Quantitative Precipitation Forecasting and Estimating During the HMT Field Experiment: Ensemble Applications

John A. McGinley, PhD
Chief, Forecast Applications Branch
Global Systems Division
Earth Systems Research Laboratory
National Oceanic and Atmospheric Administration
325 Broadway, Mail Code R/ GSD 07
Boulder, CO 80305-3337

Tel: 303-497-6161
E-mail: john.a.mcginley@noaa.gov
Web: www.fsl.noaa.gov

BIOGRAPHICAL SKETCH

John McGinley has been a professional meteorologist for 37 years serving in the USAF Air Weather Service (69-76), receiving a PhD from the University of Oklahoma in 1981, then serving as a research scientist at the National Severe Storms Laboratory (82-86) and since then assigned to what is now the Earth Systems Research Laboratory in Boulder Colorado. He supervises a branch of 20 individuals: graduate level meteorologists, physicists, mathematicians, graphics and GUI designers, and students. Work involves technology transfer of systems designed to enhance short range forecasting.

The branch currently has analysis and forecast systems installed at the Eastern and Western Space Ranges (Cape Canaveral and Vandenberg AFB), many offices within the National Weather Service and in the AWIPS workstation, a US Army/USAF system for precision parachute drops, the US Forest Service for fire fighting and mitigation, and the Taiwan Central Weather Bureau for heavy rain and typhoon prediction.

The group has developed and uses LAPS (the Local Analysis and Prediction System) along with state of the art mesoscale models such as RAMS, MM5, and WRF. The group specializes in data assimilation and model tuning to provide useful precipitation forecast s in the 0- to 72-hour period, and in conjunction with NOAA partners has been supporting the Hydrometeorological Testbed activity in California. The branch also works on model post processing, probabilistic forecasting, ensembles, and super-ensembling.

ABSTRACT

ESRL/GSD has been supporting the Hydrometeorlogical Testbed focused on precipitation in the American River Basin in the California Sierras during the last 3 winters. GSD's contribution has been to run an experimental, high-resolution (3-km) set of state-of-the-art, non-hydrostatic prediction models (the WRF-ARW and WRF-NMM in various configurations) to form an ensemble aimed at prediction of quantitative precipitation (QPF) and probabilistic QPF (PQPF). Products from these ensembles were made available to collaborating NWS WFOs over the last two years with variable levels of success using next generation workstation technology.

This talk will focus on two areas: 1) a QPF-focused case study of the recent, powerful 4-7 January, 2008 storm that impacted central California, and summary results from the last two years of running the experimental ensemble; and 2) an exploration of utilizing a running ensemble to improve the diagnosis or estimate of precipitation in real time. In the former (1) we found that the ensemble mean captured the time-evolving precipitation patterns with some onset and cessation error and more RMS error as the precipitation amounts increased. Ensemble mean ETS scores were clearly superior to any of the individual models and were significantly better than the model configuration of the current NWS NAM model, running at 3km resolution. Verification of the probabilistic products did show that the ensemble had some skill for predicting rain rates as high as 25.4mm/6hr, but did not show skill for higher rates. For the second area (2), we will demonstrate that a 3-D variational approach where the needed error covariance can be specified fully in 2-D space, can improve the areal estimates of precipitation relative to the standard methods that interpolate rain gauges to a grid. By withholding random sets of rain gauges 183 times, we found that the 3-D var method that combines the model ensemble precipitation structure with precise measurements at gauge locations, can provide improved precipitation estimates relative to current methods.

Quantitative Precipitation Forecasting and Estimating During the HMT Field Experiment: Ensemble Applications

John McGinley
NOAA/OAR/ESRL/GSD

HMT Team

- Paul Schultz - NOAA
- Ed Tollerud - NOAA
- Huiling Yuan - CIRES
- Tomi Vukicevic - CIRES
- Steve Albers - CIRA
- Chris Anderson - CIRA
- Isidora Jankov - CIRA
- Chungu Lu - CIRA
- Steve Mullen - Univ. of Arizona

Outline of Talk

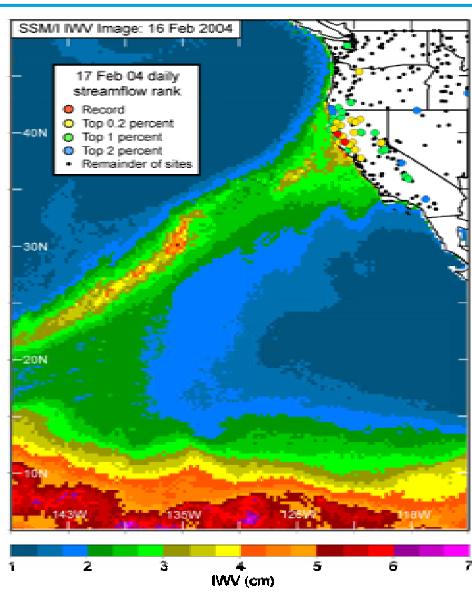
1. Performance of current model ensemble for Quantitative Precipitation Forecasting (QPF)

   a. IOP 4, 4-7 Jan 2008
   b. Summary performance for previous years

2. Use of Ensemble for Quantitative Precipitation Estimation (QPE)

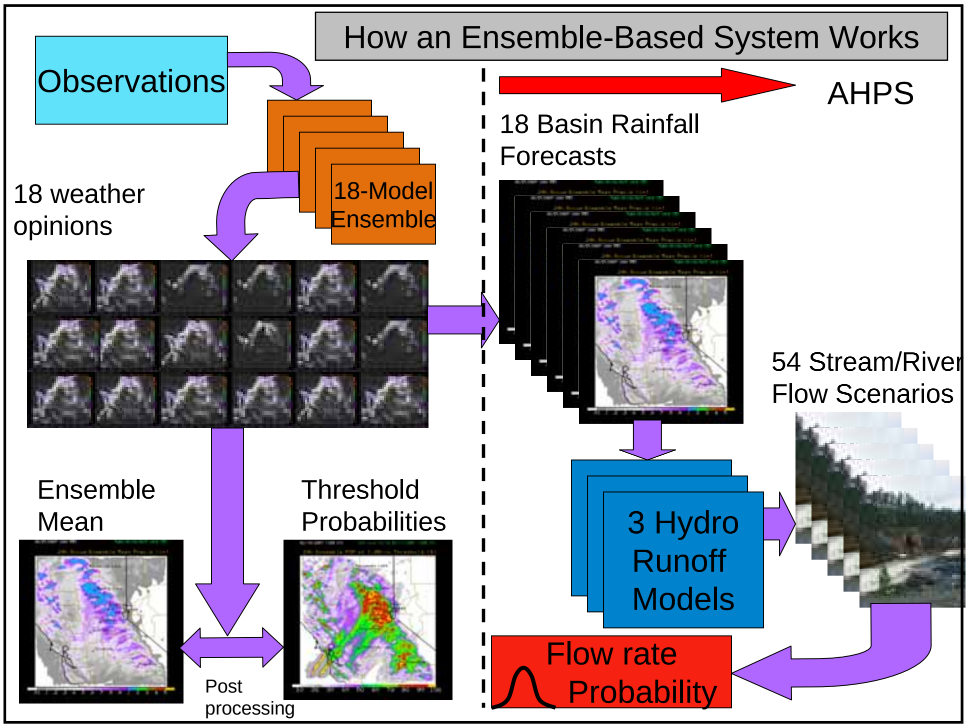
Earth System Research Laboratory
Global Systems Division

National Oceanic and Atmospheric Administration
Hydrometeorology Testbed Program



ATMOSPHERIC RIVERS

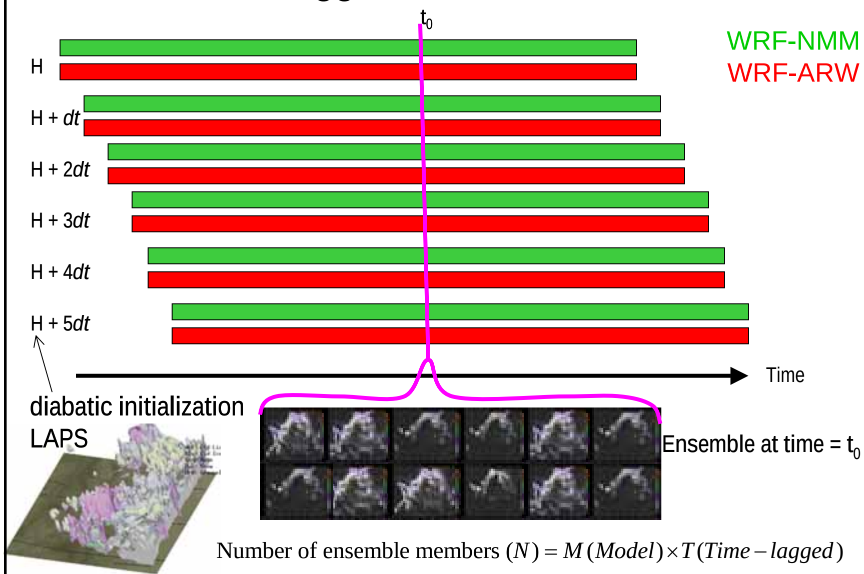
•SSM/I satellite image shows an atmospheric-river (AR) plume of integrated water vapor (IWV) impacting California
•SSM/I IWV analysis shows there were 35 ARs impacting CA during the last 8 winters
•Storms with imbedded ARs produced more rain and snow than other storms (Neiman et al., 2007, *JHM*)



The HMT Ensemble

- 3 versions of WRF-ARW with different microphysics (Ferrier, Thompson, Schultz)
- 1 version of WRF-NMM (Ferrier)
- 3-km grid resolution
- All initialized with LAPS diabatic scheme
- Each run out to 72 hrs, every 6 hours
- Ensemble is multi-model and time phased
  - a total of 32 members used in a 24-hour ensemble mean prediction (4 models, 8 verification times)
  - 40 members for a 12-hr mean

Time-lagged multimodel ensembles



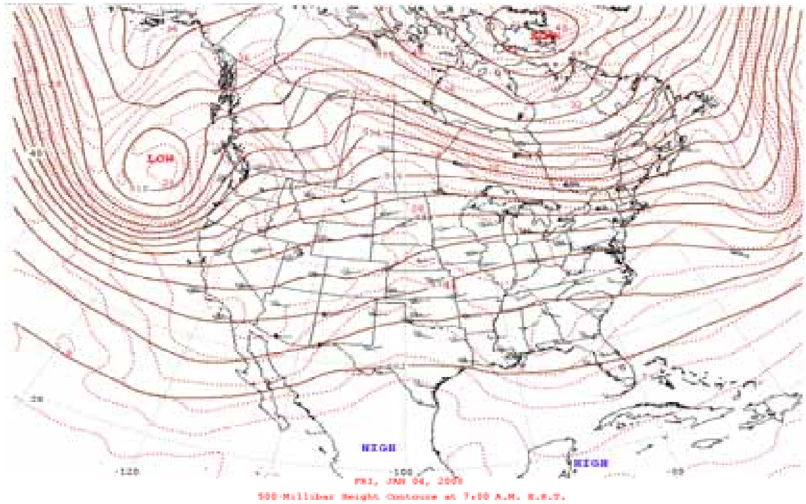
Number of ensemble members $(N) = M\,(Model) \times T\,(Time-lagged)$

$$N = M \times T = M \times INT\left(\frac{\text{Maximum forecast projection - Lead time } (h)}{\text{Model initial interval } (dt)} + 1\right)$$

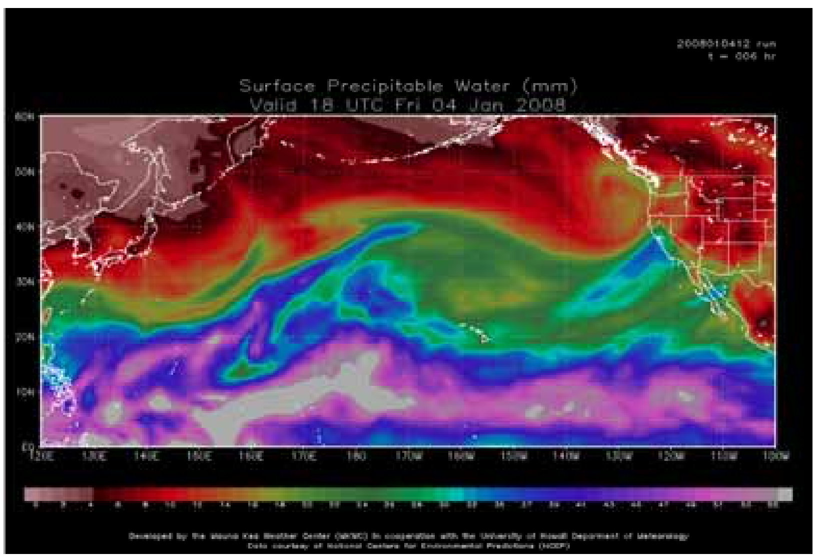
Part 1: HMT Ensemble Performance IOP 4 (4-7 Jan 2008)

- IOP 4 was heaviest rainfall event in 10 years
- Up to 8 inches of liquid
- Had high winds and extensive damage to trees, structures and power lines

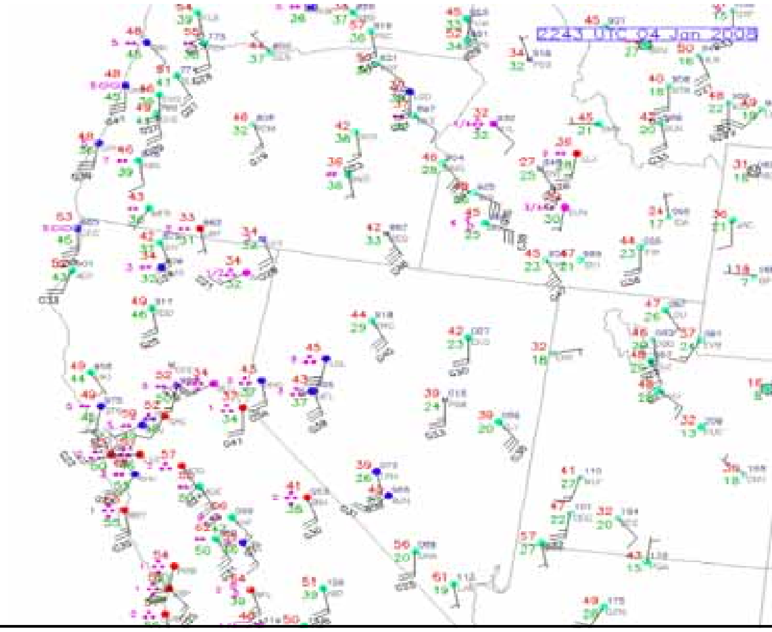
500 MB Chart for 12 UTC 4 Jan



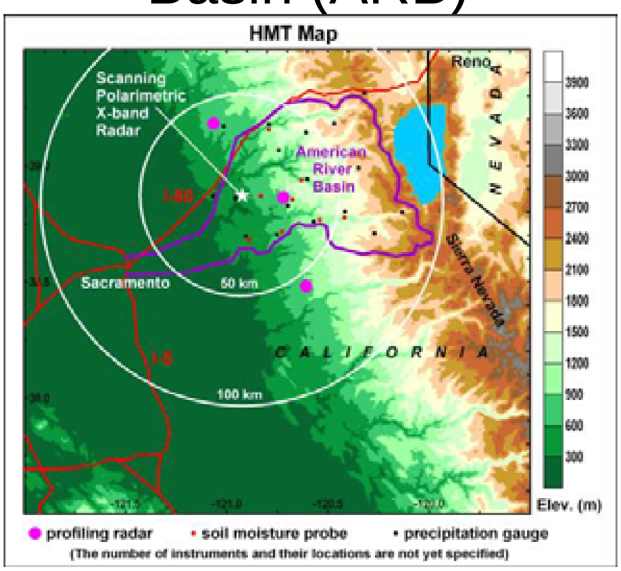
6hr Forecast IPW - 18UTC 4 Jan 08



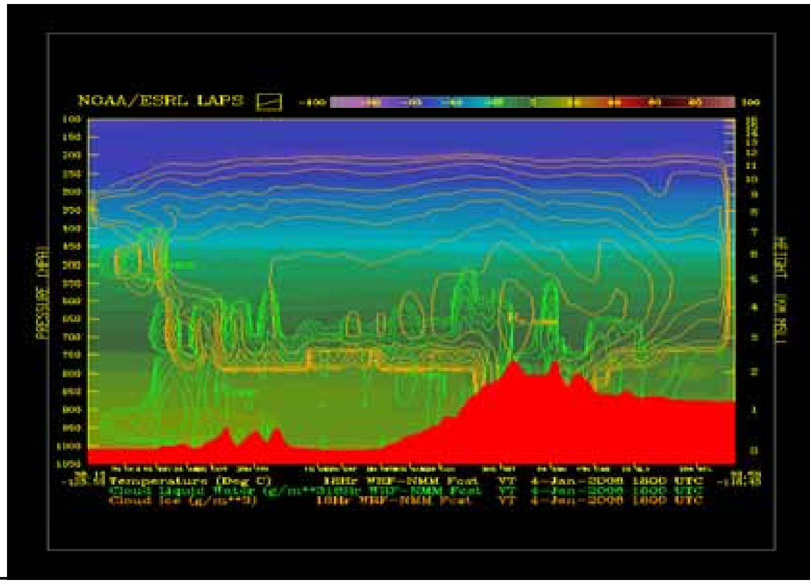
Surface obs - 2243UTC 4 Jan 2008



Study domain – American River Basin (ARB)

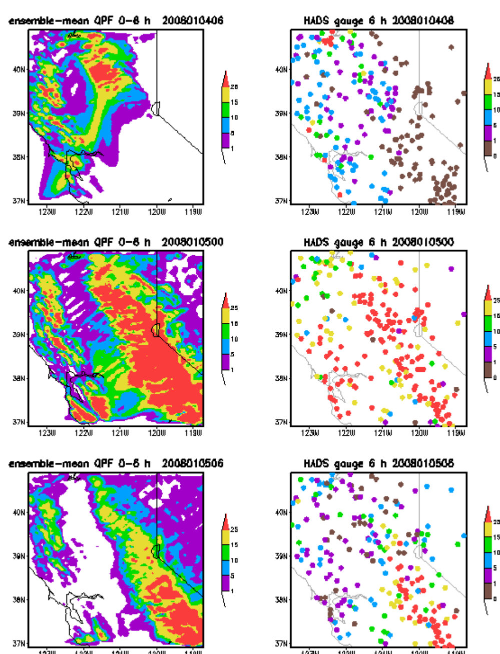


Cross-section from NMM ensemble member - used for rain/snow determination - 18UTC 4 Jan 08



Ensemble mean, 0-6 and HADS

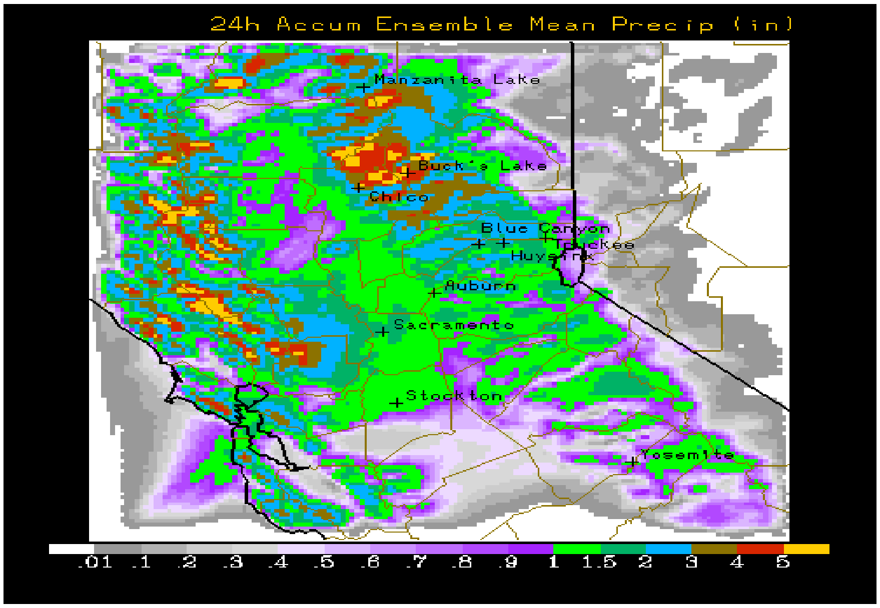
- verification time:
- 2008010406
- 2008010500
- 2008010506
- unit: mm



The Stages

- Onset period: 3 Jan 18 UTC to 4 Jan 18 UTC (precip started about 14 GMT)
- Heaviest rain period: 4 Jan 00 UTC to 5 Jan 00 UTC
- Last major short wave: 5 Jan 12UTC to 6 Jan 12UTC

Ensemble Mean Precipitation Forecast 3-4 Jan 2008 00GMT (24 hr forecast ending 4/18GMT): Onset Period

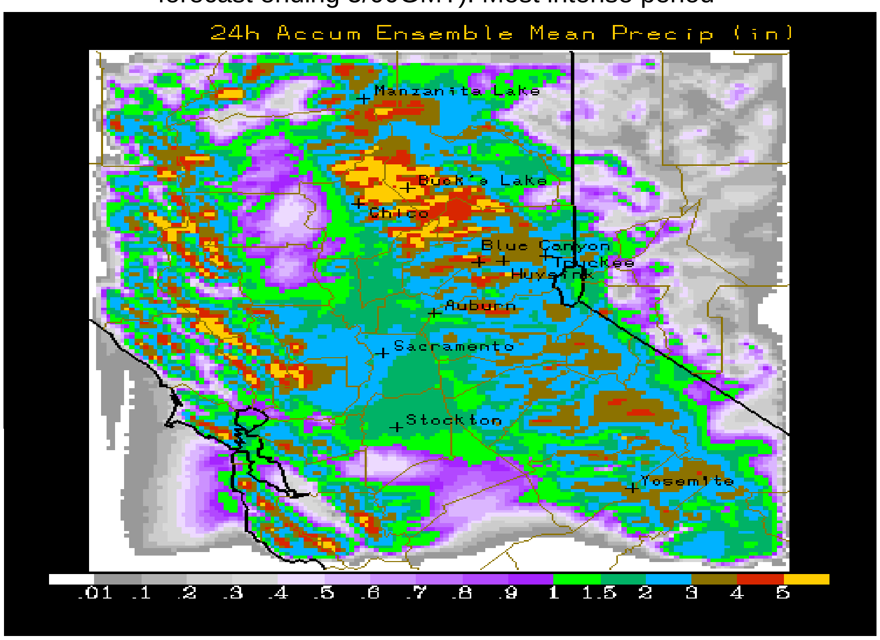


Predicted Precip in ARB Area: Onset (in)

Station	Forecast	Obs	Error
Alta	1.80	1.33	+.47
Big Bend	2.40	2.90	-.50
Blue Canyon	4.00	M	
Canada Hill	1.80	0.65	+1.15
Colfax	1.50	0.64	+.86
Forrest Hill	1.50	0.91	+.49
Greek Store	1.00	1.07	-.07
Huysink	1.80	1.82	-.02
Norden	1.85	1.80	+.05
Onion Creek	1.80	1.90	-.10
Slough House	1.10	0.52	+.58
Talbot	1.60	1.25	+.35
Truckee	1.40	0.87	+.53

MAE + 0.31in (7.9mm) RMS 0.54 (13.7mm)

Ensemble Mean Precipitation Forecast 4-5 Jan 2008 00GMT (24 hr forecast ending 5/00GMT): Most intense period

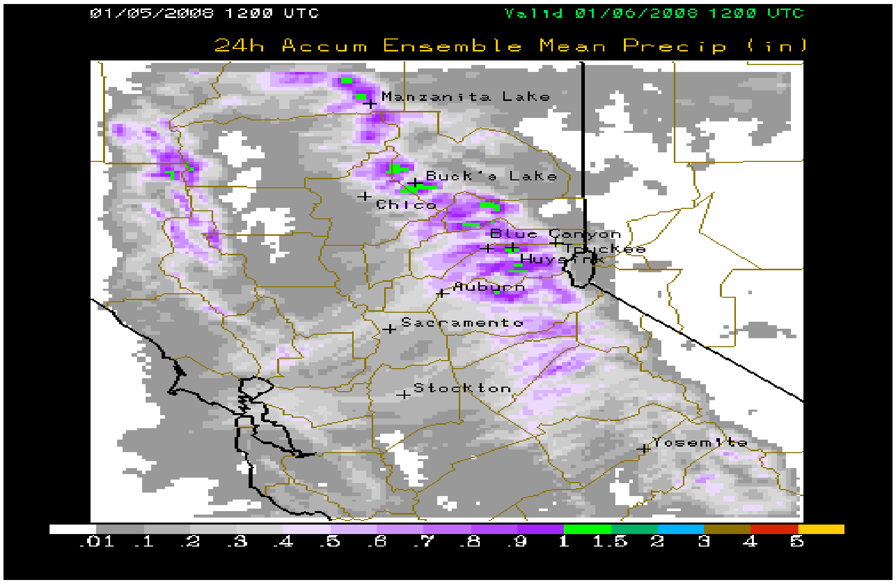


Predicted Precip in ARB Area: Most Intense Period (in)

Station	Forecast	Obs	Error
Alta	3.00	3.33	-.33
Big Bend	3.95	4.25	-.30
Blue Canyon	4.00	M	
Canada Hill	3.90	1.61	+2.29
Colfax	2.82	1.86	+.96
Forrest Hill	2.80	2.54	+.26
Greek Store	2.52	2.56	-.04
Huysink	3.20	3.42	-.22
Norden	3.40	3.63	-.23
Onion Creek	3.15	3.83	-.68
Slough House		M	
Talbot	3.00	3.00	0
Truckee	2.10	2.12	-.02

MAE + 0.15 (3.8mm) RMS 0.80 (20.3mm)

Ensemble mean Precipitation Forecast 5-6 Jan 2008 12GMT (24 hr forecast ending 6/12GMT): Last major trough



Predicted Precip in ARB Area: Final Wave (in)

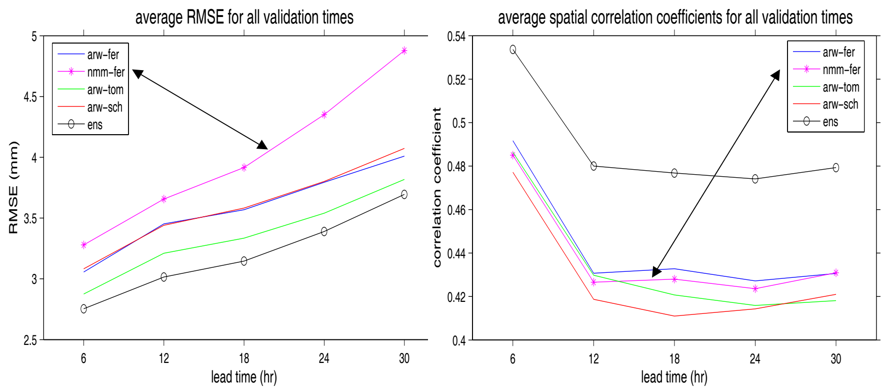
Station	Forecast	Obs	Error
Alta	0.85	1.51	-.66
Big Bend		M	
Blue Canyon		M	
Canada Hill	1.00	0.86	+.14
Colfax	0.68	0.80	-.14
Forrest Hill	0.86	1.48	-.62
Greek Store	0.95	1.85	-.90
Huysink	1.40	1.42	-.02
Norden	0.85	1.97	-1.12
Onion Creek	0.75	1.52	-.77
Slough House	0.32	0.75	-.43
Talbot	0.95	1.81	-.86
Truckee	0.45	0.47	-.02

MAE -.49 (-12.4mm) RMS 0.64 (16.3mm)

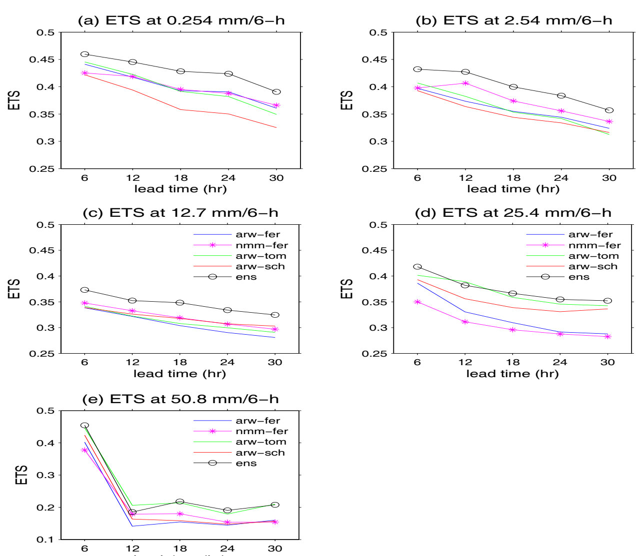
IOP 4 Summary

- Ensemble mean (0-6 h) showed consistent distribution with respect to the HADS observations.
- Errors vary station by station. Average errors increase with precipitation amounts.
- Ensemble mean brought in precipitation too early with onset accounting for a positive MAE. Canada Hill accounted for most error.
- During heavy period MAE was slightly positive but low; some problems were noted in placement of maxima relative to verifying gauges accounting for large RMS. One station, Canada Hill accounted for most error.
- During final wave, ensemble ended precip too early and missed widespread shower activity producing a negative MAE and large RMS errors.

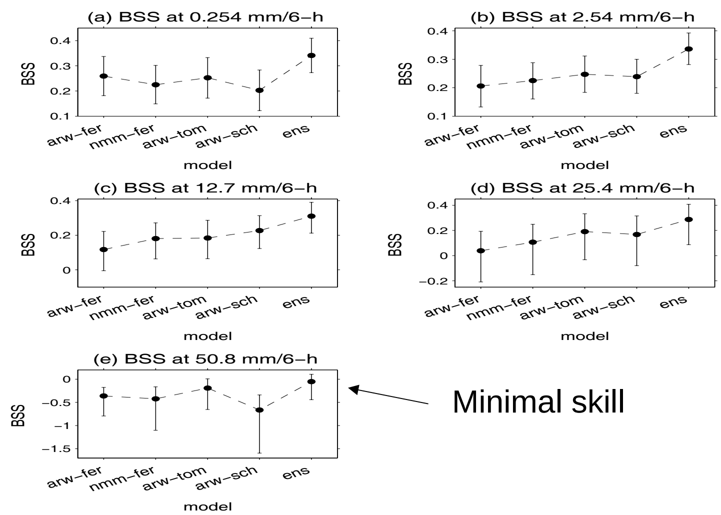
Summary Verification 8 IOPS in 2006-2007



Summary Verification 8 IOPS in 2006-2007: ETS 6h accumulation (rate)



Summary Verification 8 IOPS in 2006-2007: 24 hr Probabilistic Forecasts



2006-2007 Summary

- Ensemble provides superior performance relative to individual members at all lead times and amounts
- Ensemble mean superior to NAM proxy (the NMM-Ferrier member) at 3km resolution
- Ensemble provides better probabilistic forecasts (BSS) at 24 hrs for amounts up to 25.4mm/6h; little skill for 50.8mm/6h
- Working toward optimizing the ensemble by weighting members based on performance for both QPF and PQPF

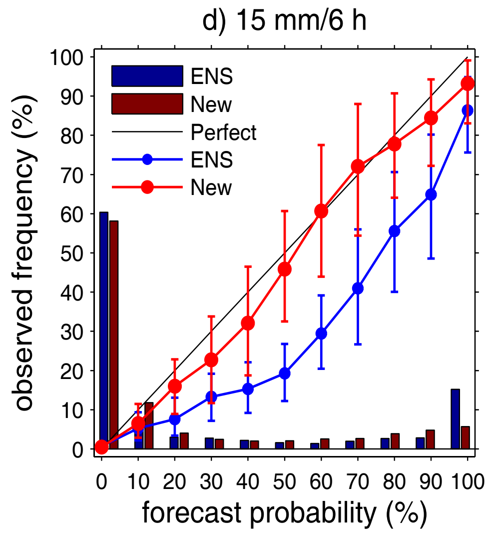
Representative

attributes diagram

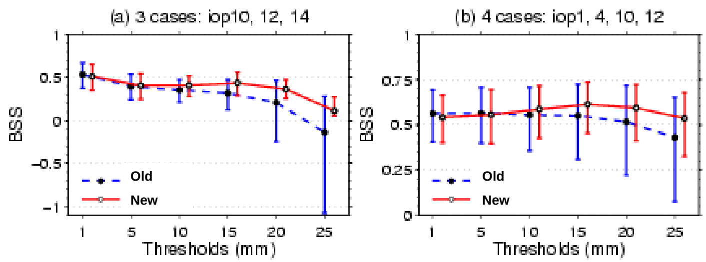
Four rerun cases:
IOP1, 4, 10, 12

Cross-validation over the ARB using Radar-based Stage IV precipitation analysis

Improvement (red) made over raw (blue) ensemble probabilities.



Brier skill score (BSS)



For both operational and rerun IOPs:

The BSS improved after bias correction for thresholds > 5 mm/6-h and uncertainties reduced.

Earth System Research Laboratory
Global Systems Division

National Oceanic and Atmospheric Administration
Hydrometeorology Testbed Program

Part 2: QPE Estimation with
Ensemble-Derived Error Covariances

Findings from HMT case studies:

1. Ensemble forecasts are positively biased
2. Terrain modulation is a common attribute of the forecasts

Major water management need:

1. Accurate QPE for run off estimates

Proposed contribution:

1. Combine gauge estimates with structure provided by model ensemble.
2. Improve QPE relative to NCEP Stage IV (radar + rain gauge) estimates.
3. Establish confidence in QPF where banded structure is evident

What is new here?

Application of a very high-resolution ensemble to obtain detailed QPE in a 3-D Var framework

Assumptions

- Structure of precipitation is heavily modulated by terrain
- High resolution structure can be captured by ensemble
- An appropriate 2-D error covariance **B** can be recovered by using ensemble precipitation variances from the ensemble mean

Minimize $$J(\mathbf{x}) = \frac{1}{2}(\mathbf{x}-\mathbf{x}_\mathbf{b})^\mathbf{T}\mathbf{B}^{-1}(\mathbf{x}-\mathbf{x}_\mathbf{b}) + \frac{1}{2}(\mathbf{y}-\mathbf{H}(\mathbf{x}))^\mathbf{T}\mathbf{R}^{-1}(\mathbf{y}-\mathbf{H}(\mathbf{x}))$$

Obs departure from background

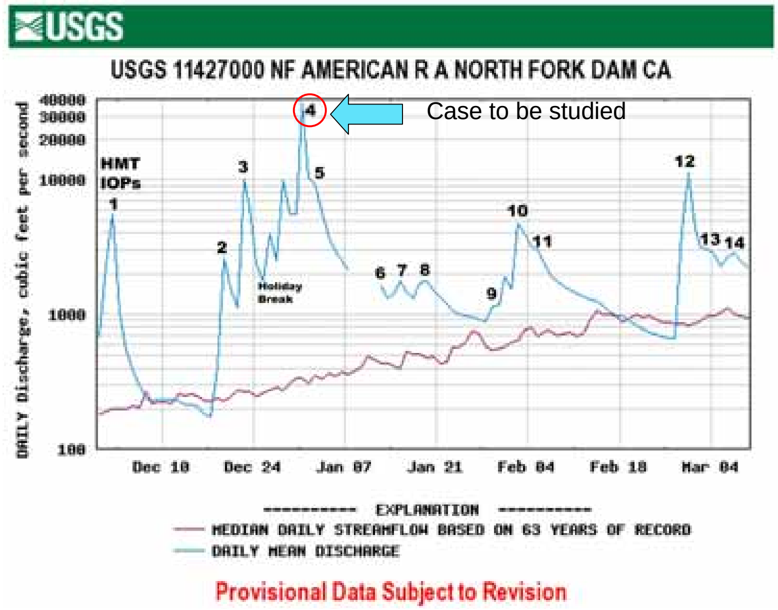
To obtain the analysis equation for precipitation x_a

$$\mathbf{x_a} = \mathbf{x_b} + \mathbf{BH}^\mathbf{T}(\mathbf{HBH}^\mathbf{T} + \mathbf{R})^{-1}\mathbf{d}$$

- Precipitation can be derived by minimizing a standard 3-D var formalism, with gauge and radar observations **y**, observation error, **R**

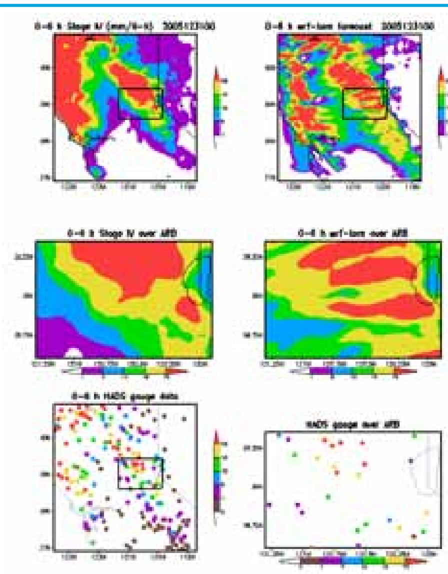
Hydrological conditions during HMT-West-2006

○ Indicates heavy precipitation events selected for study

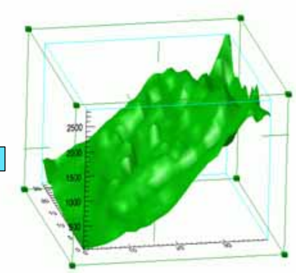


Earth System Research Laboratory
Global Systems Division

National Oceanic and Atmospheric Administration
Hydrometeorology Testbed Program



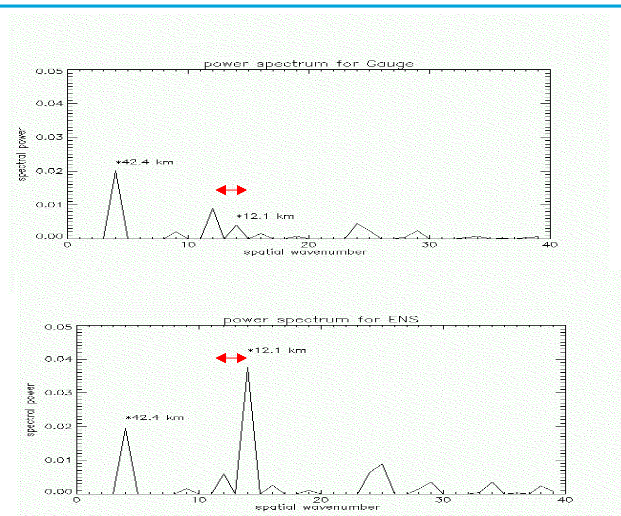
Terrain modulates precipitation
In ensemble mean forecasts. Is
It real?



Gauges hint at banding but
coverage is too sparse

Earth System Research Laboratory
Global Systems Division

National Oceanic and Atmospheric Administration
Hydrometeorology Testbed Program



Comparison of power spectra indicate that gauges under-represent the modulation due to ridges spaced at about 12-14km

Computing the Error Covariance

Ensemble forecasts, $P_{i,s}$ for grid point i, for member s

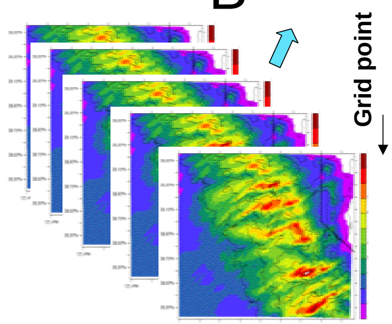
Ensemble mean at gridpoint i, $\underline{P}_i$

We define

Ensemble member →

$$B^{1/2} = \begin{bmatrix} (P_{1,1}-\underline{P}_1) & (P_{1,2}-\underline{P}_1) & (P_{1,3}-\underline{P}_1) & (P_{1,4}-\underline{P}_1) & \ldots\ldots \\ (P_{2,1}-\underline{P}_2) & (P_{2,2}-\underline{P}_2) & (P_{2,3}-\underline{P}_2) & (P_{2,4}-\underline{P}_2) & \ldots. \\ (P_{3,1}-\underline{P}_3) & (P_{3,2}-\underline{P}_3) & (P_{3,3}-\underline{P}_3) & (P_{3,4}-\underline{P}_3) & \ldots. \\ (P_{4,1}-\underline{P}_4) & (P_{4,2}-\underline{P}_4) & (P_{4,3}-\underline{P}_4) & (P_{4,4}-\underline{P}_4) & \ldots. \\ \vdots & & & & \end{bmatrix}$$

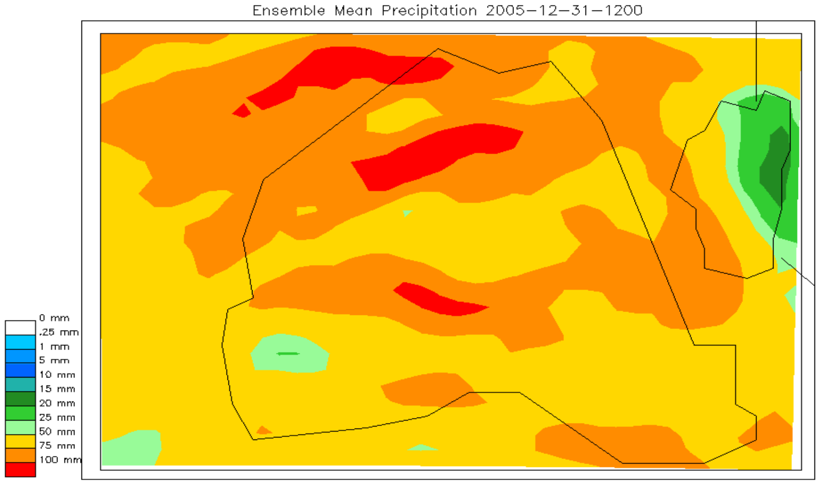
Grid point ↓



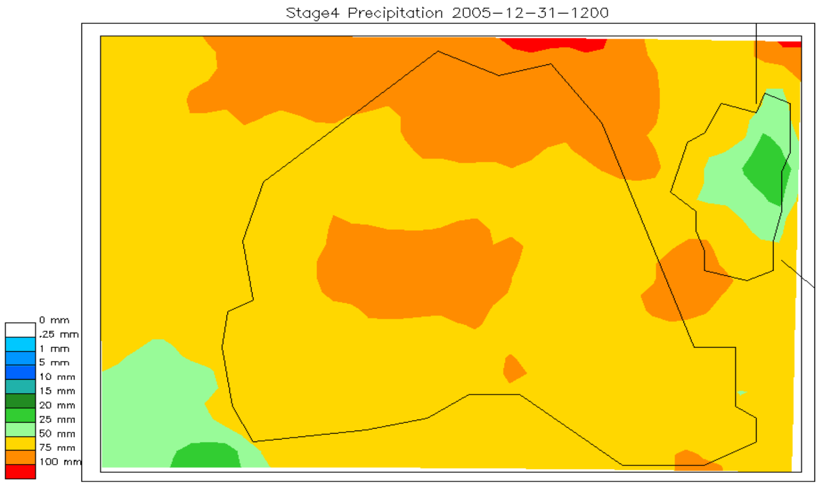
So….

$$B = a\, B^{1/2} B^{1/2T} + (1- a)\, B_{climate}$$

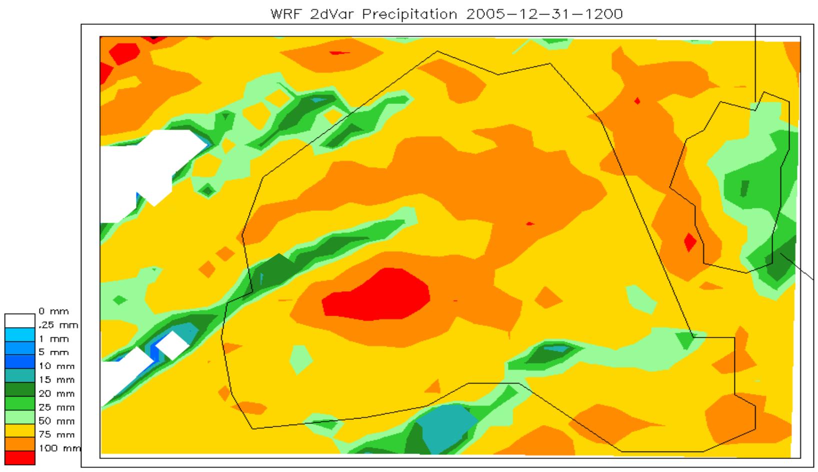
Ensemble mean precipitation - note banding



Radar + raingauge interpolation (Stage IV)

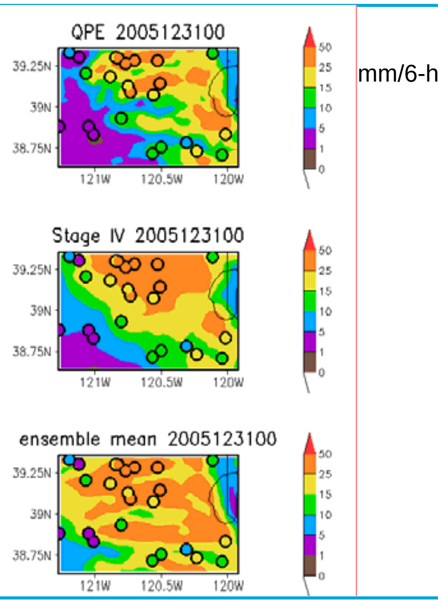


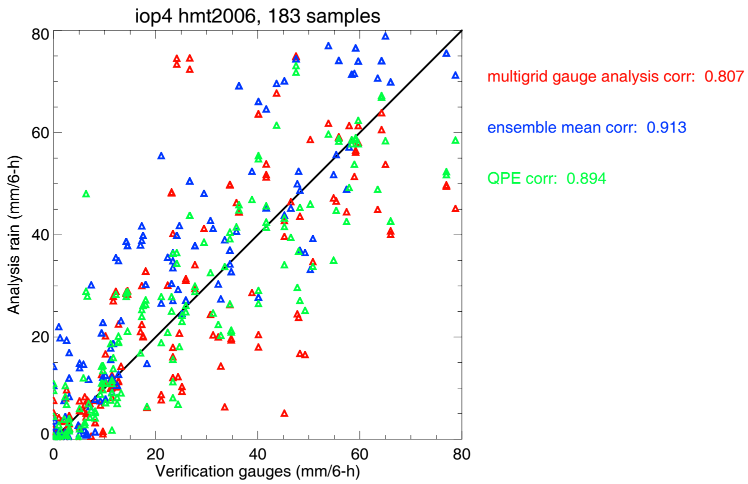
Radar + Gauge with error covariances applied



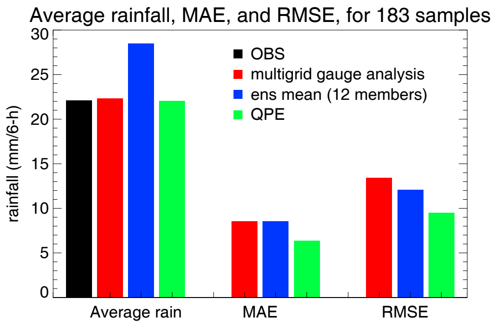
Earth System Research Laboratory
Global Systems Division

National Oceanic and Atmospheric Administration
Hydrometeorology Testbed Program



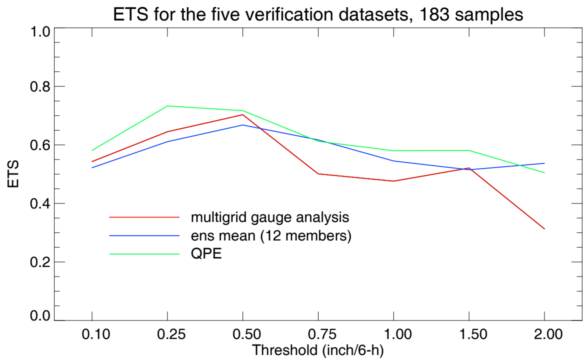


Earth System Research Laboratory
Global Systems Division
National Oceanic and Atmospheric Administration
Hydrometeorology Testbed Program



Earth System Research Laboratory
Global Systems Division

National Oceanic and Atmospheric Administration
Hydrometeorology Testbed Program



Earth System Research Laboratory
Global Systems Division

National Oceanic and Atmospheric Administration
Hydrometeorology Testbed Program

Conclusions

1) Initial results are good, but occasional anomalous fields from poorly specified error covariance

2) QPE shows an improvement over the multigrid gauge interpolation (proxy for Stage IV analysis)

3) Slightly better performance when model climatology has some weight (**a** about 0.8-0.9)

4) Shorter-range ensemble forecasts result in better QPE analysis

5) Quality control of rain gauge stations is critical