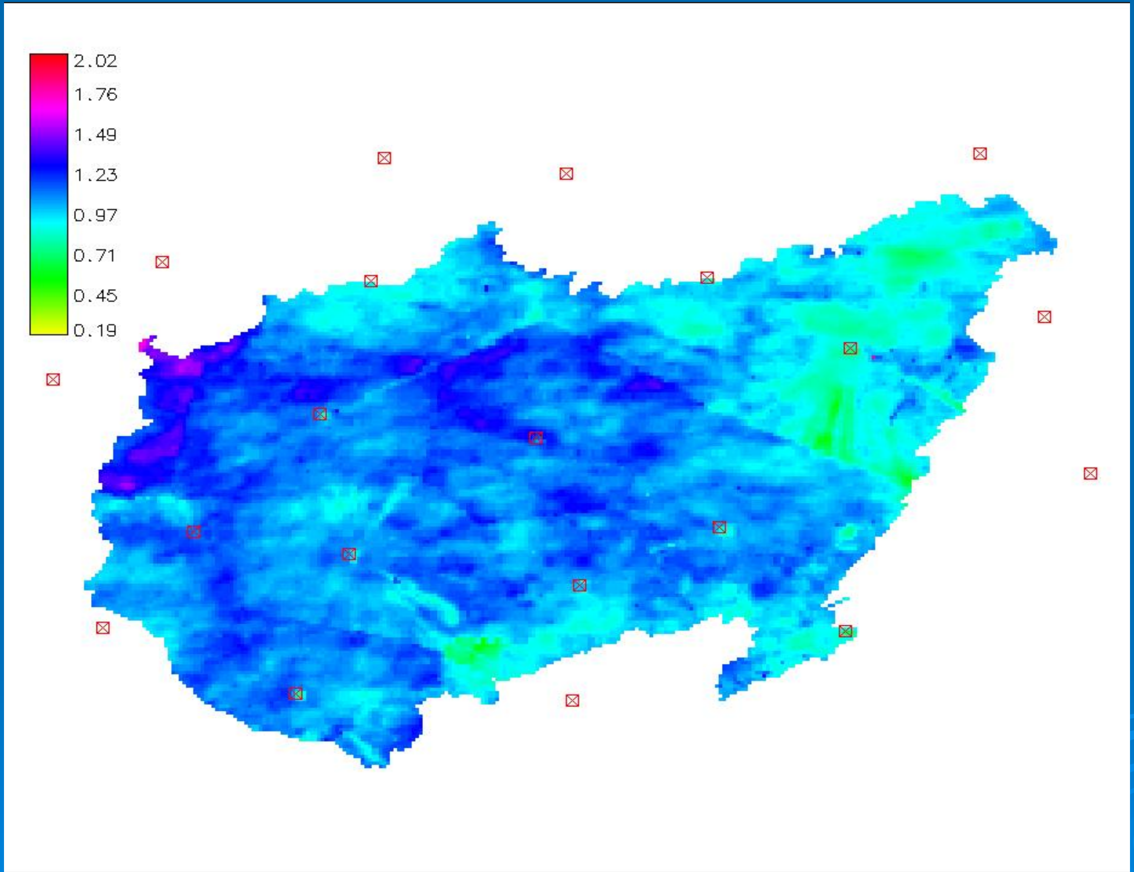


Co-op gauge network precipitation



$$bias = \frac{MPE\ xmrg\ precipitation}{Coop\ raingauge\ network\ precipitation}$$

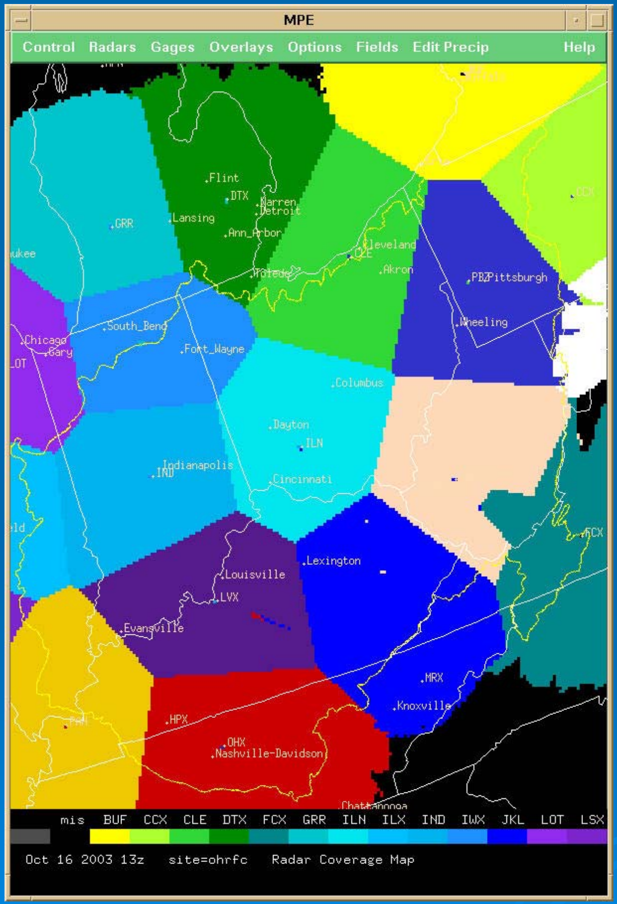
2002 Estimated MPE/xmrg Bias

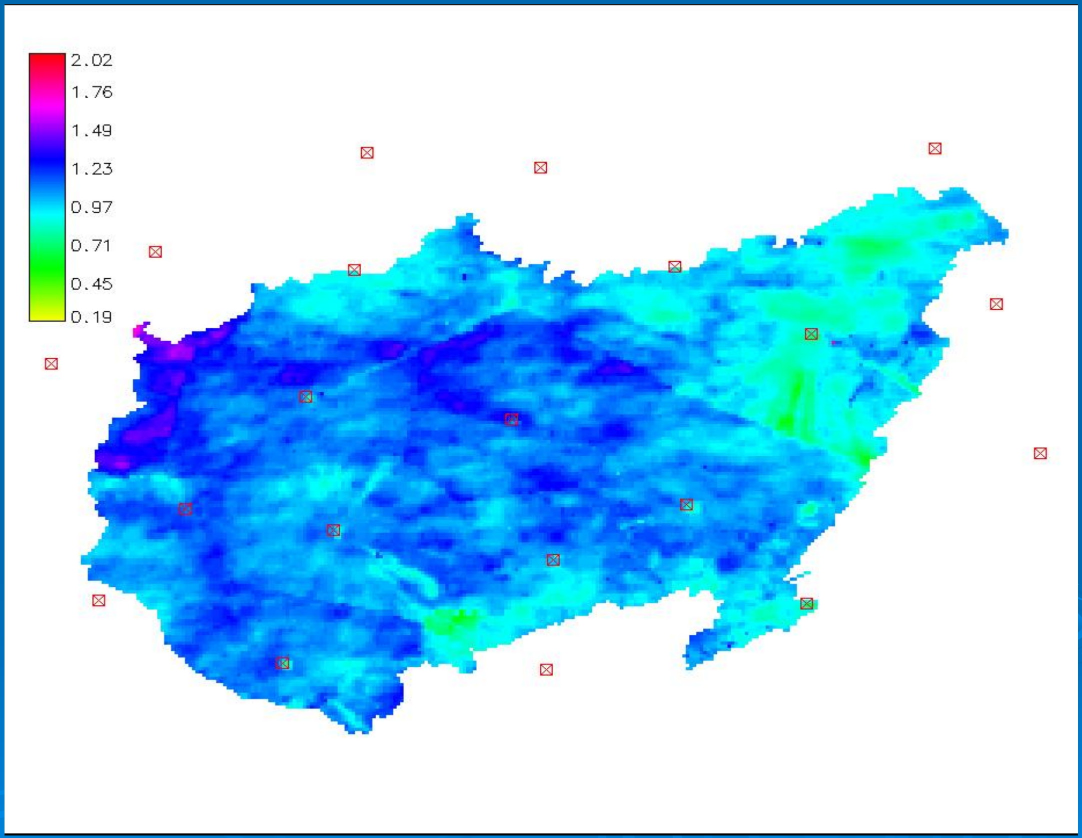


MPE/xmrg Bias Comments

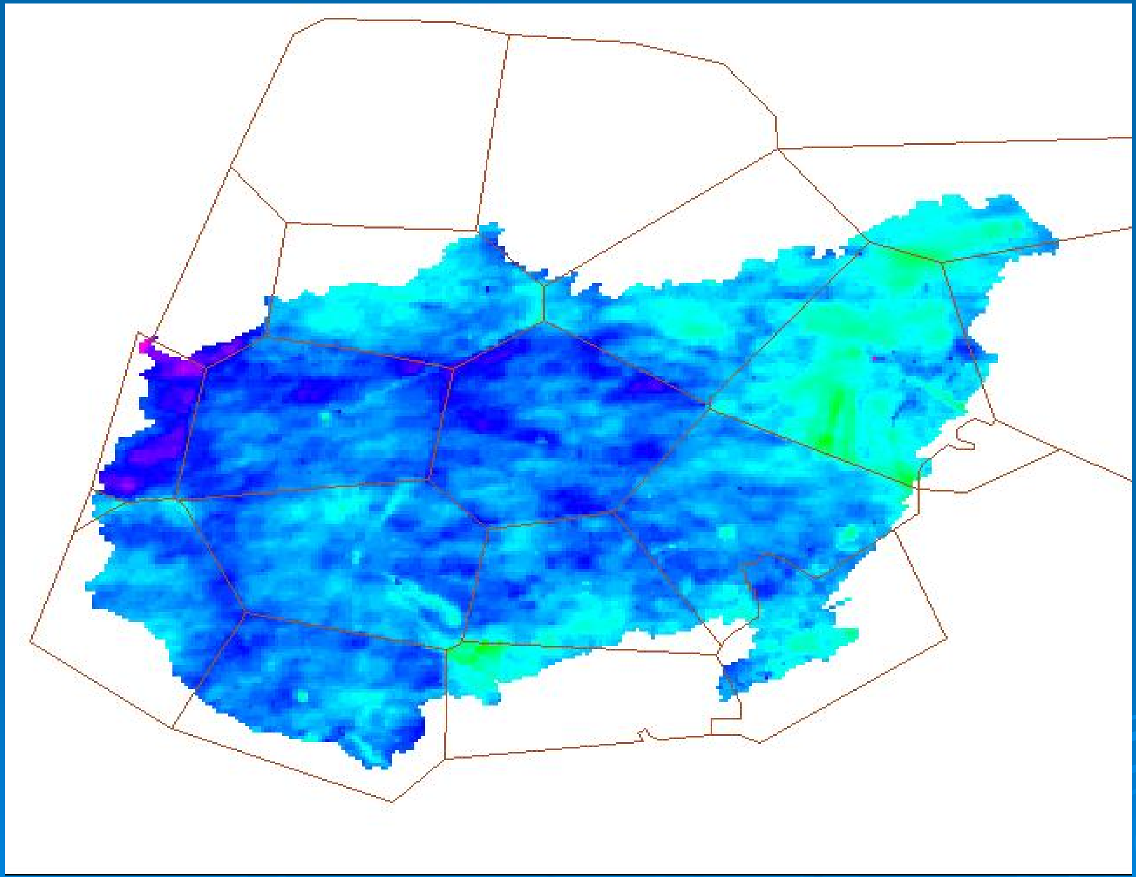
- Bias = 1.0, implies perfect agreement
  - Bias < 1.0, under-estimation
  - Bias > 1.0, over-estimation
- Distinct regions of over- & under-estimation
  - Under-estimation:
    - PBZ & BUF (Allegheny & Monongahela R. basins) and somewhat for CLE & IWX (Great Lakes drainage)
  - Over-estimation:
    - ILX, OHX, & ILN— Indiana & Ohio, Lower Cumberland R., Little Wabash, & Lower Wahash R. basins
- Features due to radar index field (*Thiessen polygons*) boundaries
- Influence of local beam blockage apparent — IND, LVX, & PBZ

MPE Radar Boundaries

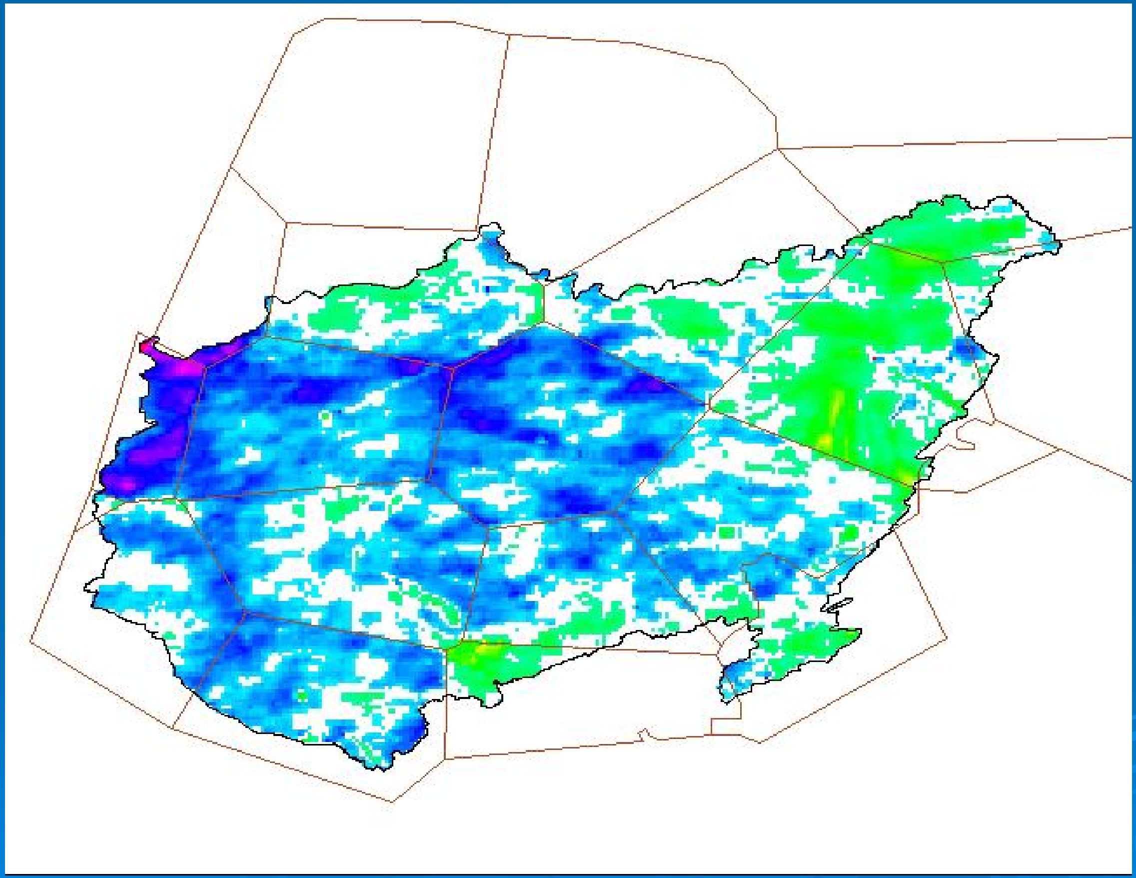




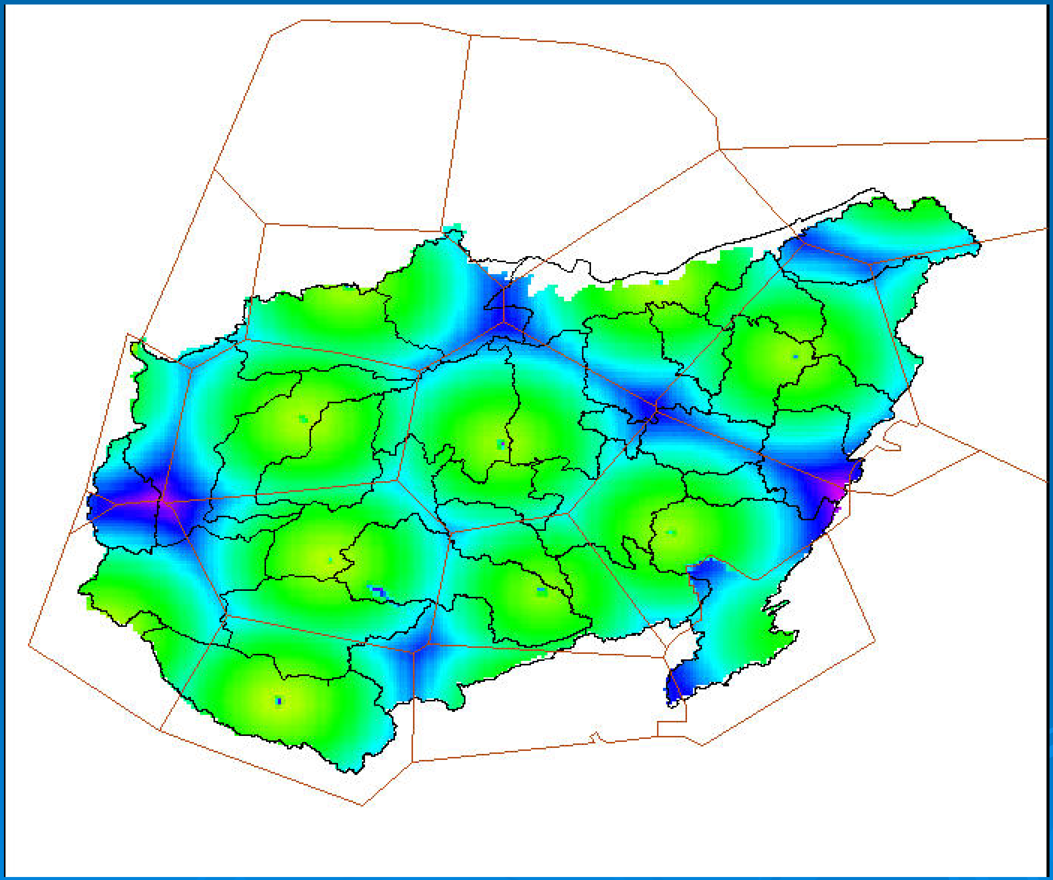
MPE Radar Boundaries (cont.)



MPE Radar Boundaries (cont.)

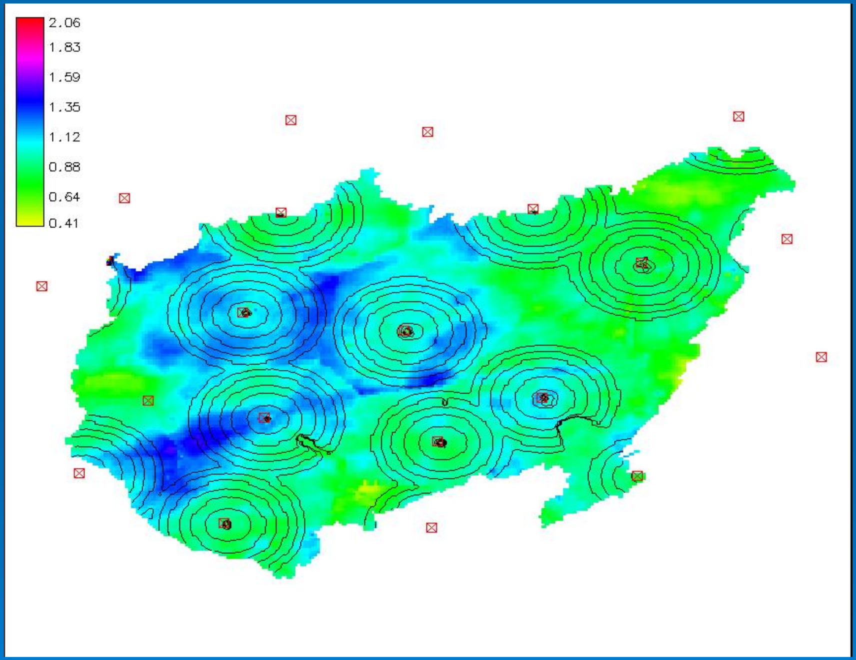


OHRFC Radar Heights Field

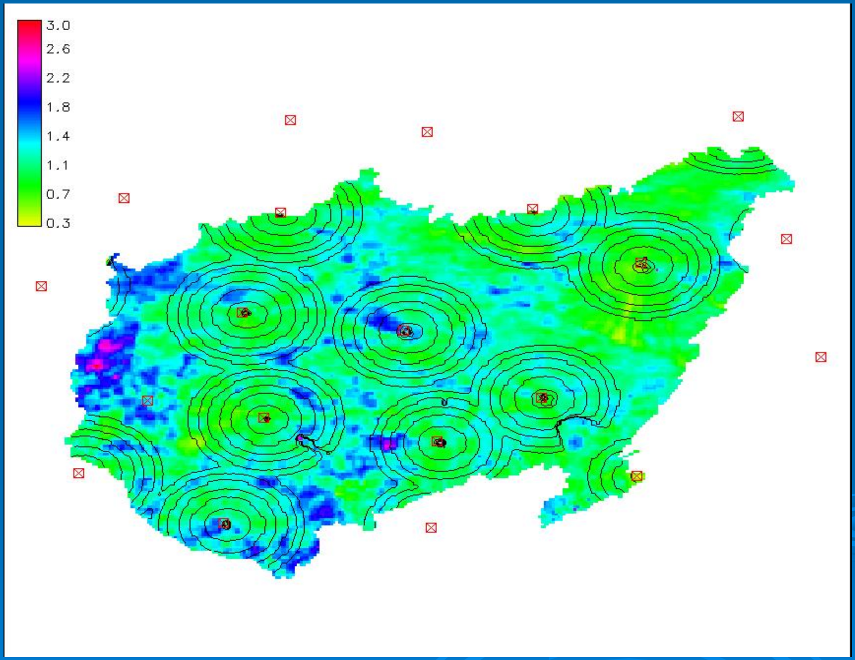


Seasonal Bias Comparison

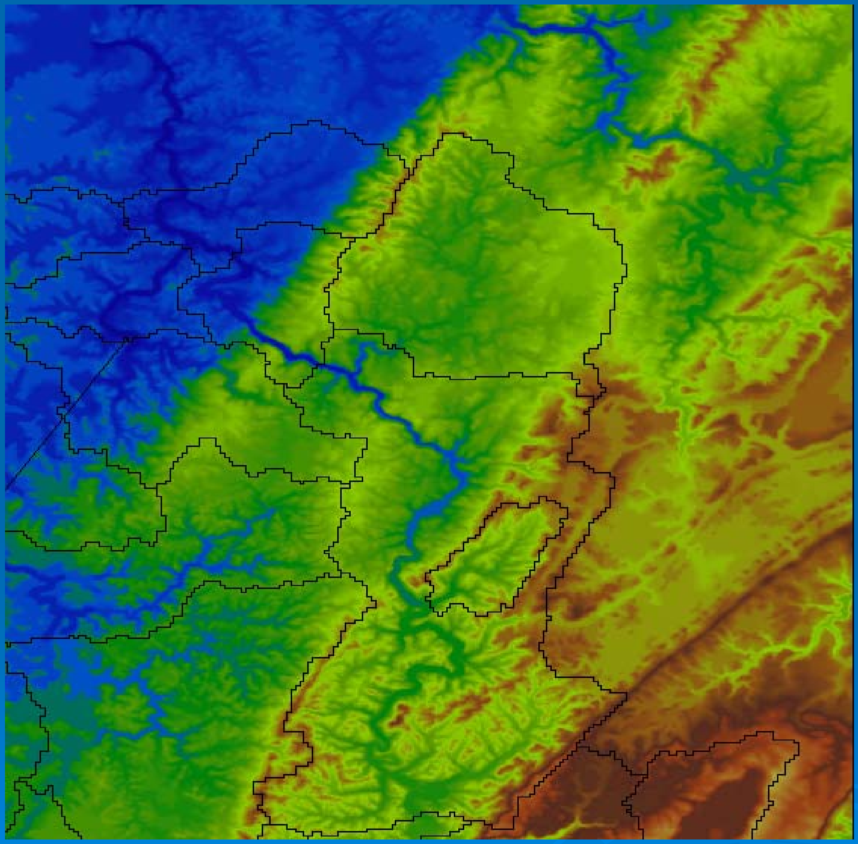
DJF

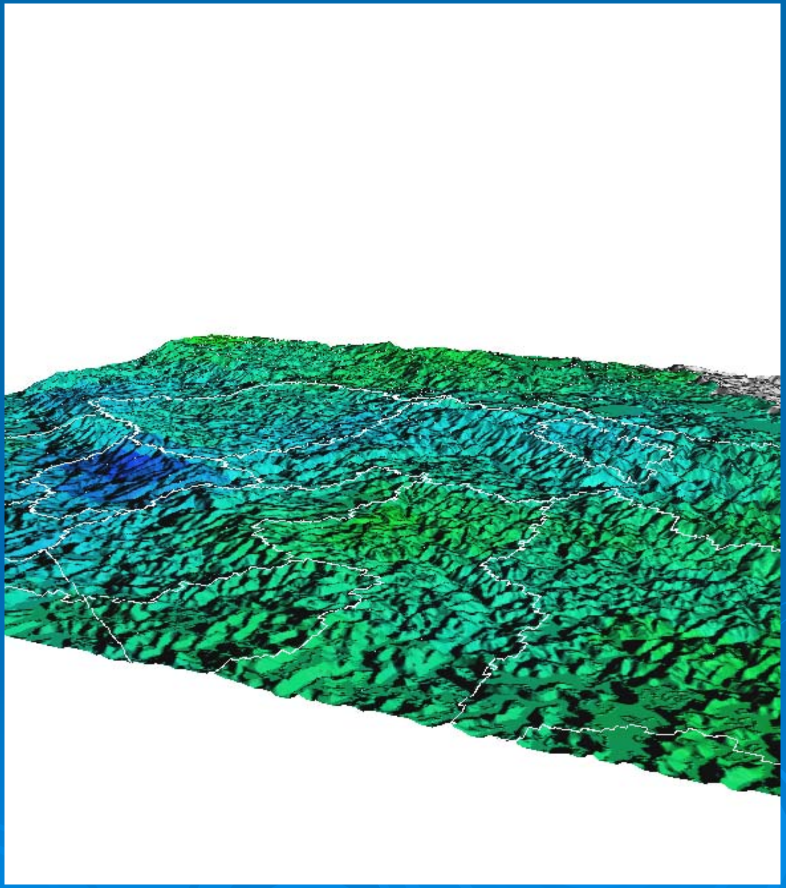


JJA



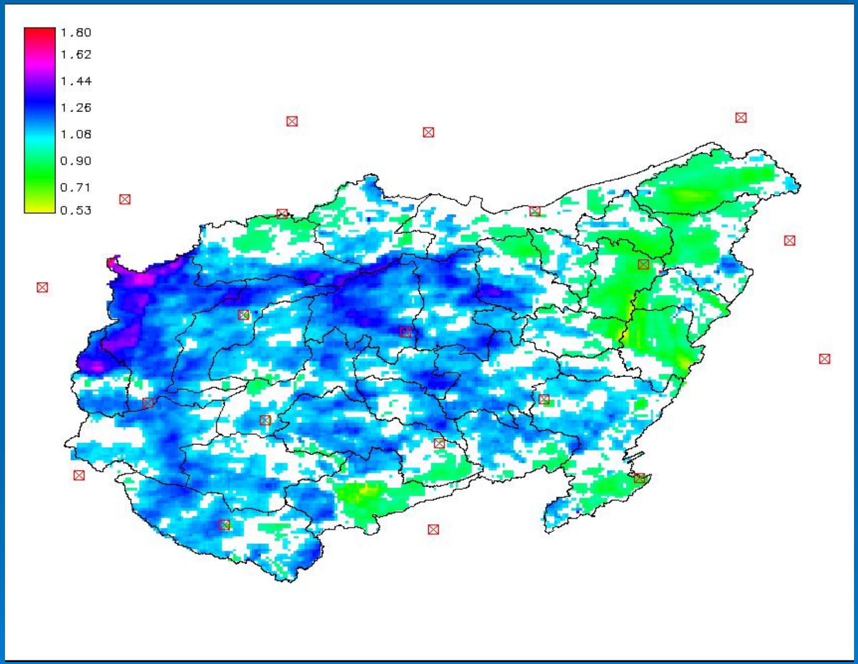
Local Effects



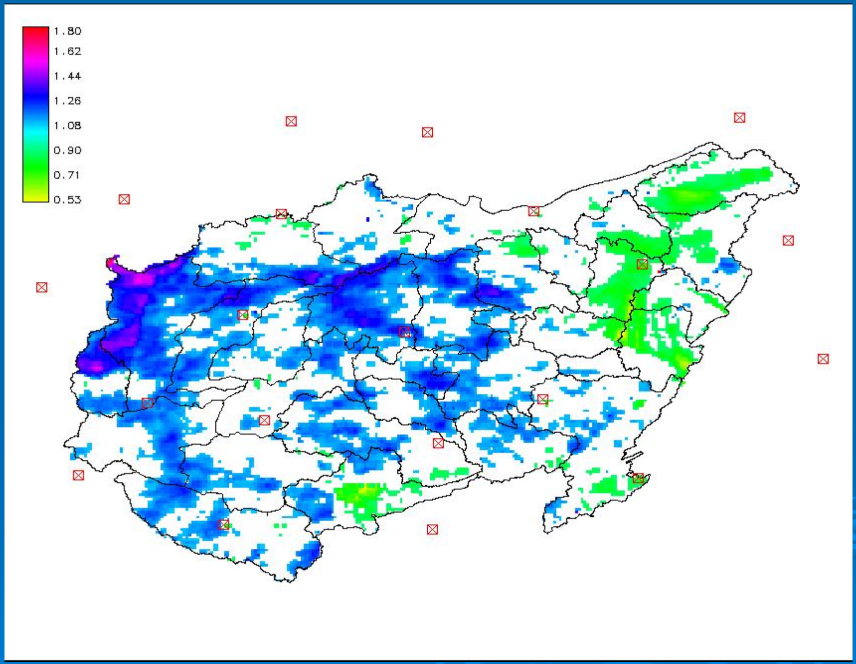


2002 Bias Comparison (cont.)

0.95 ≤ Acceptable Bias ≤ 1.05

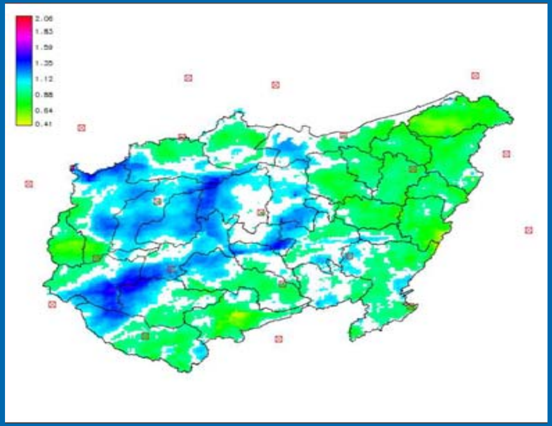


0.90 ≤ Acceptable Bias ≤ 1.10



Seasonal Bias Comparison (cont.)

DJF



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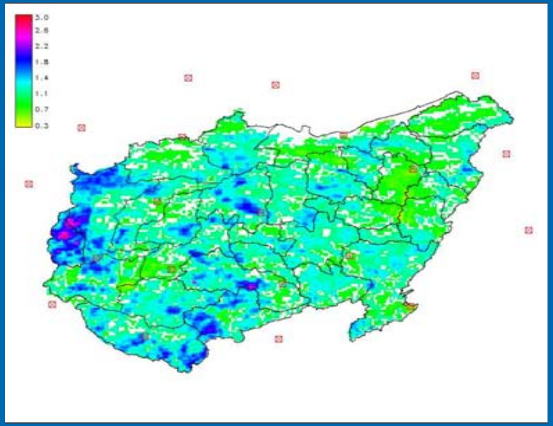
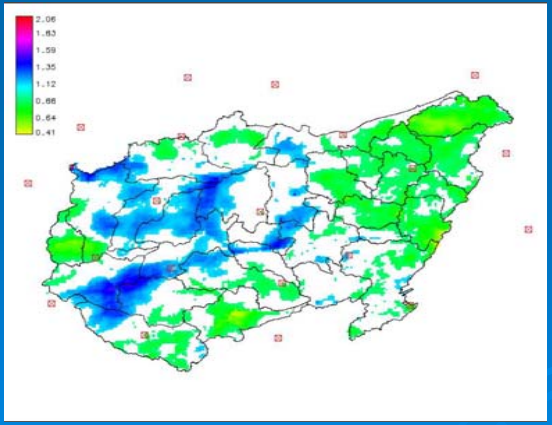
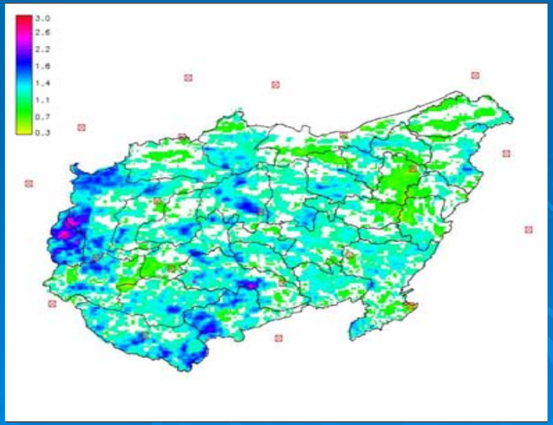


$0.95 \leq$ Acceptable Bias ≤ 1.05

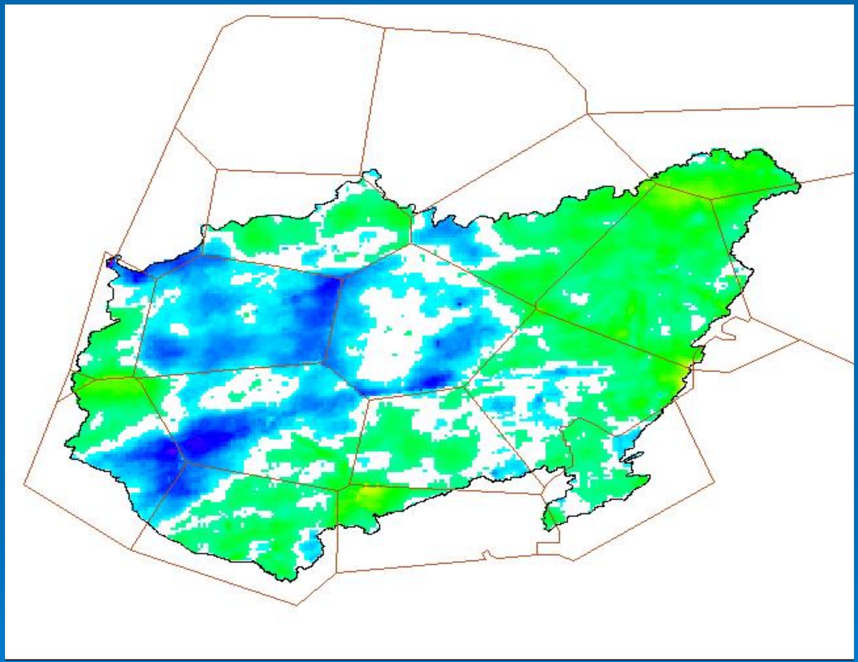




$0.90 \leq$ Acceptable Bias ≤ 1.10

Seasonal Bias Comparison (cont.)

DJF



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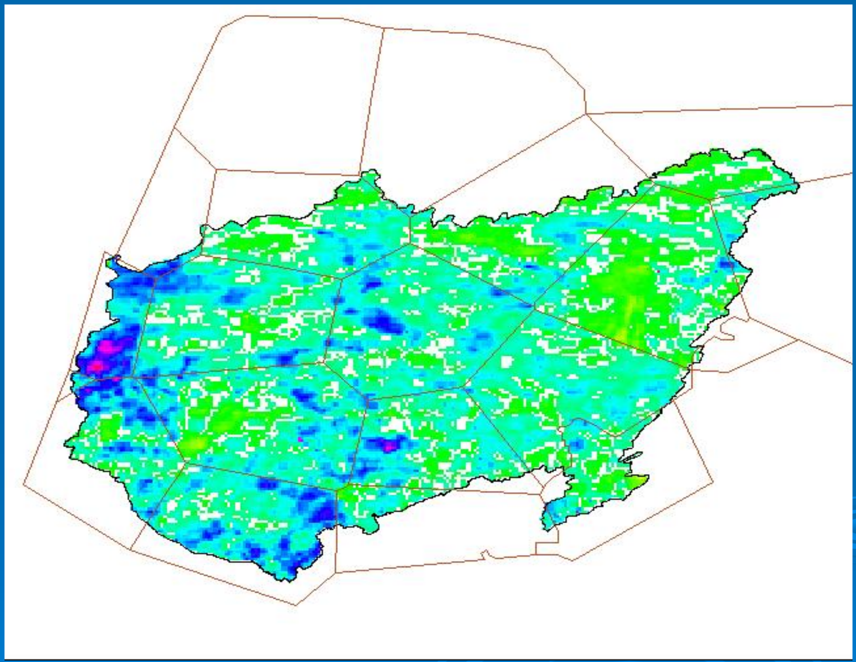
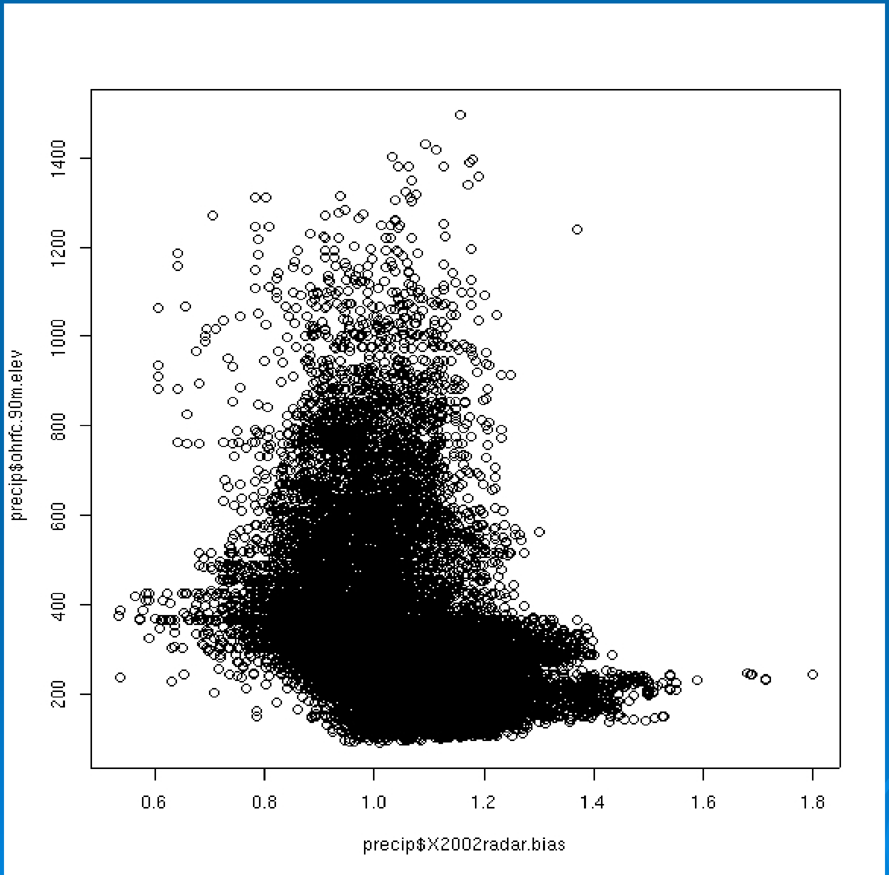
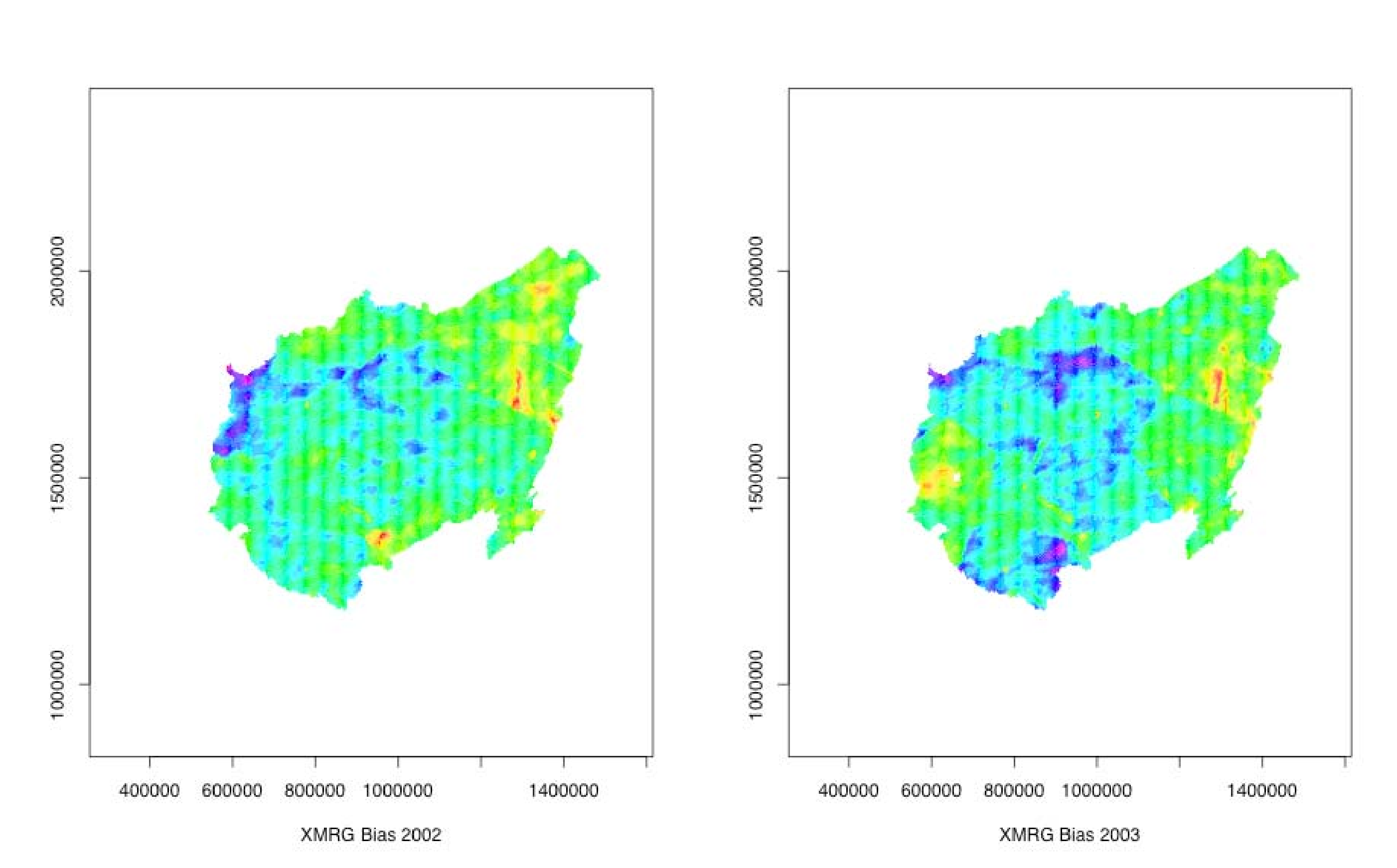


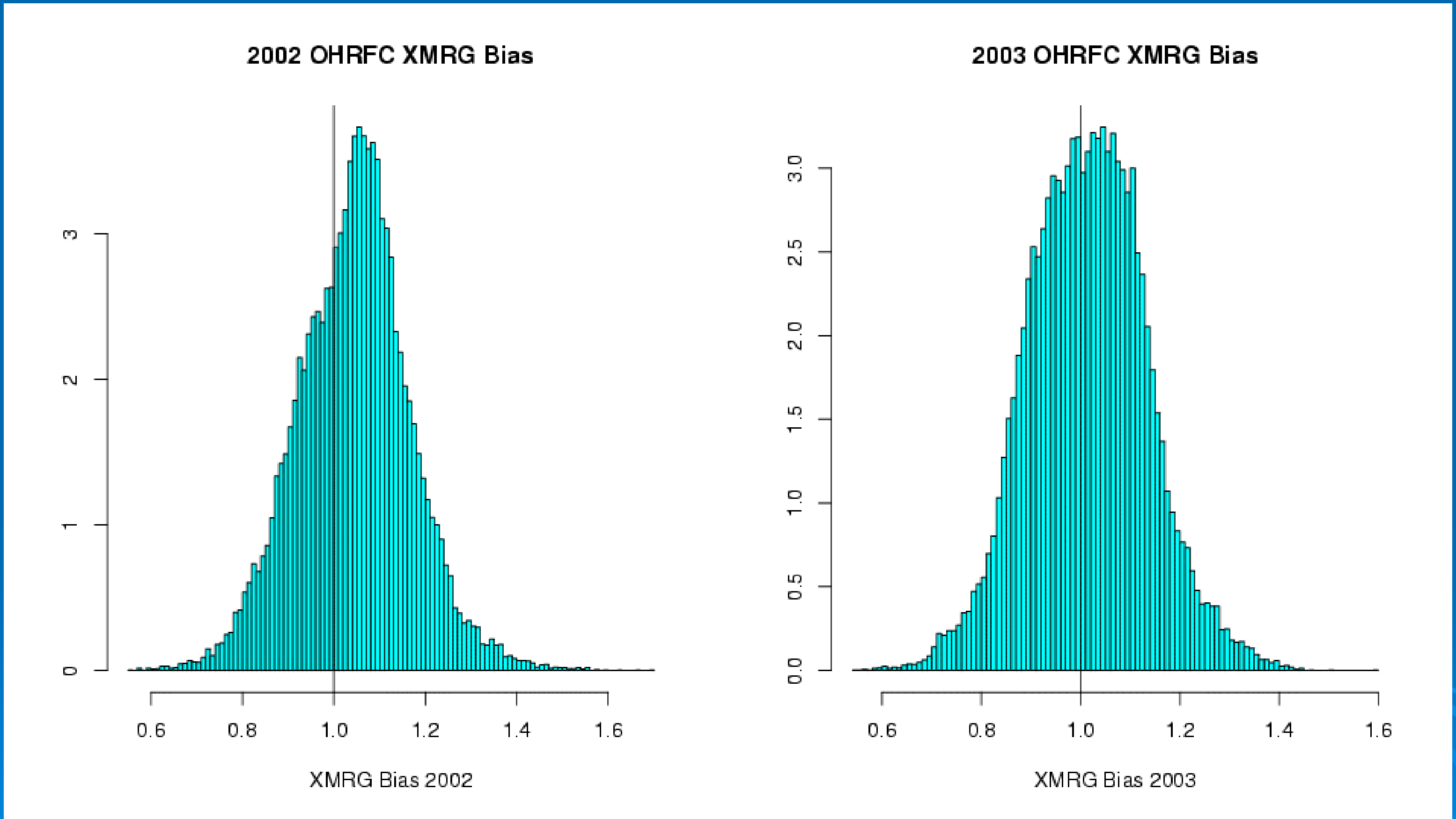
Bias as a Function of Radar Beam Height



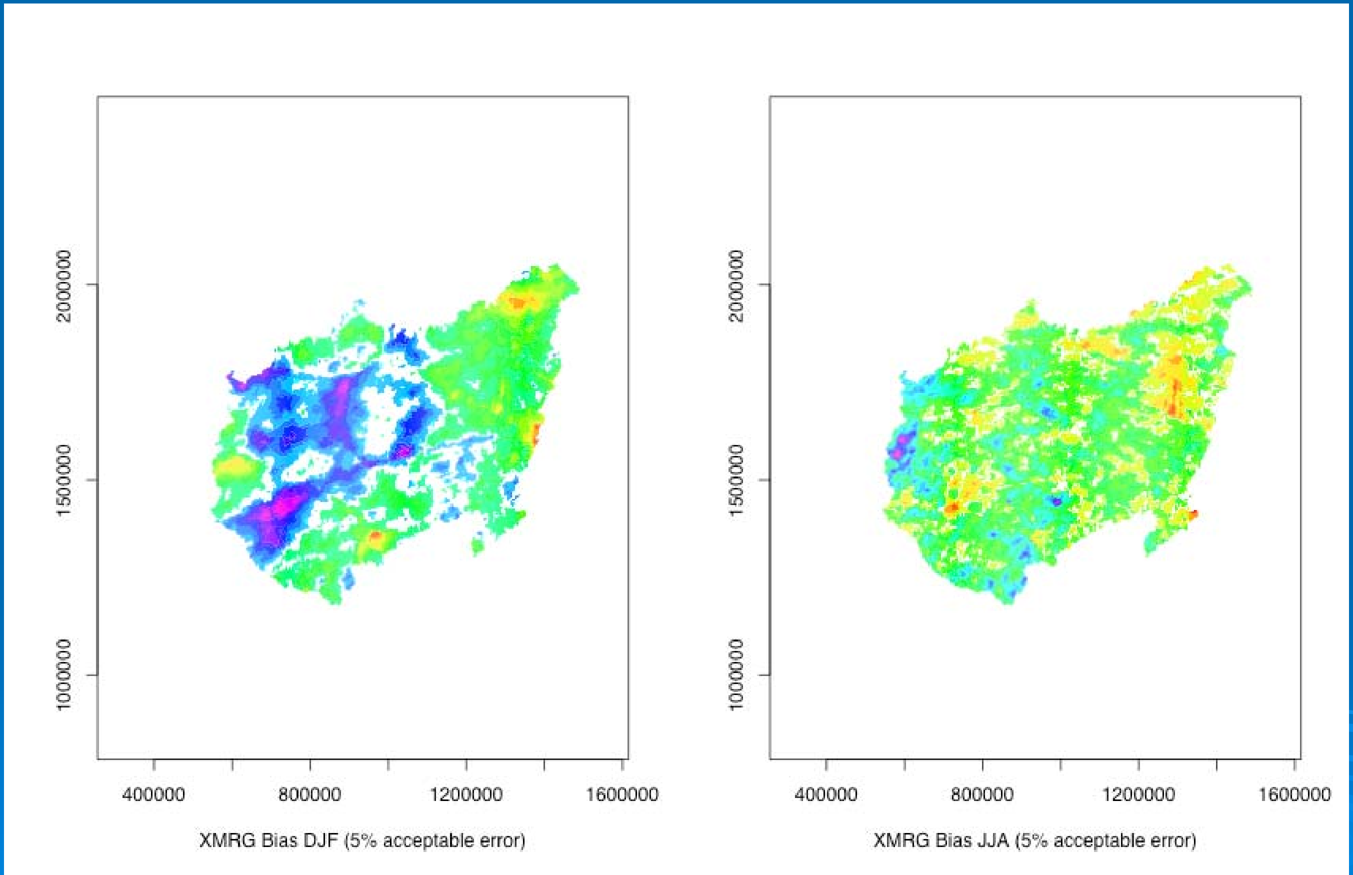
2002 & 2003 Comparison



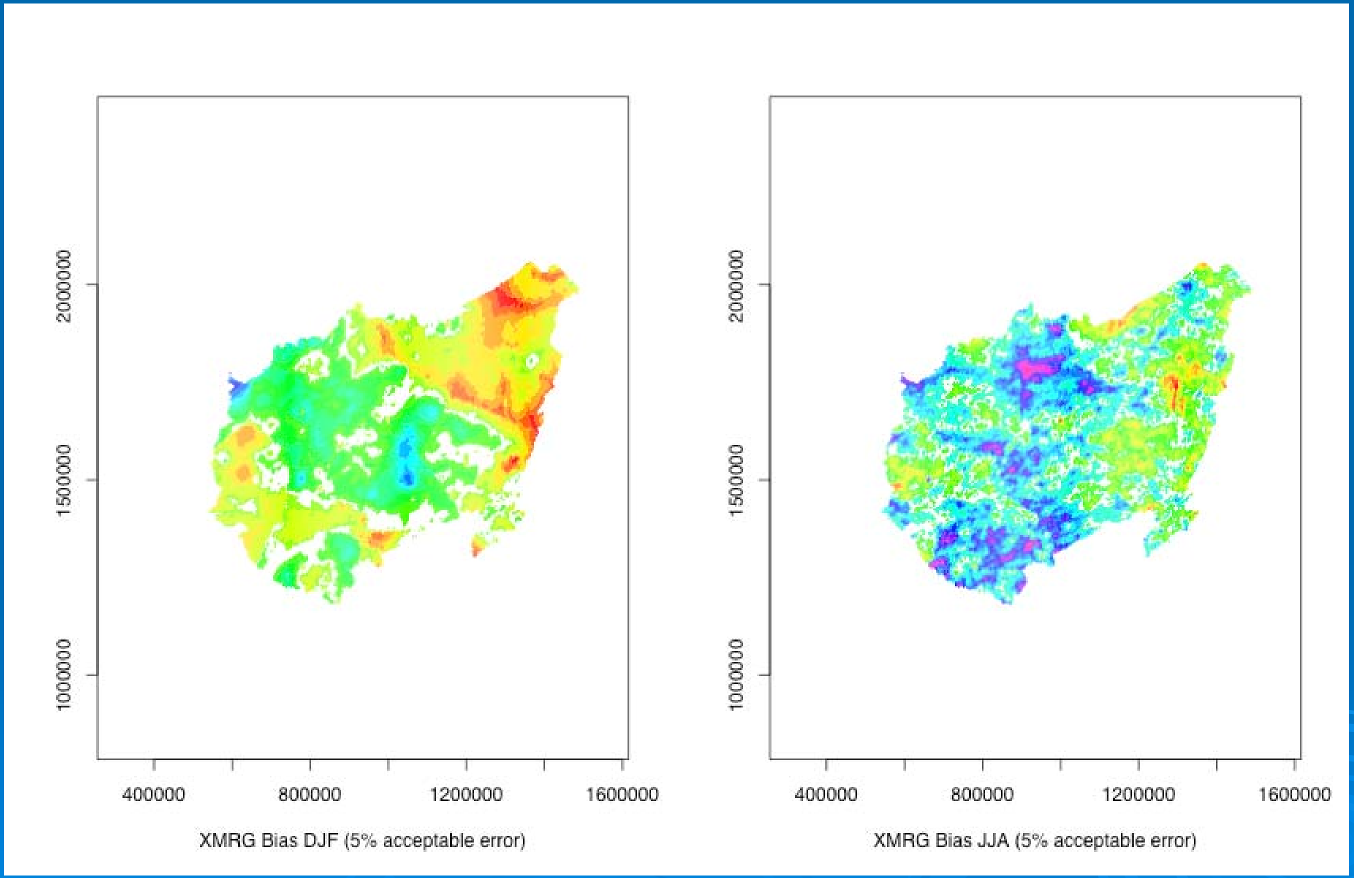
2002 & 2003 Comparison (cont.)



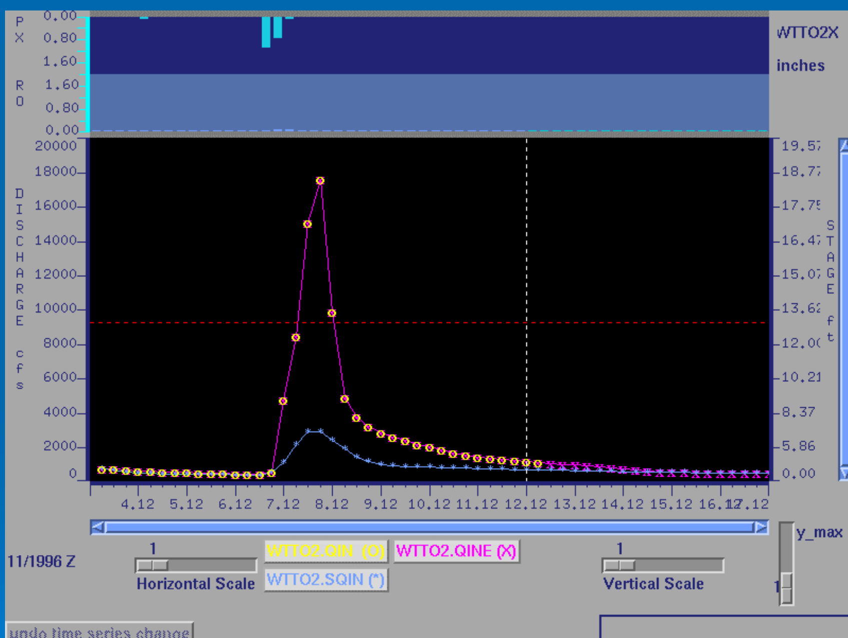
2002 Seasonal Comparison



2003 Seasonal Comparison



Hydrologic Impact of Radar-Precipitation Bias



- Hydrologic response is highly nonlinear
- Impacts to daily forecasts
  - Peak flows
  - Flow volumes
- Model states affected for long lead time ESP/AHPS forecasts
- Impacts on weekly, monthly, annual water balance
- Impacts FFG — Flash Flood watches & warnings
- Timeliness of RFC forecasts delayed due to increased staff workload to make precipitation corrections

Bias Summary 2002 by Basin

Basin	Min.	1st-Qu.	Median	Mean	3rd-Qu.	Max.
AGU	0.6645	0.8527	0.9010	0.9004	0.9428	1.2200
AGL	0.7640	0.8980	0.9476	0.9546	1.0050	1.2360
MNU	0.5342	0.8307	0.8979	0.8929	0.9641	1.1530
MNL	0.6157	0.9012	0.9481	0.9412	0.9843	1.1410
OHW	0.5646	0.8312	0.8717	0.8779	0.9250	1.7990
KAN	0.6586	0.9771	1.0400	1.0260	1.0810	1.3690
SAY	0.8347	1.0000	1.0620	1.0560	1.1160	1.2330
SCI	0.9795	1.0870	1.1390	1.1410	1.1930	1.3360
MIM	0.9820	1.1160	1.1600	1.1730	1.2310	1.3740
MAU	0.8378	0.9801	1.0360	1.0430	1.0970	1.3810
CMU	0.5372	0.9071	0.9946	0.9951	1.1060	1.2540
WBU	0.8223	0.9592	1.0520	1.0580	1.1300	1.4350
WBL	0.8854	1.1430	1.2130	1.2220	1.2920	1.7130
LWA	0.8854	1.0770	1.1680	1.1710	1.2610	1.5270

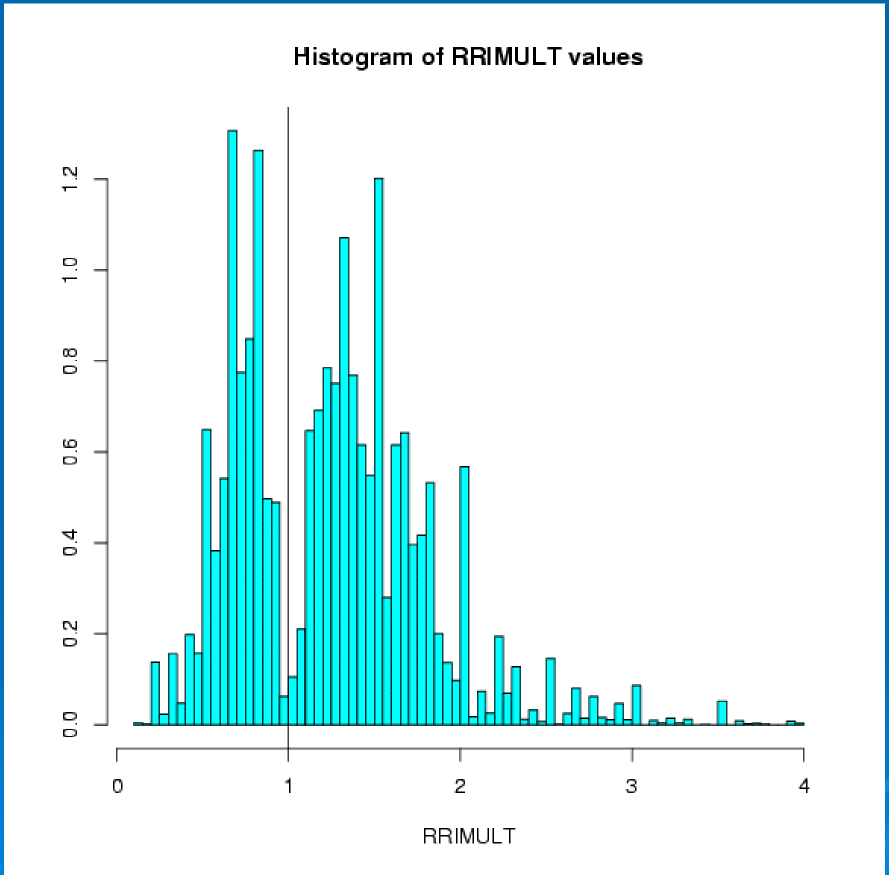
Bias Summary DJF 2002 by Basin

Basin	Min.	1st-Qu.	Median	Mean	3rd-Qu.	Max.
AGU	0.4642	0.6622	0.7241	0.7310	0.7890	1.0970
AGL	0.5750	0.7925	0.8463	0.8490	0.8993	1.1400
MNU	0.4897	0.7558	0.8285	0.8113	0.8838	0.9968
MNL	0.6294	0.8309	0.8719	0.8623	0.9059	1.1060
OHW	0.6491	0.8428	0.8701	0.8656	0.8911	1.0820
KAN	0.5215	0.8864	0.9291	0.9381	0.9907	1.2200
SAY	0.8083	0.9416	0.9716	0.9816	1.0230	1.2170
SCI	0.9171	1.0200	1.0620	1.0730	1.1150	1.4080
MIM	0.8275	1.0070	1.0630	1.0940	1.1650	1.3600
MAU	0.6927	0.8907	0.9539	0.9541	1.0090	1.2050
CMU	0.4685	0.7949	0.8936	0.8605	0.9446	1.2090
WBU	0.7852	0.9213	1.0160	1.0230	1.0970	1.4220
WBL	0.5208	0.9663	1.0710	1.0540	1.1530	2.0640
LWA	0.5511	0.7054	0.8267	0.8015	0.8929	1.0080

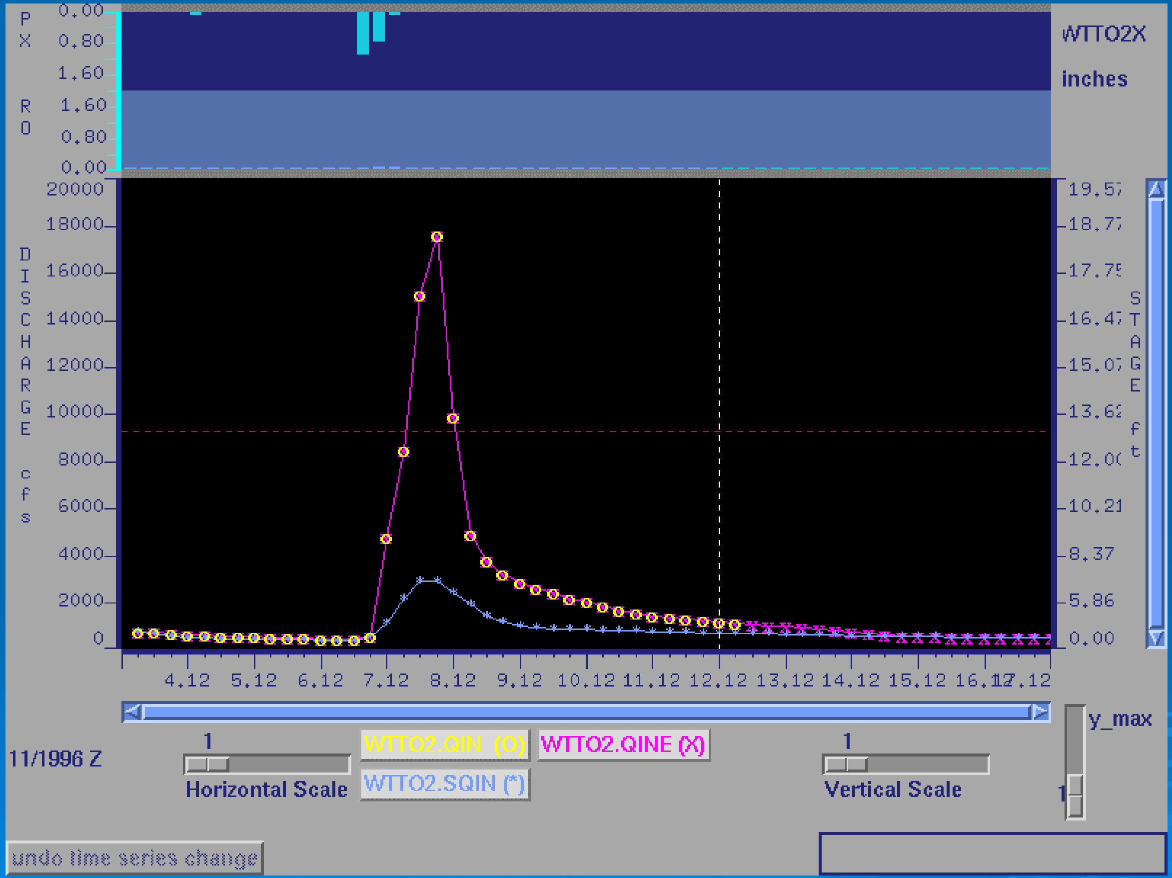
Bias Summary JJA 2002 by Basin

Basin	Min.	1st-Qu.	Median	Mean	3rd-Qu.	Max.
AGU	0.5779	0.8518	0.9298	0.9419	1.0150	1.4070
AGL	0.6979	0.9563	1.0640	1.0910	1.1930	1.8220
MNU	0.4051	0.8464	0.9874	0.9919	1.1600	1.5160
MNL	0.4819	0.8871	1.0130	0.9922	1.0930	1.5100
OHW	0.4262	0.7305	0.8246	0.8444	0.9410	2.6860
KAN	0.2876	1.0040	1.1230	1.1240	1.2450	2.2980
SAY	0.6842	1.0140	1.1700	1.1500	1.2810	1.7540
SCI	0.8257	1.0600	1.1440	1.1710	1.2550	1.7560
MIM	0.7451	1.0980	1.2320	1.2750	1.4020	2.0150
MAU	0.6897	1.0370	1.1840	1.1860	1.3390	1.9800
CMU	0.5152	1.1050	1.3320	1.3310	1.5360	2.3410
WBU	0.7537	0.9569	1.0580	1.0870	1.1960	1.7750
WBL	0.3004	1.1730	1.4180	1.4150	1.6250	2.6010
LWA	0.9977	1.4960	1.7040	1.7320	1.9500	2.9910

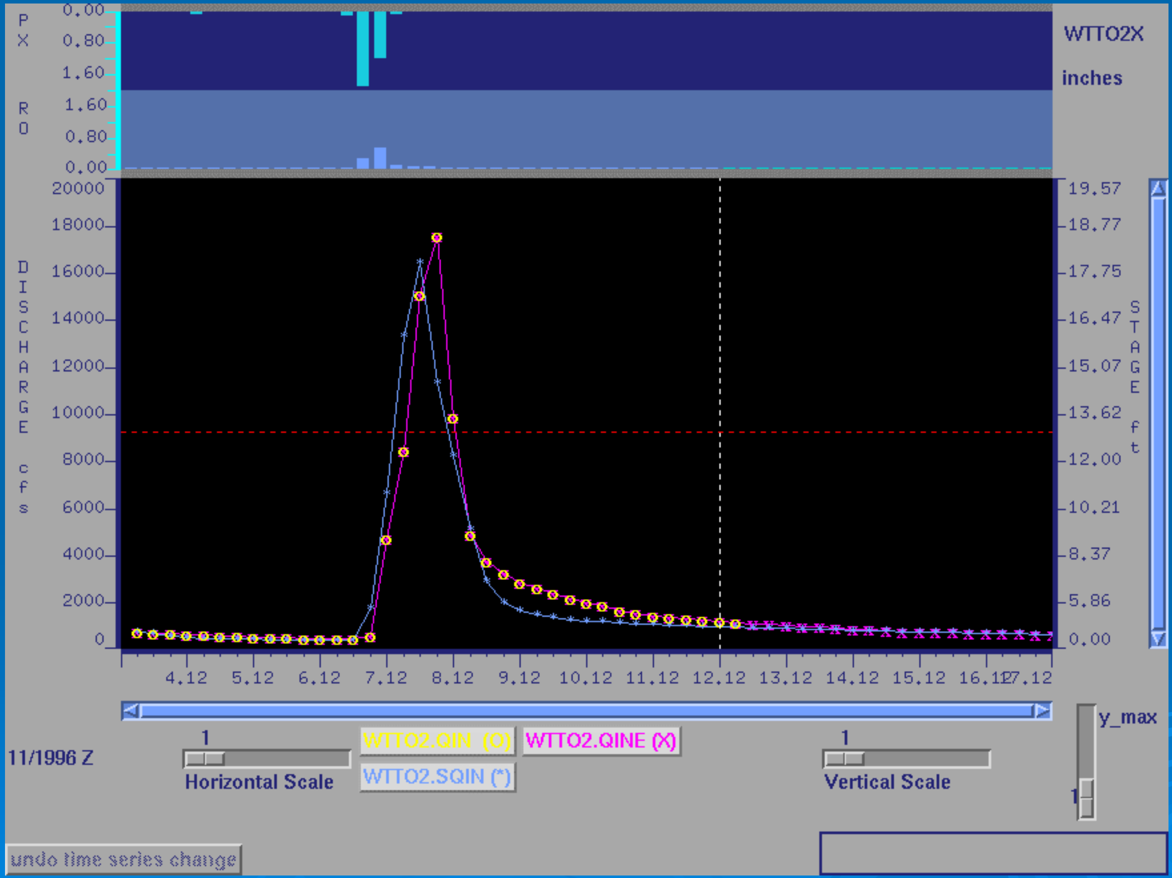
Precipitation Bias Correction during Operational Hydrologic Modeling



Hydrograph without bias correction



Hydrograph with precipitation bias correction (~1.75)



NWSRFS OFS Runtime Modifications

Mod Type	~Relative Frequency (%)
TSCHNG	28
RRIMULT	16
UHGCHNG	12
CHGBLEND	11
RRICHNG	11
BASEF	9
SACBASEF	8

Approximately 1-year (227000 Mods)

BUCW2N

Precipitation Bias by Basin	% Bias	% MONTHLY VOL RMS ERROR	DISCHARGE RATIO (SIM/OBS)	MEAN % ERROR (AVGOBSQ-AVGSIMQ)/AVGOBSQ
0.80	-36.65	54.22	0.62	-40.50
0.90	-19.69	38.43	0.87	-20.60
0.95	-11.06	33.16	1.00	-10.60
1.00	-2.26	30.90	1.13	-0.70
1.05	6.65	32.23	1.26	8.70
1.10	15.70	36.86	1.37	17.40
1.20	33.90	51.90	1.58	34.00

CARI3

Precipitation Bias by Basin	% Bias	% MONTHLY VOL RMS ERROR	DISCHARGE RATIO (SIM/OBS)	MEAN % ERROR (AVGOBSQ-AVGSIMQ)/AVGOBSQ
0.80	-41.73	64.61	0.32	-64.80
0.90	-21.44	42.83	0.57	-37.50
0.95	-10.96	34.19	0.72	-22.90
1.00	-0.11	29.83	0.86	-8.30
1.05	11.01	32.17	1.02	6.50
1.10	22.35	40.30	1.17	21.30
1.20	45.44	64.65	1.50	51.10

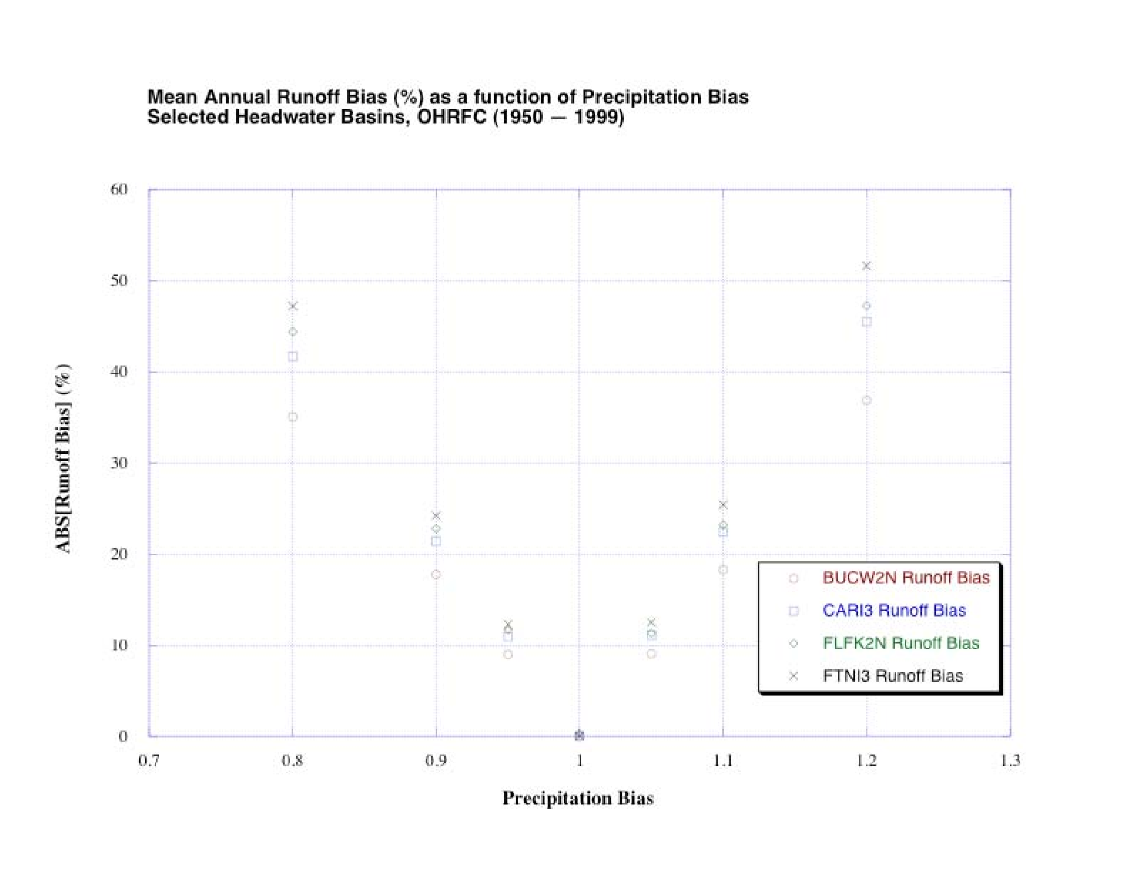
FLFK2N

Precipitation Bias by Basin	% Bias	% MONTHLY VOL RMS ERROR	DISCHARGE RATIO (SIM / OBS)	MEAN % ERROR (AVGOBSQ-AVGSIMQ) / AVGOBSQ
0.80	-44.39	73.12	0.44	-47.80
0.90	-22.78	48.40	0.69	-24.80
0.95	-11.68	39.56	0.81	-13.60
1.00	-0.28	35.55	0.93	-3.30
1.05	11.32	38.01	1.03	6.50
1.10	23.17	46.03	1.13	15.90
1.20	47.16	70.08	1.33	34.30

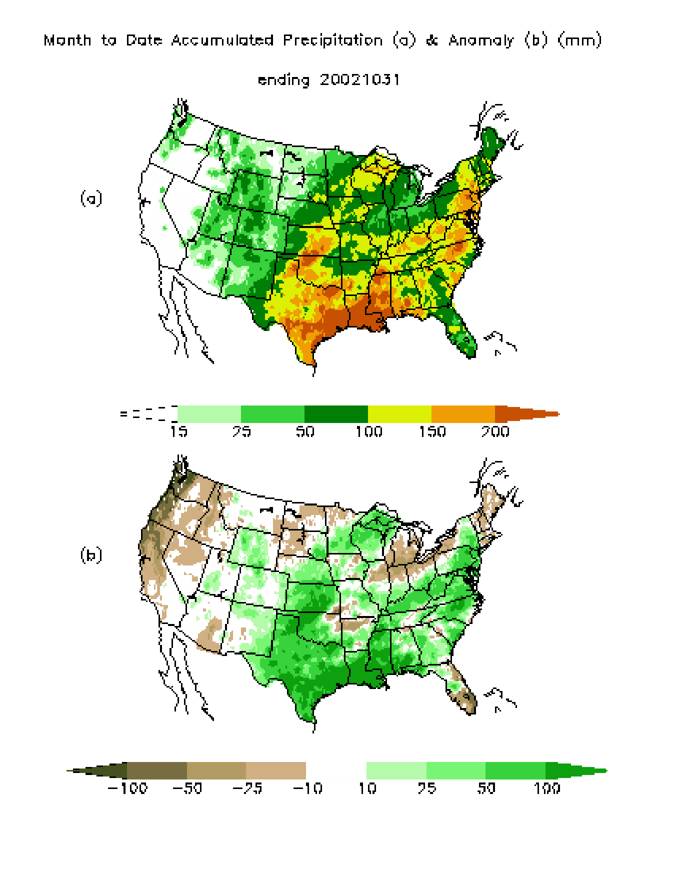
FTNI3

Precipitation Bias by Basin	% Bias	% MONTHLY VOL RMS ERROR	DISCHARGE RATIO (SIM/OBS)	MEAN % ERROR (AVGOBSQ-AVGSIMQ)/AVGOBSQ
0.80	-47.19	78.17	0.43	-53.50
0.90	-24.17	54.84	0.65	-26.60
0.95	-12.29	46.81	0.80	-10.20
1.00	-0.05	43.53	0.95	6.60
1.05	12.52	46.41	1.11	24.10
1.10	25.46	54.73	1.29	41.80
1.20	51.63	80.04	1.62	75.90

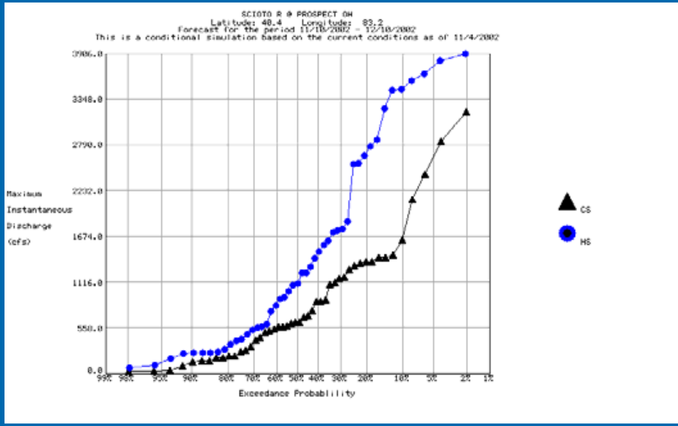
Runoff Bias versus Precipitation Bias

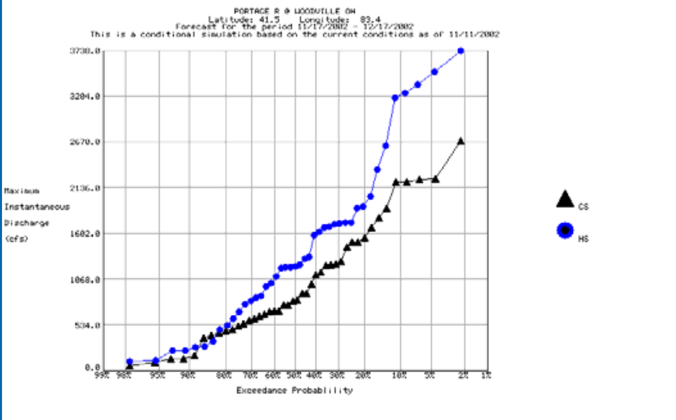


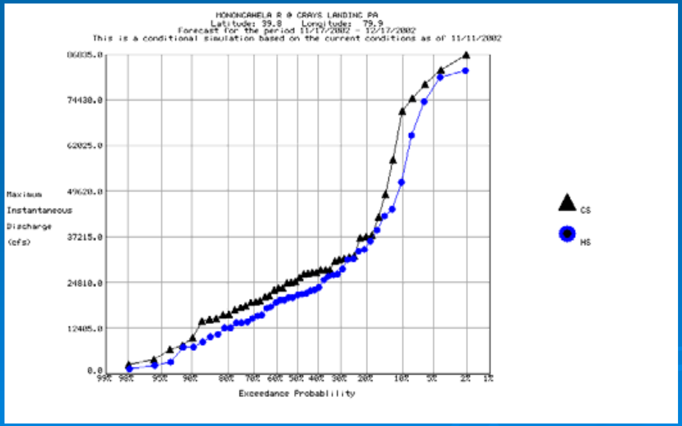
October 2002 Precipitation

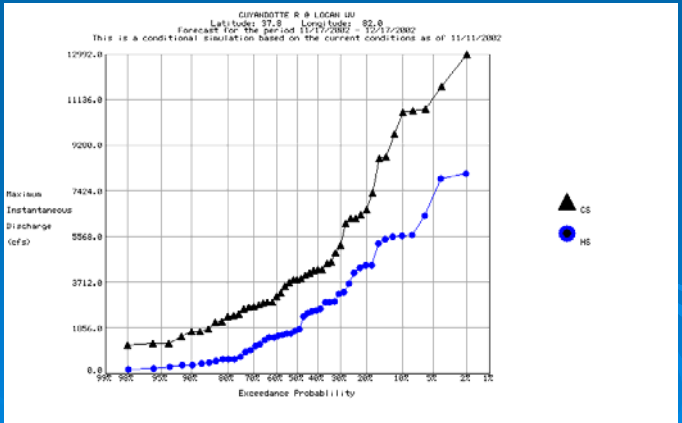


Current SAC-SMA Model States Indicated by Flow Probability of Exceedance

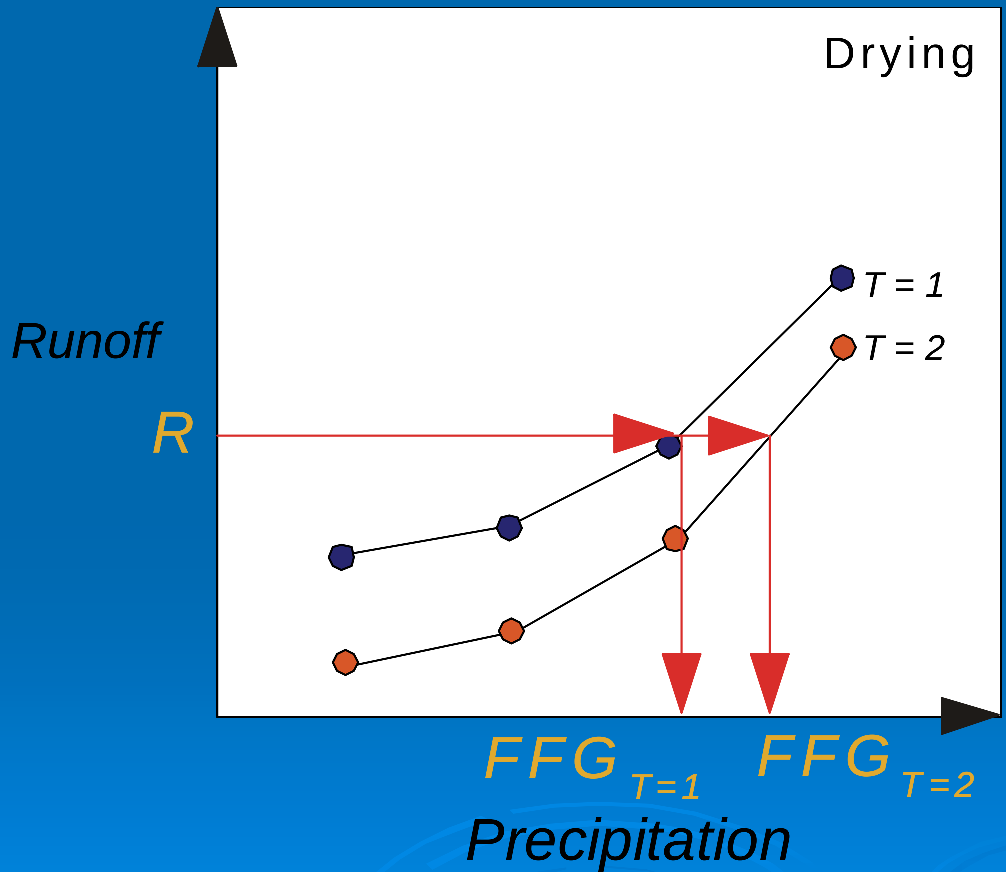






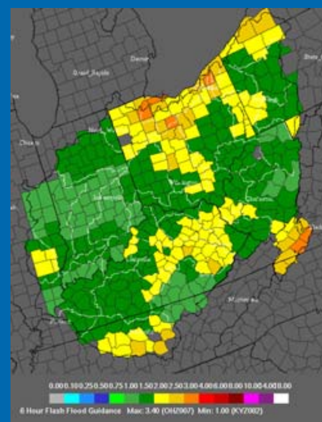


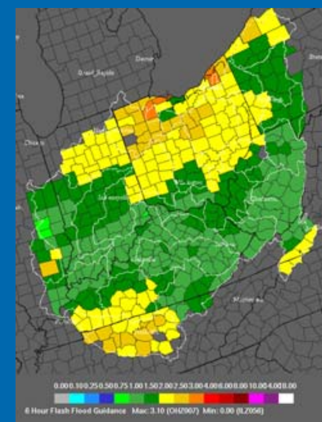
Flash Flood Guidance



Case Example: Welsh, WV May 2 - 3, 2002
OHRFC-wide FFG

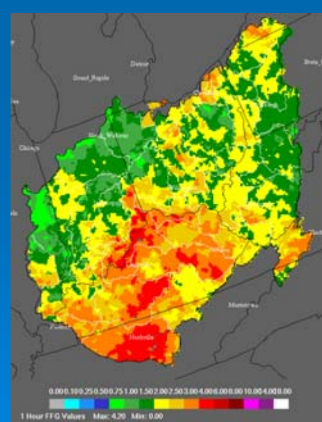
County FFG 05/01/2002

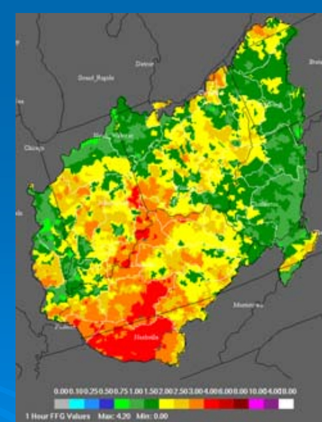




County FFG 05/03/2002

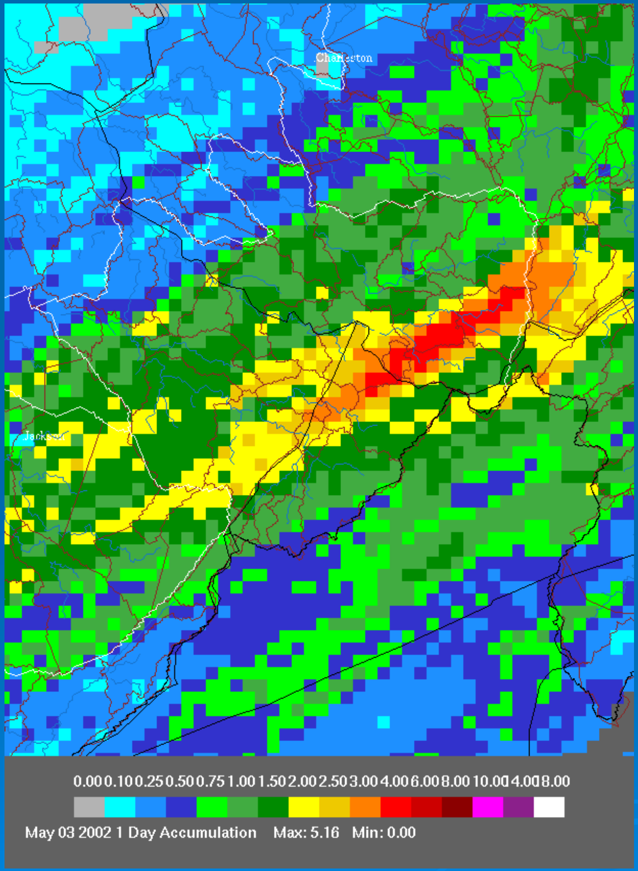
Gridded FFG 05/01/2002

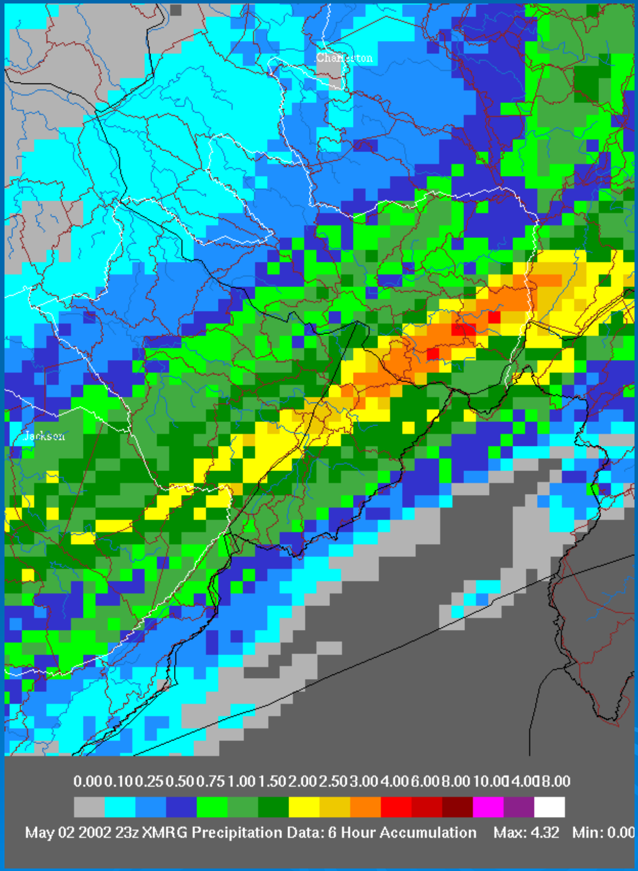




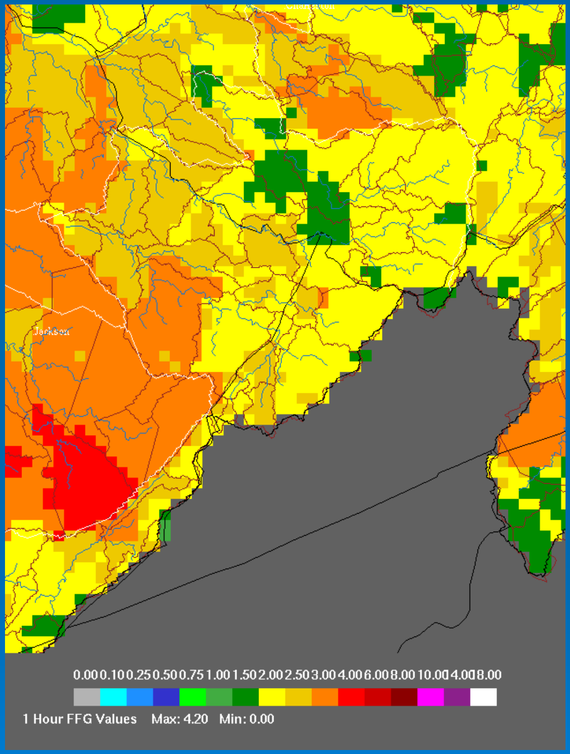
Gridded FFG 05/03/2002

Case Example: Welsh, WV May 2 - 3, 2002
24-hr & 6-hr Precipitation Accumulation

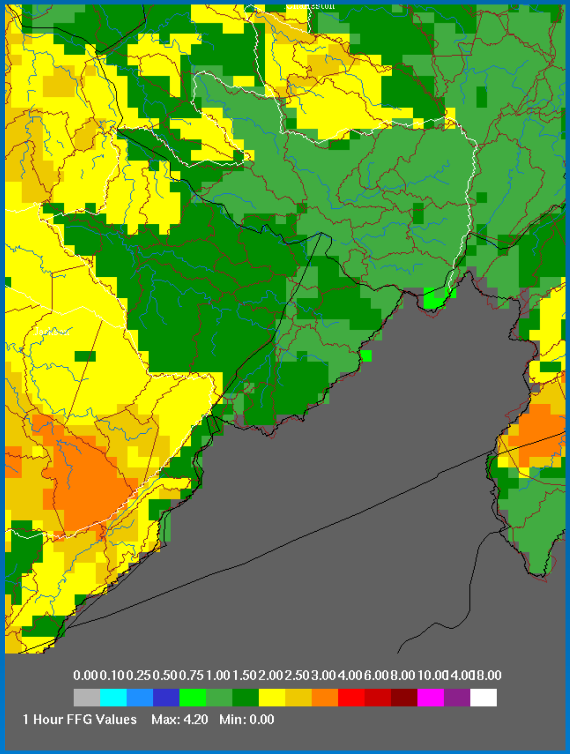




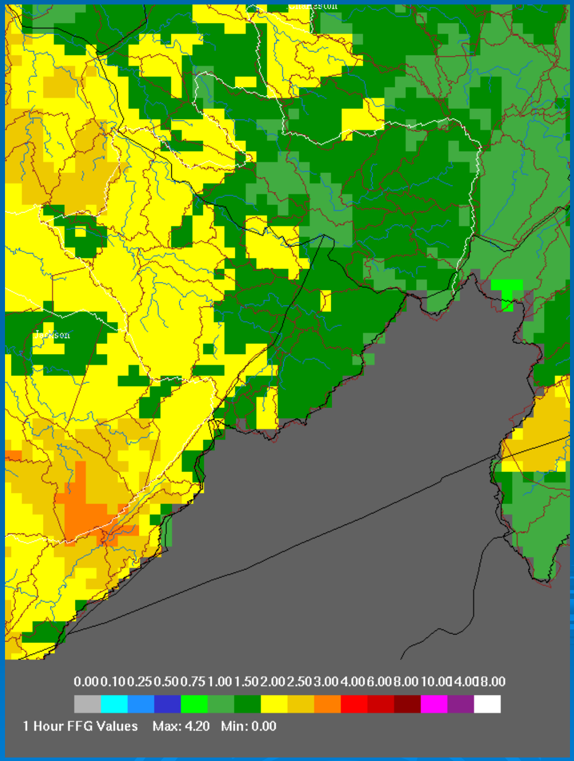
Case Example: Welsh, WV May 2 - 3, 2002
3-day Time Evolution of FFG



05/01/2002

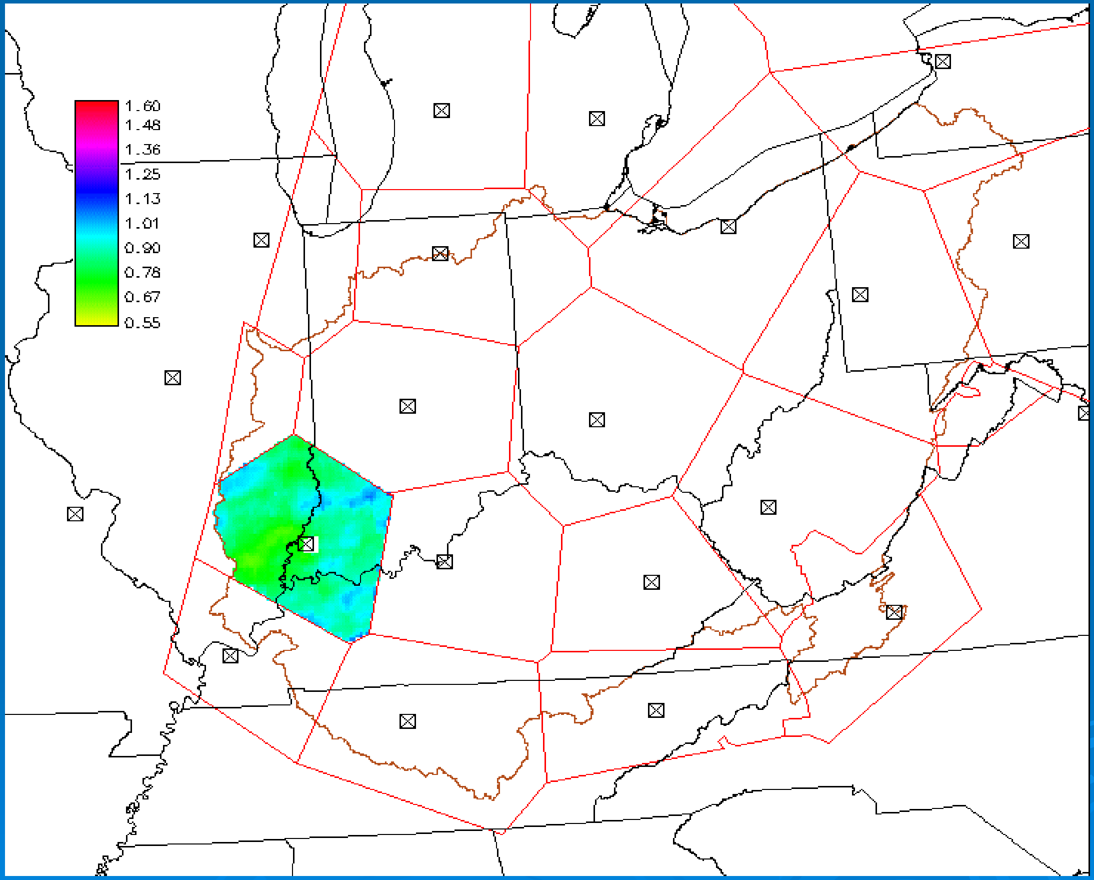


05/02/2002

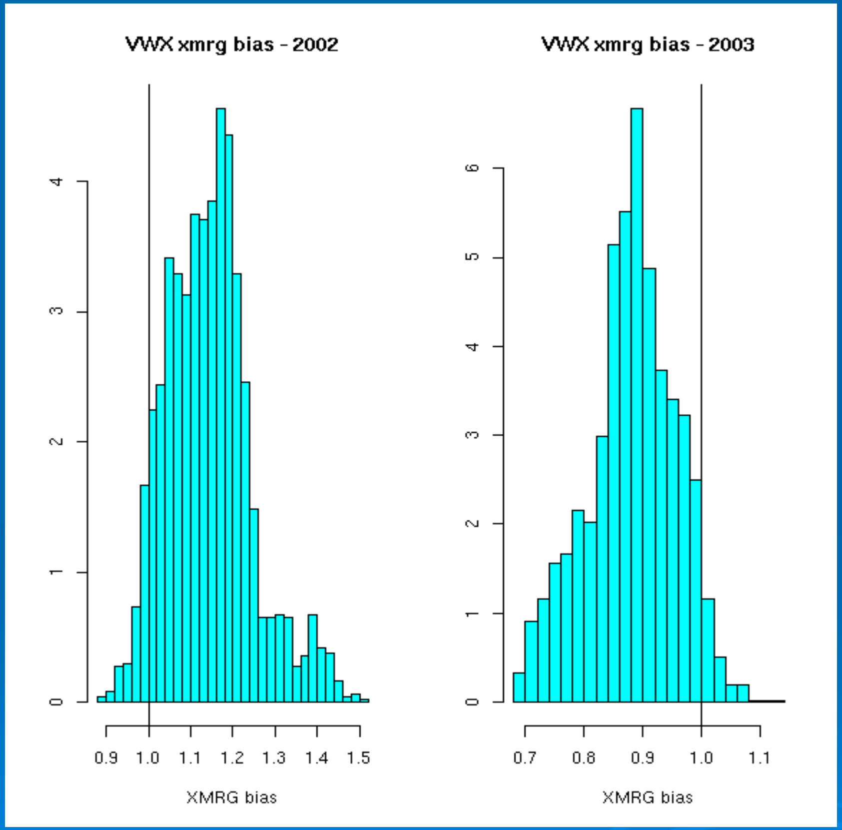


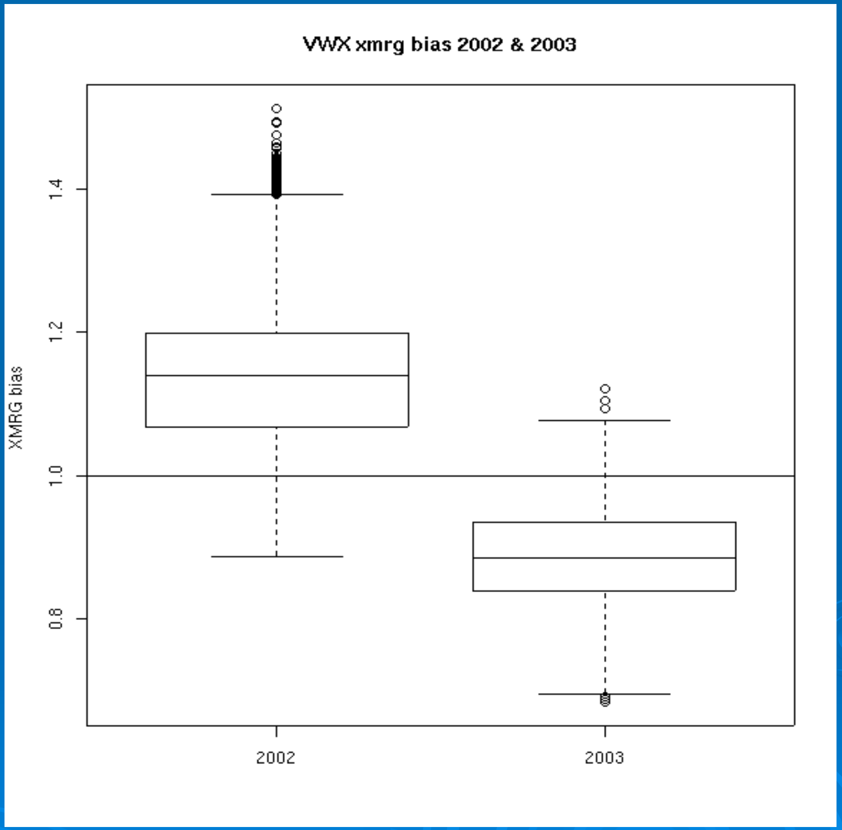
05/03/2002

Evansville Radar (VWX)

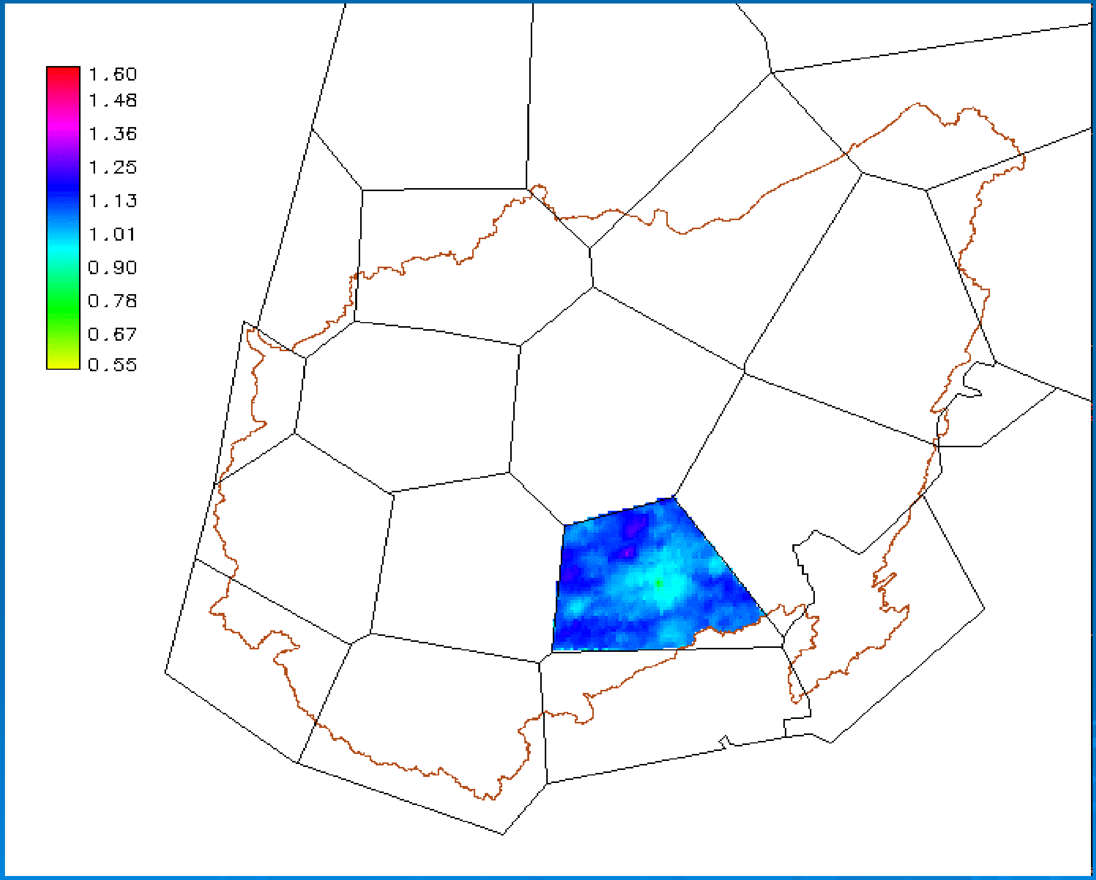


Evansville XMRG Biases

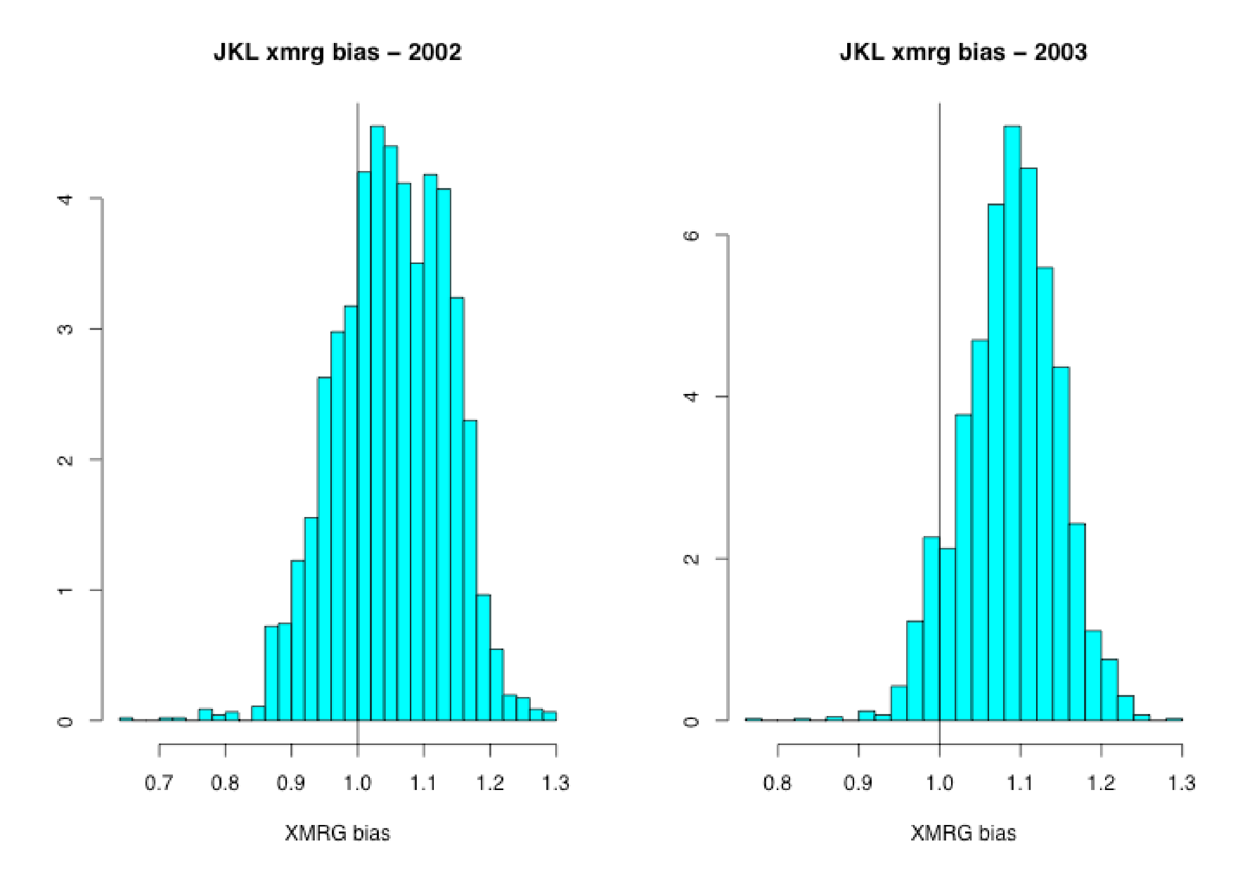




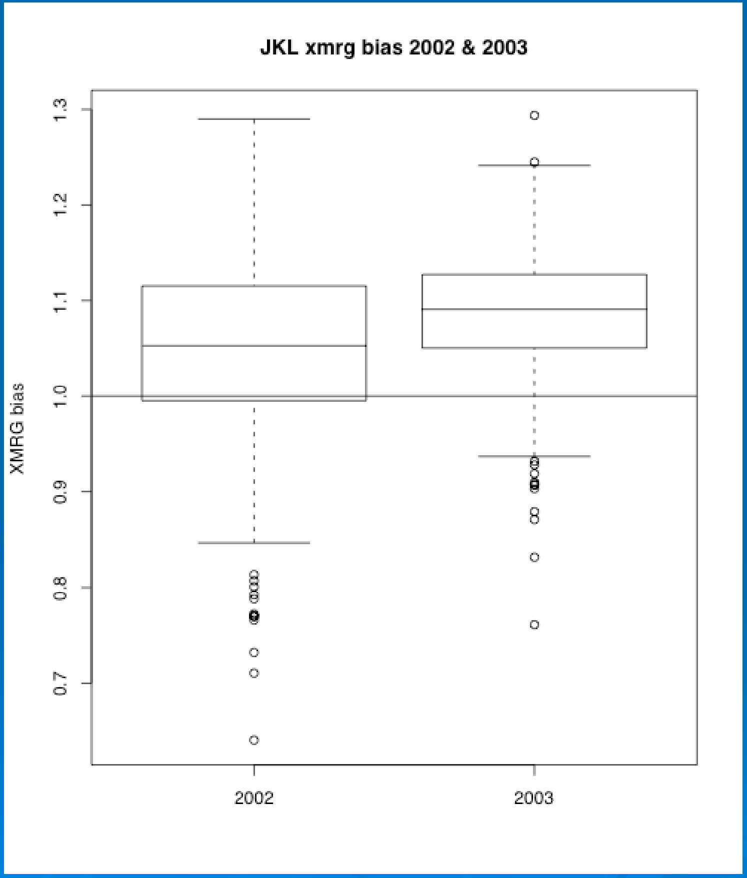
JKL



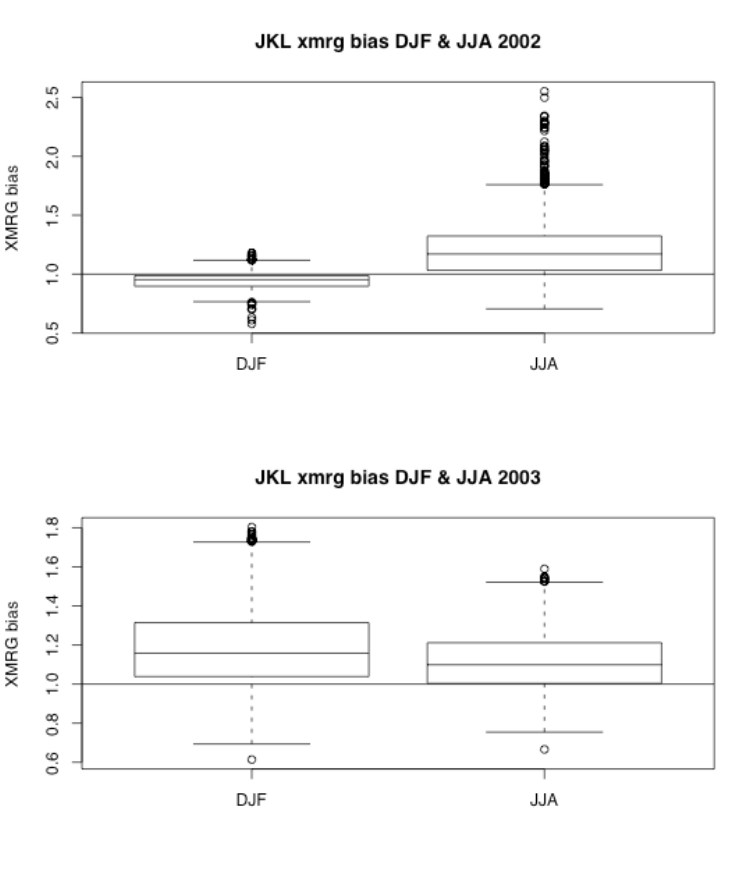
JKL 2002 & 2003 Biases



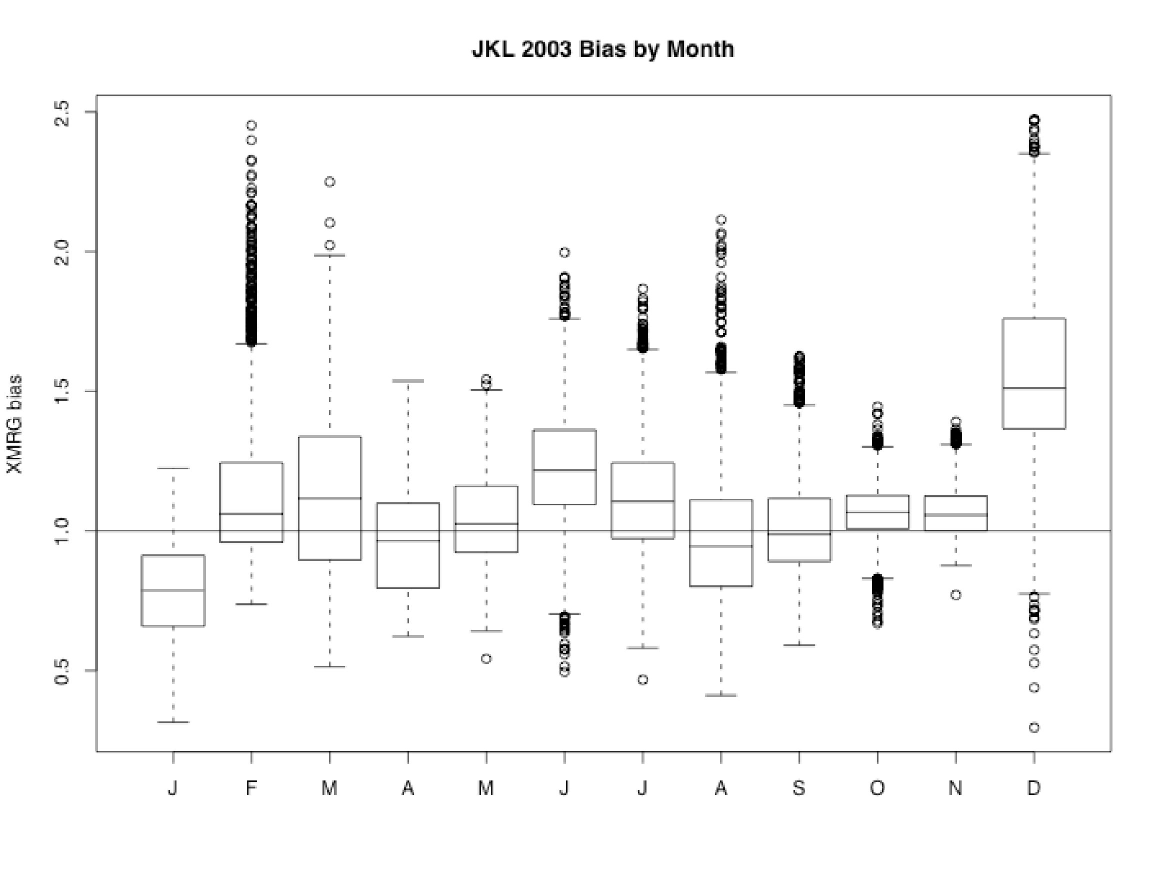
JKL 2002 & 2003 Biases (cont.)



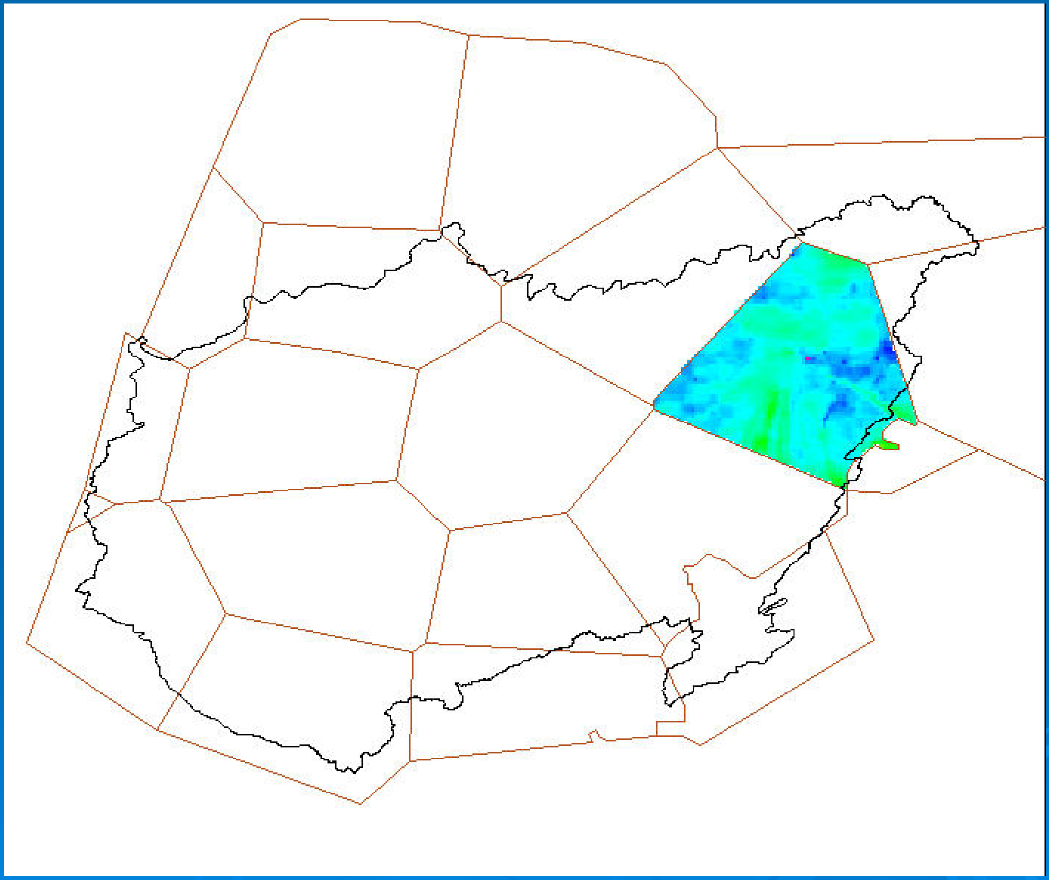
JKL 2002 & 2003 Seasonal Comparison



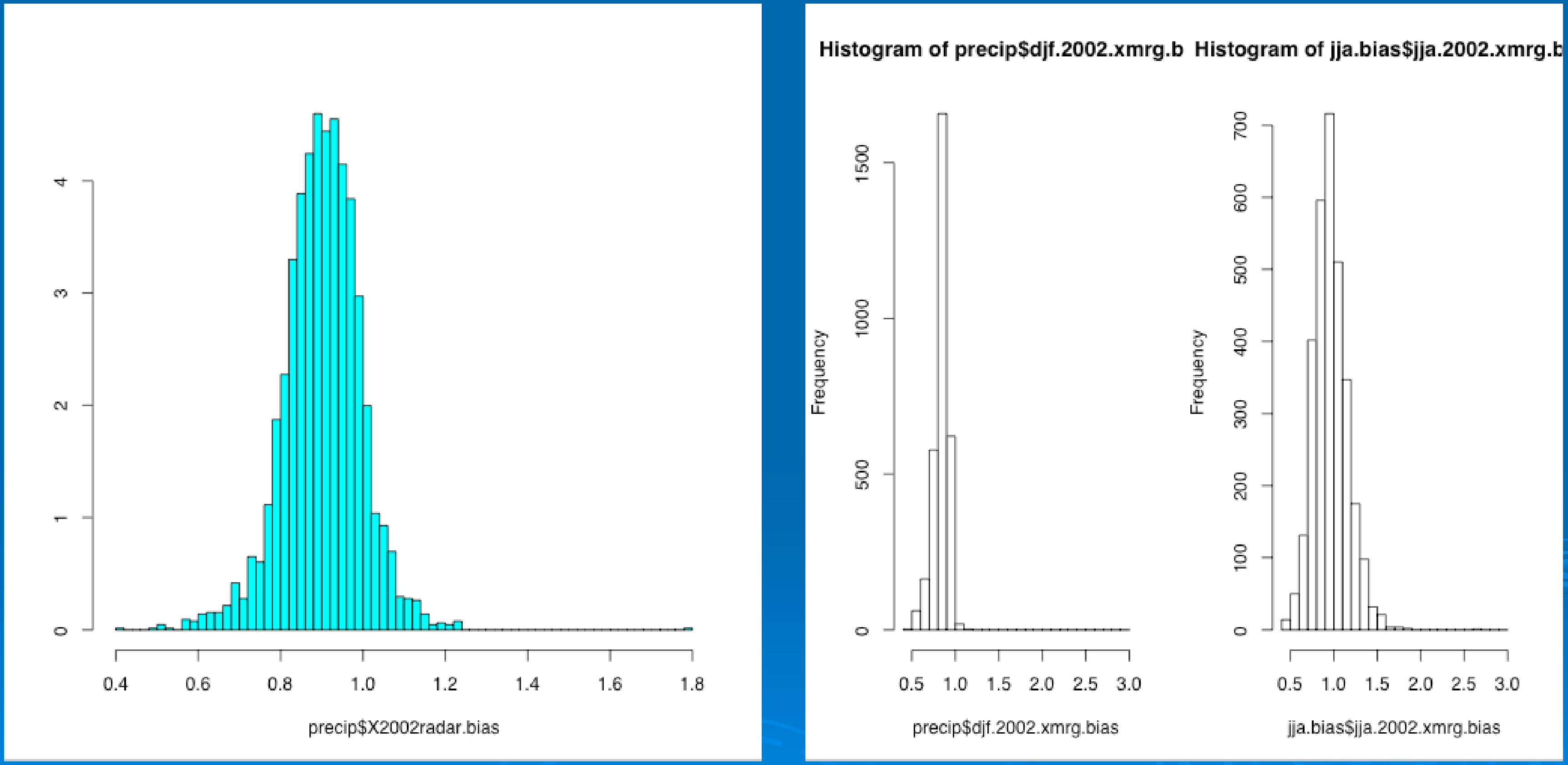
JKL 2003 Biases by Month



PBZ

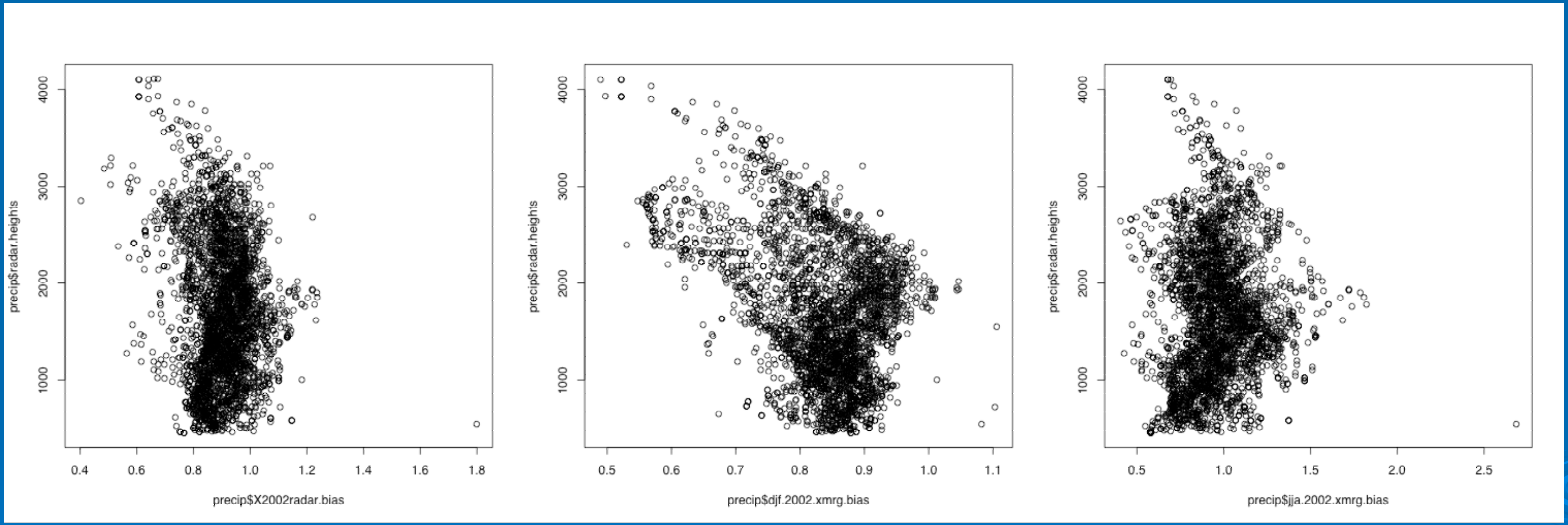


PBZ (cont.)



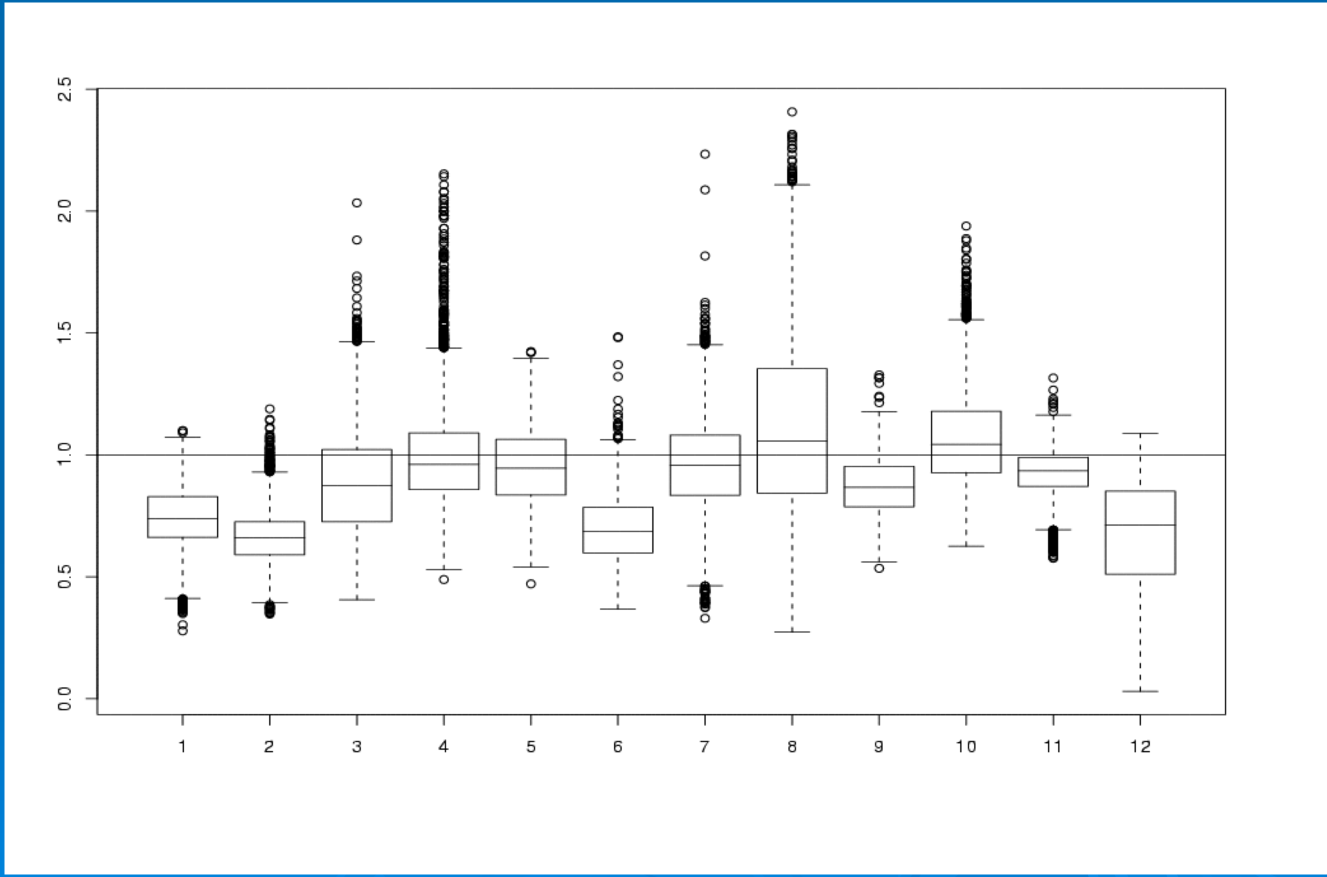
4
3
2
1
0
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
precip$X2002radar.bias
Histogram of precip$djf.2002.xmrg.b
Frequency
1500
1000
500
0
0.5
1.0
1.5
2.0
2.5
3.0
precip$djf.2002.xmrg.bias
Histogram of jja.bias$jja.2002.xmrg.b
Frequency
700
600
500
400
300
200
100
0
0.5
1.0
1.5
2.0
2.5
3.0
jja.bias$jja.2002.xmrg.bias

PBZ (cont.)

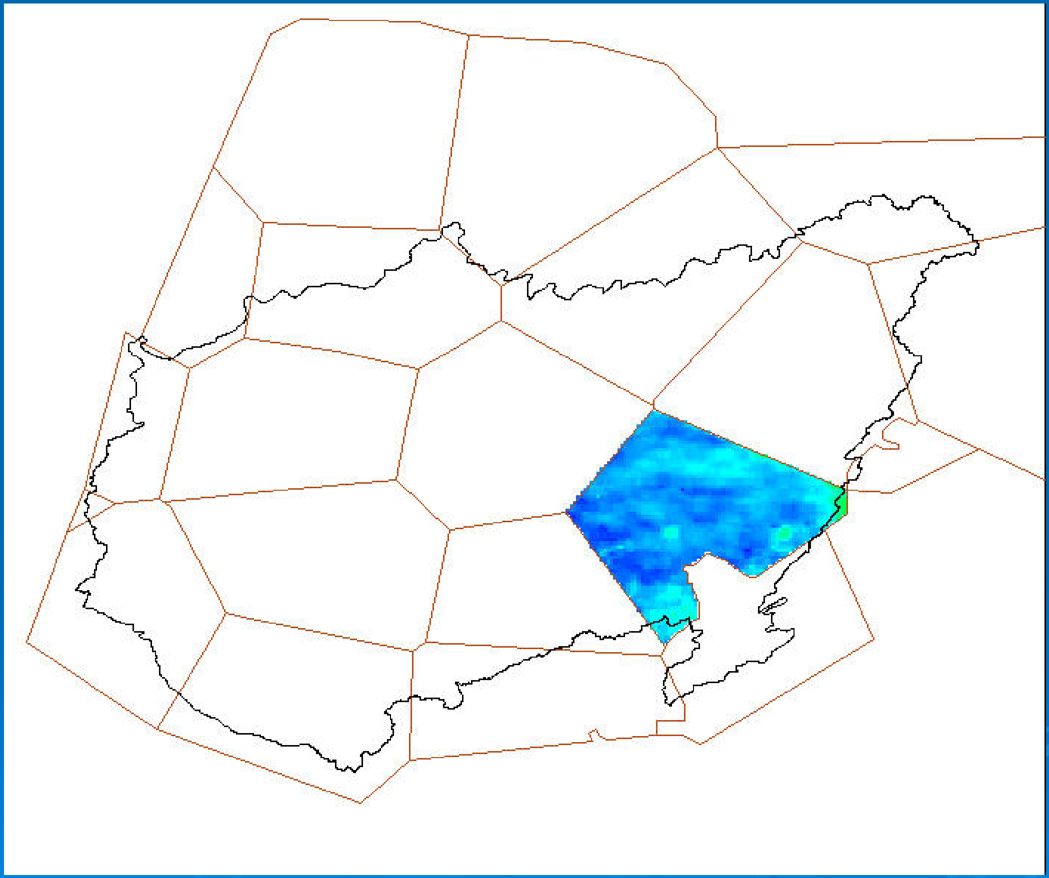


precip$radar.heights
precip$X2002radar.bias
precip$radar.heights
precip$djf.2002.xmrg.bias
precip$radar.heights
precip$jja.2002.xmrg.bias

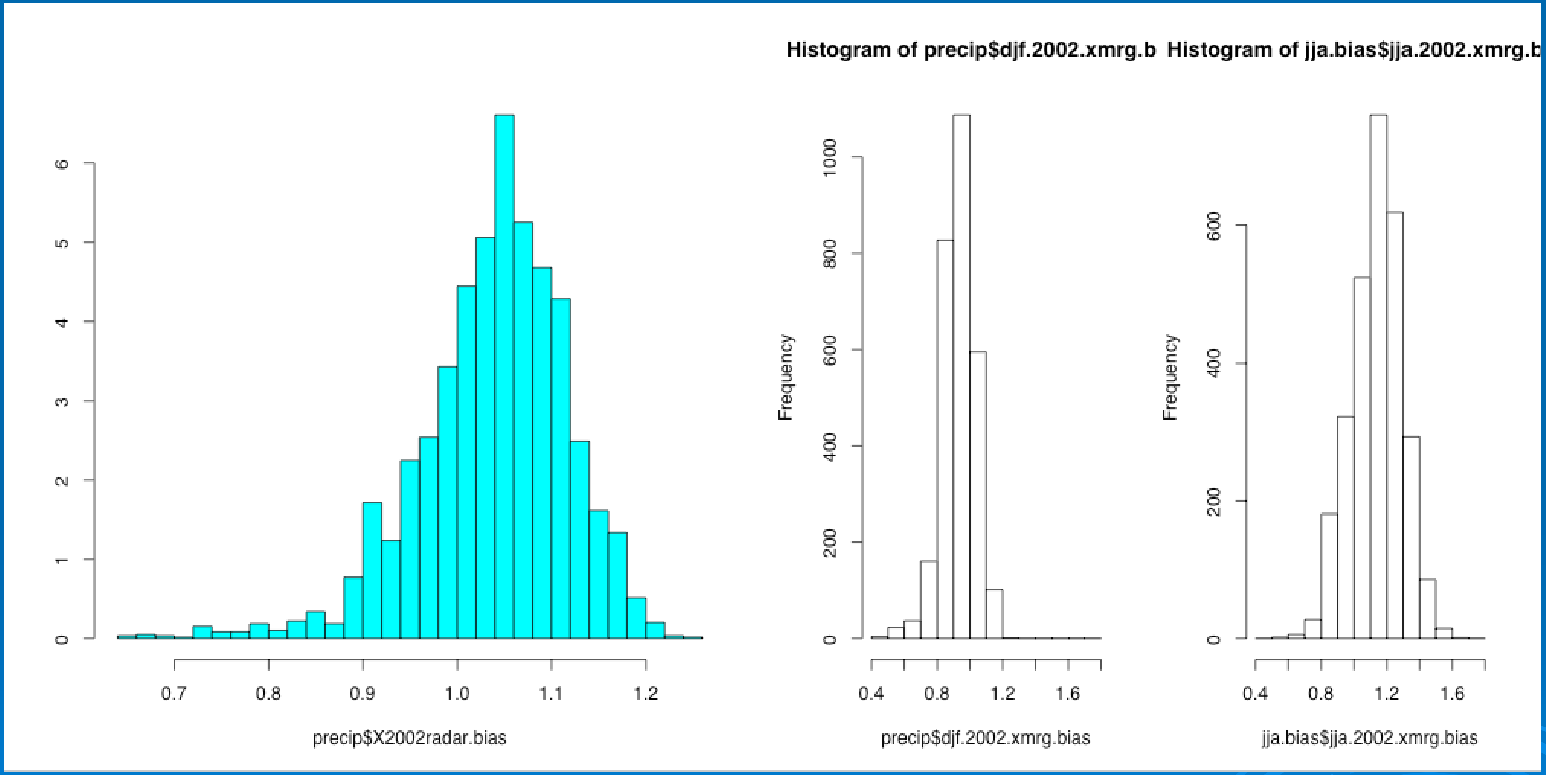
PBZ 2003 XMRG Bias by Month



RLX

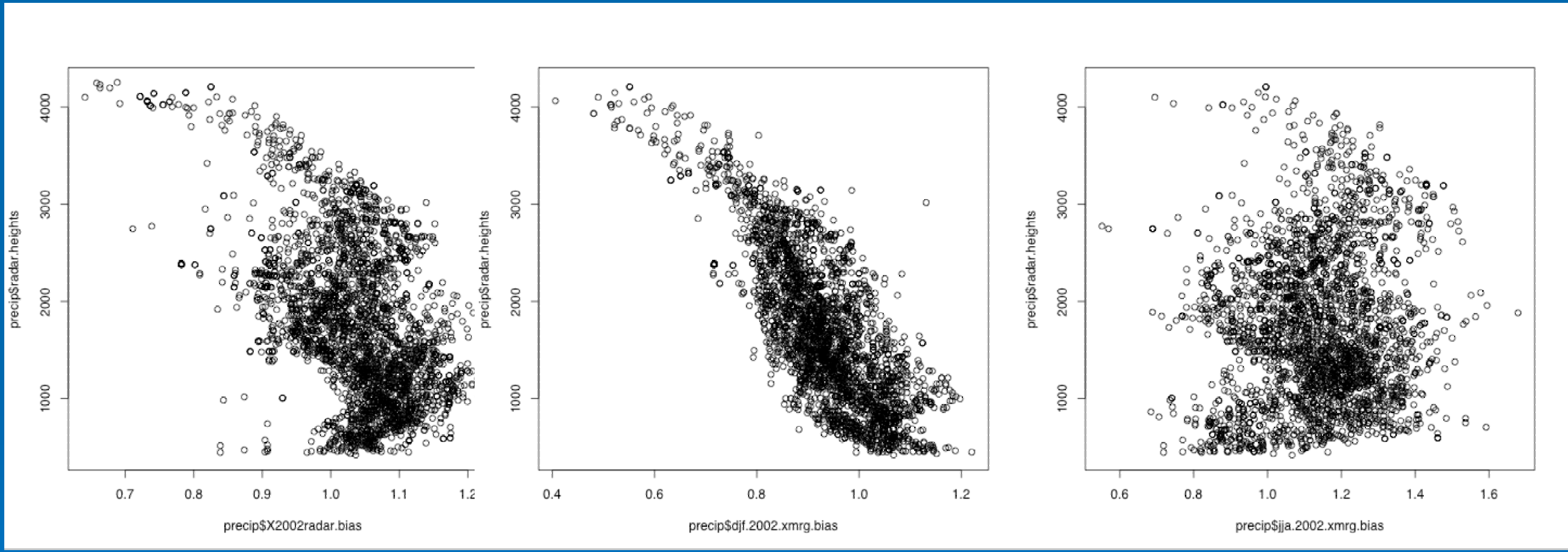


RLX (cont.)



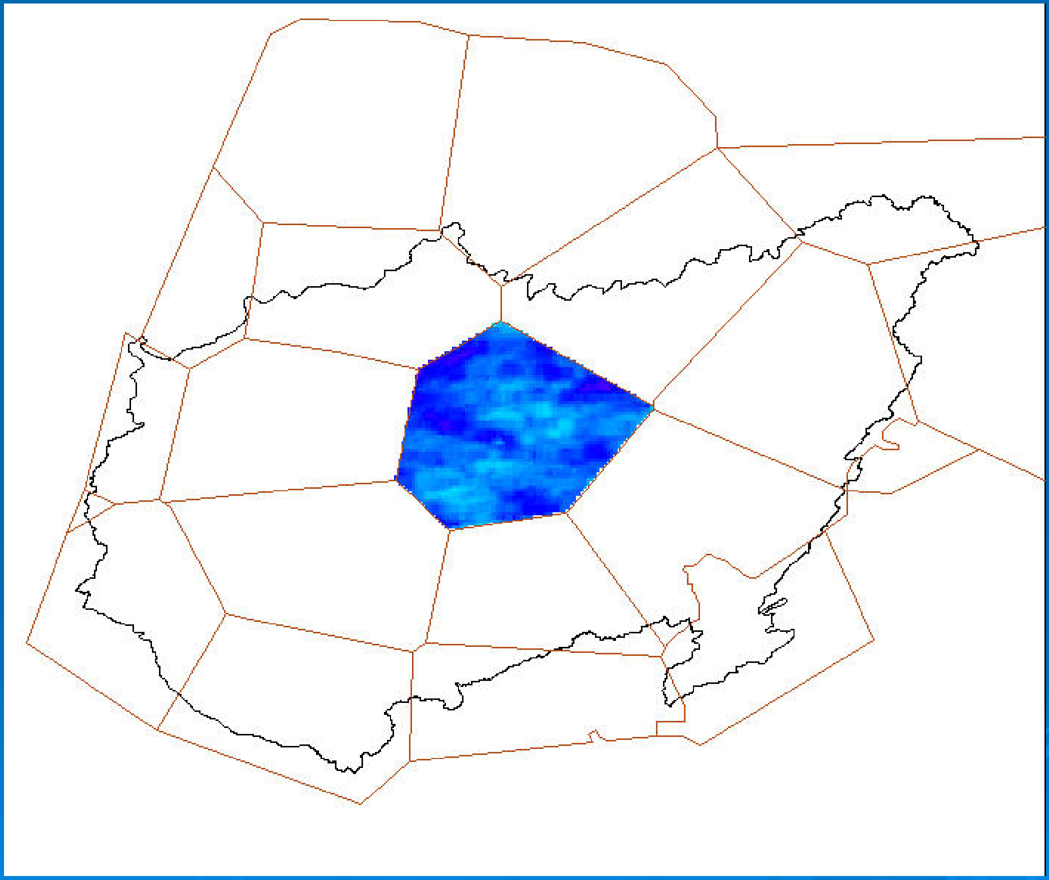
Histogram of precip$djf.2002.xmrg.b
Histogram of jja.bias$jja.2002.xmrg.b
0
1
2
3
4
5
6
0.7
0.8
0.9
1.0
1.1
1.2
precip$X2002radar.bias
Frequency
0
200
400
600
800
1000
0.4
0.8
1.2
1.6
precip$djf.2002.xmrg.bias
Frequency
0
200
400
600
0.4
0.8
1.2
1.6
jja.bias$jja.2002.xmrg.bias

RLX (cont.)

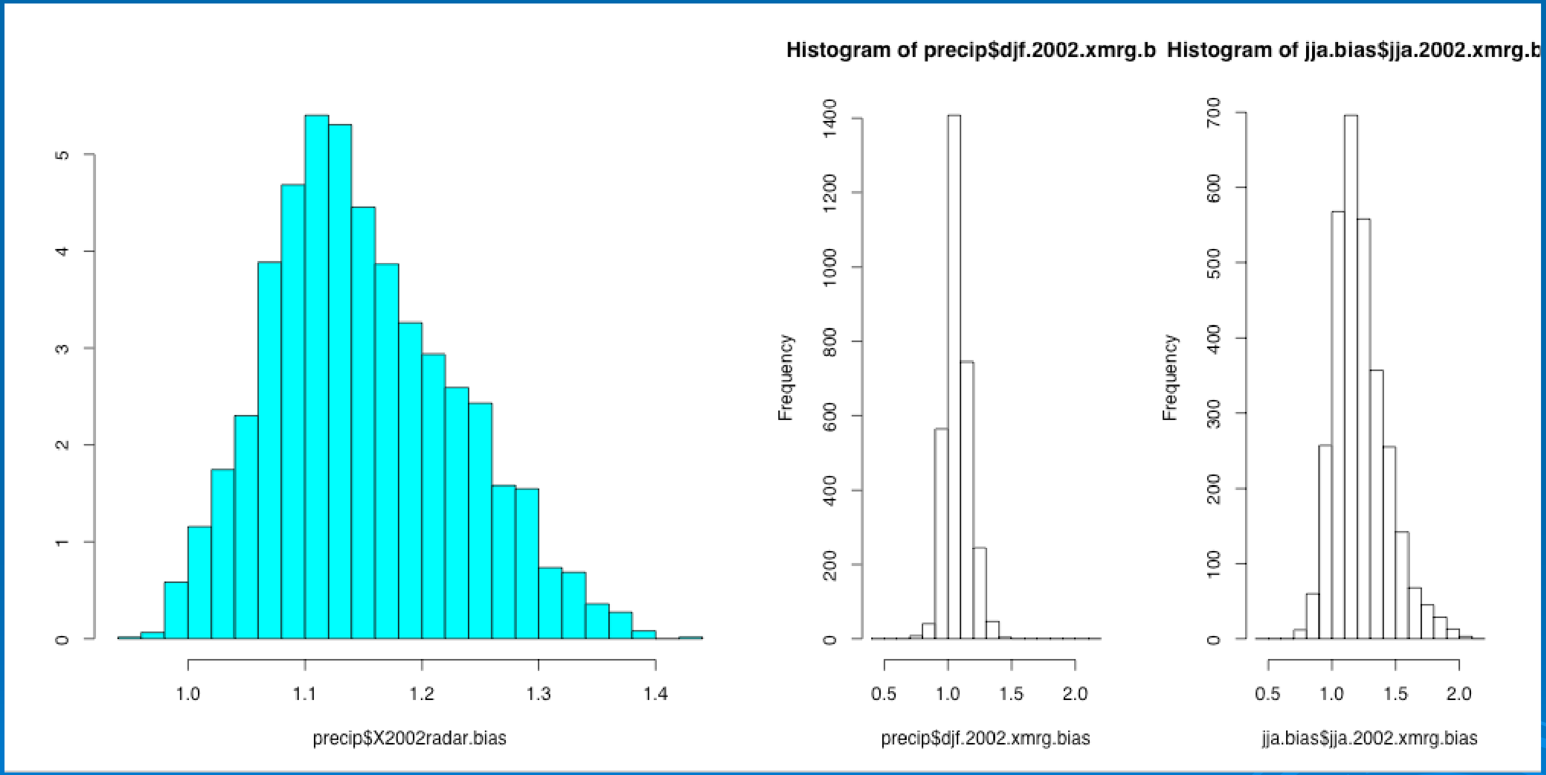


precip$radar.heights
1000
2000
3000
4000
0.7
0.8
0.9
1.0
1.1
1.2
precip$X2002radar.bias
precip$radar.heights
1000
2000
3000
4000
0.4
0.6
0.8
1.0
1.2
precip$djf.2002.xmrg.bias
precip$radar.heights
1000
2000
3000
4000
0.6
0.8
1.0
1.2
1.4
1.6
precip$jja.2002.xmrg.bias

ILN

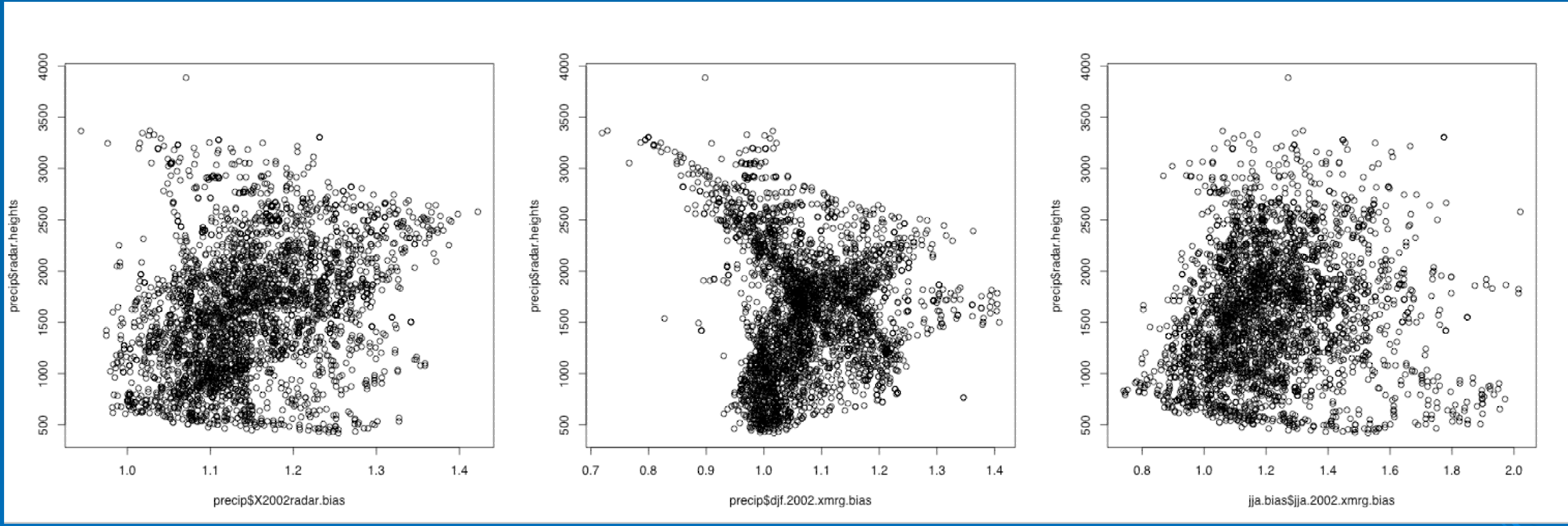


ILN (cont.)



Histogram of precip$djf.2002.xmrg.b
Histogram of jja.bias$jja.2002.xmrg.b
0
1
2
3
4
5
1.0
1.1
1.2
1.3
1.4
precip$X2002radar.bias
Frequency
0
200
400
600
800
1000
1200
1400
0.5
1.0
1.5
2.0
precip$djf.2002.xmrg.bias
Frequency
0
100
200
300
400
500
600
700
0.5
1.0
1.5
2.0
jja.bias$jja.2002.xmrg.bias

ILN (cont.)



precip$radar.heights
precip$X2002radar.bias
precip$djf.2002.xmrg.bias
jja.bias$jja.2002.xmrg.bias

Purposes of RCA/CSSA

- **David Kitzmiller, Dongjun Seo, Feng Ding, David Riley(Hydrologic Science and Modeling Branch) and Christine Dietz, Cham Pham, Dennis Miller (Hydrologic Software Engineering Branch) — TAC Briefing, July 2004**
- Range Correction Algorithm (RCA)
  - Mitigate rainfall overestimation associated with bright band
  - Mitigate rainfall underestimation at longer ranges
- Convective-Stratiform Separation Algorithm (CSSA)
  - Identify areas of shallow and deep convective precipitation
  - Data from convective zones is excluded from RCA adjustment

Operational Needs

- Errors in precipitation estimates are often magnified in runoff errors
- Cool-season radar rainfall estimates often feature bright-band and range-degradation features that negatively affect:
  - Operational precipitation analyses and verification
  - Hydrologic forecasts
  - River Forecast Center workload
- Mosaic algorithms and local gauge corrections are often inadequate to mitigate these effects

Operational Needs

- Statement of Need from OS&T and OCCWS in June 2003
- NEXRAD Active Technical Needs, TAC TN-10 states:

  "Problems have been noted with VCP constraints, range-dependent effects, the radar bright band, ground clutter and beam occultation, ice-phase precipitation, and other factors."
- Demands on radar data are increasing:
  - Implementing advances in hydrologic modeling requires utilization of radar input
  - National Digital Forecast Database verification also requires accurate radar input
  - Radar-based estimates are disseminated publicly

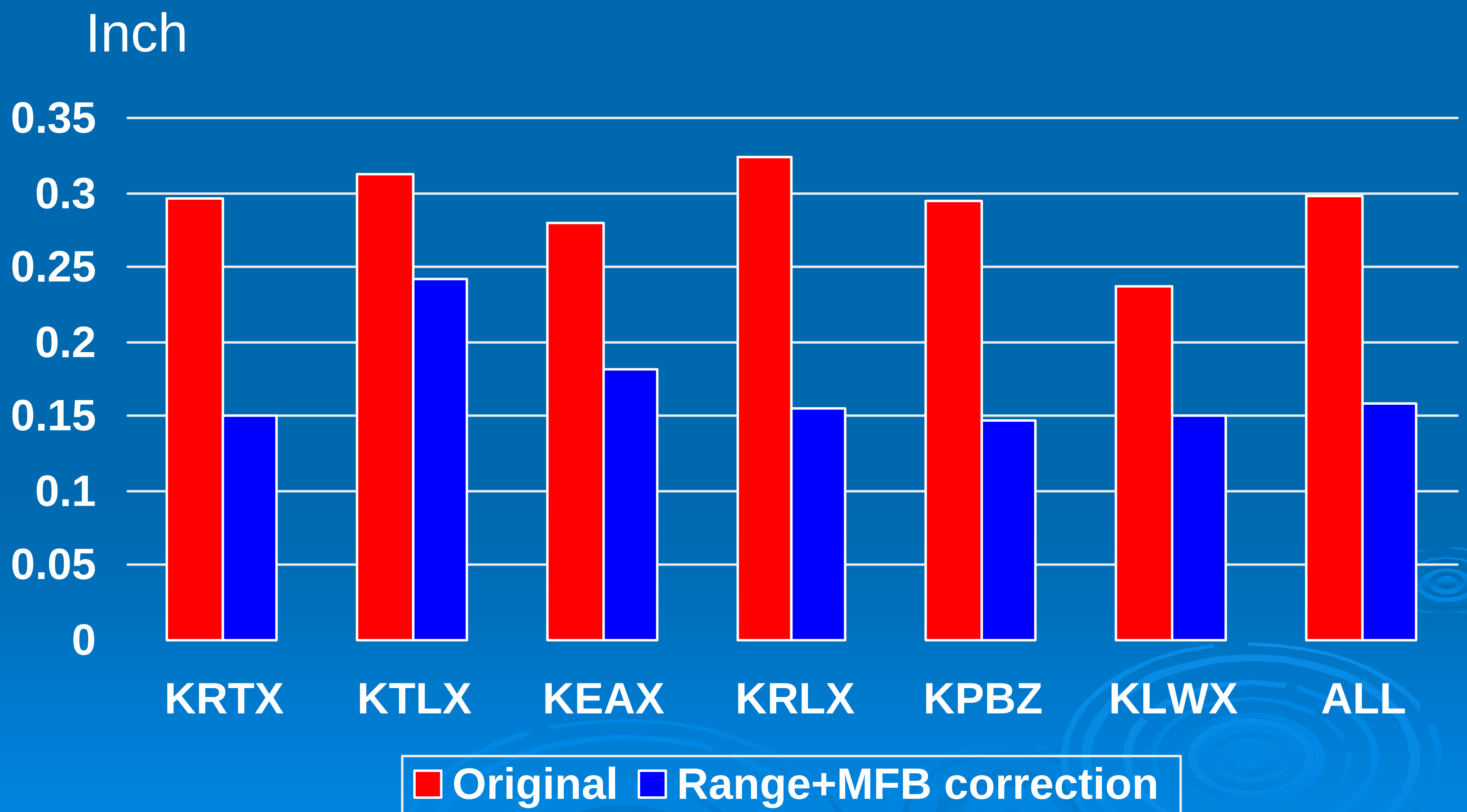
RCA Process

- Construct areal-mean Vertical Profile of Reflectivity (VPR) from latest volumetric scan
- Observations close to radar provide information on reflectivity near surface
- Use VPR to estimate near-surface reflectivity at ranges where lowest radar beam intersects melting layer, snow, or differing hydrometeor distribution aloft

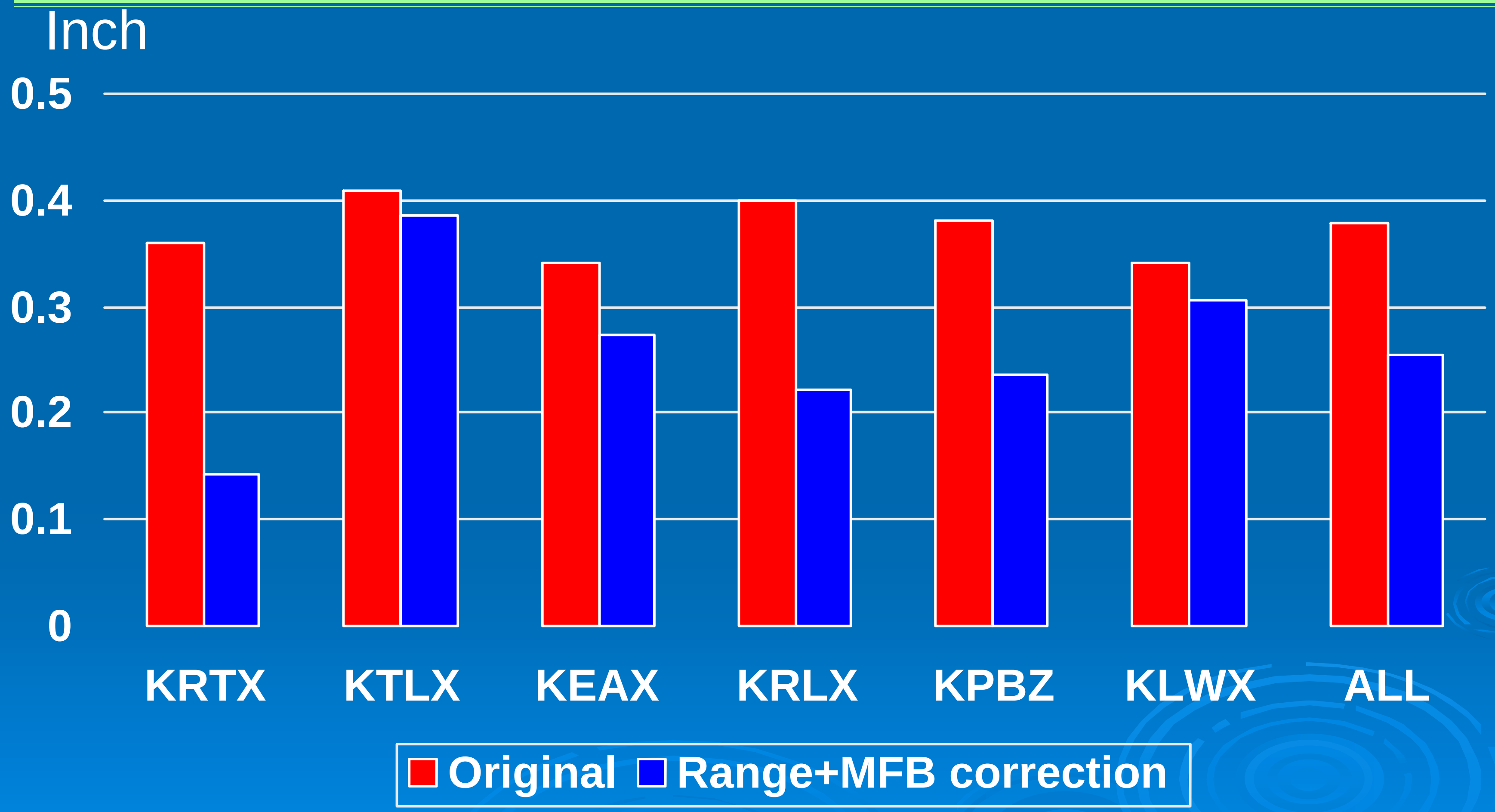
Post Analysis of Field Results

- By applying range adjustment and mean-field bias correction, obtained consistent and significant improvement in radar estimates, in terms of:
  - Bias with respect to gauge amounts
  - Mean absolute error (MAE)
  - Root-mean squared (RMS) error
  - Relative frequency of large errors

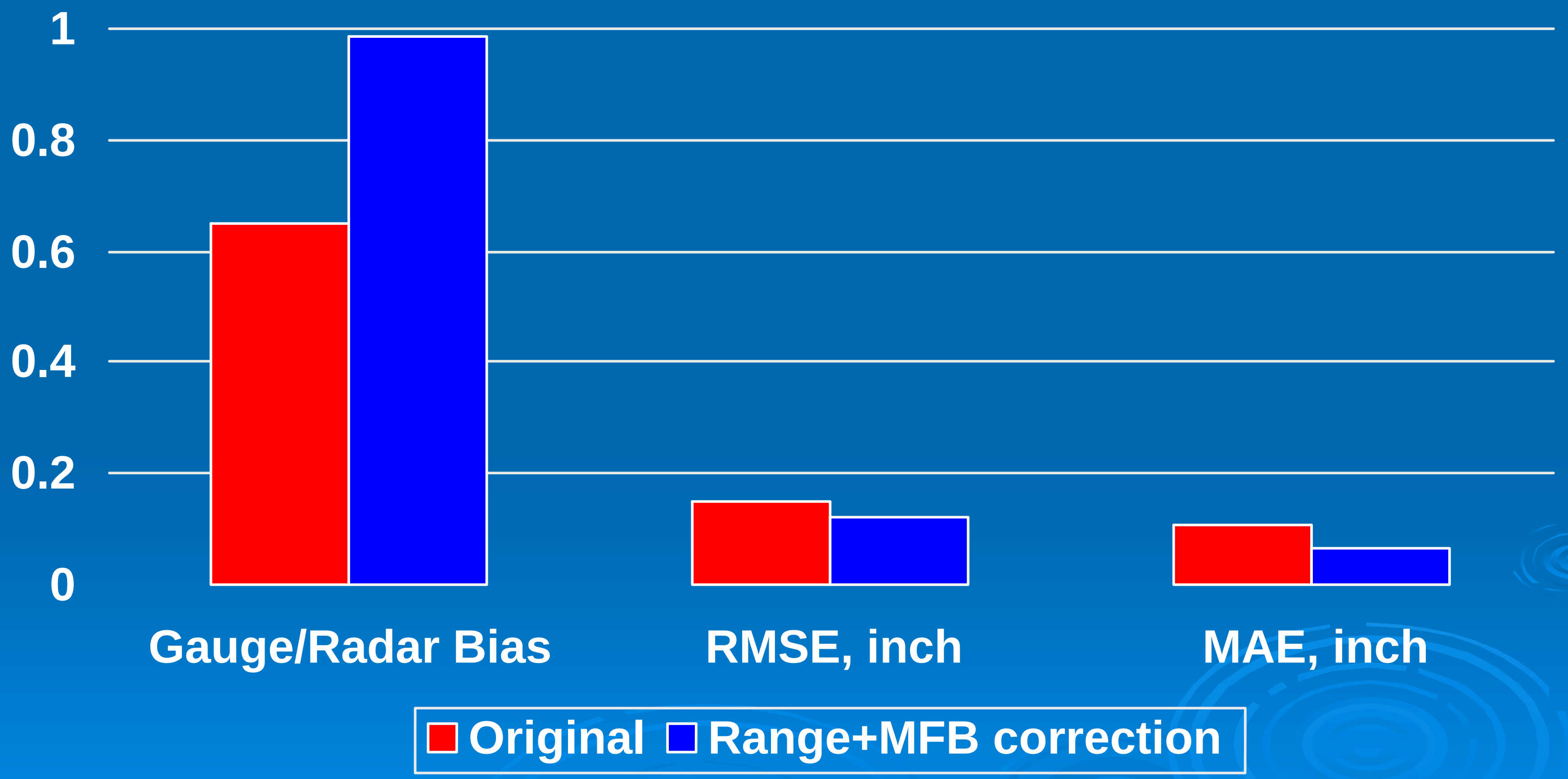
Improvement Due To Corrections:
Radar/Gauge Mean Absolute Error (3-hour)



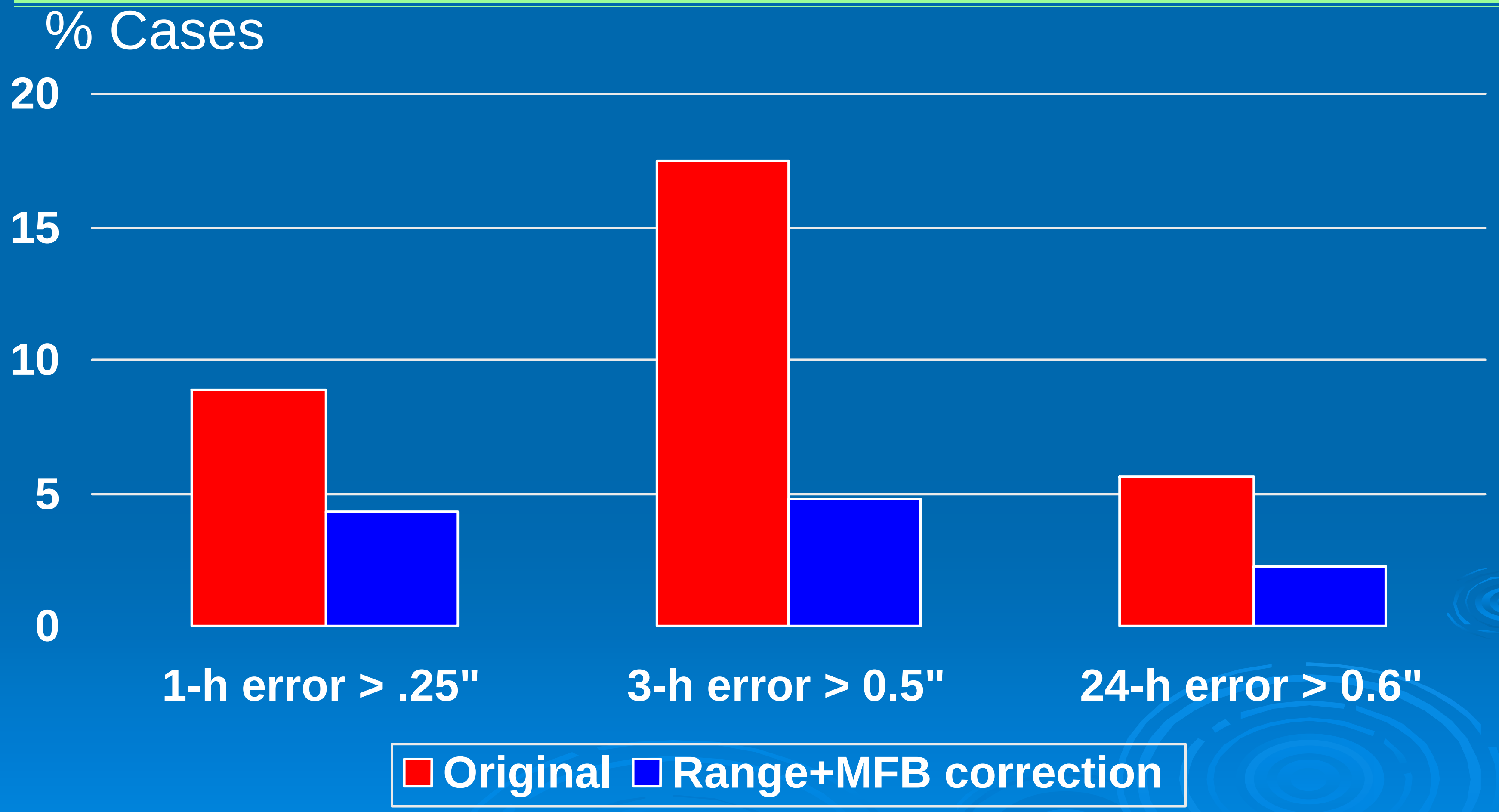
Improvement Due To Corrections: Radar/Gauge RMS Error (3-Hour)



Improvement Due To Corrections: Improvements in 1-h Verification

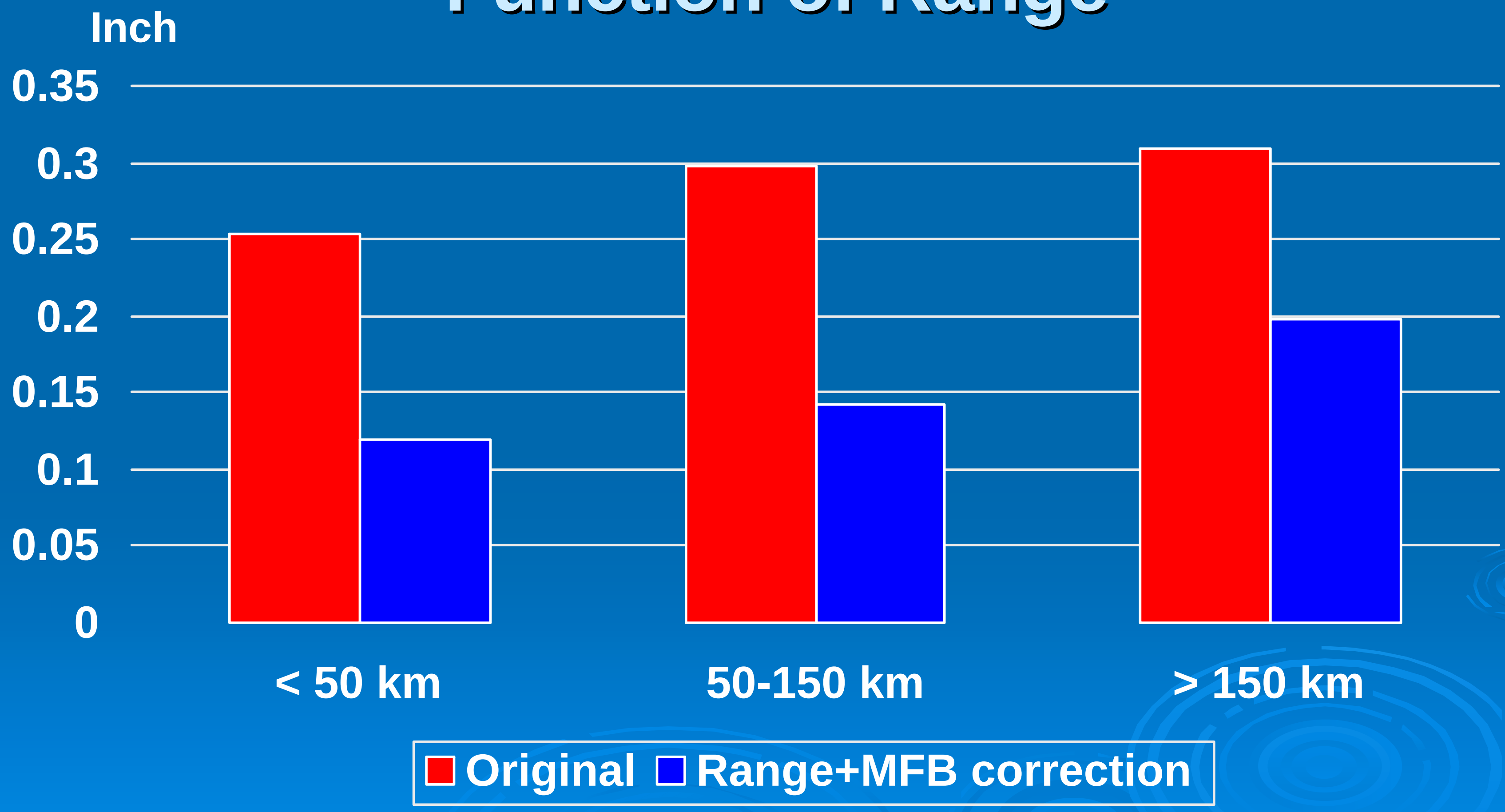


Improvement Due To Corrections: Reduction In Number of Large Errors



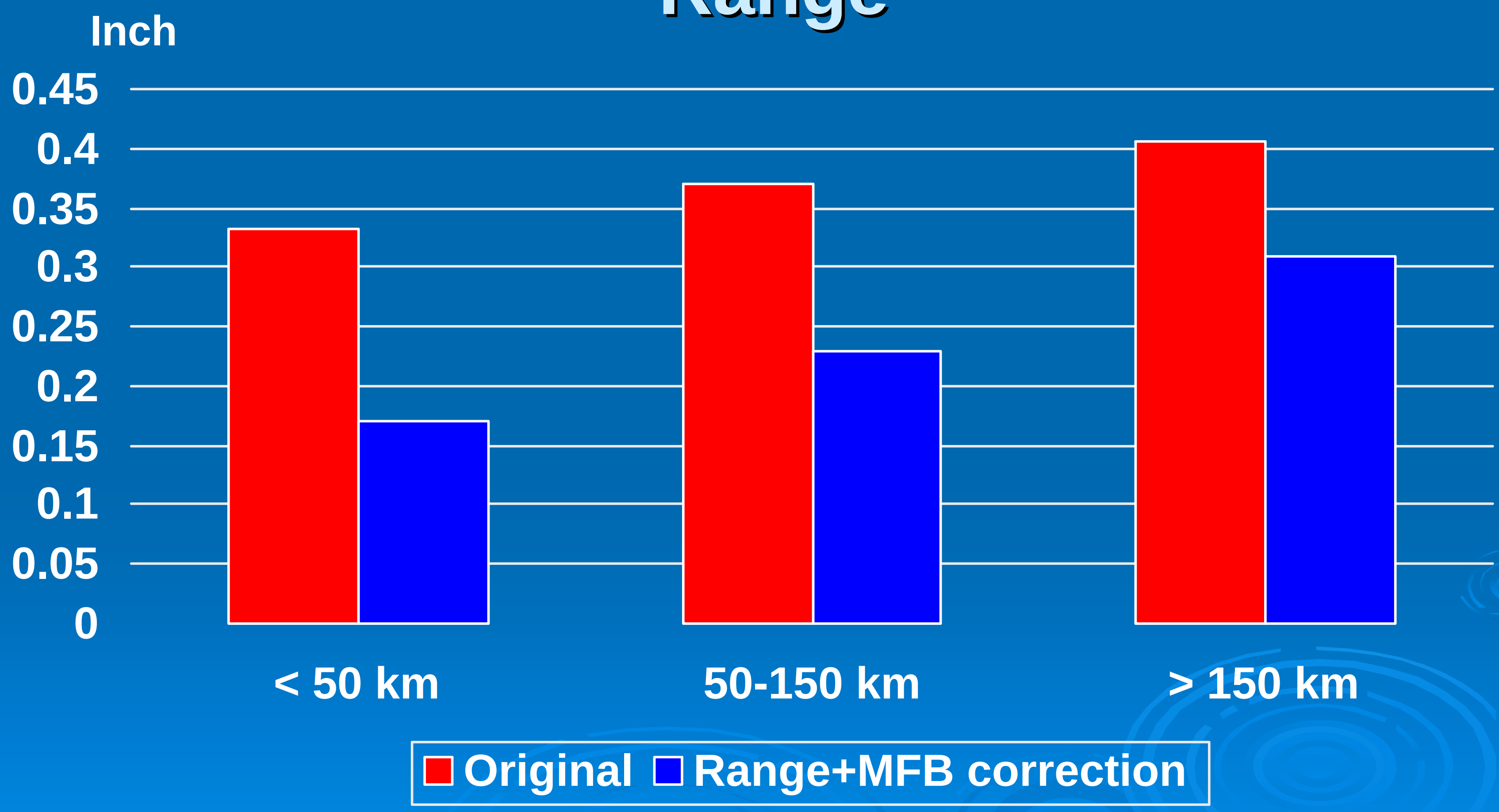
Improvements Apparent At All Ranges:

3-h Radar/Gauge Mean Absolute Error as Function of Range



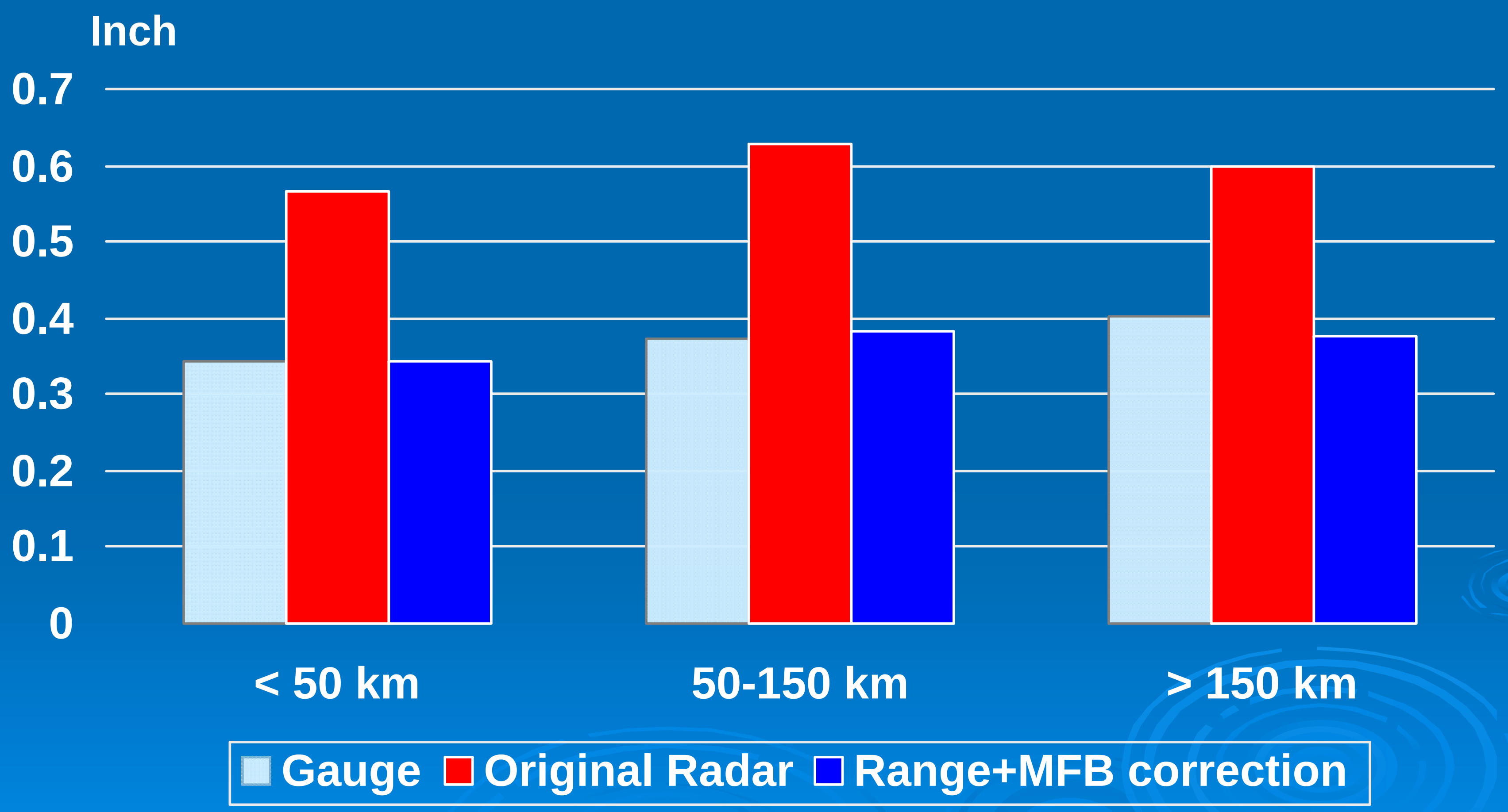
Improvements Apparent At All Ranges:

3-h Radar/Gauge RMS Error as Function of Range



Improvements Apparent At All Ranges:

3-h Radar/Gauge Bias



Conclusions

- OHRFC NEXRAD/MPE biases are significant — both over- & under-estimation
- The hydrologic impact of precipitation biases are very significant:
  - Hydrologic response is highly nonlinear
  - Impacts to daily forecasts
    - Peak flows
    - Flow volumes
  - Model states affected for long lead time ESP/AHPS forecasts
  - Impacts on weekly, monthly, annual water balance
  - Impacts FFG — Flash Flood watches & warnings
  - Timeliness of RFC forecasts delayed due to increased staff workload to make precipitation corrections
- Sources of biases are well documented in scientific literature
- Proposals made by the Office of Hydrologic Development (Hydrologic Science and Modeling Branch & Hydrologic Software Engineering Branch) for Range Correction Algorithm (RCA) and Convective-Stratiform Separation Algorithm (CSSA)
- RCA & CSSA will substantially reduce precipitation biases experienced at all RFCs, leading to substantial improvements in the accuracy of hydrologic forecasts and their timeliness