Model Output Statistics (MOS) - Objective Interpretation of NWP Model Output

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Mark S. Antolik
Meteorological Development Laboratory
Statistical Modeling Branch
NOAA/National Weather Service
Silver Spring, MD

(301) 713-0023 ext. 110
email: mark.antolik@noaa.gov

MOS Operational System "Fun Facts"

With apologies to David Letterman, of course!

- **9 million regression equations**
- **75 million forecasts per day**
- **1200 products sent daily**
- **400,000 lines of code – mostly FORTRAN**
- **180 min. supercomputer time daily**
- **All developed and maintained by ~ ~~12~~ 8 MDL / SMB meteorologists!**

OUTLINE

1. Why objective statistical guidance?
2. What is MOS?
   - Definition and characteristics
   - The “traditional” MOS product suite (GFS, NAM)
   - Other additions to the lineup
3. Simple regression examples / REEP
4. Development strategy - MOS in the “real world”
5. Verification
6. Dealing with NWP model changes
7. Where we’re going – GMOS and the future

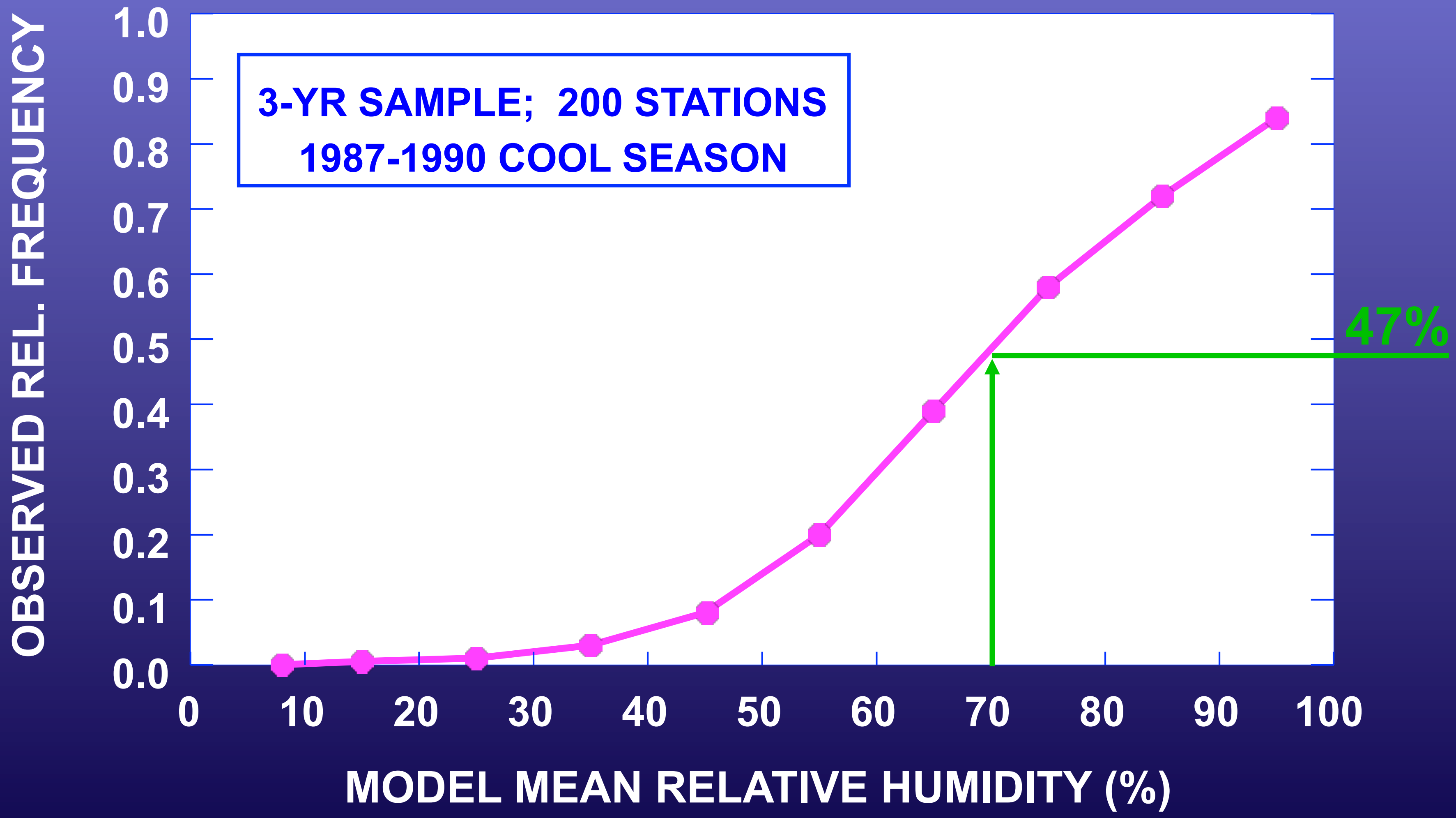
WHY STATISTICAL GUIDANCE?

- **Add value to direct NWP model output**
  - Objectively interpret model
    - remove systematic biases
    - quantify uncertainty
  - Predict what the model does not
  - Produce site-specific forecasts
    - (i.e. a "downscaling" technique)

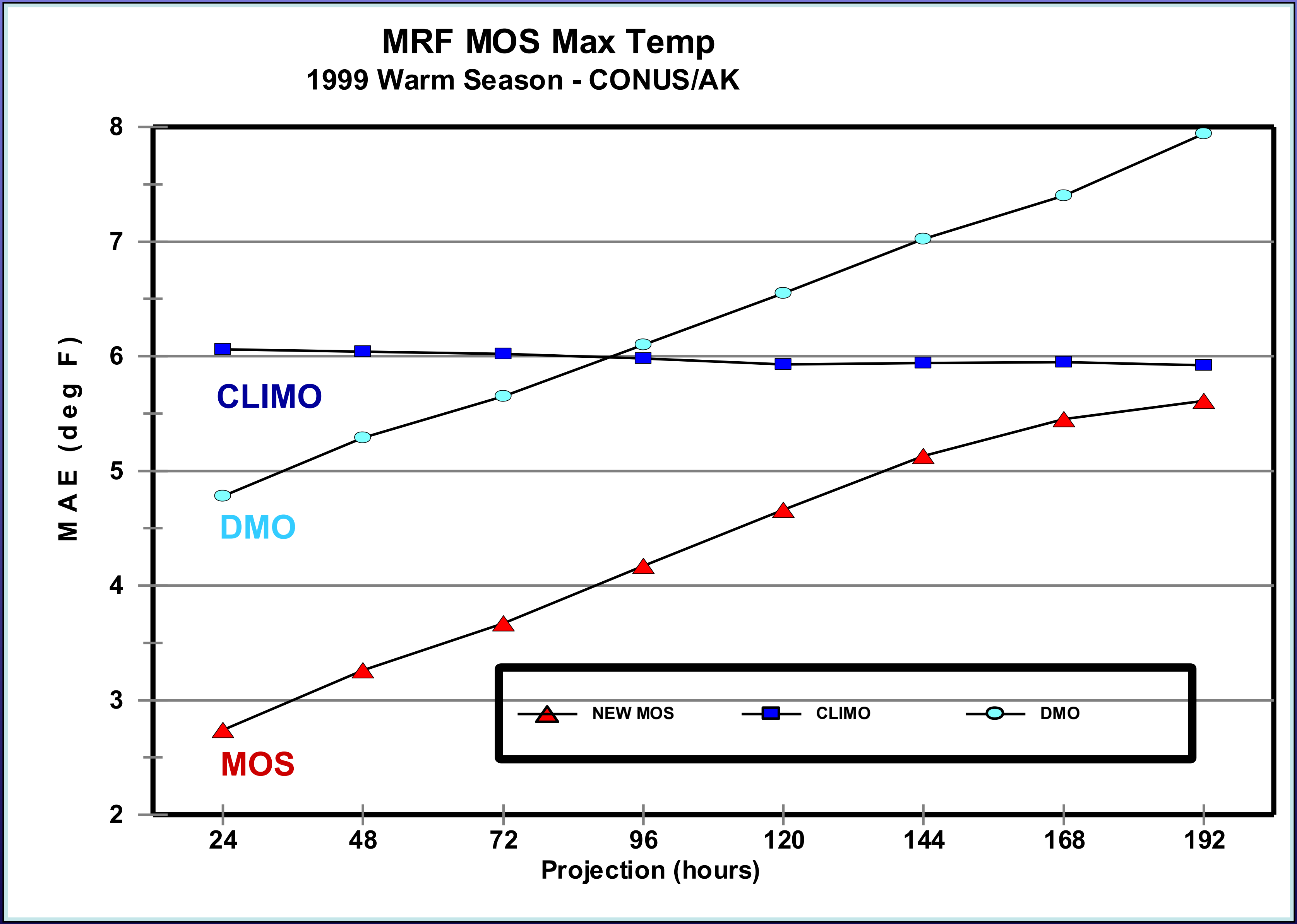
- **Assist forecasters**
  - "First Guess" for expected local conditions
  - "Built-in" model/climo memory for new staff

A SIMPLE STATISTICAL MODEL

Relative Frequency of Precipitation as a Function of 12-24 Hour Model-Forecast Mean RH



MOS Max Temp vs. Direct Model Output



What is MOS?

MODEL OUTPUT STATISTICS (MOS)

Relates observed weather elements (PREDICTANDS) to appropriate variables (PREDICTORS) via a statistical approach

Predictors are obtained from:

1. Numerical Weather Prediction (NWP) Model Forecasts
2. Prior Surface Weather Observations
3. Geoclimatic Information

Current Statistical Method:

MULTIPLE LINEAR REGRESSION
(Forward Selection)

MODEL OUTPUT STATISTICS (MOS)

Properties

- Mathematically simple, yet powerful
- Need historical record of observations at forecast points
  (Hopefully a long, stable one!)
- Equations are applied to future run of similar forecast model

MODEL OUTPUT STATISTICS (MOS)

Properties (cont.)

- Non-linearity can be modeled by using NWP variables and transformations
- Probability forecasts possible from a single run of NWP model
- Other statistical methods can be used e.g. Polynomial or logistic regression; Neural networks

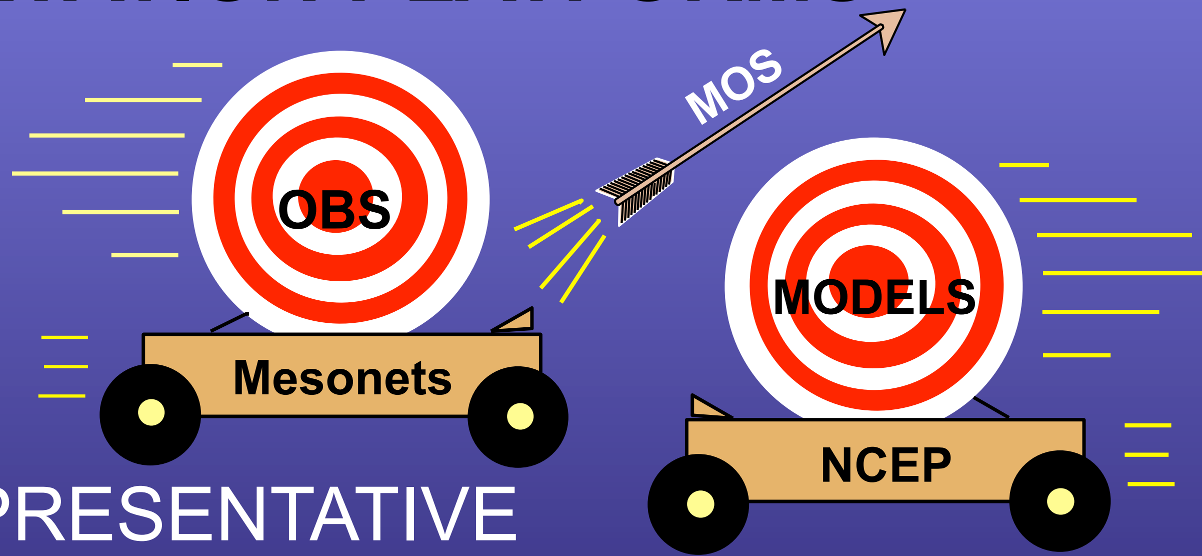
MODEL OUTPUT STATISTICS (MOS)

- **ADVANTAGES**
  - Recognition of model predictability
  - Removal of some systematic model bias
  - Optimal predictor selection
  - Reliable probabilities
  - Specific element and site forecasts

- **DISADVANTAGES**
  - Short samples
  - Changing NWP models
  - Availability & quality of observations

MAJOR CHALLENGE TO MOS DEVELOPMENT:

RAPIDLY EVOLVING NWP MODELS AND OBSERVATION PLATFORMS



Can make for:

1. SHORT, UNREPRESENTATIVE DATA SAMPLES
2. **DIFFICULT COLLECTION OF APPROPRIATE PREDICTAND DATA**

New observing systems:	(ASOS, WSR-88D, Satellite) (Co-Op, Mesonets)
Same “old” predictands:	The elements don’t change!

“Traditional” MOS text products

GFS MOS GUIDANCE MESSAGE
FOUS21-26 (MAV)

```
KLNS   GFS MOS GUIDANCE   11/29/2004  1200 UTC
DT /NOV  29/NOV  30                /DEC   1                /DEC   2
HR   18 21 00 03 06 09 12 15 18 21 00 03 06 09 12 15 18 21 00 06 12
N/X                    28          48          35          49    33
TMP  43 44 39 36 33 32 31 39 46 45 41 38 37 39 41 44 45 44 40 40 35
DPT  27 27 28 29 29 29 29 33 35 35 36 35 36 39 41 42 37 34 30 30 28
CLD  CL BK BK BK OV OV OV OV OV OV OV OV OV OV OV OV OV BK CL CL CL
WDR  34 36 00 00 00 00 00 00 00 14 12 12 10 11 12 19 28 29 29 29 28
WSP  06 02 00 00 00 00 00 00 00 01 02 04 04 06 07 08 15 17 18 09 05
P06         0     0     4     3    11    65    94    96     7  0  0
P12                     6          19          94          96     0
Q06         0     0     0     0     0     3     4     4     0  0  0
Q12                     0           0           4           2     0
T06      0/ 0  0/18  0/ 3  0/ 0  0/ 0  0/18  2/ 1 10/ 4  0/ 3  1/ 0
T12            0/26        0/17        0/27       10/25     1/38
POZ   2  0  0  1  2  4  4  0  1  1  2  3  3  1  1  0  2  1  2  3  1
POS  13  2  1  2  1  0  0  0  0  0  0  0  0  2  0  0  0  3  0  9 28
TYP   R  R  R  R  R  R  R  R  R  R  R  R  R  R  R  R  R  R  R  R  R
SNW                     0                       0                 0
CIG   8  8  8  8  7  7  7  8  8  7  7  7  4  2  3  3  6  7  8  8  8
VIS   7  7  7  7  7  7  7  7  7  7  7  7  5  5  4  2  6  7  7  7  7
OBV   N  N  N  N  N  N  N  N  N  N  N  N BR BR BR BR  N  N  N  N  N
```

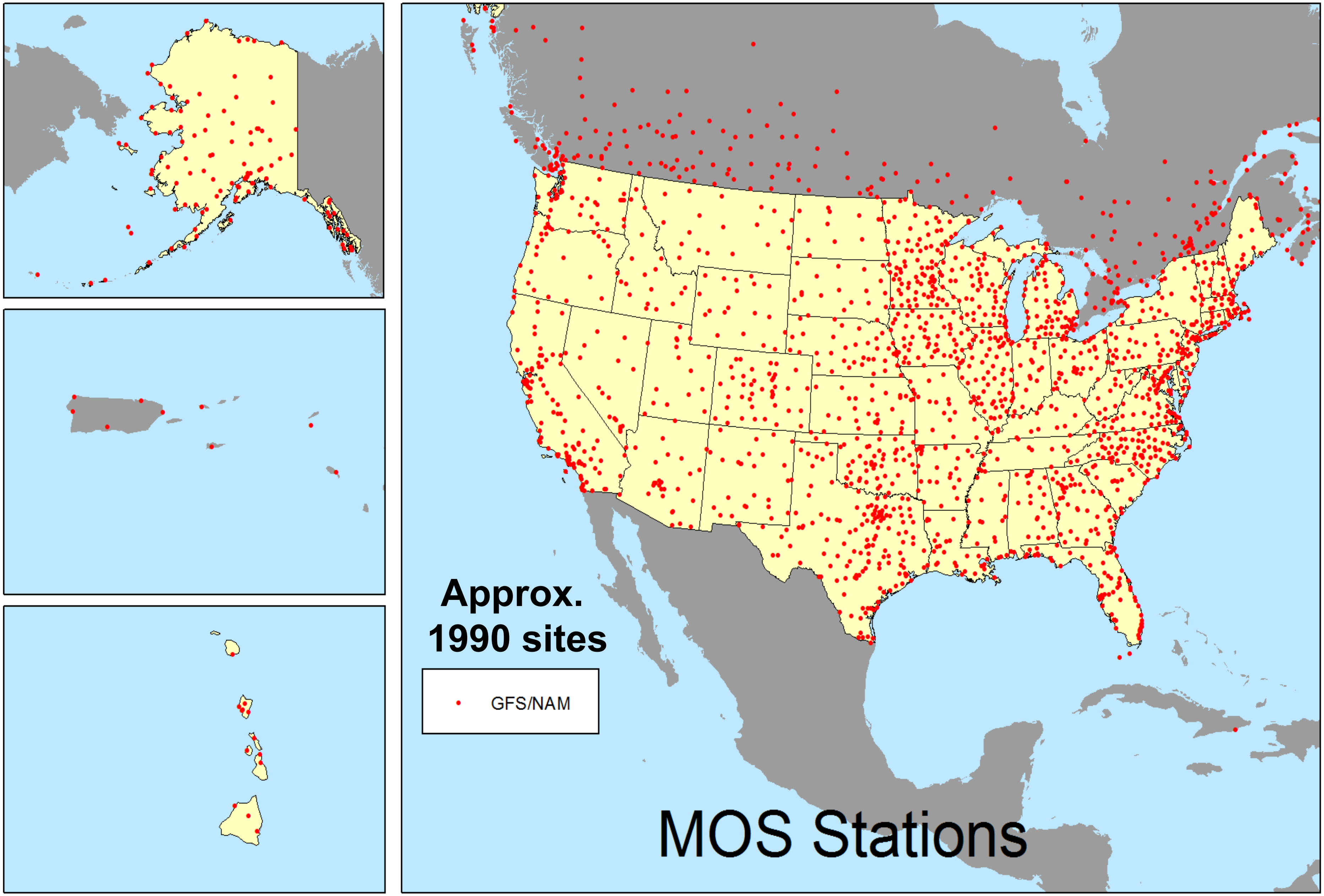
NAM MOS GUIDANCE MESSAGE FOUS44-49 (MET)

KBWI NAM MOS GUIDANCE 2/27/2009 1200 UTC

DT	/FEB 27		/FEB 28								/MAR 1								/MAR 2		
HR	18	21	00	03	06	09	12	15	18	21	00	03	06	09	12	15	18	21	00	06	12
N/X							38				46				32				41		24
TMP	59	58	55	54	49	43	38	38	43	45	40	38	37	35	33	34	37	38	33	29	25
DPT	46	47	48	46	37	30	24	22	22	22	24	27	28	26	25	24	24	21	17	12	10
CLD	OV	OV	OV	OV	OV	SC	SC	SC	CL	BK	OV	OV	OV	OV	OV	OV	OV	OV	OV	OV	BK
WDR	21	20	22	25	31	32	34	36	01	03	05	04	01	36	35	35	35	34	35	33	34
WSP	15	09	08	06	10	11	10	12	10	09	08	10	12	13	14	16	11	13	15	16	17
P06			89		10		3		2		2		76		73		13		17	27	19
P12							10				3				81				17		30
Q06			1		0		0		0		0		4		1		0		0	0	0
Q12							0				0				4				0		0
T06			2/ 9		0/ 5		0 /0		0/ 5		3/ 1		5/ 3		0/ 0		0/ 2		2/ 5		0/ 0
T12					2/ 9				0/ 5				5/ 3				1/ 2			7/ 5	
SNW							0								0						0
CIG	6	6	4	5	7	8	8	8	8	8	7	6	4	3	4	3	4	4	7	6	7
VIS	7	7	6	7	7	7	7	7	7	7	7	7	3	6	5	7	7	7	7	7	7
OBV	N	N	N	N	N	N	N	N	N	N	N	N	BR	N	BR	N	N	N	N	N	N

Short-range (GFS / NAM) MOS

- **STATIONS:**
  Now at approx. 1990 Forecast Sites
  (CONUS, AK, HI, PR, Canada)


Approx.
1990 sites
GFS/NAM
MOS Stations

Short-range (GFS / NAM) MOS

- **STATIONS:**
  Now at approx. 1990 Forecast Sites
  (CONUS, AK, HI, PR)
- **FORECASTS:**
  Available at projections of 6-84 hours
  GFS available for 0600 and 1800 UTC cycles
- **RESOLUTION:**
  GFS predictors on 95.25 km grid; NAM on 32 km
  Predictor fields available at 3-h timesteps
- **DEPENDENT SAMPLE NOT "IDEAL":**
  Fewer seasons than older MOS systems
  Non-static underlying NWP model

GFSX MOS GUIDANCE MESSAGE FEUS21-26 (MEX)

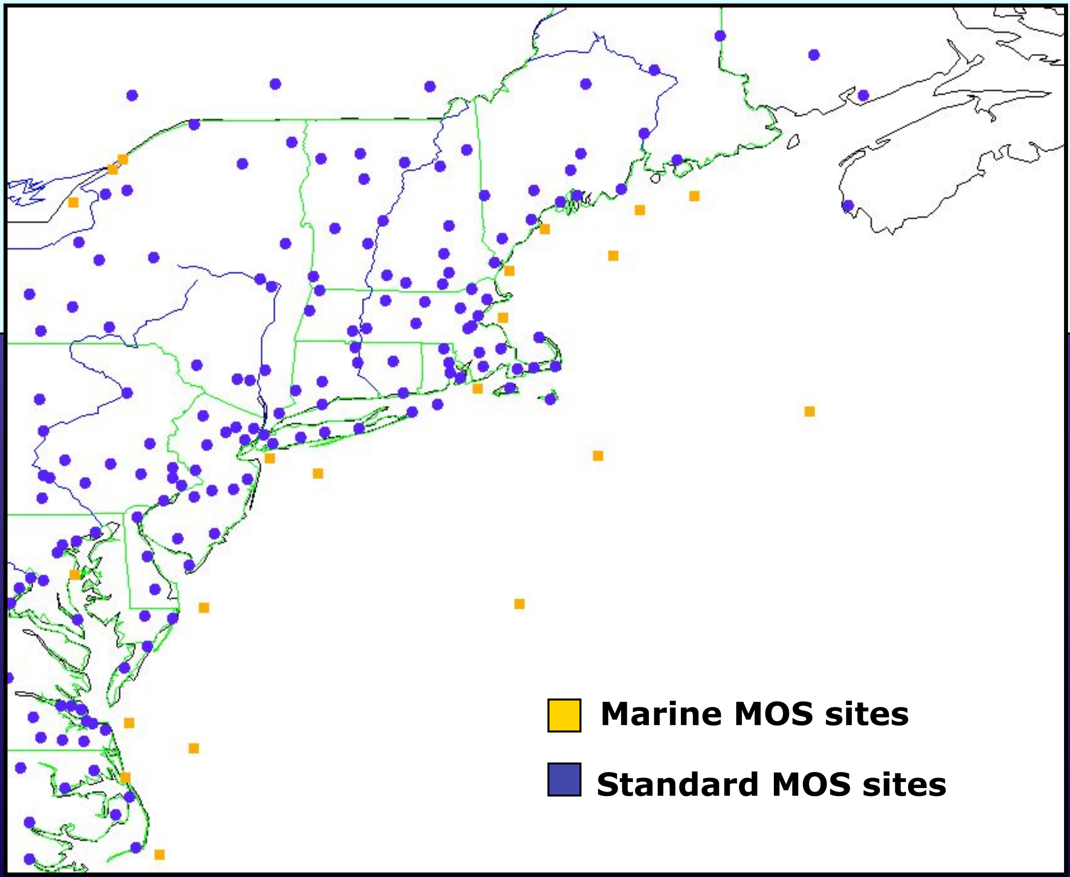
```
KCXY   GFSX MOS GUIDANCE  11/26/2004  0000 UTC
FHR  24| 36  48| 60  72| 84  96|108 120|132 144|156 168|180 192
FRI  26| SAT 27| SUN 28| MON 29| TUE 30| WED 01| THU 02| FRI 03 CLIMO
X/N  43| 29  47| 40  55| 35  51| 29  45| 32  40| 36  42| 30  45 31 46
TMP  37| 32  43| 43  46| 37  41| 32  39| 35  36| 38  37| 33  37
DPT  24| 27  37| 40  32| 28  28| 26  31| 32  30| 32  27| 24  25
CLD  PC| OV  OV| OV  PC| CL  PC| PC  OV| OV  OV| PC  CL| CL  CL
WND  10|  5  11| 11  16| 10  10|  5   9|  6  10| 12  14| 12  12
P12   0|  5  13| 91  13|  3   9| 14  24| 52  54| 48  21| 12  25 20 18
P24    |     16|    100|      9|     26|     62|     72|     25    29
Q12   0|  0   0|  3   0|  0   0|  0   0|  2   2|  2    |
Q24    |      0|      3|      0|      0|      4|       |
T12   0|  0   0|  3   0|  0   0|  0   4|  6   4|  3   1|  1   1
T24    |  0    |  3    |  0    |  0    |  6    |  4    |  1
PZP  12|  9  12|  4   3|  5   6| 10   8|  8   3| 16  10| 12   8
PSN  62| 15   3|  0   0| 10   9| 15  24|  1   0|  9  32| 27  18
PRS  26| 24   7|  0  17| 18  20| 13  15|  1   2| 18   9| 11  11
TYP   S| RS   R|  R   R|  R   R|  R  RS|  R   R|  R  RS| RS   R
SNW    |      0|      0|      0|      0|       |       |
```

MOS station-oriented products: Other additions

Marine MOS

```
44004   GFS MOS GUIDANCE    11/22/2005  1200 UTC
DT   /NOV 22/NOV 23                    /NOV 24                     /NOV 25
HR     18 21 00 03 06 09 12 15 18 21 00 03 06 09 12 15 18 21 00 03 06
TMP    58 53 49 49 50 48 46 44 44 45 47 48 51 54 56 60 62 61 59 51 47
WD     23 25 27 28 28 29 29 28 28 27 27 25 22 22 22 23 23 23 24 27 28
WS     33 31 29 25 23 22 24 25 23 18 14 12 14 19 26 29 30 29 29 28 24
WS10   36 34 31 26 25 24 26 27 25 19 15 13 15 21 28 31 32 31 31 30 26

DT   /NOV 25          /
HR     09 12 15 18 21 00
TMP    45 45 45 47 47 47
WD     29 29 28 30 29 34
WS     18 15 10 10 13 12
WS10   20 16 11 11 14 13
```



Max/Min Guidance for Co-op Sites

GFS-BASED MOS COOP MAX/MIN GUIDANCE 3/01/05 1800 UTC

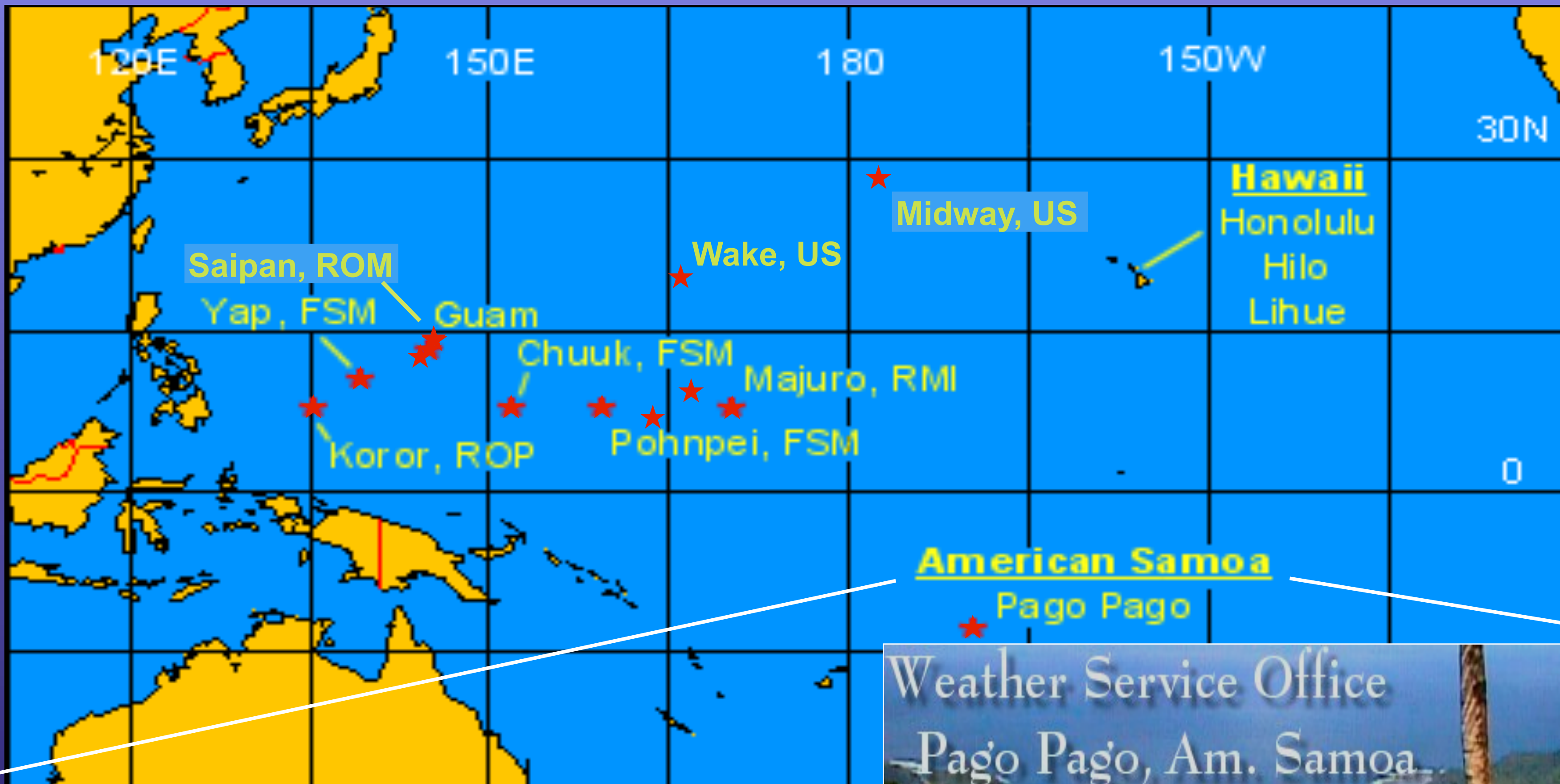
	WED	02	THU	03	FRI	04
ANNM2	26	46	24	45	25	46
BERM2	28	41	25	39	25	43
BTVM2	23	39	21	38	20	43
CBLM2	20	40	18	39	20	46
CHEM2	25	42	21	39	21	44
CNWM2	21	42	21	40	20	45
DMAM2	20	37	18	37	20	42
ELCM2	25	41	21	41	18	45
EMMM2	23	42	20	41	20	43
FREM2	23	46	21	42	23	44
FRSM2	17	27	13	27	13	36
GLDM2	21	37	18	39	18	43
HAGM2	23	43	18	43	19	45
KAPG	27	41	23	37	22	43
LRLM2	23	44	21	42	22	46
MECM2	24	47	20	42	20	45
MILM2	25	48	22	41	20	39
MLLM2	22	39	18	37	18	41
OLDM2	18	31	13	28	12	35
OXNM2	23	42	22	40	23	48
PRAM2	22	49	22	45	18	45

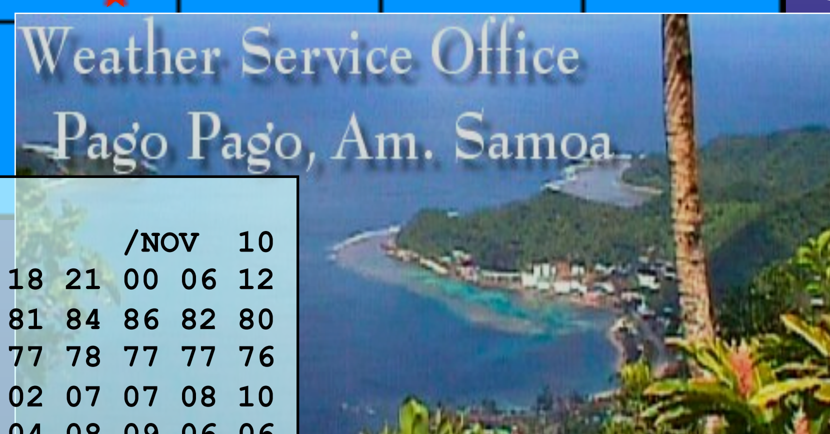
Beltsville, MD (BTVM2)

Glenn Dale, MD (GLDM2)

Laurel 3 W (LRLM2)

Western Pacific MOS Guidance





NSTU GFS MOS GUIDANCE 11/07/2008 1200 UTC

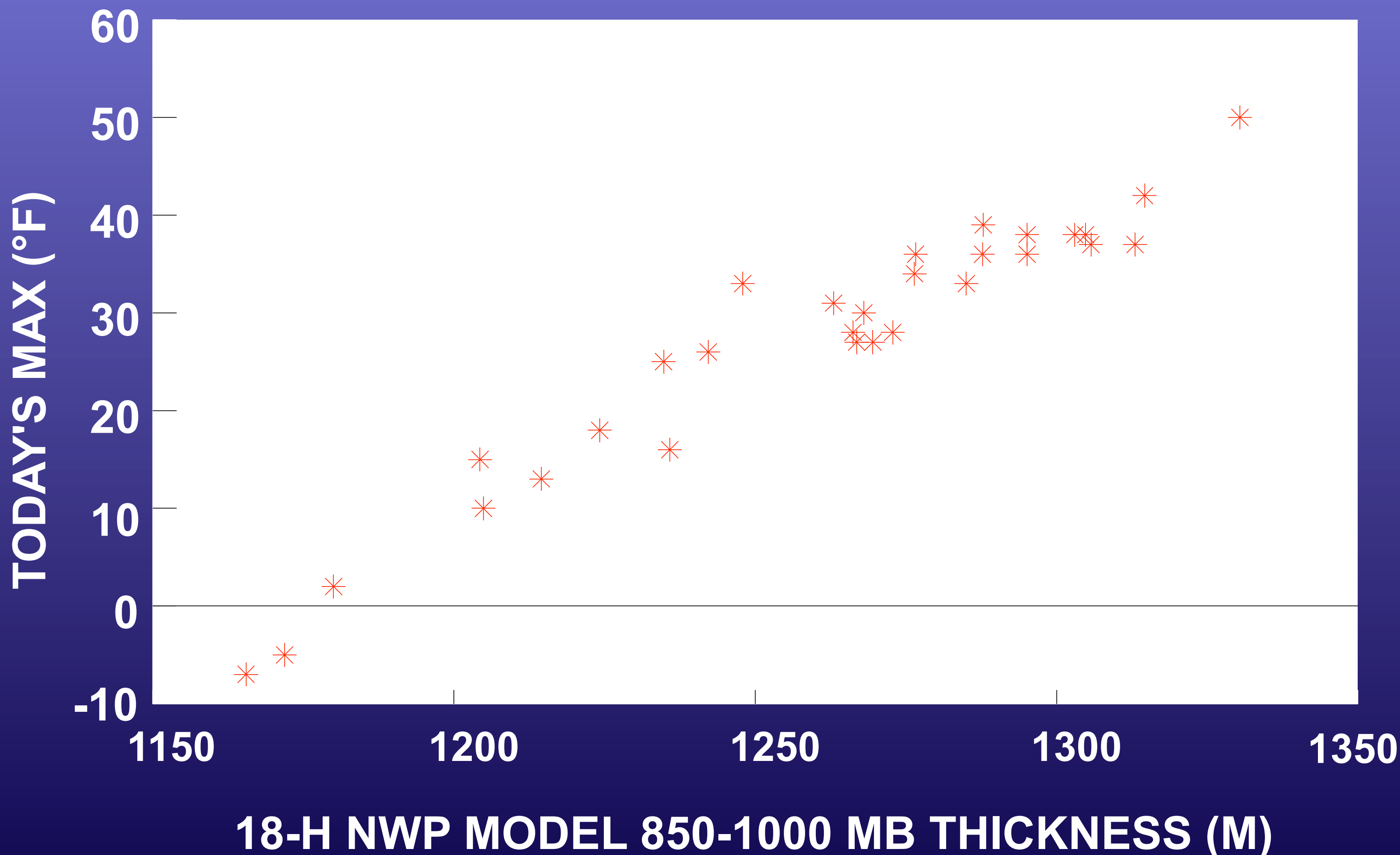
DT /NOV		7/NOV		8						/NOV		9						/NOV		10
HR	18	21	00	03	06	09	12	15	18	21	00	03	06	09	12	15	18	21	00	06	12
TMP	84	85	85	85	82	82	81	79	80	83	84	83	81	81	80	79	81	84	86	82	80
DPT	77	77	78	77	76	77	76	75	77	78	77	77	76	77	76	75	77	78	77	77	76
WDR	08	08	08	09	08	07	05	04	06	07	08	07	05	02	35	01	02	07	07	08	10
WSP	17	17	15	13	11	08	07	07	07	08	09	08	07	05	04	04	04	08	09	06	06
P06			36		37		47		46		50		43		25		35		43	30	31
P12					60				66				60				59			47	

Application of Linear Regression to MOS Development

MOS LINEAR REGRESSION

JANUARY 1 - JANUARY 30, 1994 0000 UTC

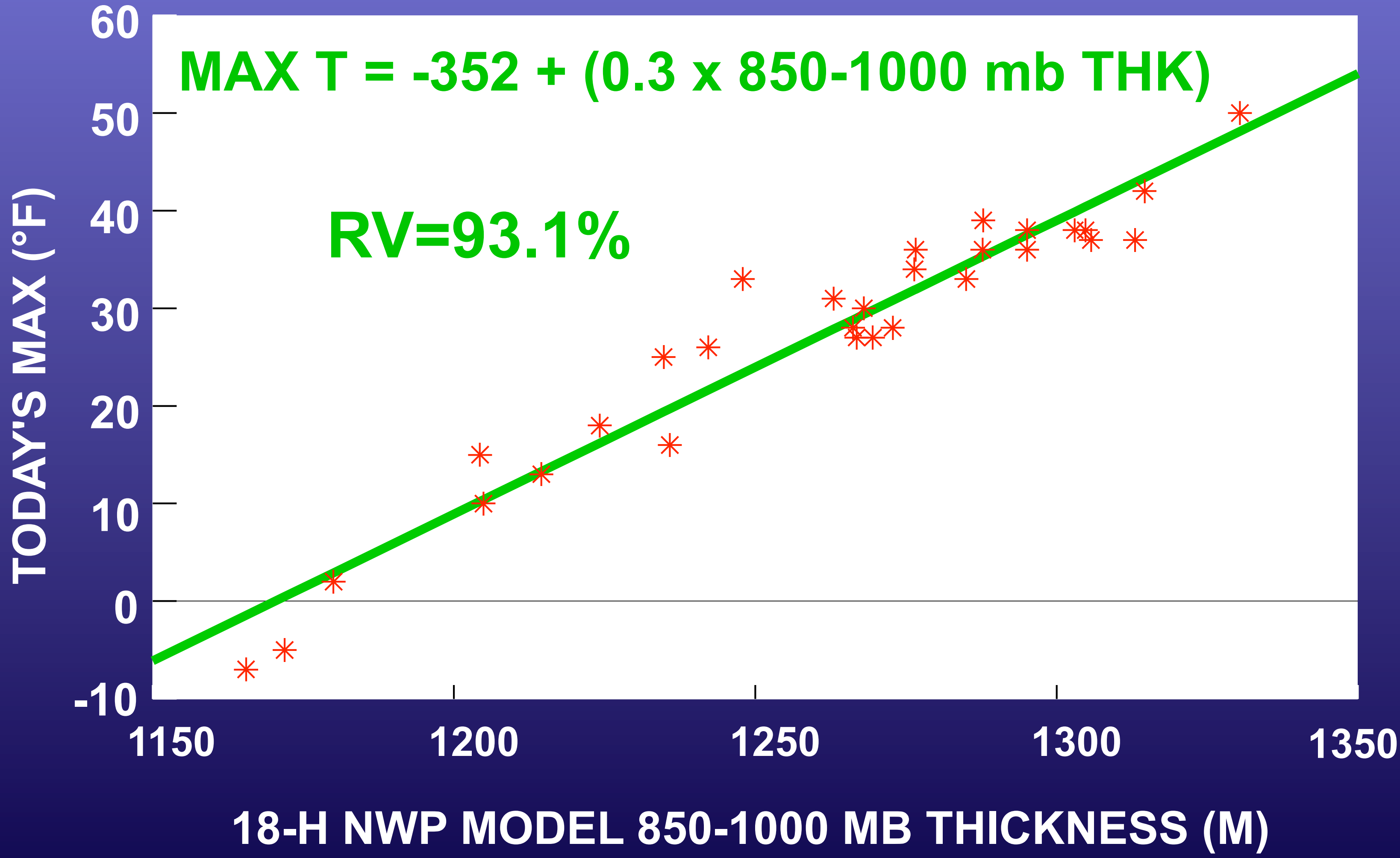
KCMH



MOS LINEAR REGRESSION

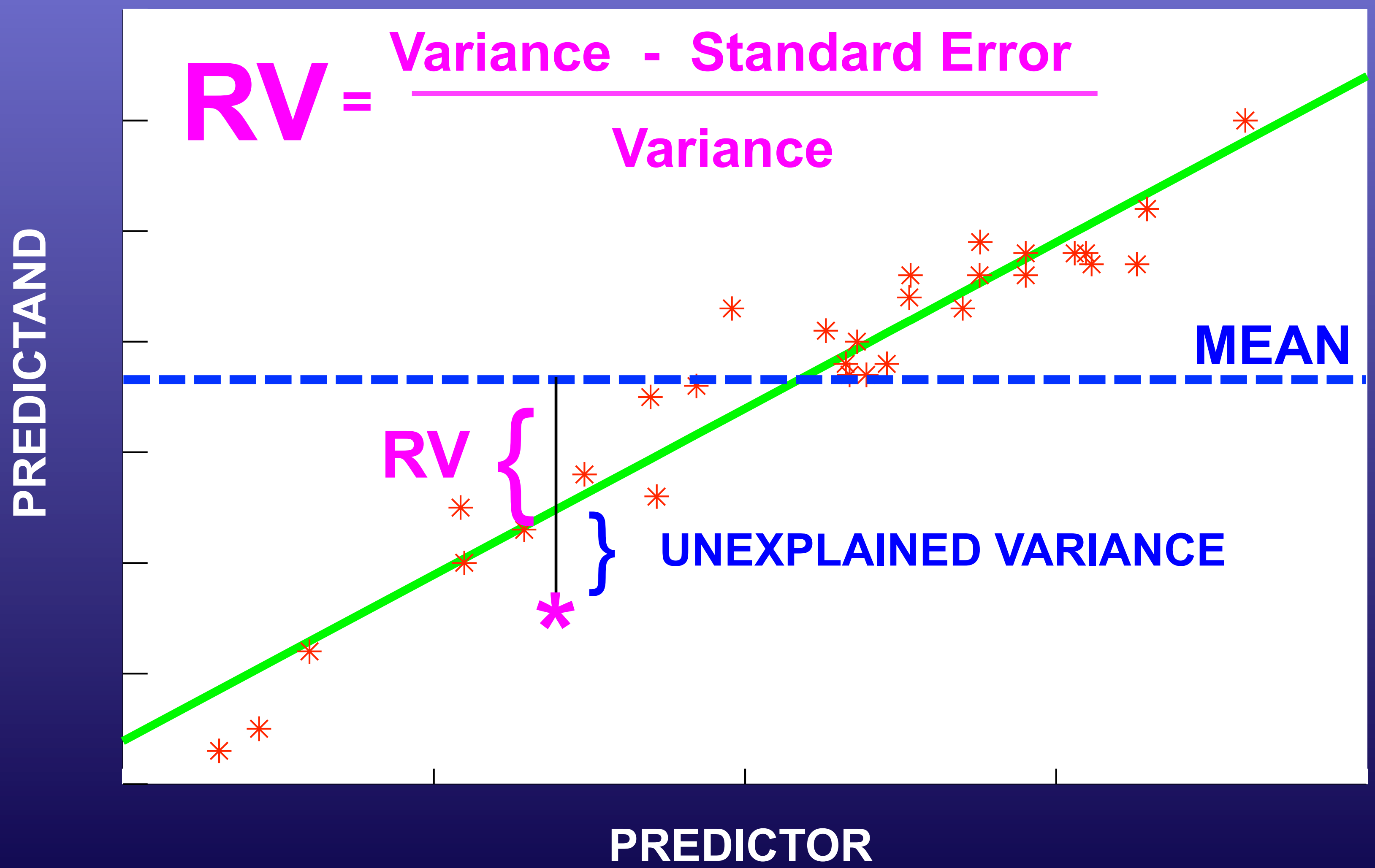
JANUARY 1 - JANUARY 30, 1994 0000 UTC

KCMH



REDUCTION OF VARIANCE

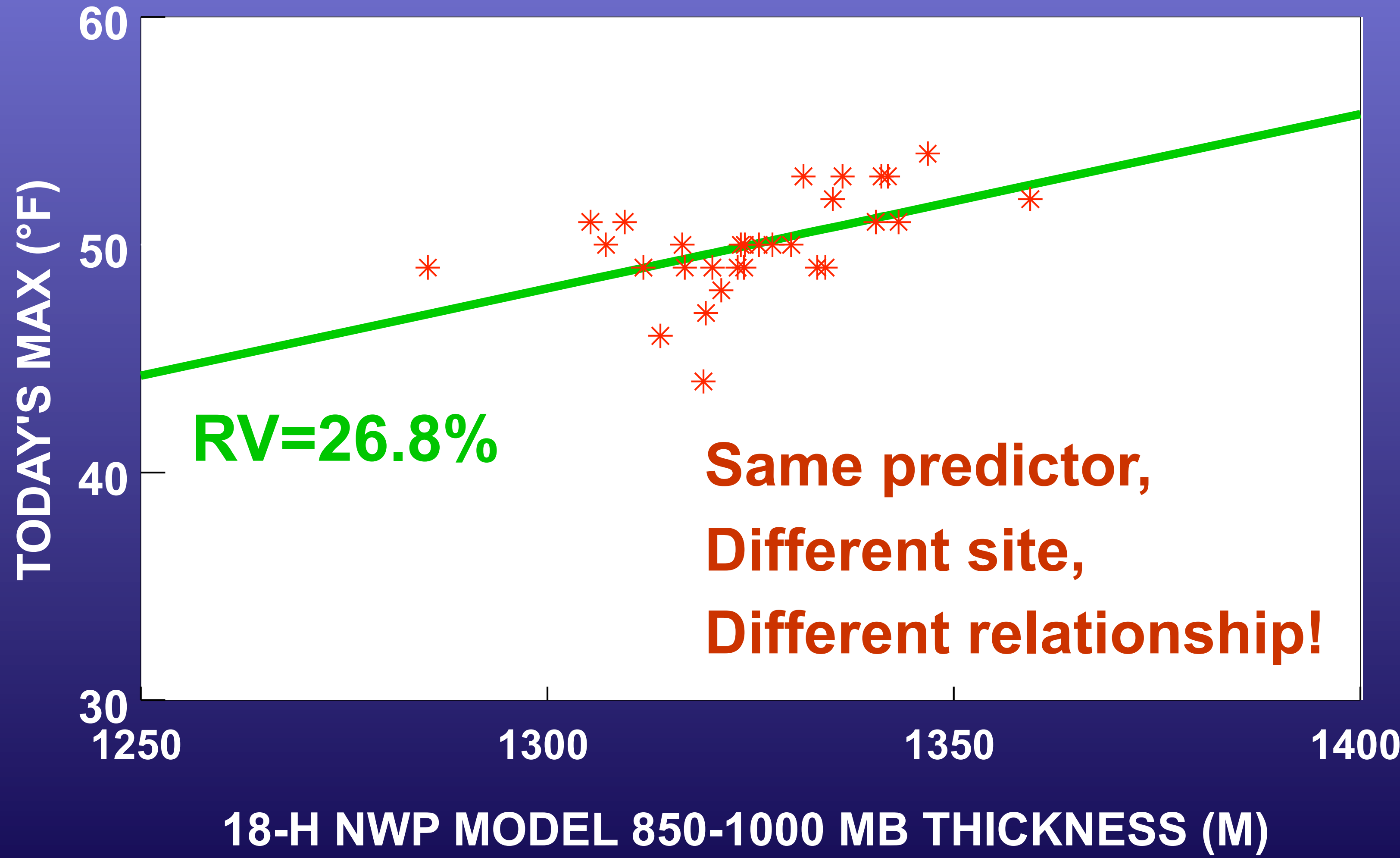
A measure of the "goodness" of fit and
Predictor / Predictand correlation



MOS LINEAR REGRESSION

JANUARY 1 - JANUARY 30, 1994 0000 UTC

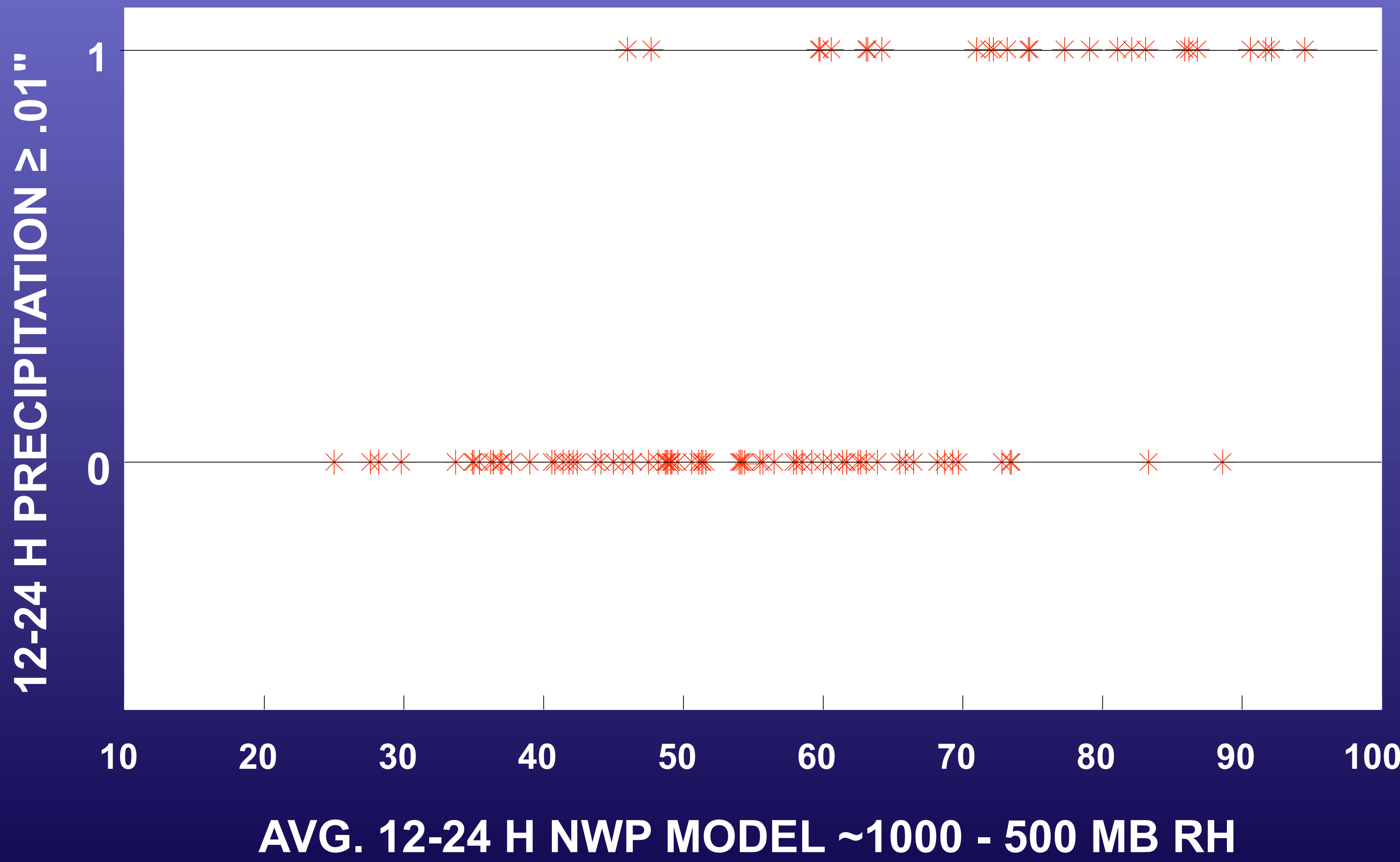
KUIL



MOS LINEAR REGRESSION

DECEMBER 1 1993 - MARCH 5 1994   0000 UTC

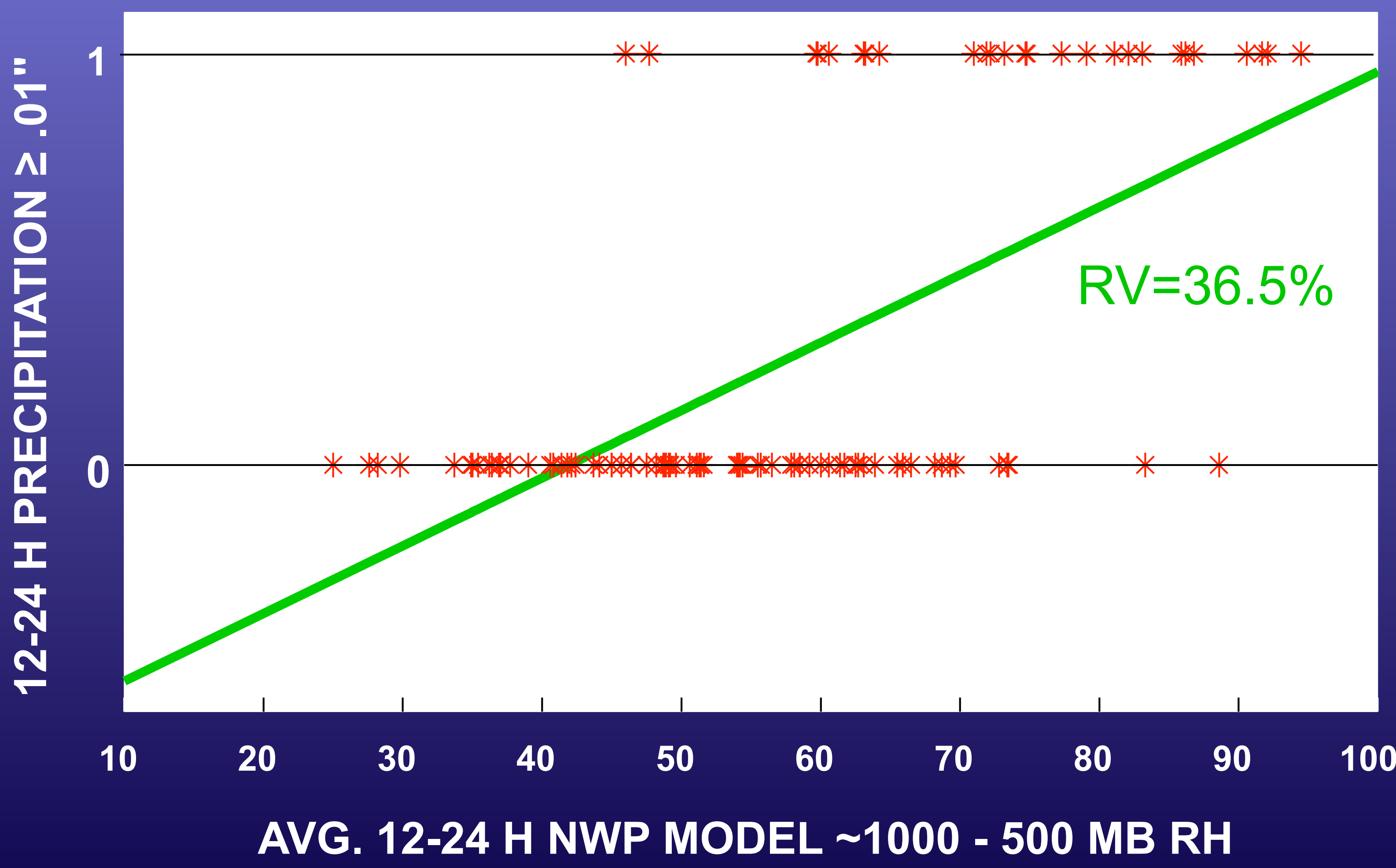
KCMH



MOS LINEAR REGRESSION

DECEMBER 1 1993 - MARCH 5 1994   0000 UTC

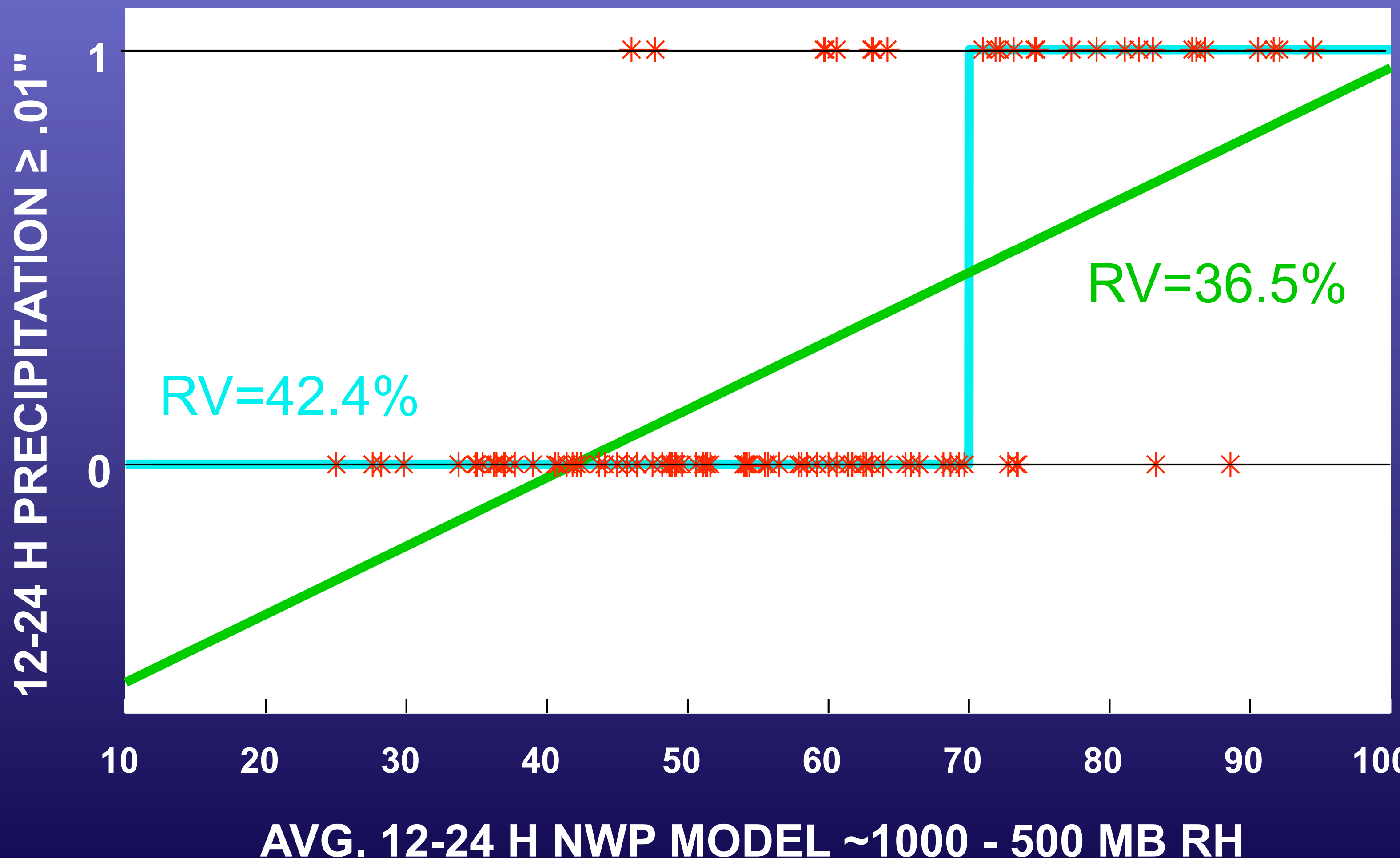
KCMH



MOS LINEAR REGRESSION

DECEMBER 1 1993 - MARCH 5 1994   0000 UTC

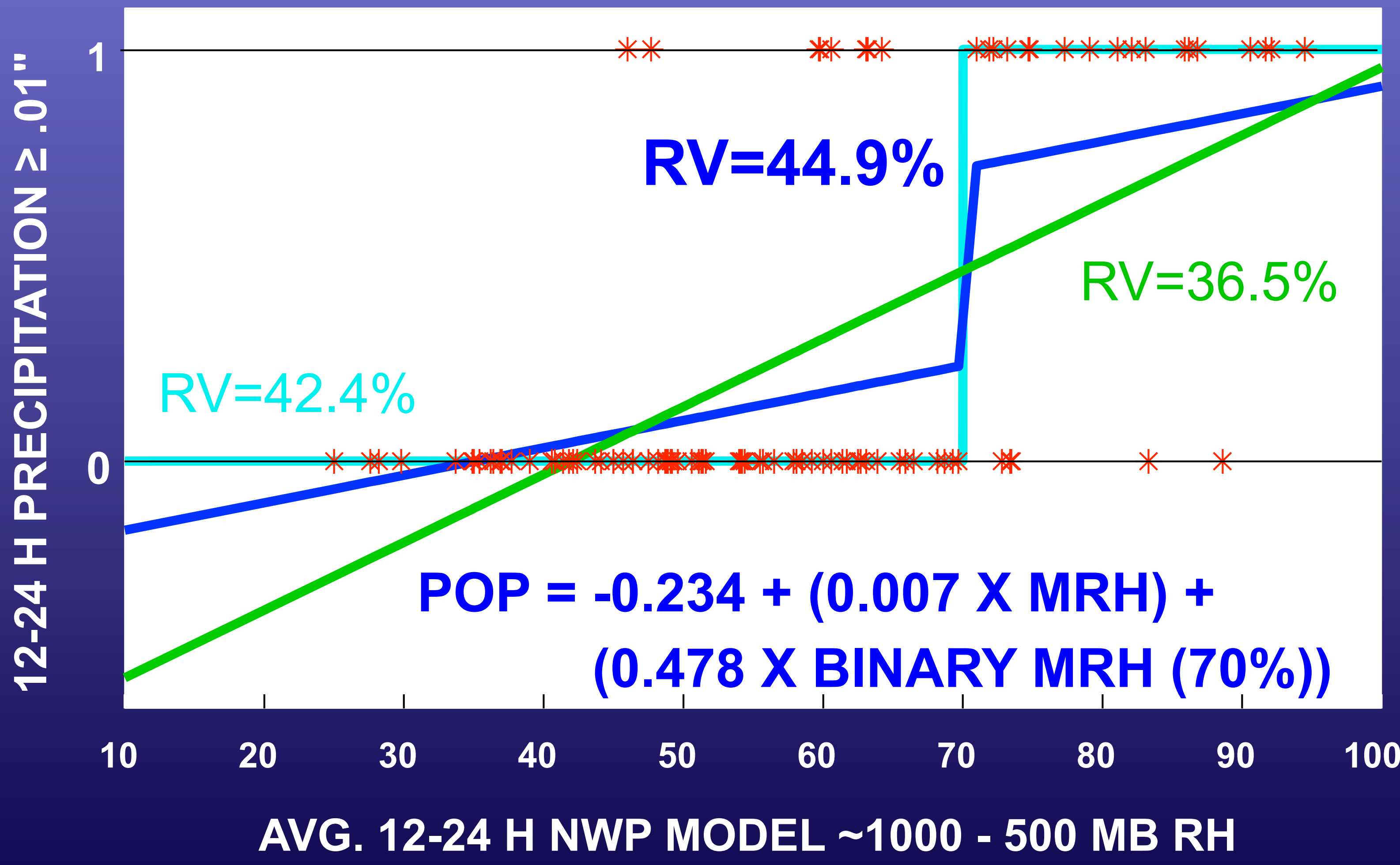
KCMH



MOS LINEAR REGRESSION

DECEMBER 1 1993 - MARCH 5 1994   0000 UTC

KCMH



EXAMPLE REGRESSION EQUATIONS

$$Y = a + bX$$

CMH MAX TEMPERATURE EQUATION

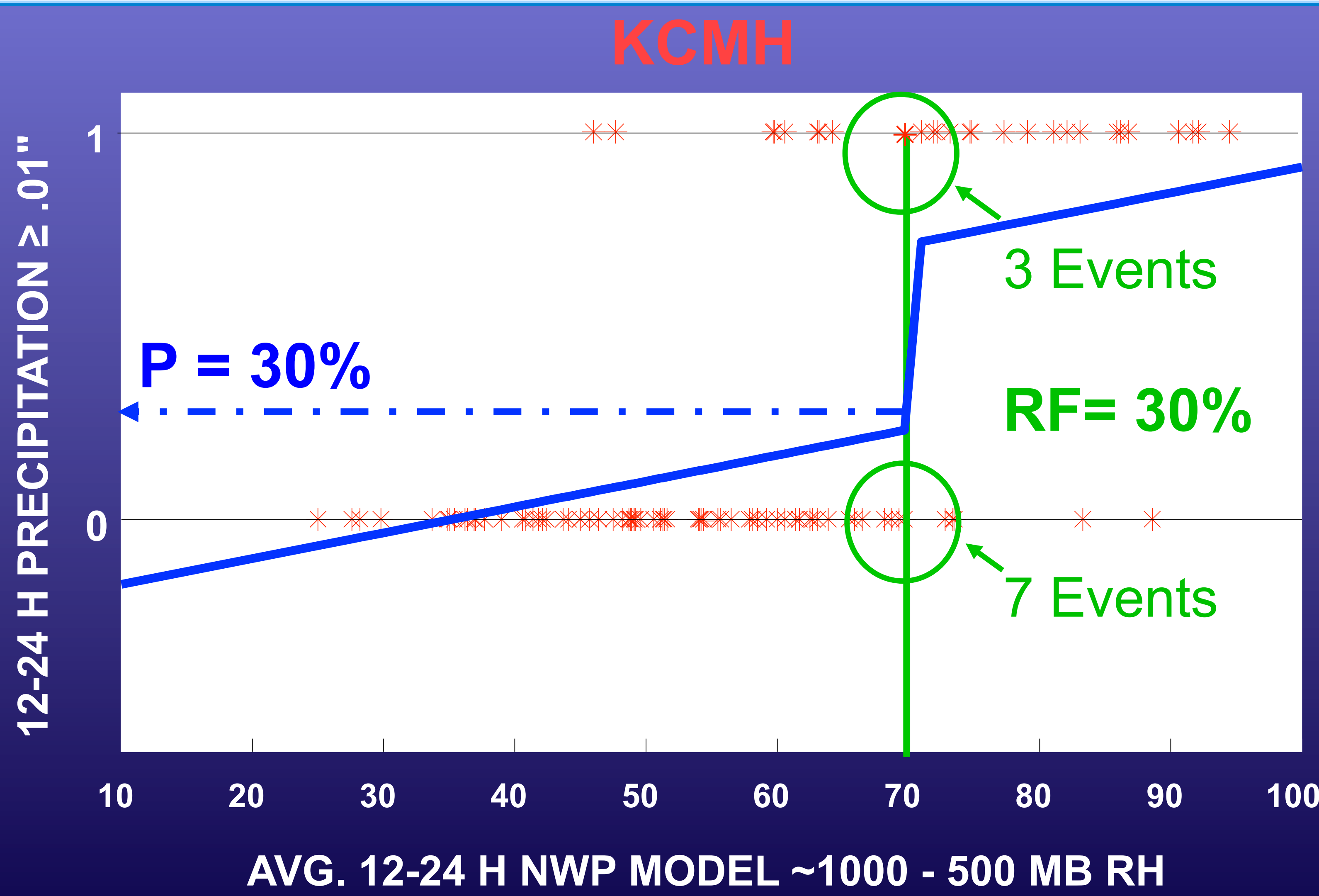
MAX T = -352 + (0.3 x 850 -1000 mb THICKNESS)

CMH PROBABILITY OF PRECIPITATION EQUATION

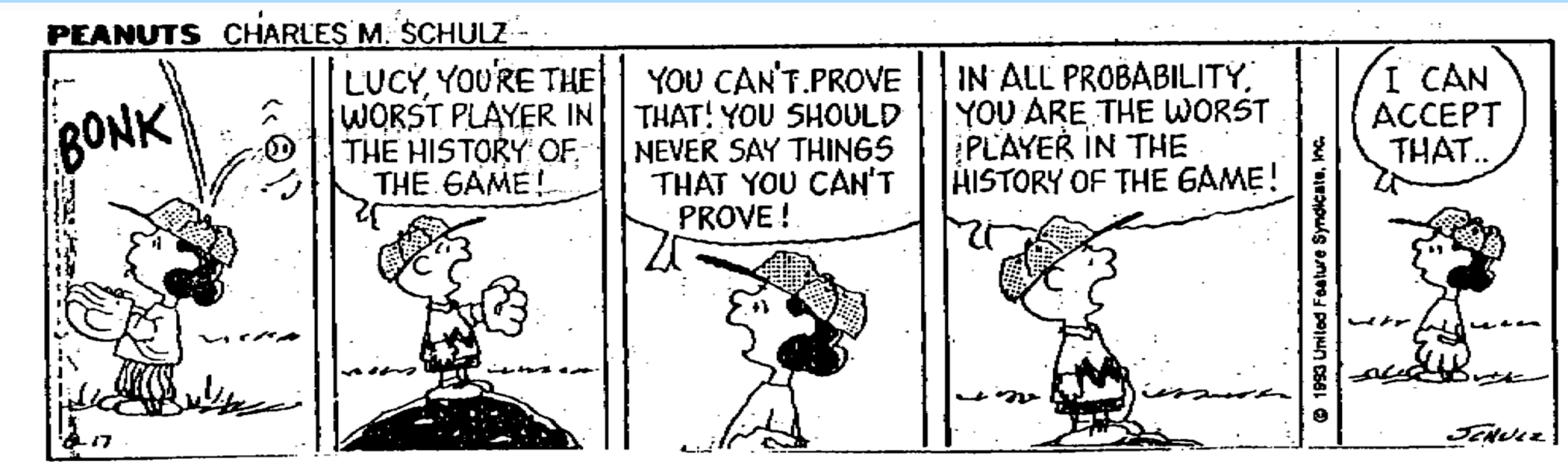
POP = -0.234 + (0.007 x MEAN RH)
+ (0.478 x BINARY MEAN RH CUTOFF AT 70%)*

*(IF MRH ≥ 70% BINARY MRH = 1; else BINARY MRH = 0)

If the predictand is BINARY, MOS regression equations produce estimates of event PROBABILITIES...



Making a PROBABILISTIC statement...



Quantifies the uncertainty !

DEFINITION of PROBABILITY

(Wilks, 2006)

- The degree of belief, or ***quantified judgment***, about the occurrence of an uncertain event.

OR

- The long-term relative frequency of an event.

PROBABILITY FORECASTS

Some things to keep in mind

Assessment of probability is ***EXTREMELY*** dependent upon how predictand “event” is defined:

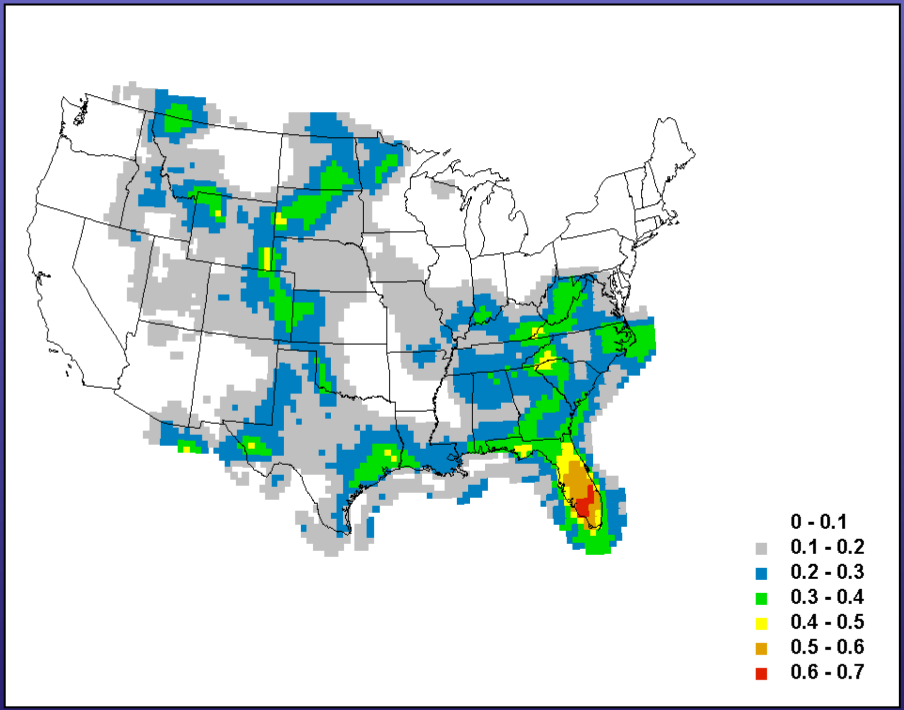
-Time period of consideration
-Area of occurrence
-Dependent upon another event?

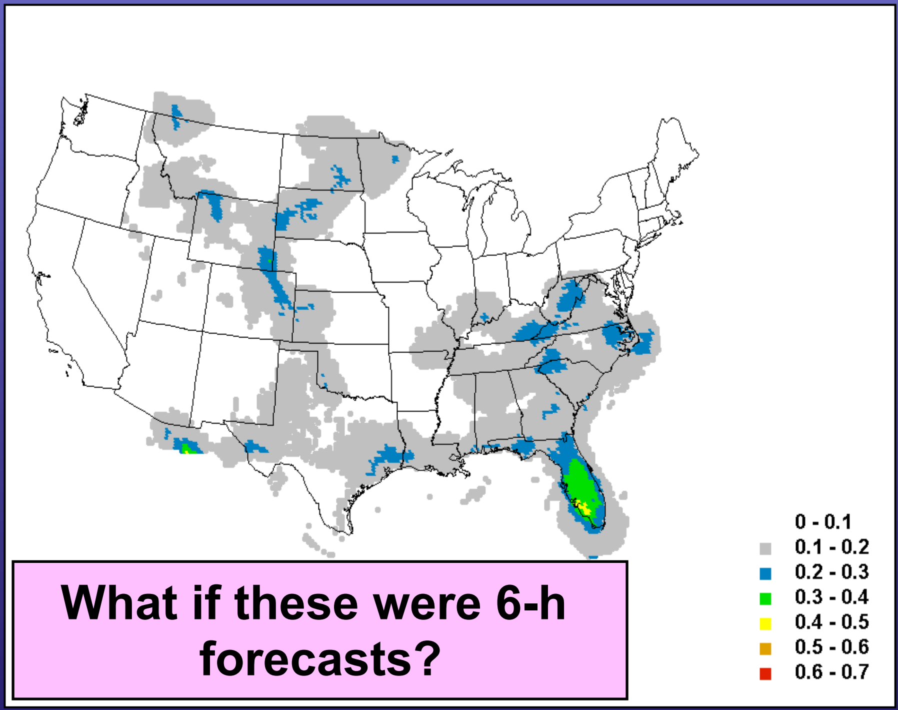
MOS forecasts can be:

- POINT PROBABILITIES
- AREAL PROBABILITIES
- CONDITIONAL PROBABILITIES

AREAL PROBABILITIES

3H Eta MOS thunderstorm probability forecasts valid 0000 UTC 8/27/2002 (21-24h proj)





40-km gridbox
10% contour interval

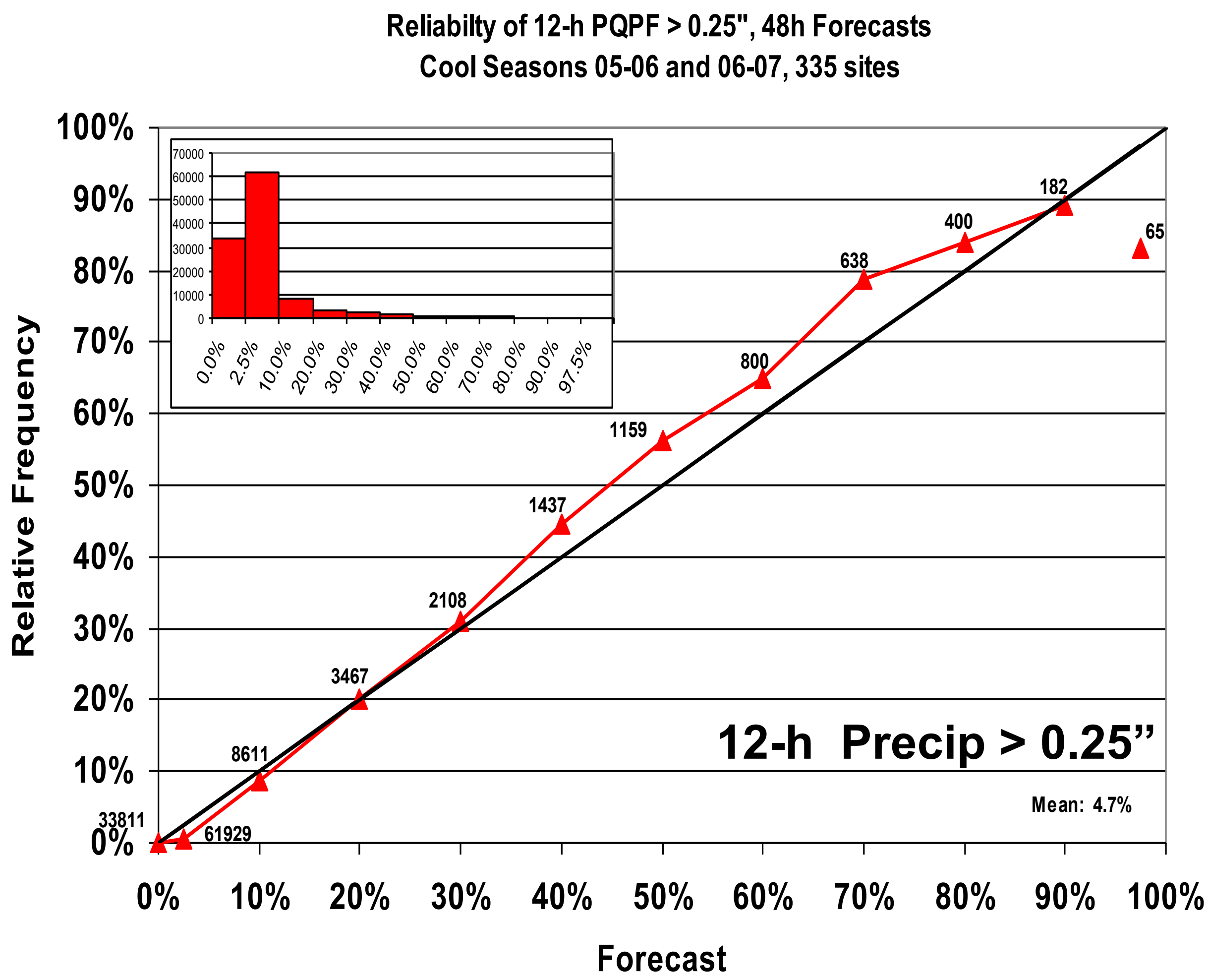
20-km gridbox
10% contour interval

PROPERTIES OF
MOS PROBABILITY FORECASTS

- **Unbiased**
  Average forecast probability equals long-term relative frequency of event
- **Reliable**
  Conditionally or “Piecewise” unbiased over entire range of forecast probabilities
- **Reflect predictability of event**
  Range narrows and approaches event RF as NWP model skill declines
    - extreme forecast projection
    - rare events

Reliable Probabilities…

Even for rare events



Designing an Operational MOS System:

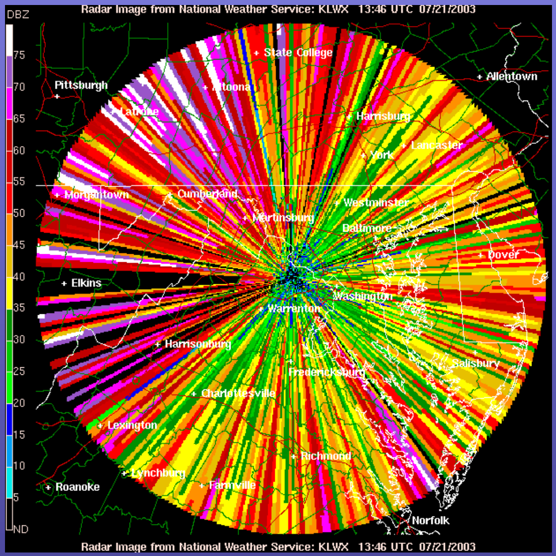
Putting theory into practice…

DEVELOPMENTAL CONSIDERATIONS

MOS in the real world

- **Selection (and QC!) of Suitable Observational Datasets**
  ASOS? Remote sensor? Which mesonet?

Suitable observations?



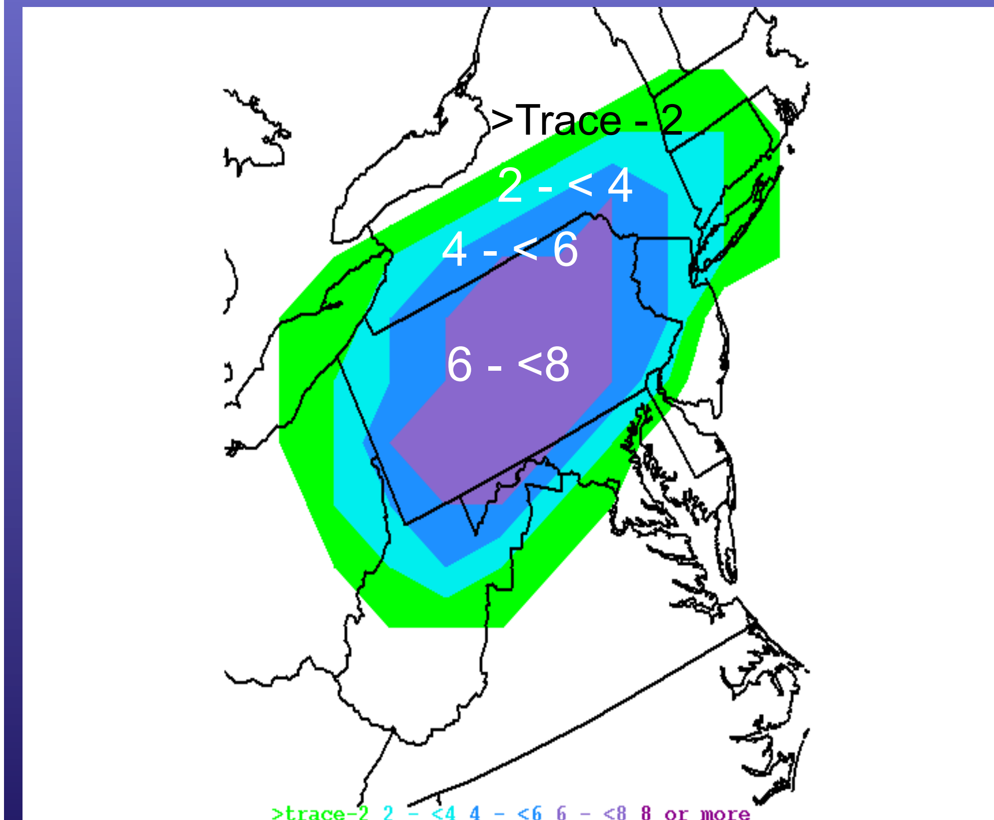
Appropriate Sensor?

Real or Memorex?

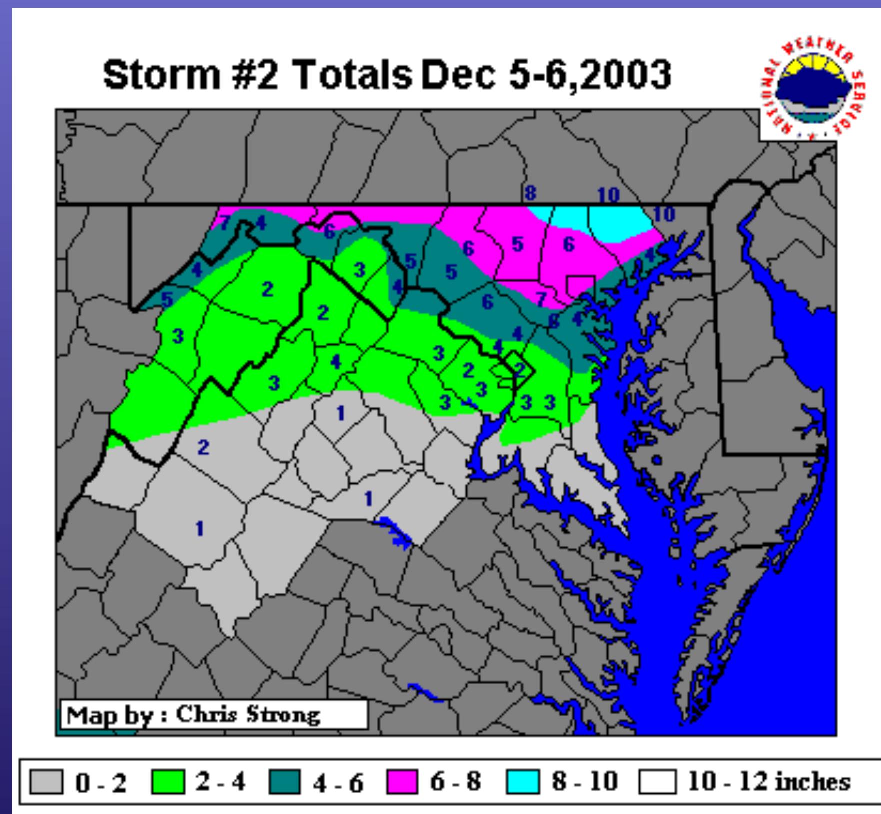
Good siting?

MOS Snowfall Guidance

Uses Observations from Cooperative Observer Network



36-hr forecast
12Z 12/05/03 – 12Z 12/06/03



Verification

DEVELOPMENTAL CONSIDERATIONS

MOS in the real world

- **Selection (and QC!) of Suitable Observational Datasets**
  ASOS?   Remote sensor?   Which mesonet?

- **Predictand Definition**
  Must be precise !!

PREDICTAND DEFINITION

Max/Min and PoP

Daytime Maximum Temperature

"Daytime" is 0700 AM - 0700 PM LST *

Nighttime Minimum Temperature

"Nighttime" is 0700 PM - 0800 AM LST *

* CONUS – differs in AK

Probability of Precipitation

Precipitation occurrence is accumulation of ≥ 0.01 inches of liquid-equivalent at a gauge location within a specified period

PREDICTAND DEFINITION

GFSX 12-h Average Cloud Amount

- Determined from 13 consecutive hourly ASOS observations, satellite augmented
- Assign value to each METAR report:

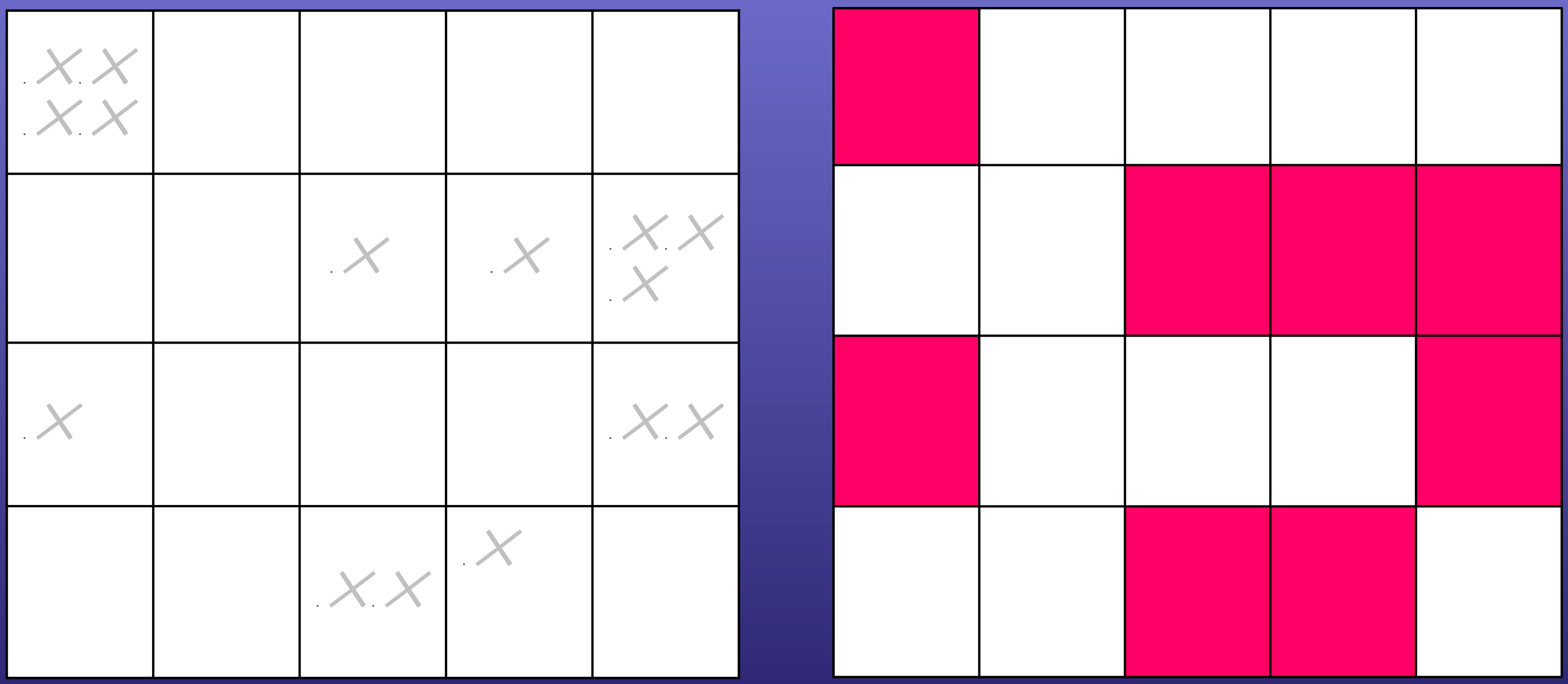
  CLR; FEW; SCT; BKN; OVC

  0 ; 0.15; 0.38; 0.69; 1
- Take weighted average of above
- Categorize:

  CL < .3125 ≤ PC ≤ .6875 < OV

Creating a Gridded Predictand

Lightning strikes are summed over the “appropriate” time period and assigned to the center of “appropriate” grid boxes



A thunderstorm is deemed to have occurred when one or more lightning strikes are observed within a given gridbox:

= thunderstorm

= no thunderstorm

DEVELOPMENTAL CONSIDERATIONS

MOS in the real world

- **Selection (and QC!) of Suitable Observational Datasets**
  ASOS?   Remote sensor?   Which mesonet?

- **Predictand Definition**
  Must be precise !!

- **Choice of Predictors**
  "Appropriate" formulation
  Binary or other transform?

"APPROPRIATE" PREDICTORS

- DESCRIBE PHYSICAL PROCESSES ASSOCIATED WITH OCCURRENCE OF PREDICTAND

i.e. for POP:

PRECIPITABLE WATER
VERTICAL VELOCITY
MOISTURE DIVERGENCE
MODEL PRECIPITATION

1000-500 MB THK
TROPOPAUSE HGT

- "MIMIC" FORECASTER THOUGHT PROCESS

(VERTICAL VELOCITY) X (MEAN RH)

POINT BINARY PREDICTOR

24-H MEAN RH   CUTOFF = 70%

INTERPOLATE ; STATION RH ≥ 70% , BINARY = 1

BINARY = 0 OTHERWISE

96	86	89	94
87	73	76	90
76	60	69	92
64	54	68	93

KCMH

(71%) ●

RH ≥70% ; BINARY AT KCMH = 1

GRID BINARY PREDICTOR

24 H MEAN RH CUTOFF = 70%

WHERE RH ≥ 70% ; GRIDPOINT = 1 ; INTERPOLATE

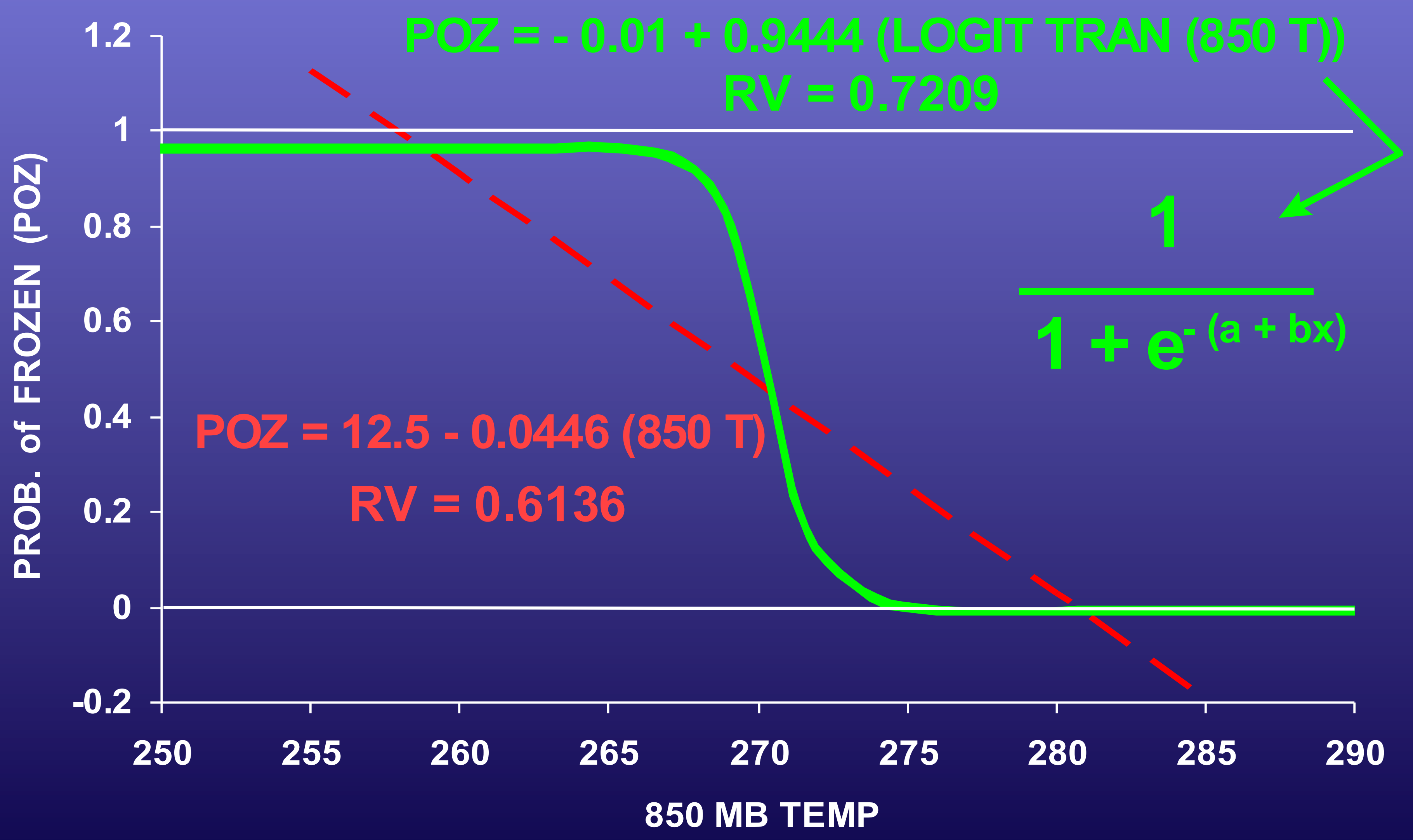
1	1	1	1
1	1	1	1
1	0	0	1
0	0	0	1

(.21) ● KCMH

0 ≤ VALUE AT KCMH ≤ 1

Logit Transform Example

KPIA (Peoria, IL)   0000 UTC ; 18-h projection



DEVELOPMENTAL CONSIDERATIONS

(cont.)

- **Terms in Equations; Selection Criteria**

"REAL" REGRESSION EQUATIONS

MOS regression equations are MULTIVARIATE , of form:

$$Y = a_0 + a_1 X_1 + a_2 X_2 + \ldots + a_N X_N$$

Where,

the "a's" represent COEFFICIENTS

the "X's" represent PREDICTOR variables

The maximum number of terms, N, can be ***QUITE*** large:

For GFS QPF, N = 15 For GFS VIS, N = 20

The **FORWARD SELECTION** procedure determines the predictors and the order in which they appear.

FORWARD SELECTION

- METHOD OF PREDICTOR SELECTION ACCORDING TO CORRELATION WITH PREDICTAND
- "BEST" OR STATISTICALLY MOST IMPORTANT PREDICTORS CHOSEN FIRST

- **FIRST** predictor selected accounts for greatest reduction of variance (RV)
- Subsequent predictors chosen that give greatest RV in conjunction with predictors already selected
- 

selection when desired maximum number of terms is reached or new predictors provide less than a user-specified minimum RV

DEVELOPMENTAL CONSIDERATIONS

(cont.)

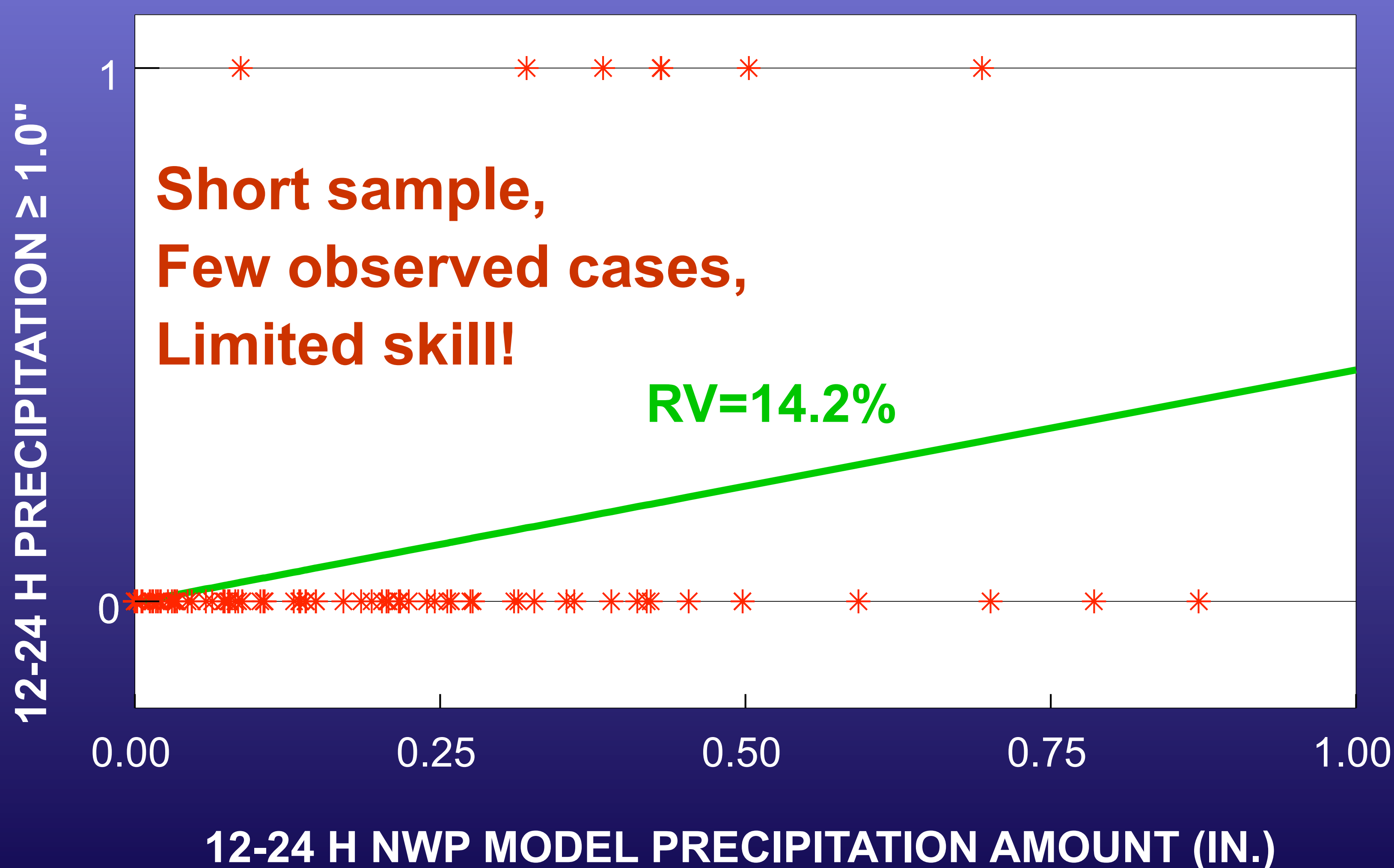
- Terms in Equations; Selection Criteria

- Dependent Data
  - Sample Size, Stability, Representativeness
    - AVOID OVERFIT !!
  - Stratification - Seasons
  - Pooling – Regions

MOS LINEAR REGRESSION

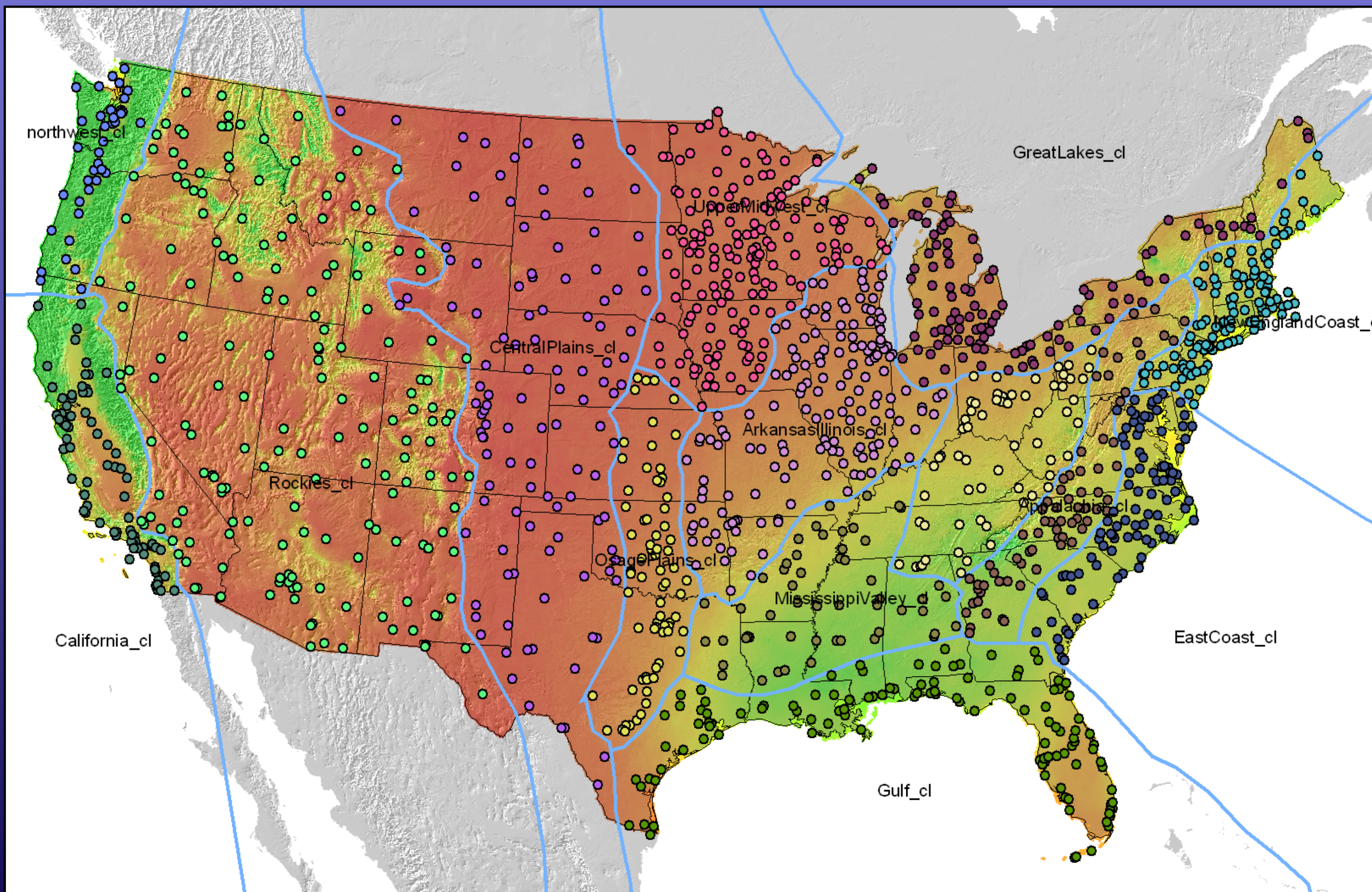
OCTOBER 1 1993 - MARCH 31 1994   0000 UTC

KUIL



GFS MOS Cool Season PoP/QPF Regions

With GFS MOS forecast sites (1720) + PRISM



DEVELOPMENTAL CONSIDERATIONS

(cont.)

- Terms in Equations; Selection Criteria

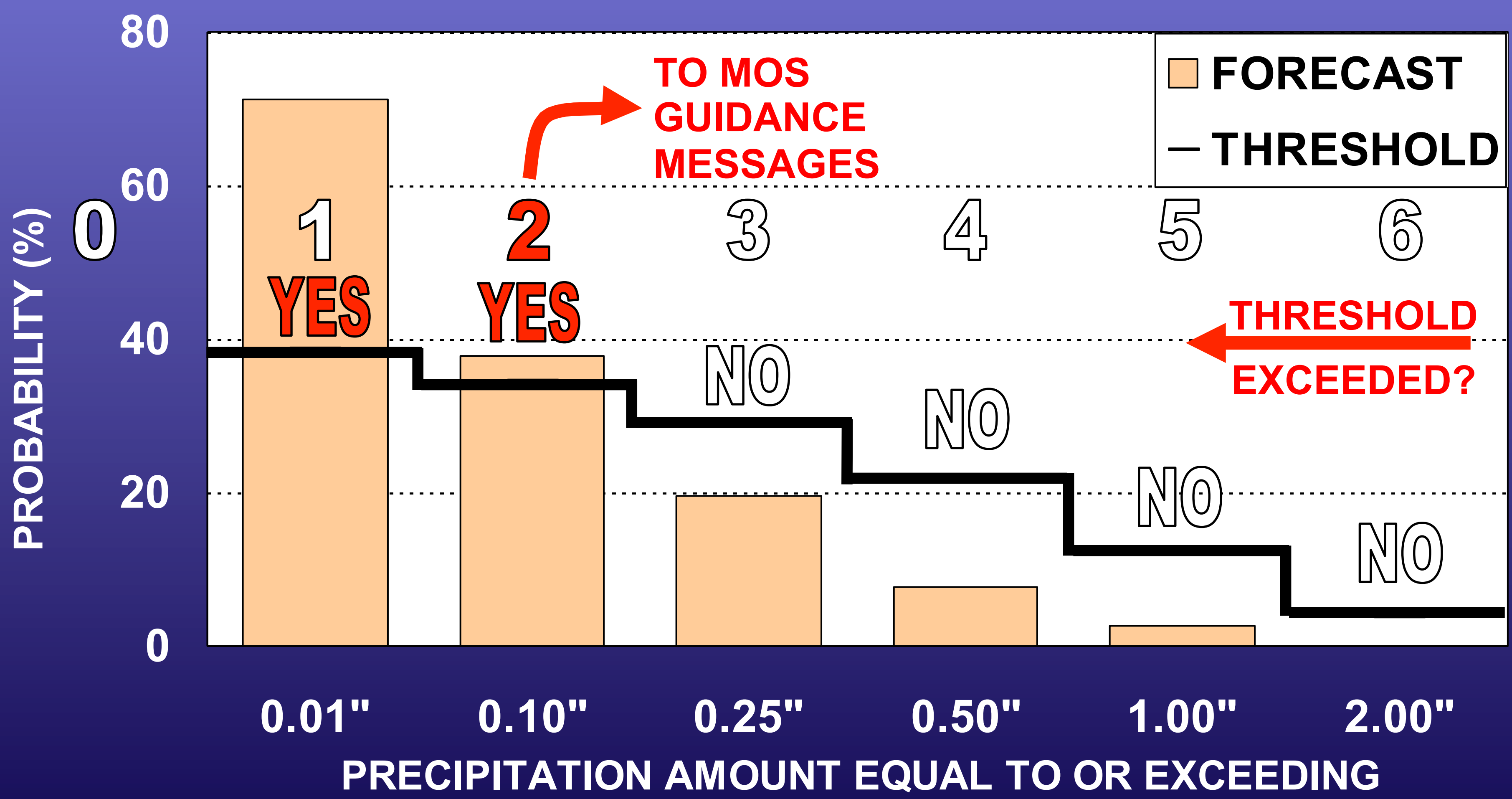
- Dependent Data
  - Sample Size, Stability, Representativeness
    - AVOID OVERFIT !!
  - Stratification - Seasons
  - Pooling – Regions

- Categorical Forecasts?

MOS BEST CATEGORY SELECTION

KDCA 12-Hour QPF Probabilities

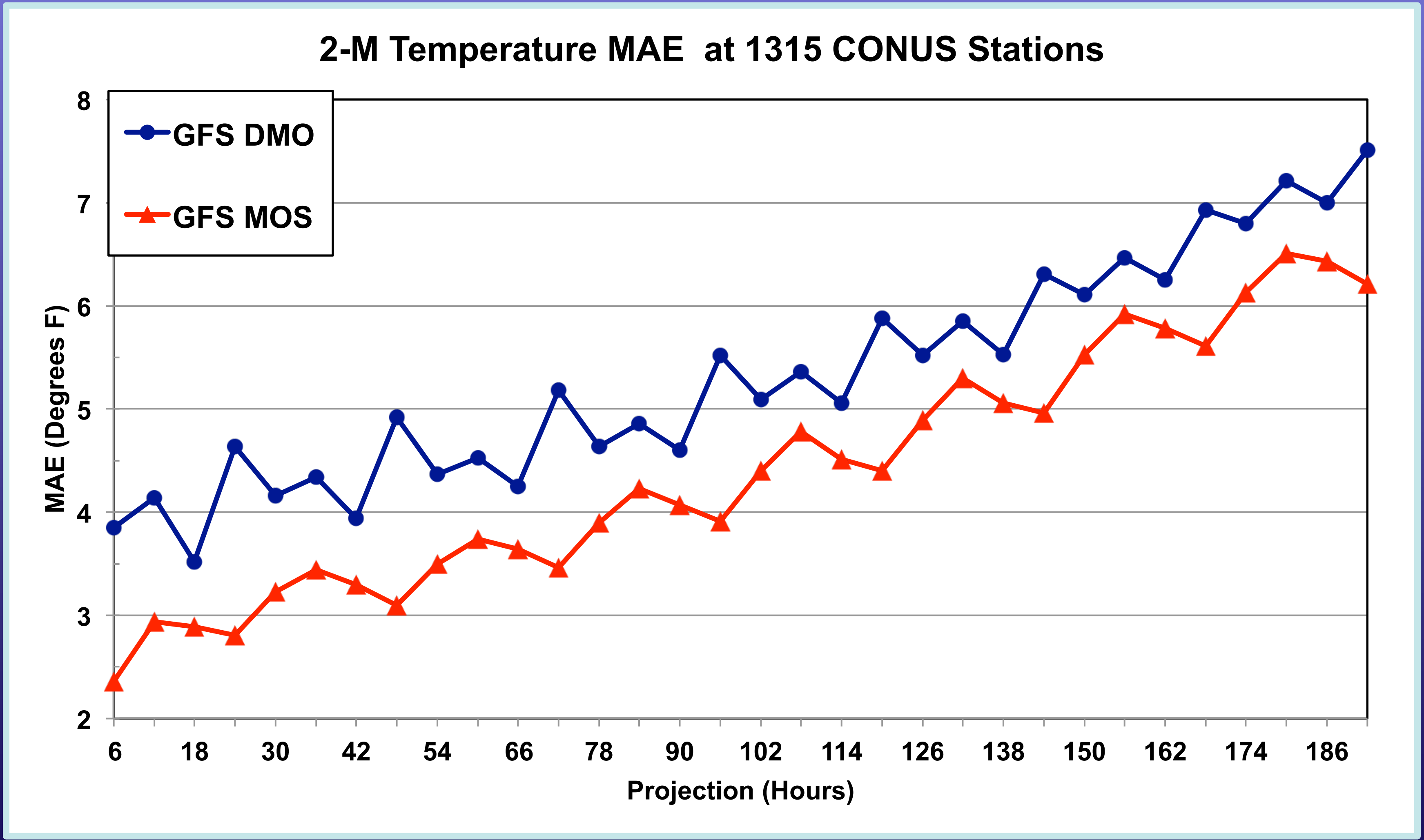
48-Hour Projection valid 1200 UTC 10/31/93



How well do we do?

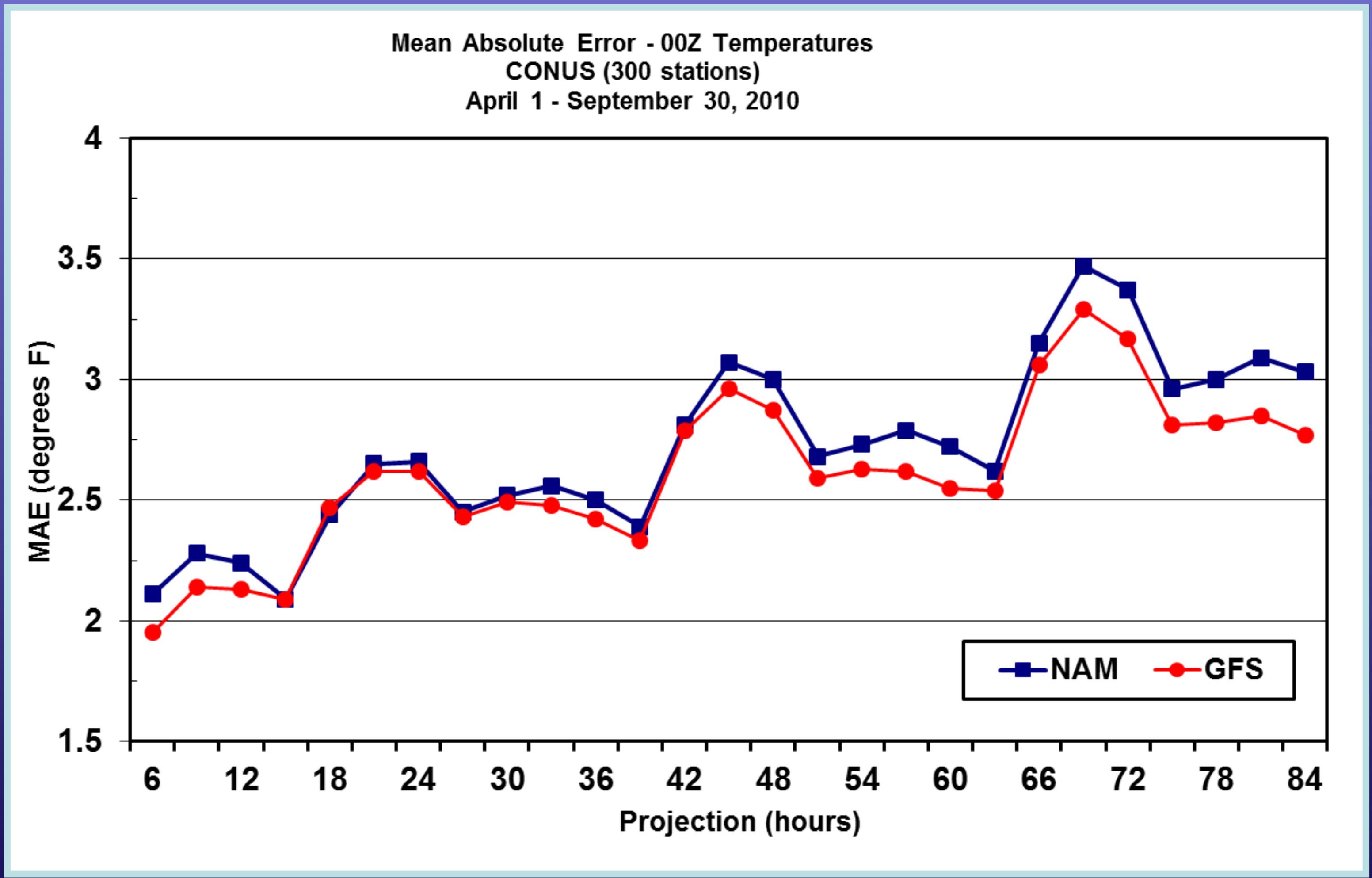
MOS Verification

Temperature Verification - 0000 UTC
GFS MOS vs. GFS DMO (10/2011 - 3/2012)



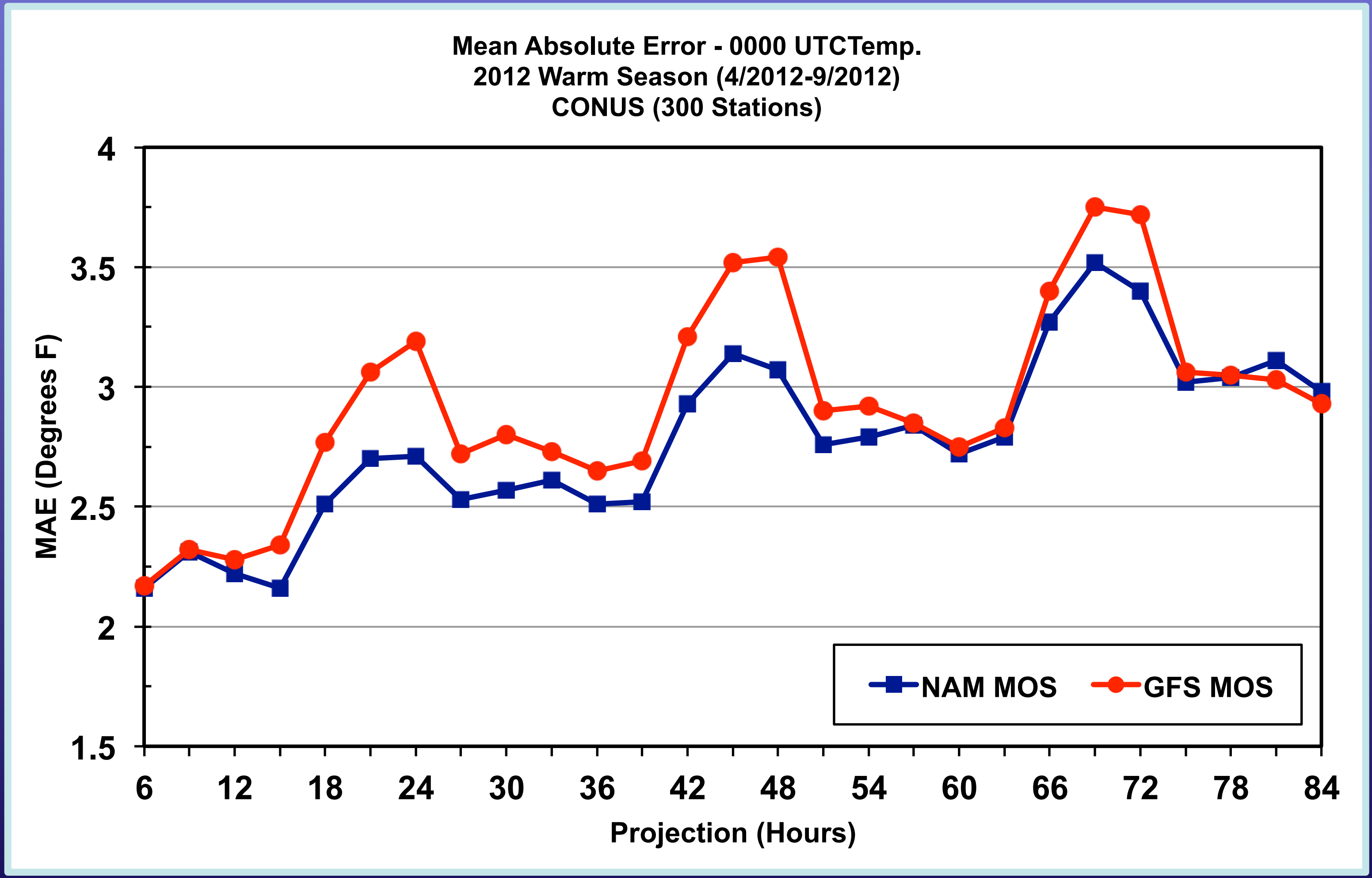
MOS Temperature Verification - 0000 UTC

2010 Warm Season (4/2010 – 9/2010)

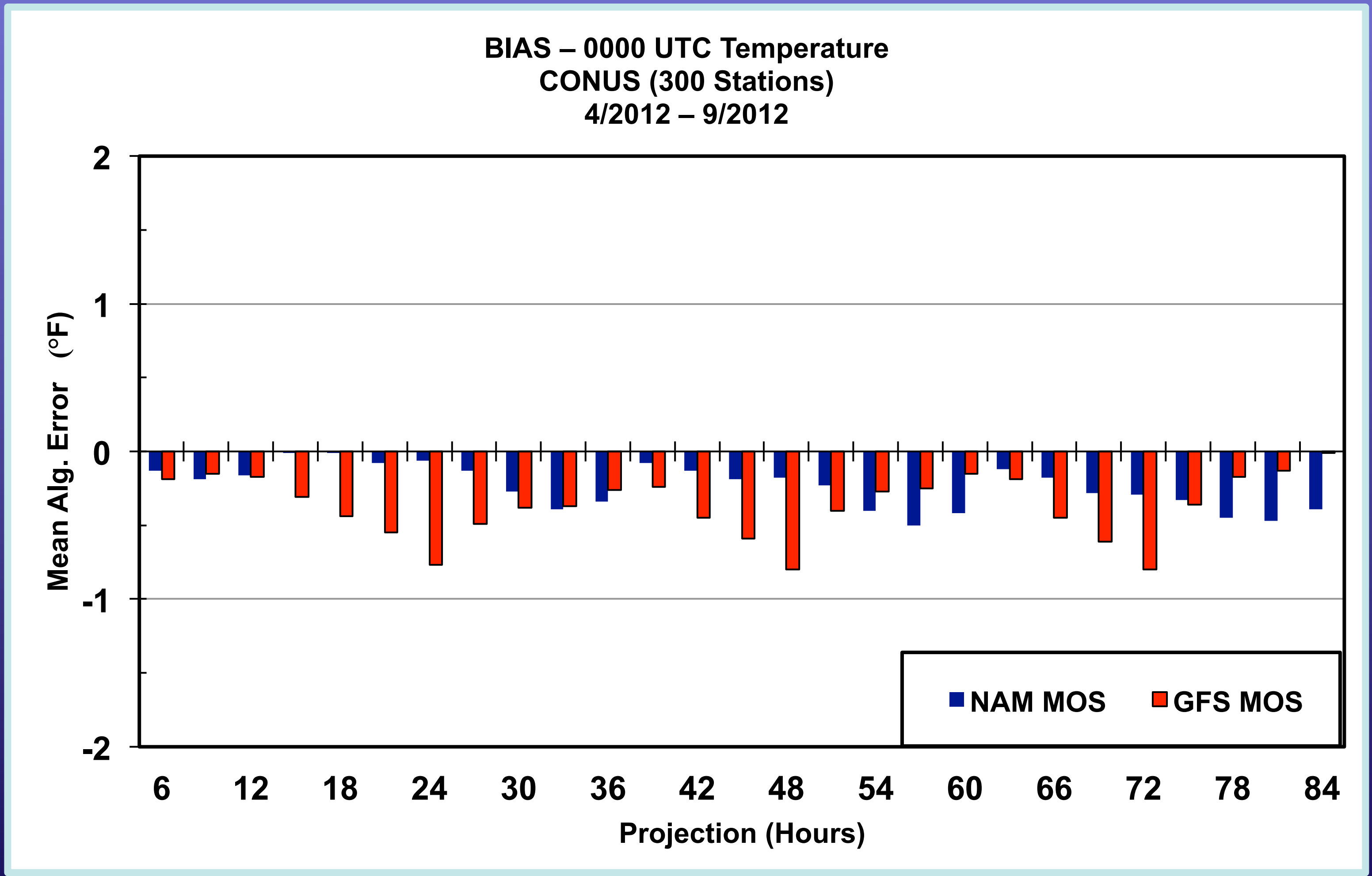


MOS Temperature Verification - 0000 UTC

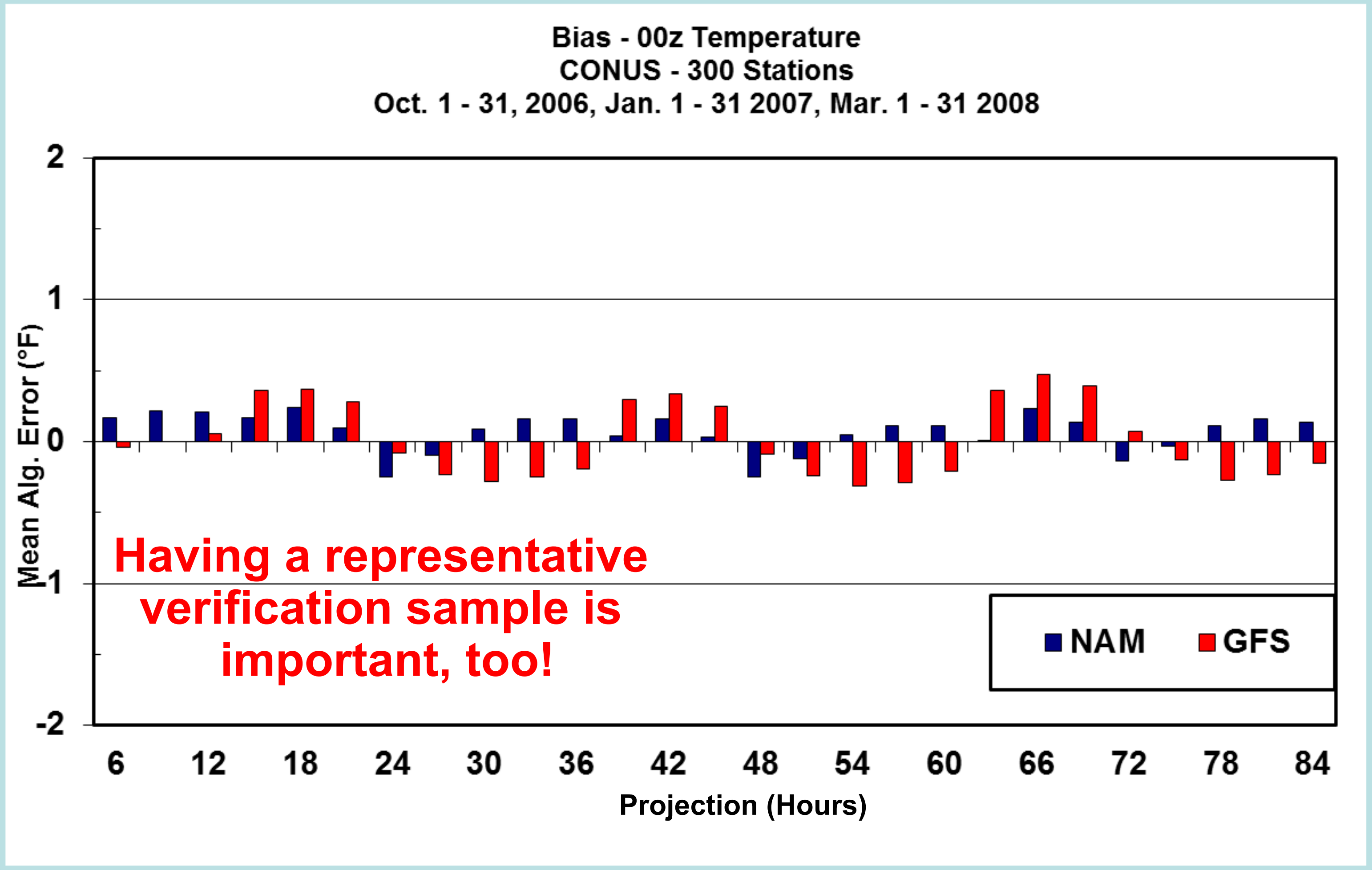
2012 Warm Season (4/2010 – 9/2010)



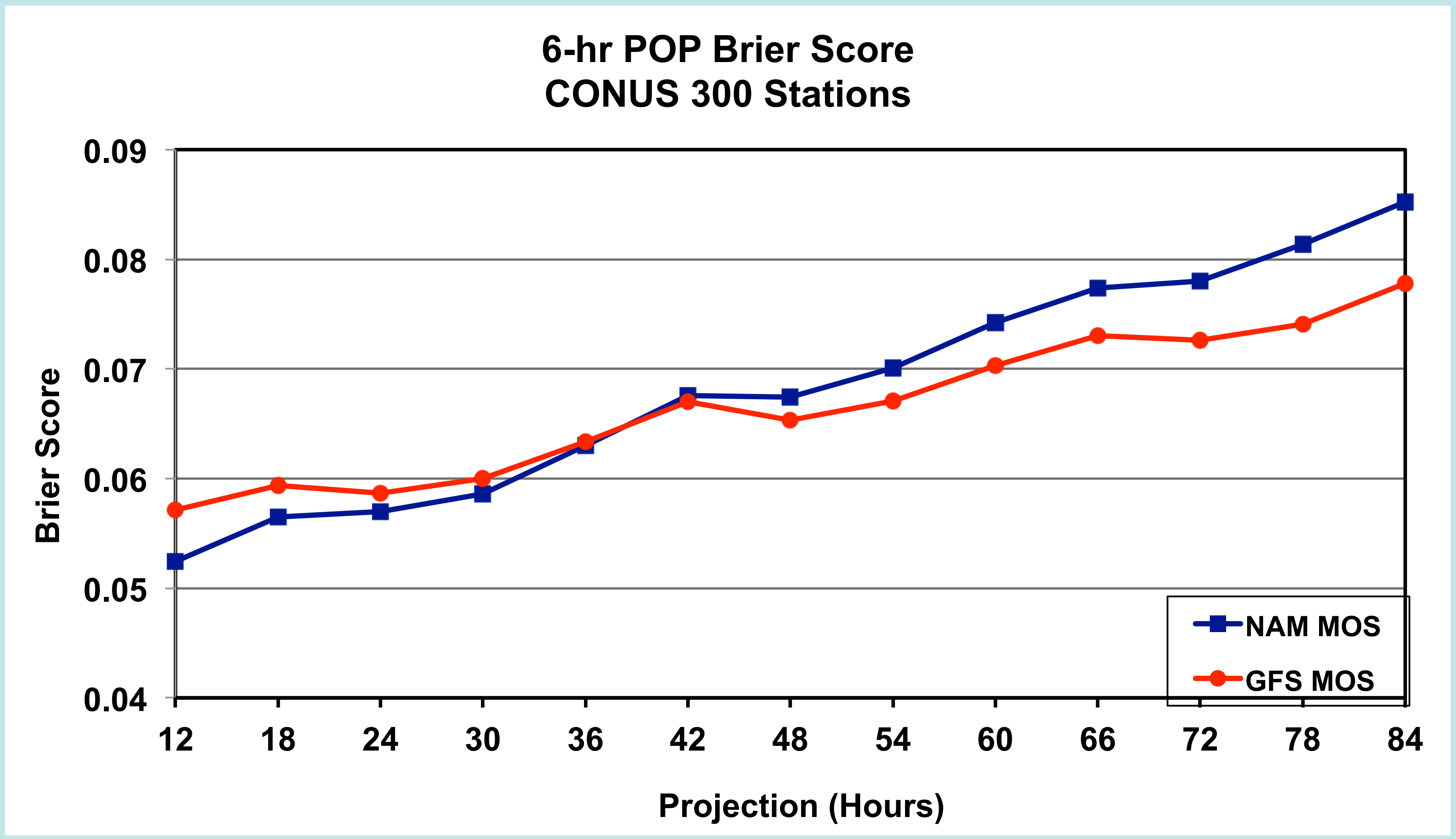
MOS Temperature Bias - 0000 UTC
2012 warm season (4/2012 – 9/2012)



MOS Temperature Bias - 0000 UTC
10/06; 01/07; 03/08



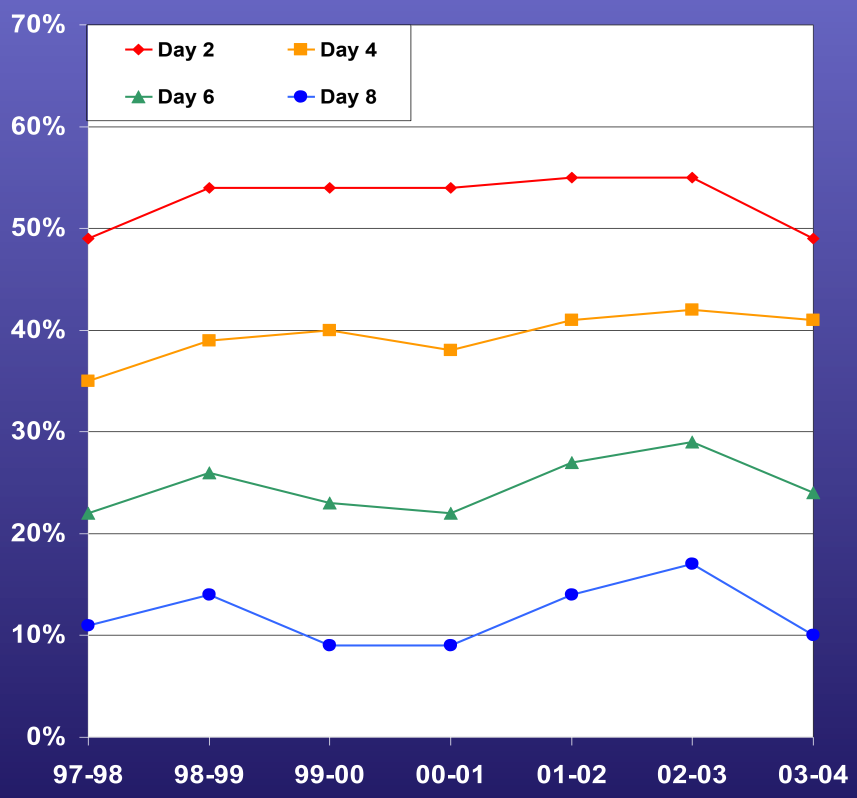
6h PoP Verification - 0000 UTC
2012-13 Cool Season (10/12 – 01/13)

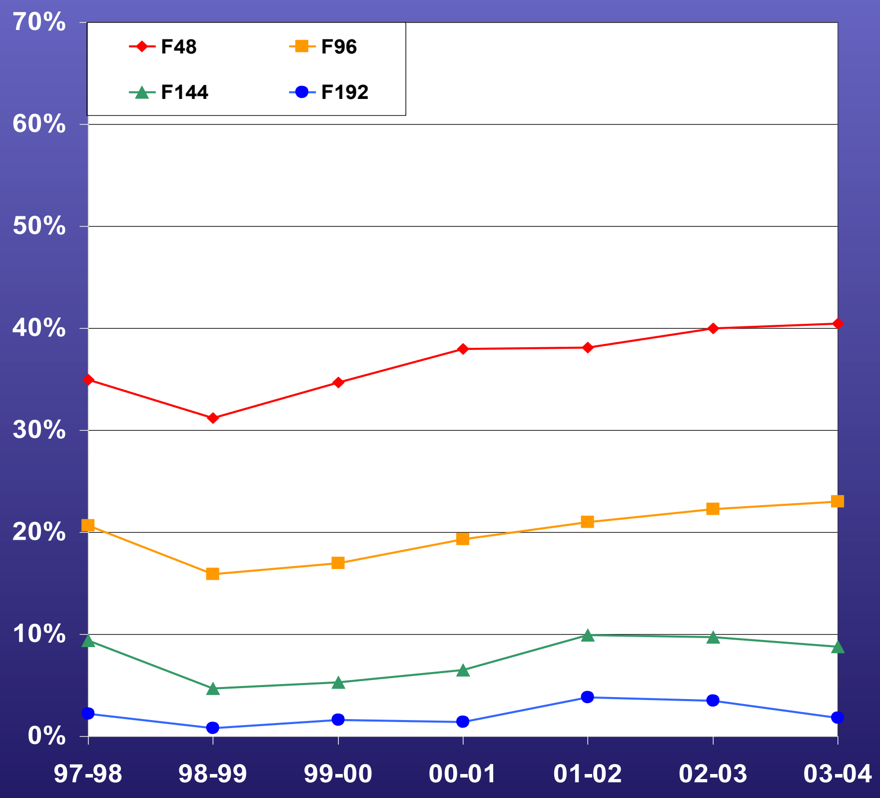


GFSX 12-h Forecast Skill - 0000 UTC

Max Temperatures and PoP

% Improvement over Climate
Cool Season 1997 - 2003



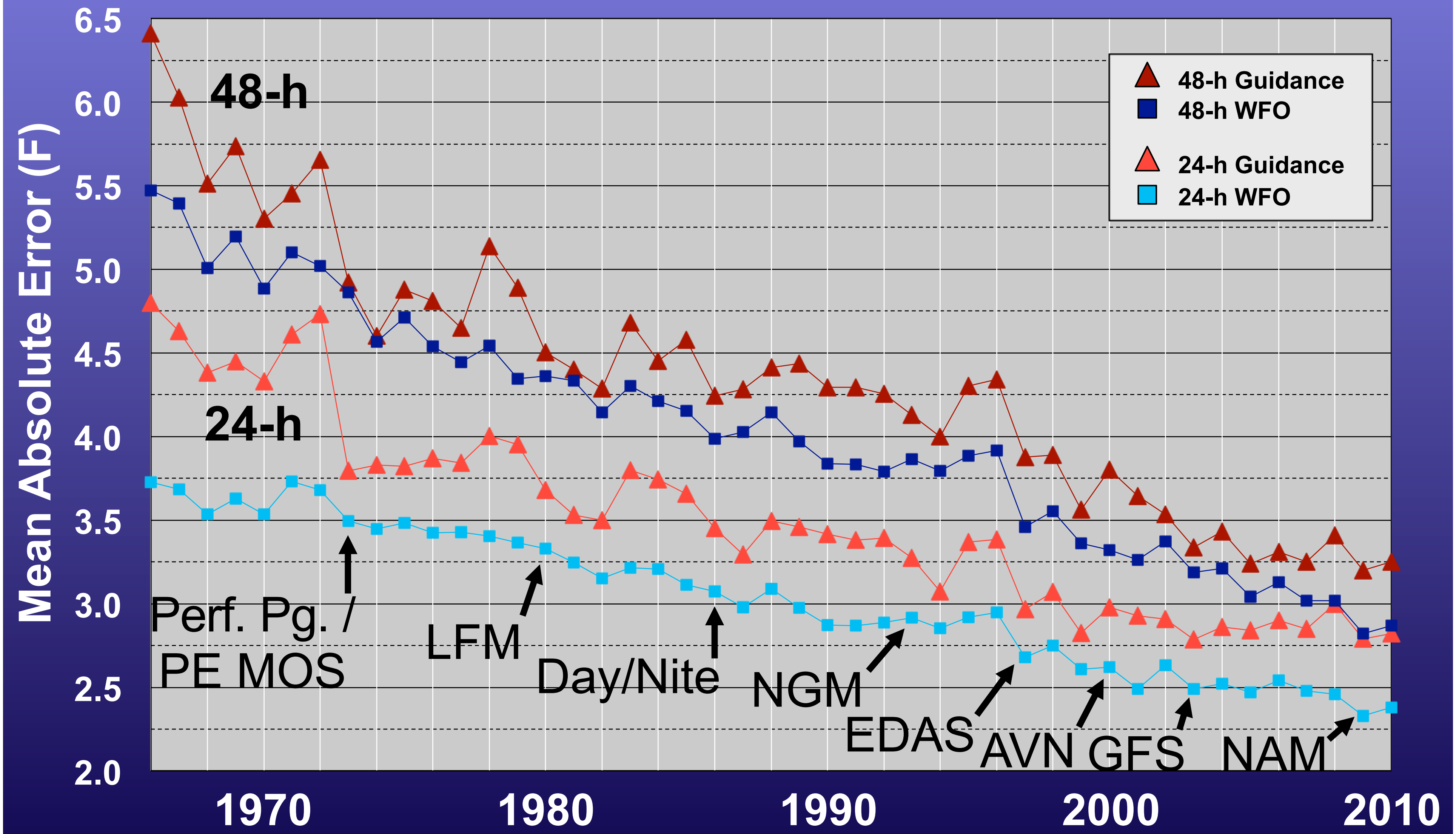


Max T

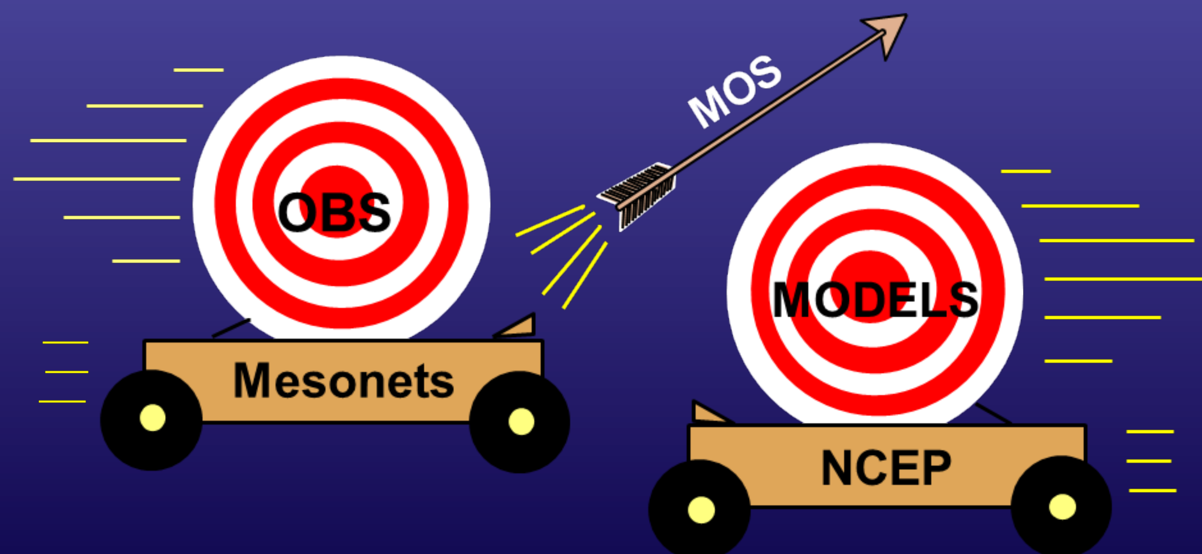
PoP

45-yr Max Temperature Verification

Guidance / WFO; Cool Season 1966 - 2010

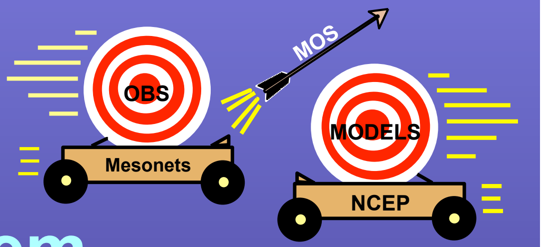


Dealing with NWP model changes



Mitigating the effects on development

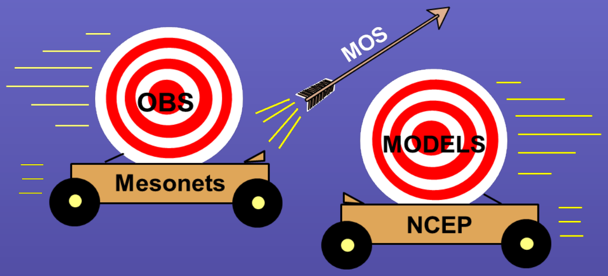
To help reduce the impact of model changes and small sample size, we rely upon...



1. Improved model realism
   - better model = better statistical system
2. Coarse, consistent archive grid
   - smoothing of fine-scale detail
   - constant mesh length for grid-sensitive calculations
3. Enlarged geographic regions
   - larger data pools help to stabilize equations
4. Use of "robust" predictor variables
   - fewer boundary layer variables
   - variables likely immune to known model changes; (e.g. combinations of state variables only)

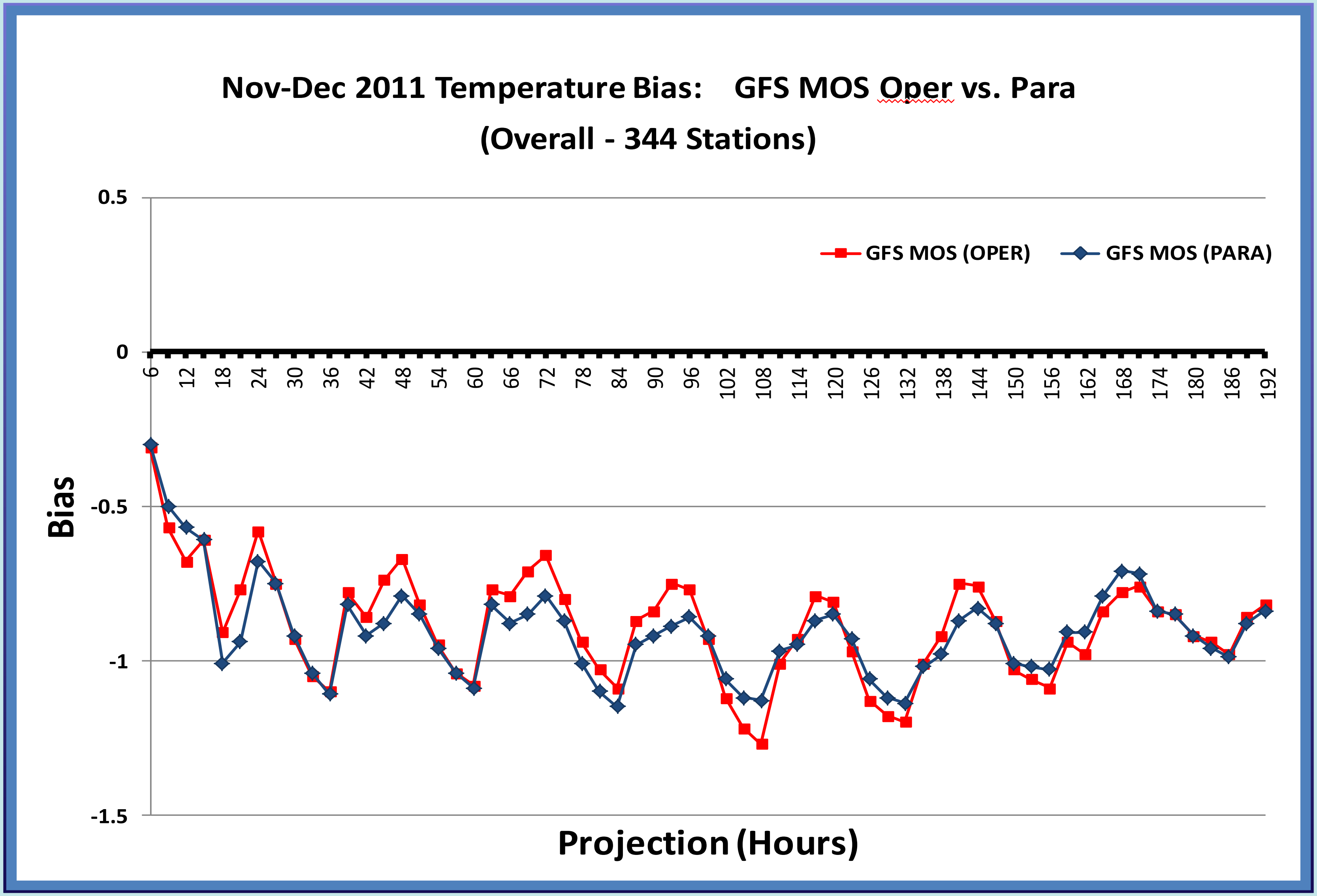
Responding to NWP Model Changes

- **Parallel evaluation**
  - Run MOS…new vs. old NWP model
  - Assess impacts on MOS skill



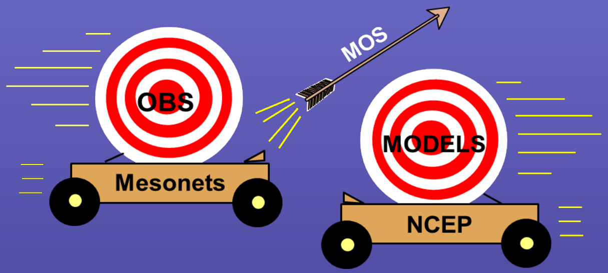
Responding to NWP Model Changes

GFS: Hybrid EnKF parallel evaluation



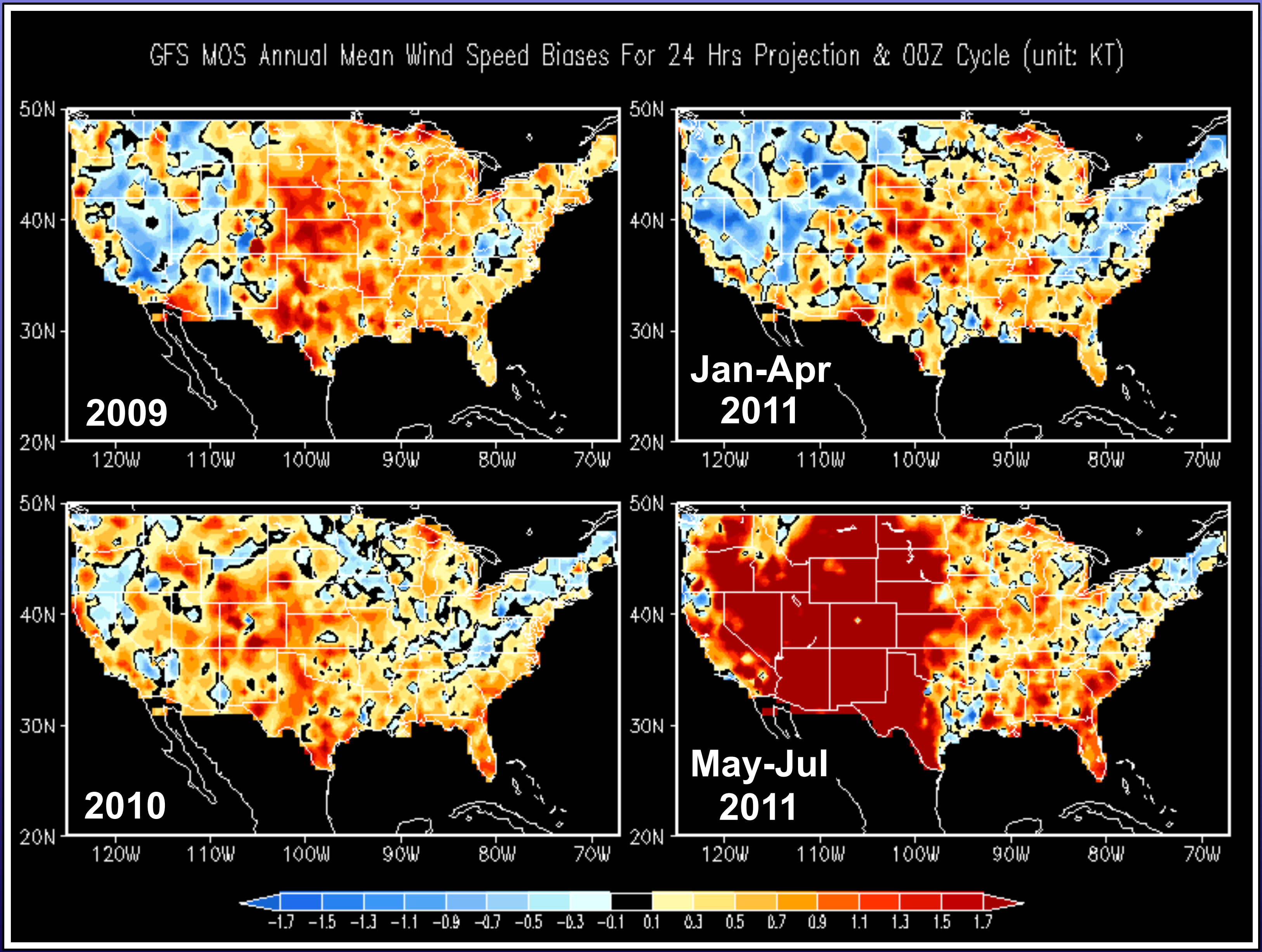
Responding to NWP Model Changes

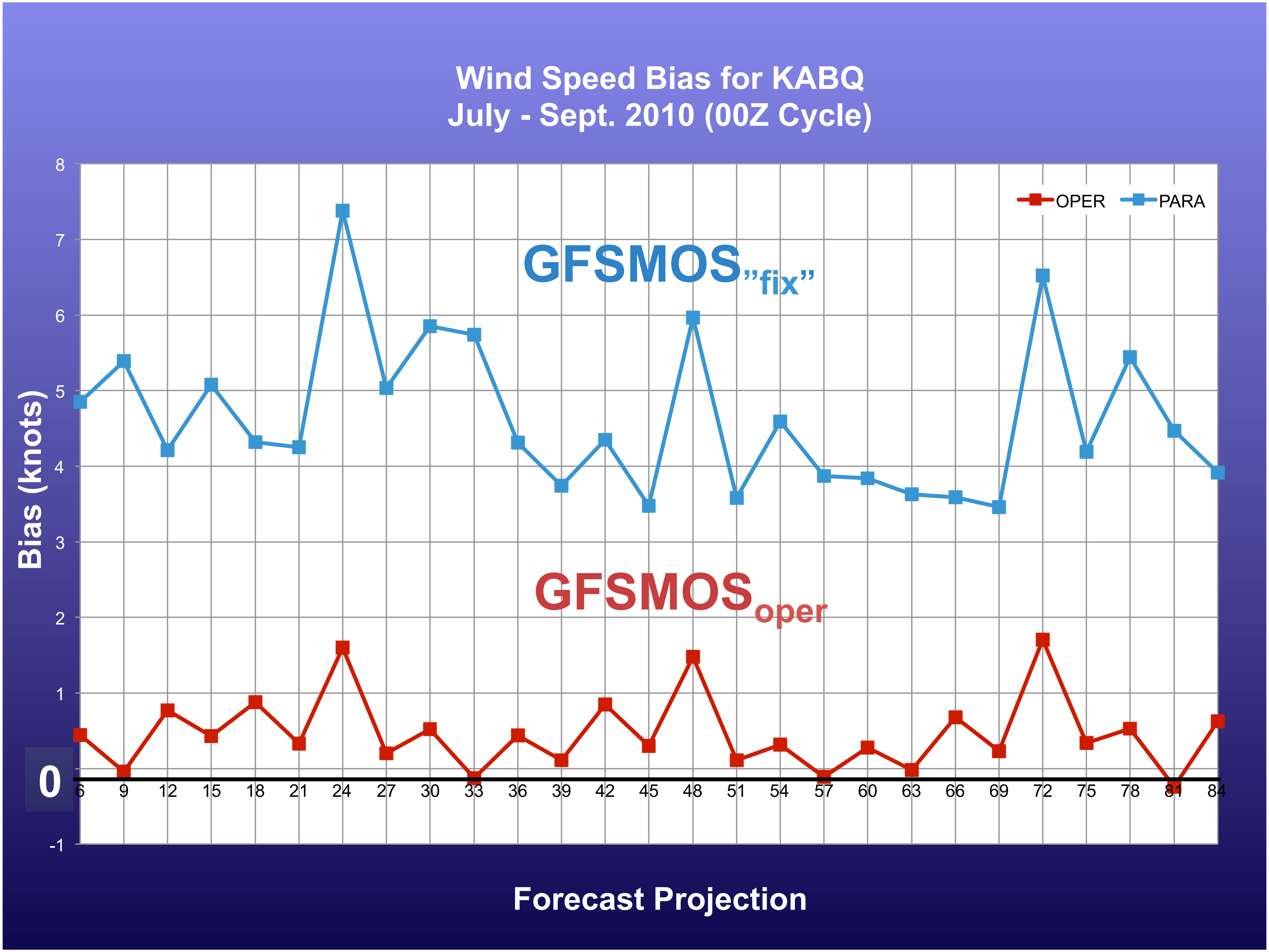
- **Parallel evaluation**
  - Run MOS…new vs. old NWP model
  - Assess impacts on MOS skill



- **Do nothing?**
  - OK if impacts are minimal
  - But, often they aren't! (GFS wind / temps)

2009 - 2011 GFS MOS Wind Bias

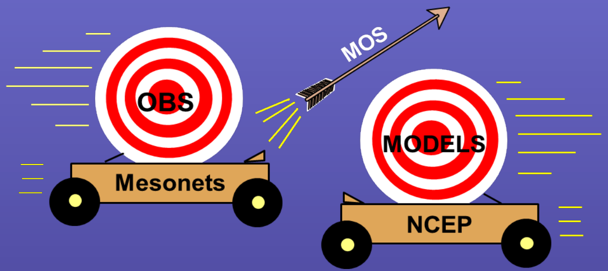




Wind Speed Bias for KABQ
July - Sept. 2010 (00Z Cycle)
Bias (knots)
Forecast Projection
OPER
PARA
GFSMOS"fix"
GFSMOSoper
8
7
6
5
4
3
2
1
0
-1
6 9 12 15 18 21 24 27 30 33 36 39 42 45 48 51 54 57 60 63 66 69 72 75 78 81 84

Responding to NWP Model Changes

- **Parallel evaluation**
  - **Run MOS…new vs. old NWP model**
  - **Assess impacts on MOS skill**

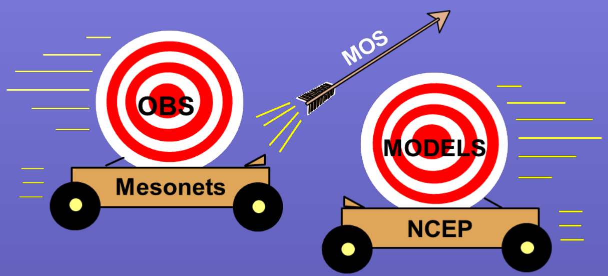


- **Do nothing?**
  - **OK if impacts are minimal**
  - **But, often they aren't! (GFS wind / temps)**

- **OK, now what?**
  - **Model changes may be recent**
    - i.e. limited sample available from newest version
  - **Error characteristics significantly different**
  - **Undesirable effects on MOS performance**

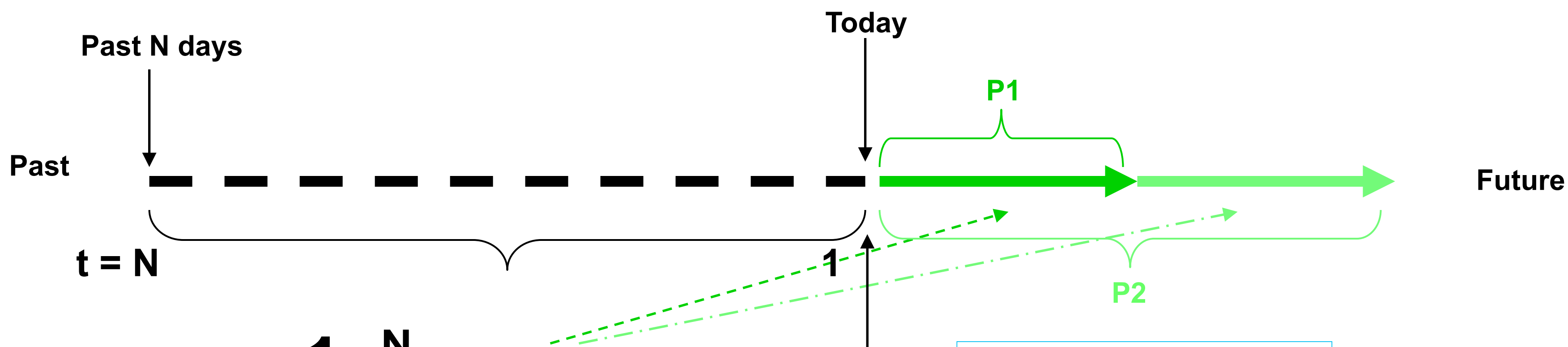
Responding to NWP Model Changes

- Bias Correction for MOS?



Daily Bias Correction

based on past N (7, 10, 20 or 30)- day forecast errors



$$\text{Bias} = \frac{1}{N}\sum_{t=1}^{N}[F(t) - O(t)]$$

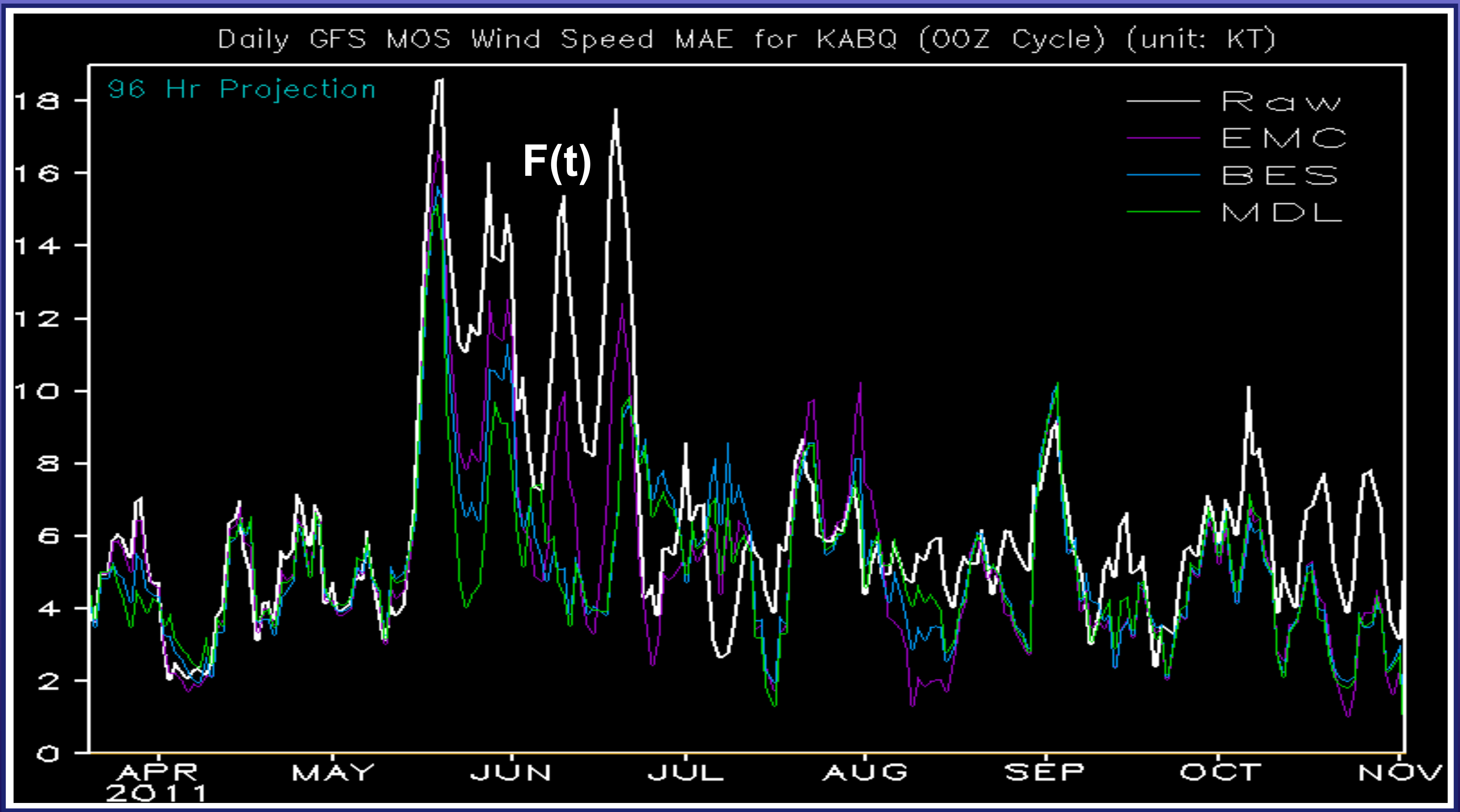
Bias correction:
$F' = F(t) - \text{Bias}$

F = Forecasts ; O = Observations
N = Days in training sample
(typically, N = 7, 10, 20, or 30)

Daily biases can be treated equally or weighted to favor most recent days, etc.

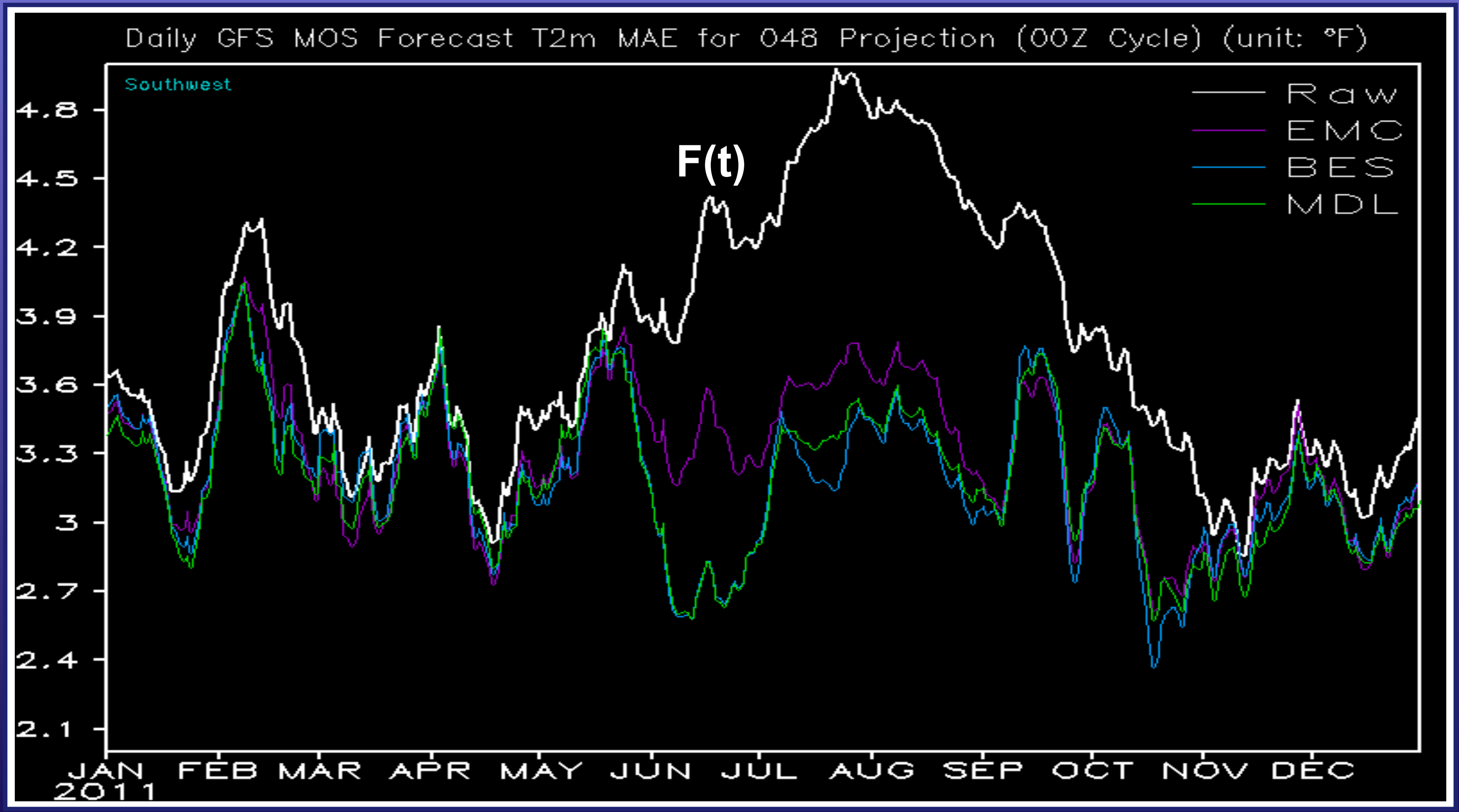
Raw / Corrected GFS MOS Wind MAE

KABQ – 00UTC, 96-h Projection

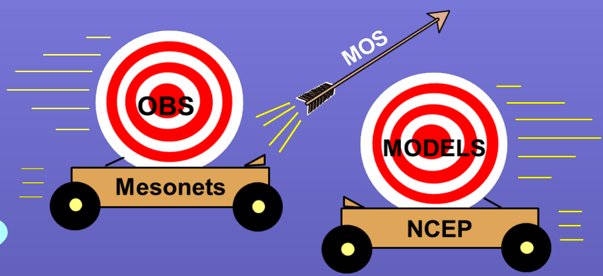


Raw / Corrected GFS MOS Temp MAE

Southwest U.S. – 00UTC, 48-h Projection



Responding to NWP Model Changes



- **Bias Correction for MOS?**
  - **Apply to Temps? Winds?**
  - **Run continuously in background?**
  - **Satisfactory in rapidly-varying conditions?**
- **Redevelop?**
  - **Short sample from new model or “mixed”?**
  - **Full System, selected elements?**
    - Biggest impacts on single-station equations (Temp, Wind)

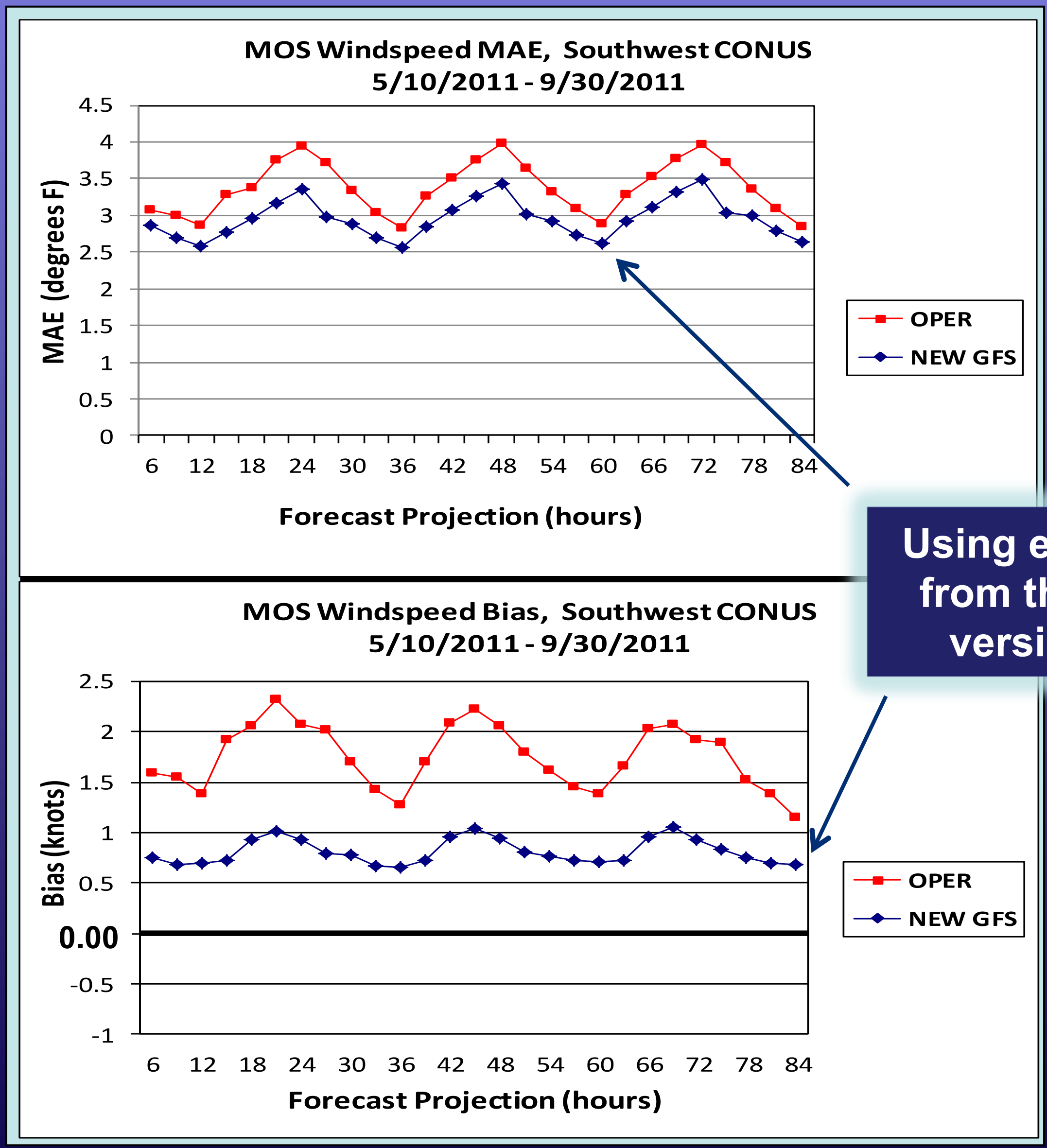
GFS MOS Wind Verification Results*

5/10/2011 – 9/30/2011

Windspeed - Southwest CONUS

MAE

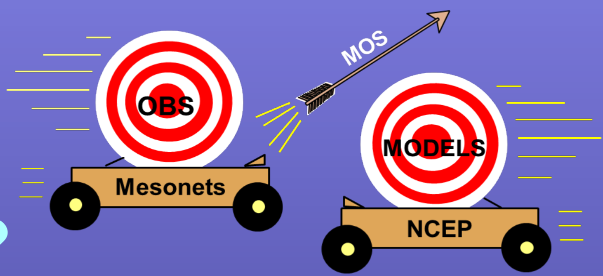
Bias



Using even just a little data from the new NWP model version can be helpful!

*** 2-season dependent sample (4/2010 – 9/2011)**

Responding to NWP Model Changes

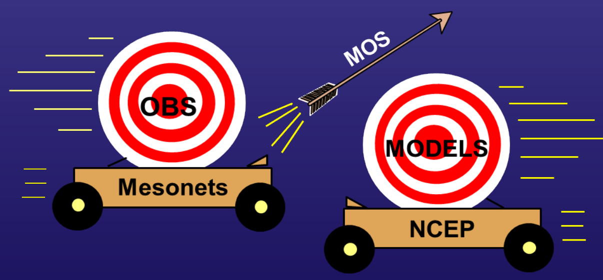


- **Bias Correction for MOS?**
  - Apply to Temps? Winds?
  - Run continuously in background?
  - Satisfactory in rapidly-varying conditions?
- **Redevelop?**
  - Short sample from new model or “mixed”?
  - Full System, selected elements?
    - Biggest impacts on single-station equations (Temp, Wind)
- **Reforecasts?**
  - 1-2 year sample probably sufficient for T, Wind
  - Rare elements need longer or “mixed” sample?
  - Requires additional supercomputer resources

Responding to NWP Model Changes

Four recent examples

- **GFS/GFSX MOS Wind replacement** (6/2012)
  Fix errors introduced by 5/2011 GFS roughness length change (2-season sample)
- **NAM MOS T/T_d /Max-Min refresh** (pending)
  NMM-b implementation (12/2011); SW US cool bias fix
- **GFS MOS full-system update** (3/2010)
  Correct accumulated drift from several minor model changes
- **NAM MOS** (12/2008)
  Respond to Eta/NMM transition
  "Mixed" samples except for sky, snow (Eta-based)



MOS: Today and Beyond

The Future of MOS

"Traditional" Station-oriented Products

- **GFS / GFSX MOS:**
  - Update GFSX Sky Cover equations
    - (Completes 1200 UTC text message)
  - Make Day 10 GFSX elements available to public
  - Update climate normals (1981-2010 NCDC)
  - Bias-corrected T, Td, Max/Min?

- **NAM MOS:**
  - Add precipitation type suite (TYP, POZ, POS)
  - Add 0600 and 1800 UTC cycles?
  - Update remaining eta-based elements
  - Update temperature suite with NMM-b data

The Future of MOS

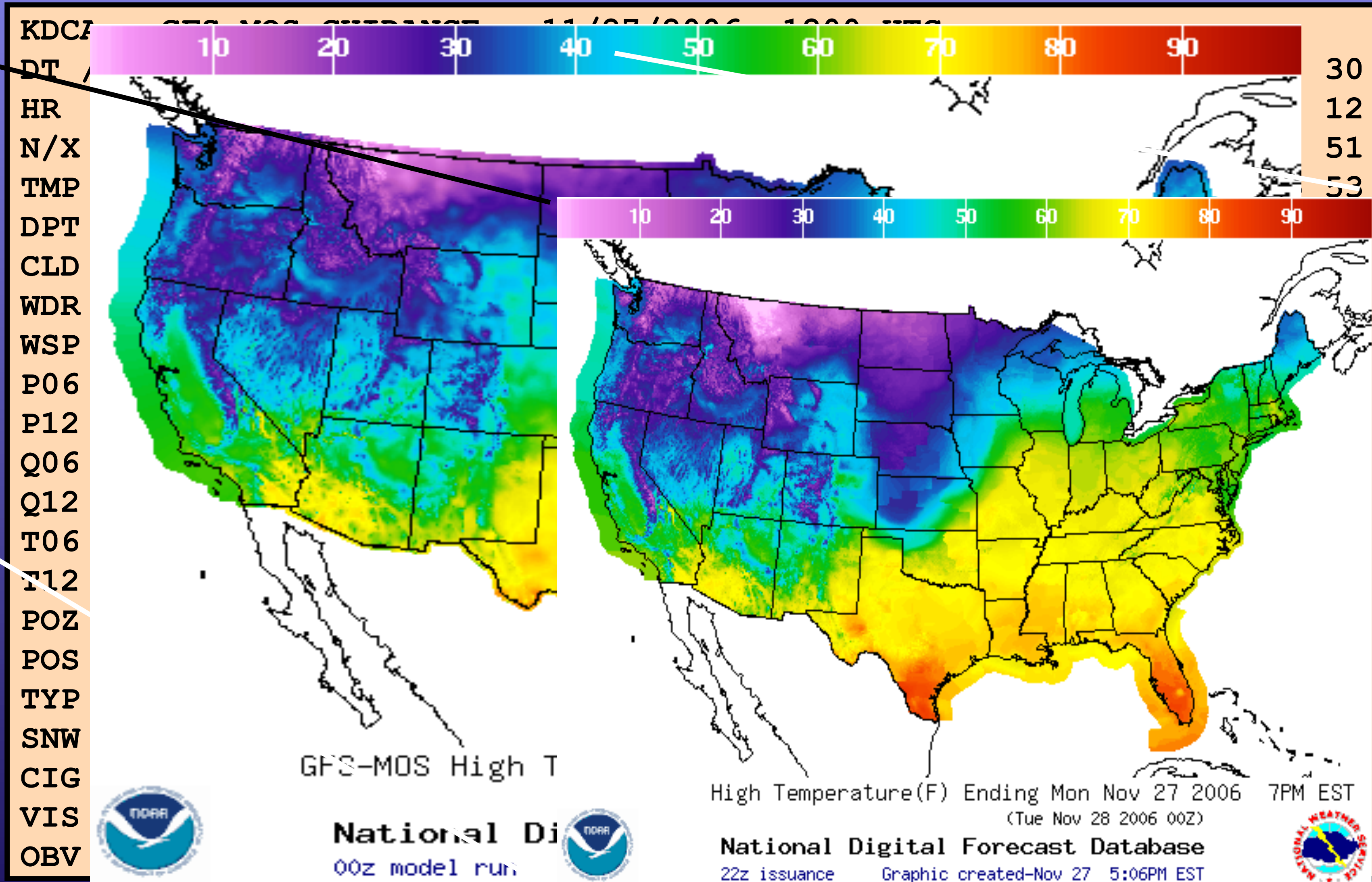
"Traditional" Station-oriented Products (contd.)

- **Western Pacific MOS**
  Add new elements (Sky Cover, CIG)

- **"Consensus" MOS:**
  Weights based on recent performance
  Blends GFS, NAM, ECMWF, Ensemble MOS
  Use Bayesian Model Averaging (BMA)

- **General:**
  Evaluate impacts of NWP model changes
  Periodic addition of new CONUS sites
  New products utilizing station probabilities

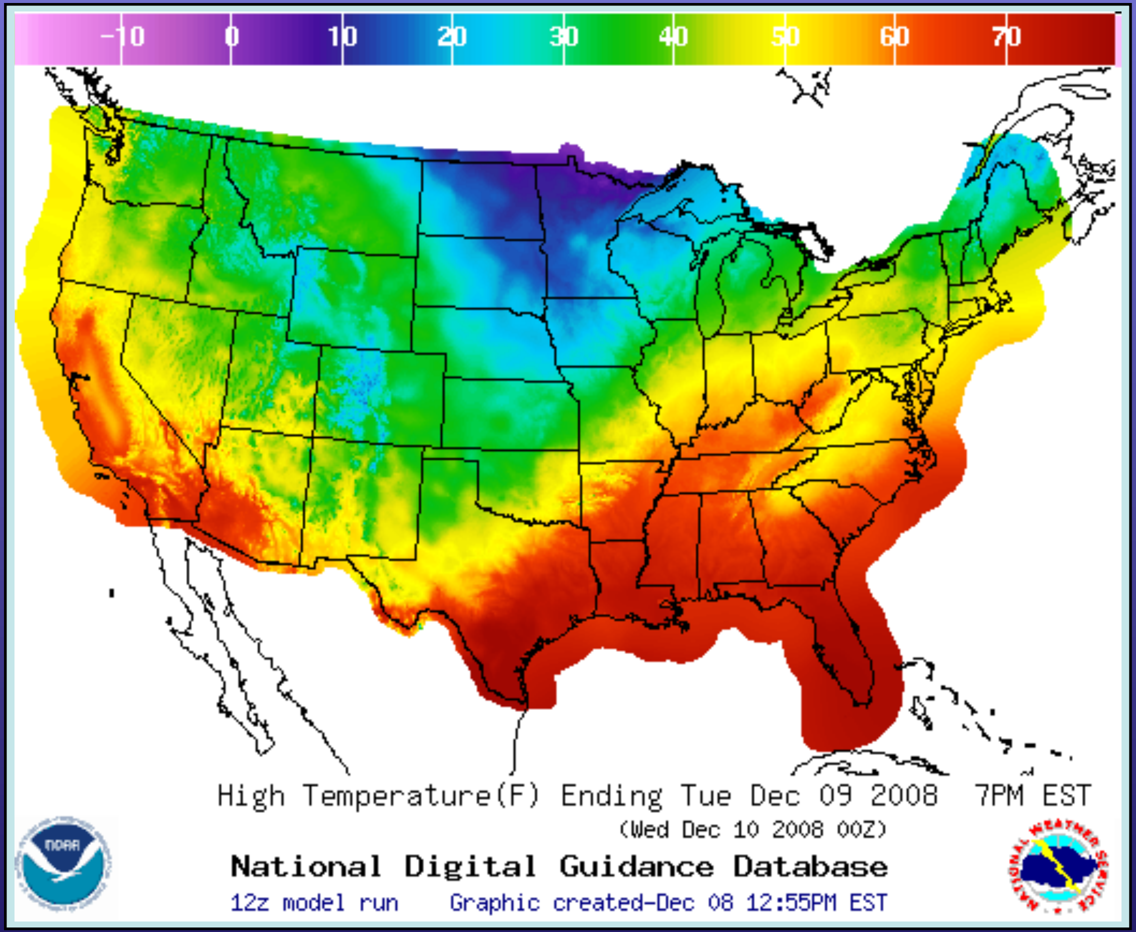
End of an era?



WANTED! High-resolution, gridded guidance for NDFD

Gridded MOS

GFS-based   CONUS-wide @ 2.5km



Max / Min

PoP

Temp / Td

RH

Tstm

Winds

QPF

Snowfall

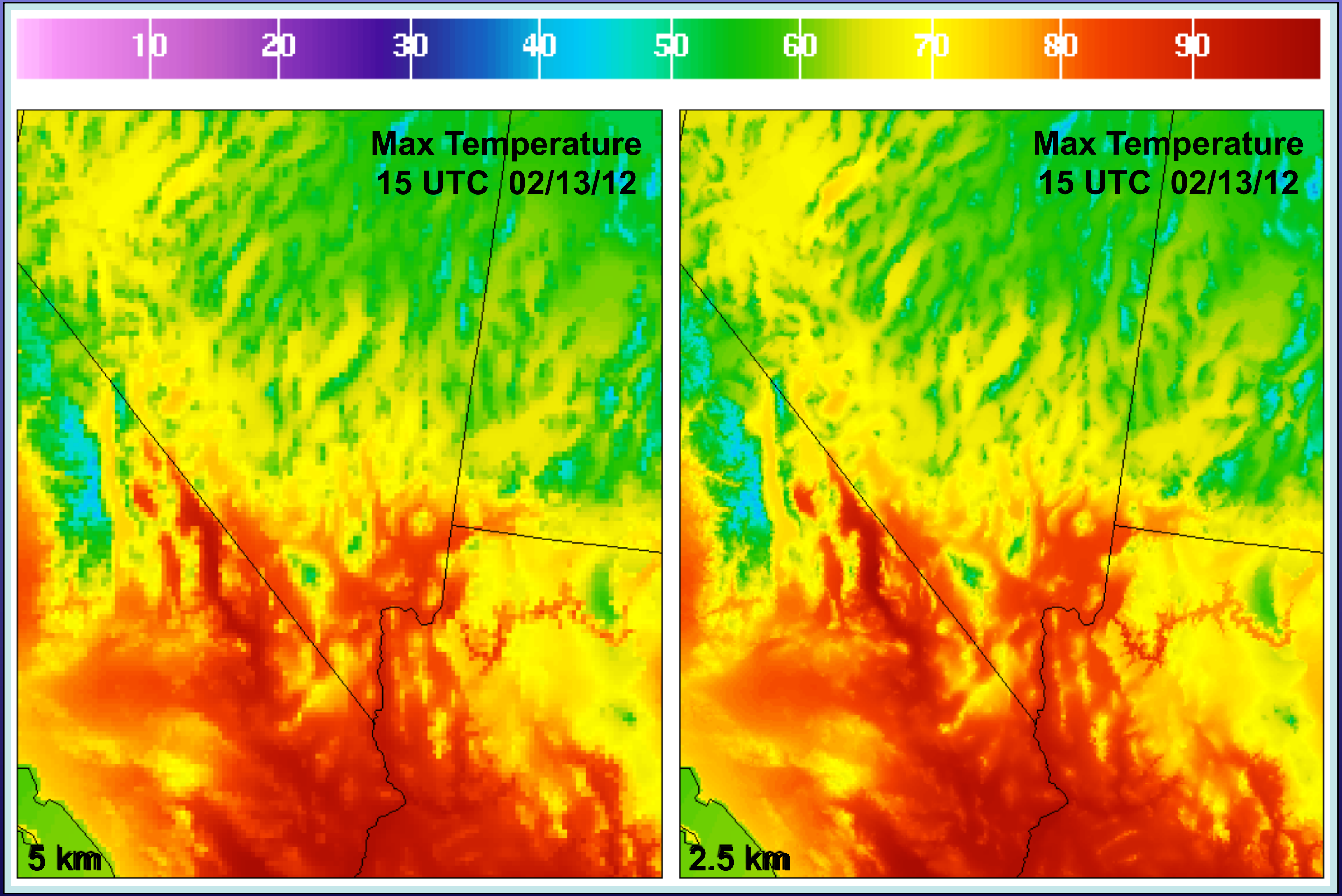
Gusts

Sky Cover

http://www.weather.gov/mdl/synop/gridded/sectors/index.php

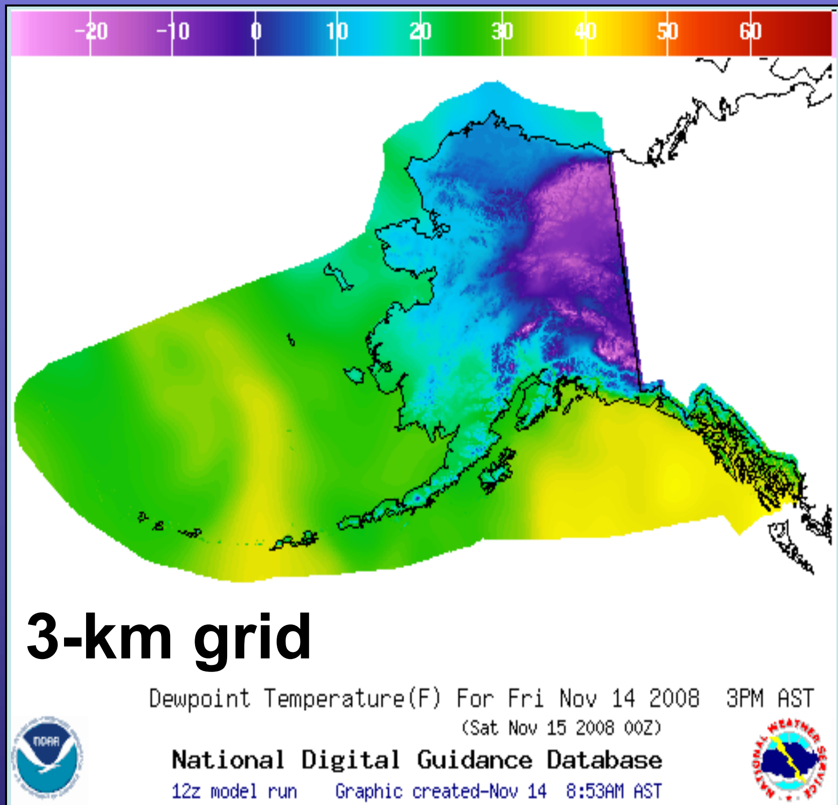
2.5-km vs. 5-km

2.5-km CONUS GMOS introduced Feb. 27, 2012



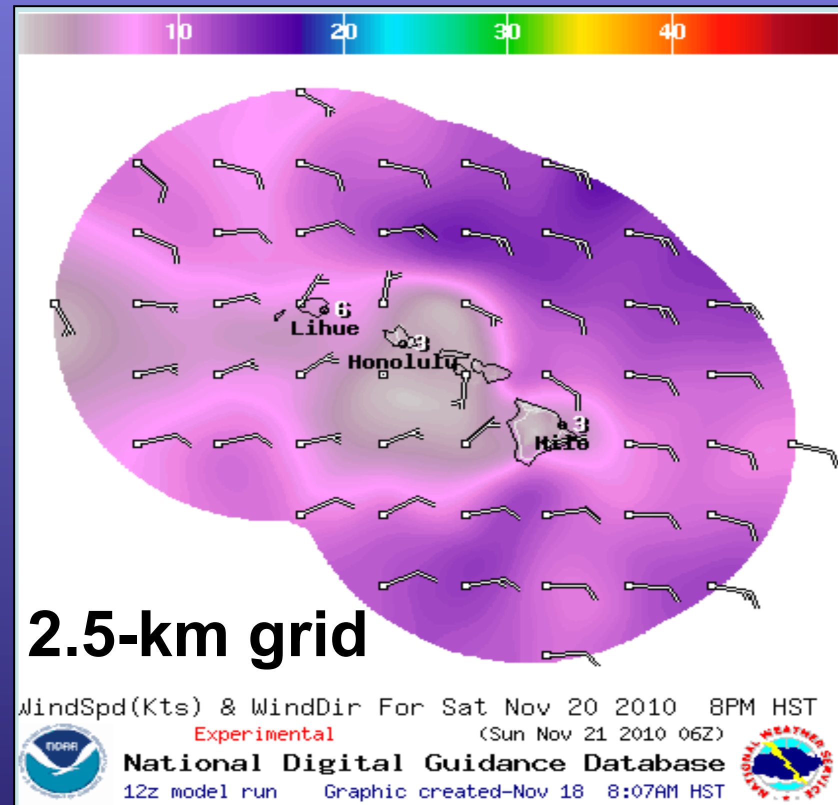
Alaska / Hawaii Gridded MOS

AK: GFS-based, 3-km grid



All CONUS elements

HI: GFS-based, 2.5-km grid



Max / Min	RH
PoP	Winds
Temp / Td	Gusts

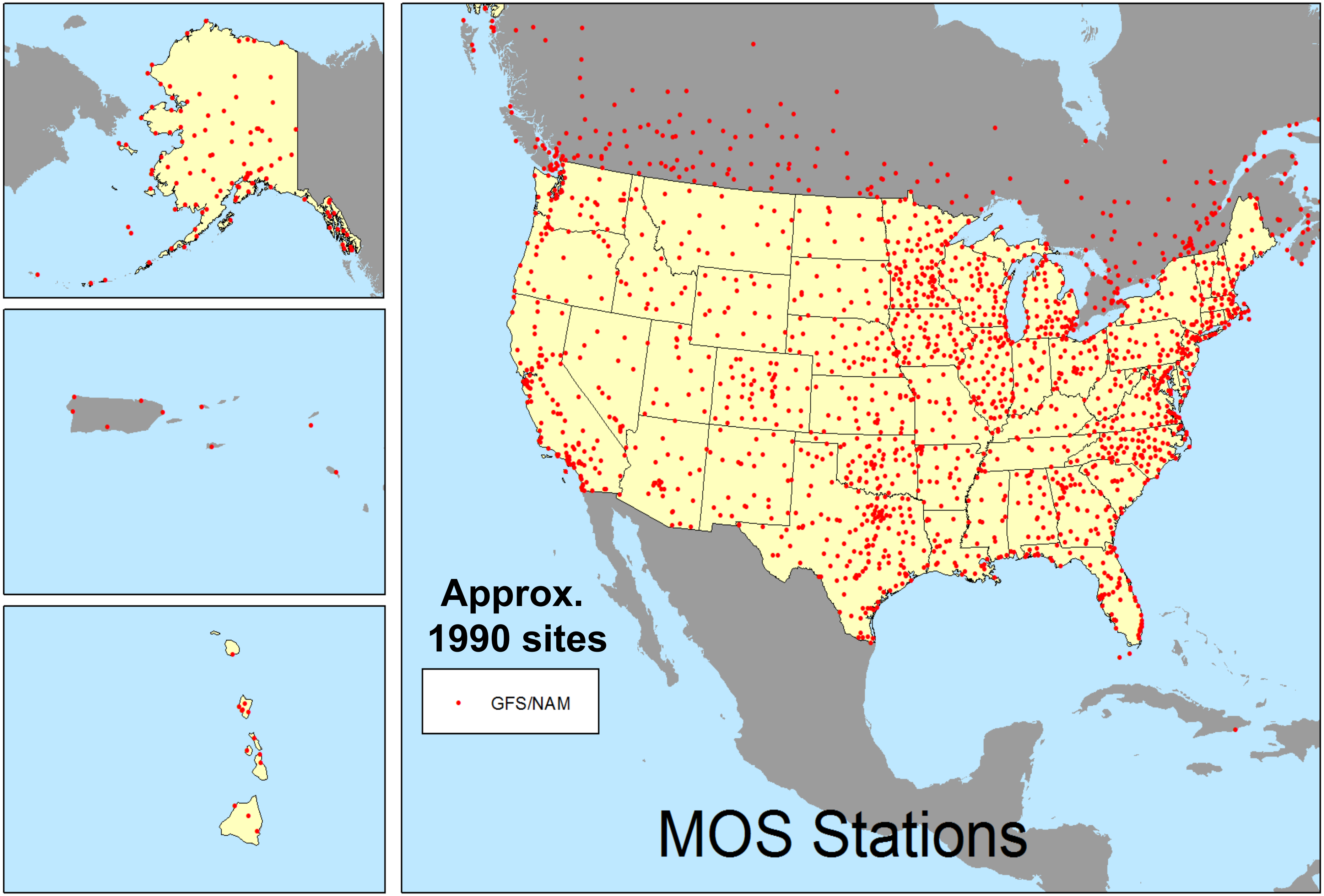
The Future of MOS

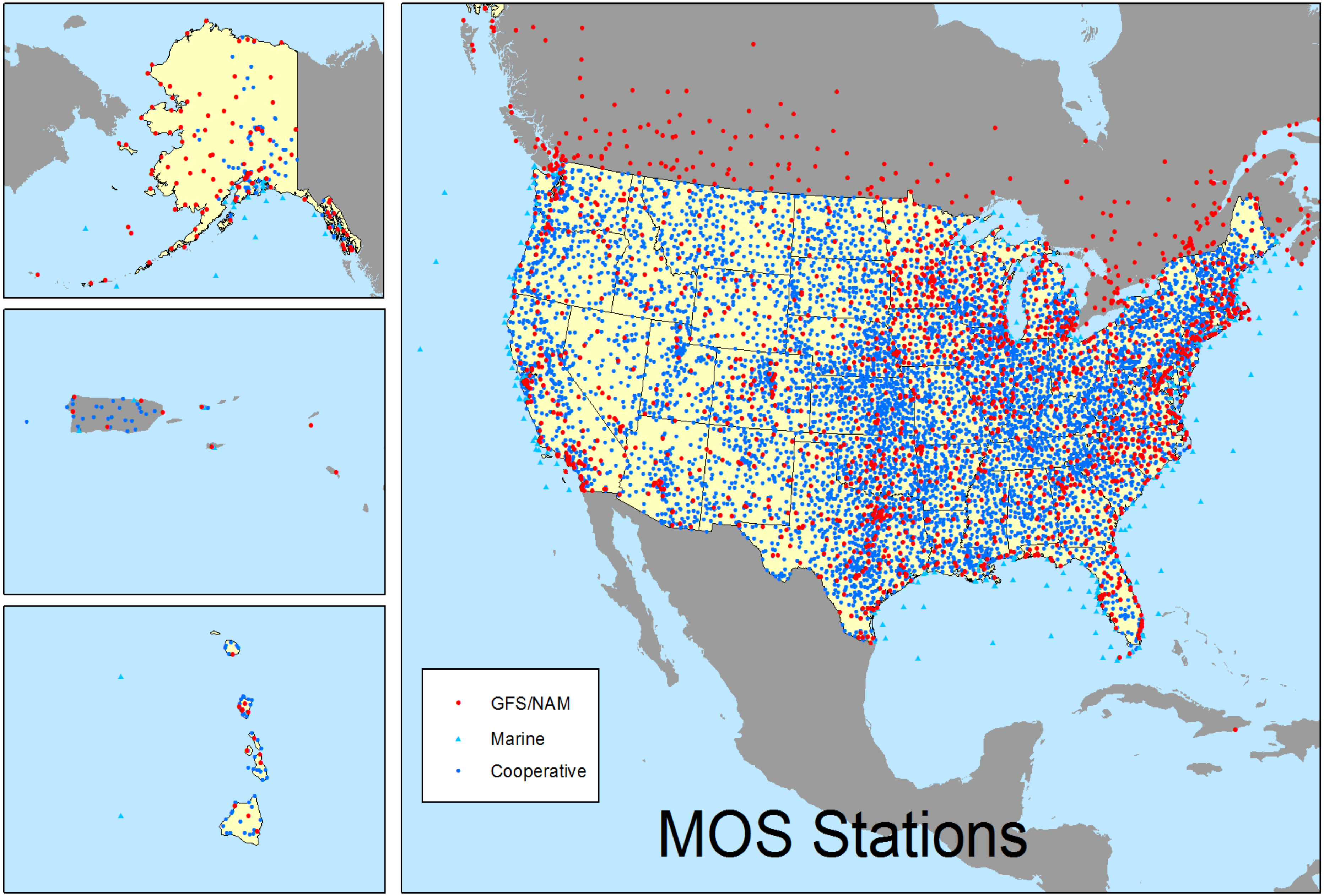
"Enhanced-Resolution" Gridded MOS Systems

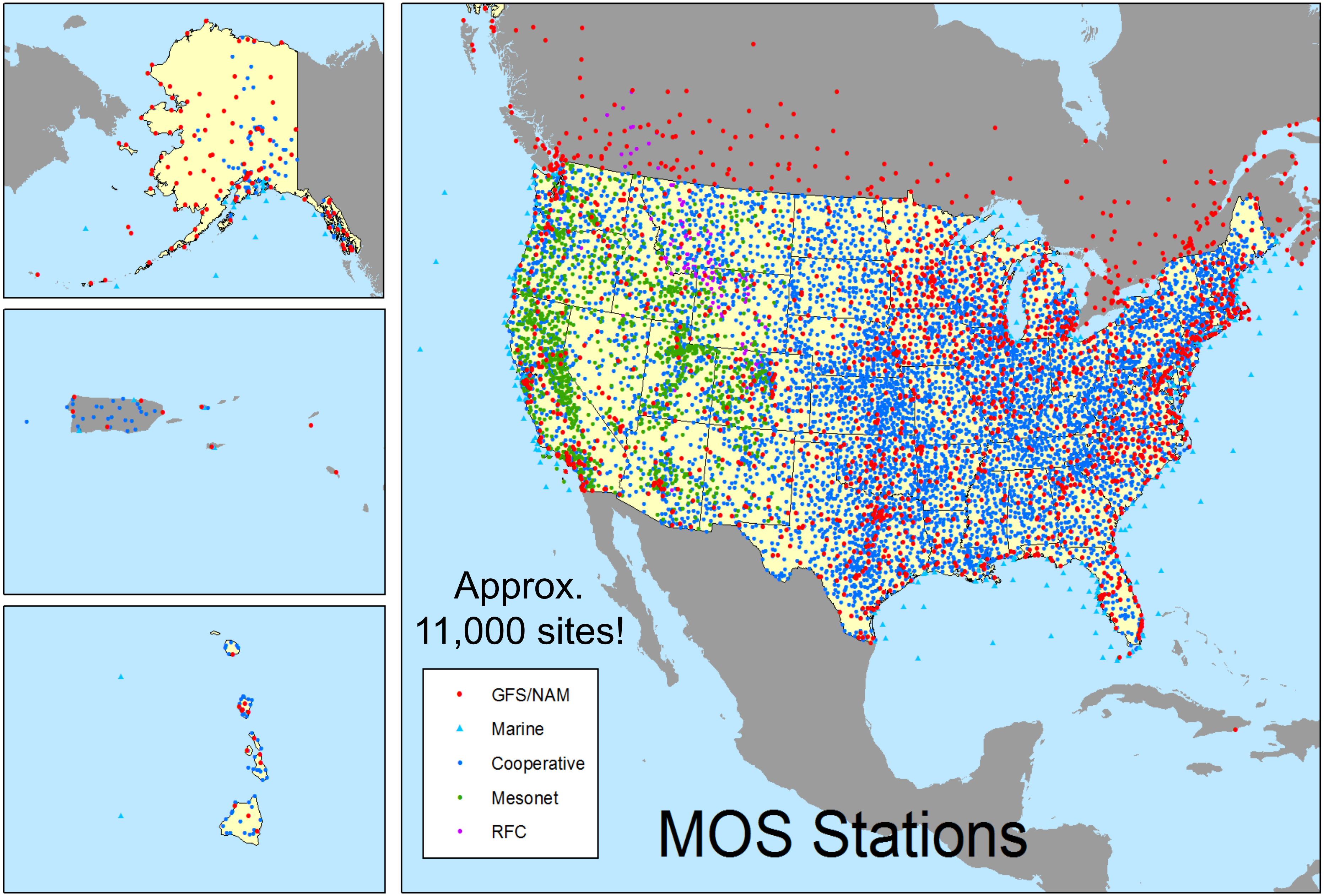
- **"MOS at any point" (e.g. GMOS)**
  - **Support NWS digital forecast database**
    - **2.5 km - 5 km resolution**
  - **Equations valid *away* from observing sites**
  - **Emphasis on high-density surface networks**
  - **Use high-resolution geophysical data**

Surface observation systems used in GMOS

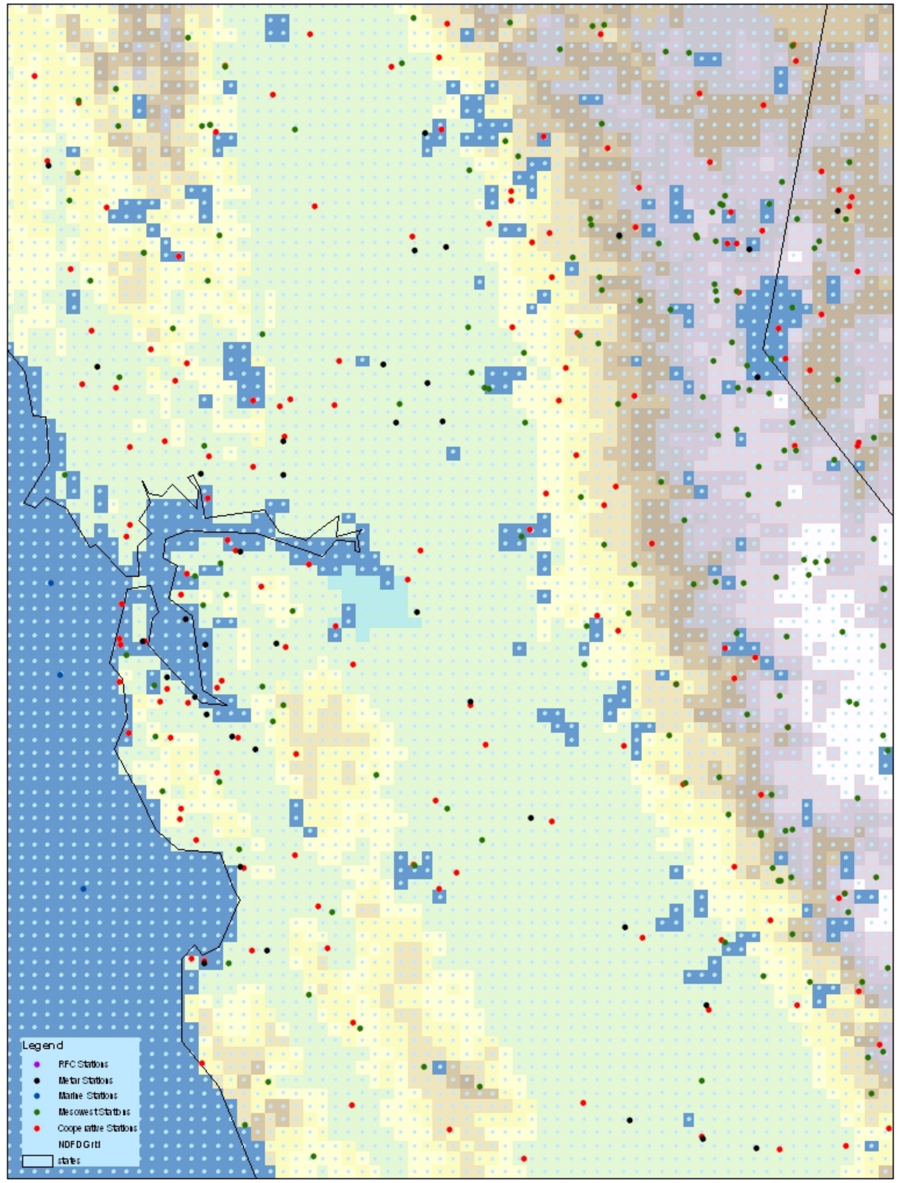
- METAR
- Buoys/C-MAN
- Mesonet (RAWS/SNOTEL/Other)
- NOAA cooperative observer network
- RFC-supplied sites


Approx.
1990 sites
GFS/NAM
MOS Stations

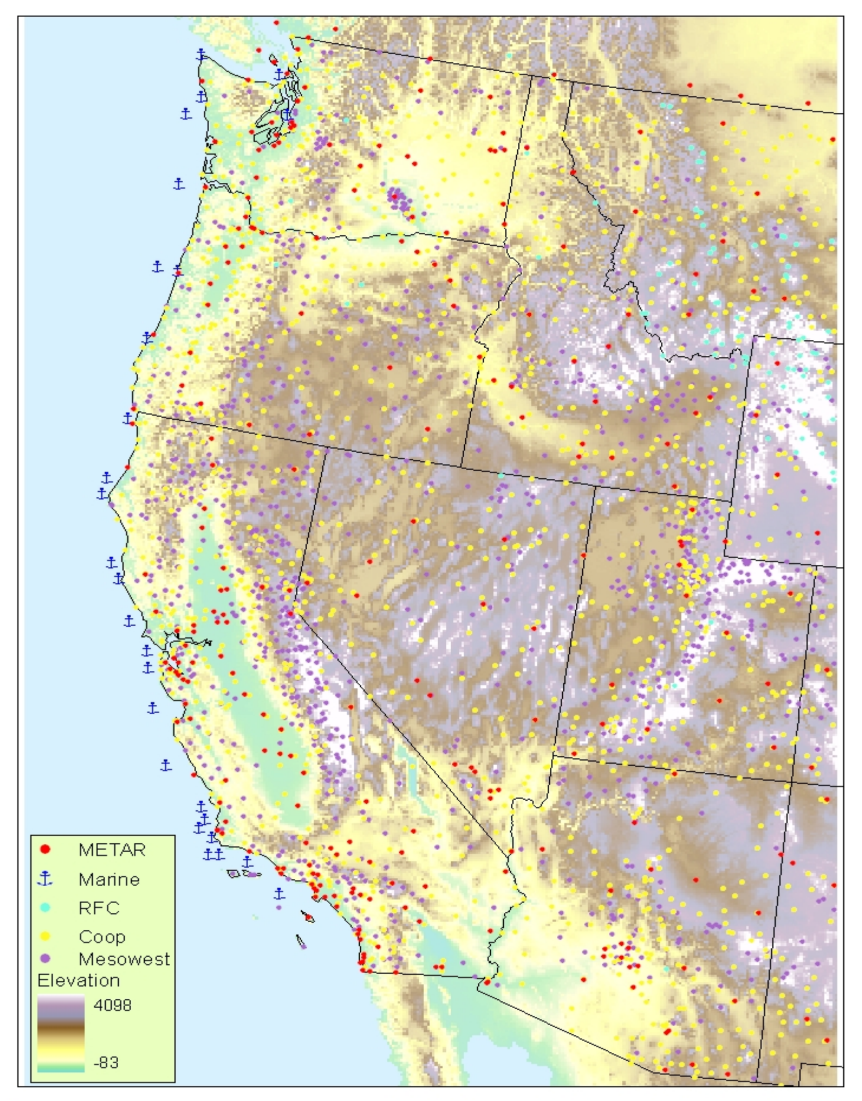

GFS/NAM
Marine
Cooperative
MOS Stations


Approx.
11,000 sites!
GFS/NAM
Marine
Cooperative
Mesonet
RFC
MOS Stations

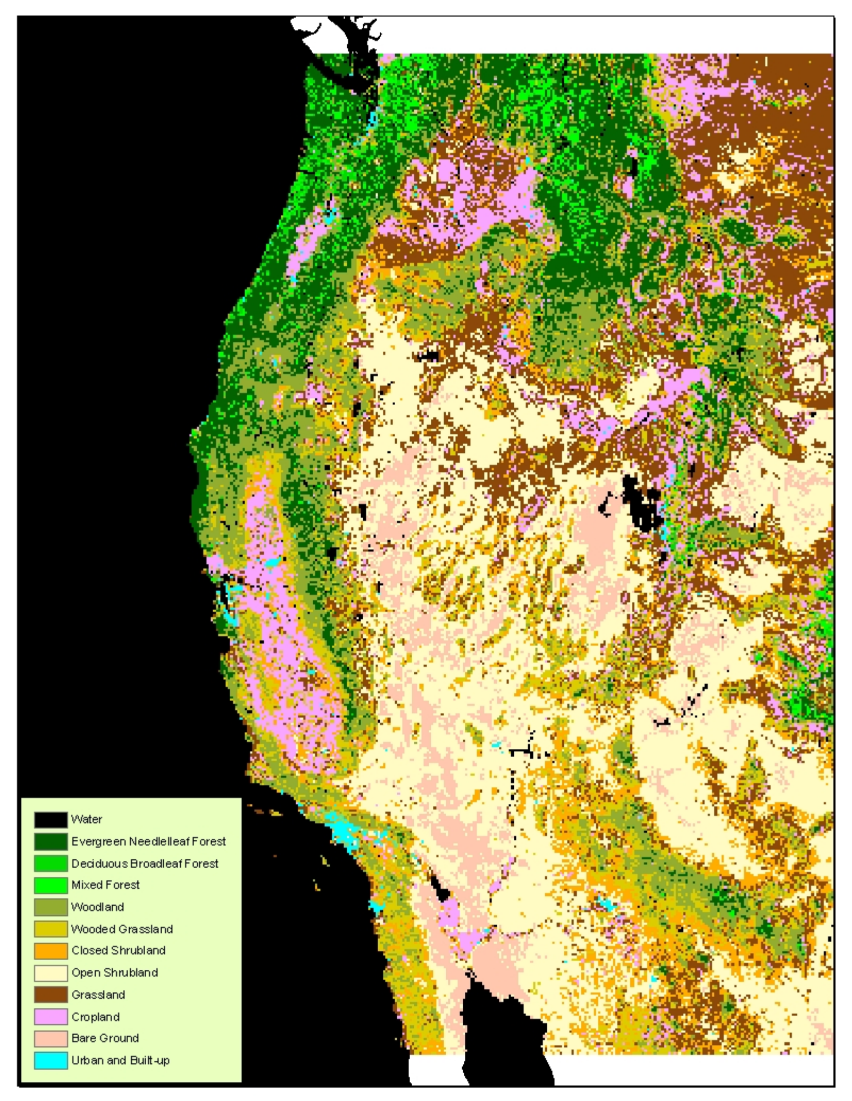
Gridded MOS – Central CA



Geophysical Datasets



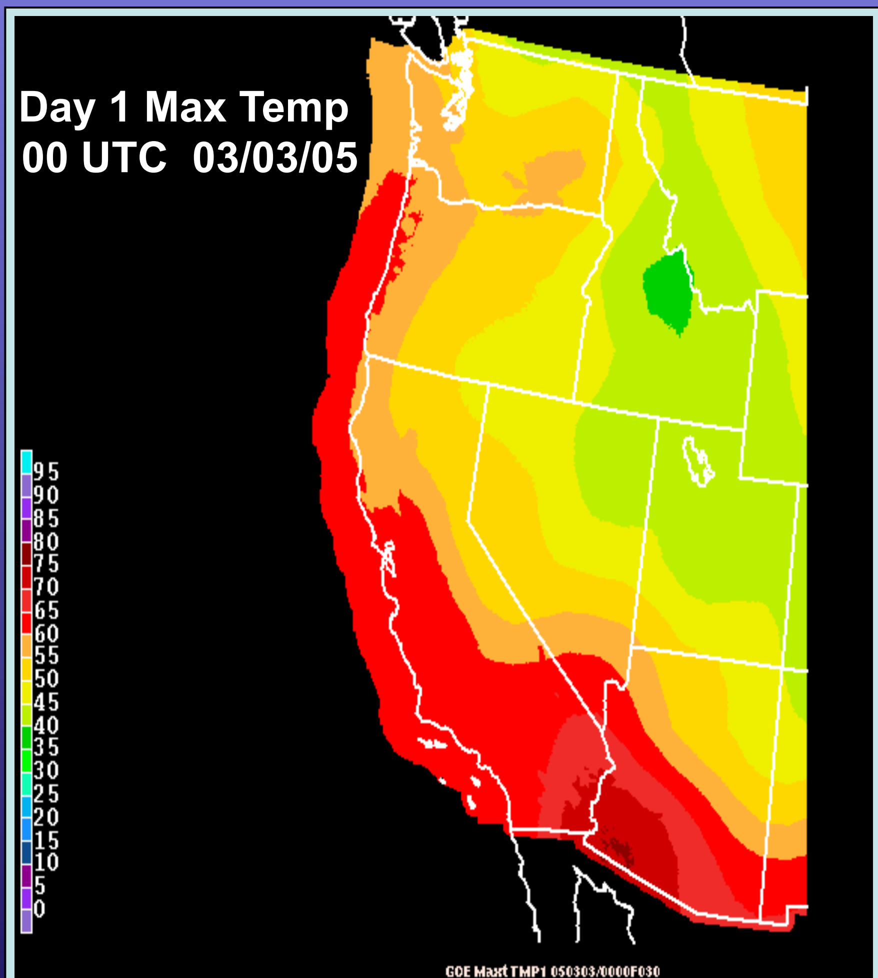
5-km Terrain



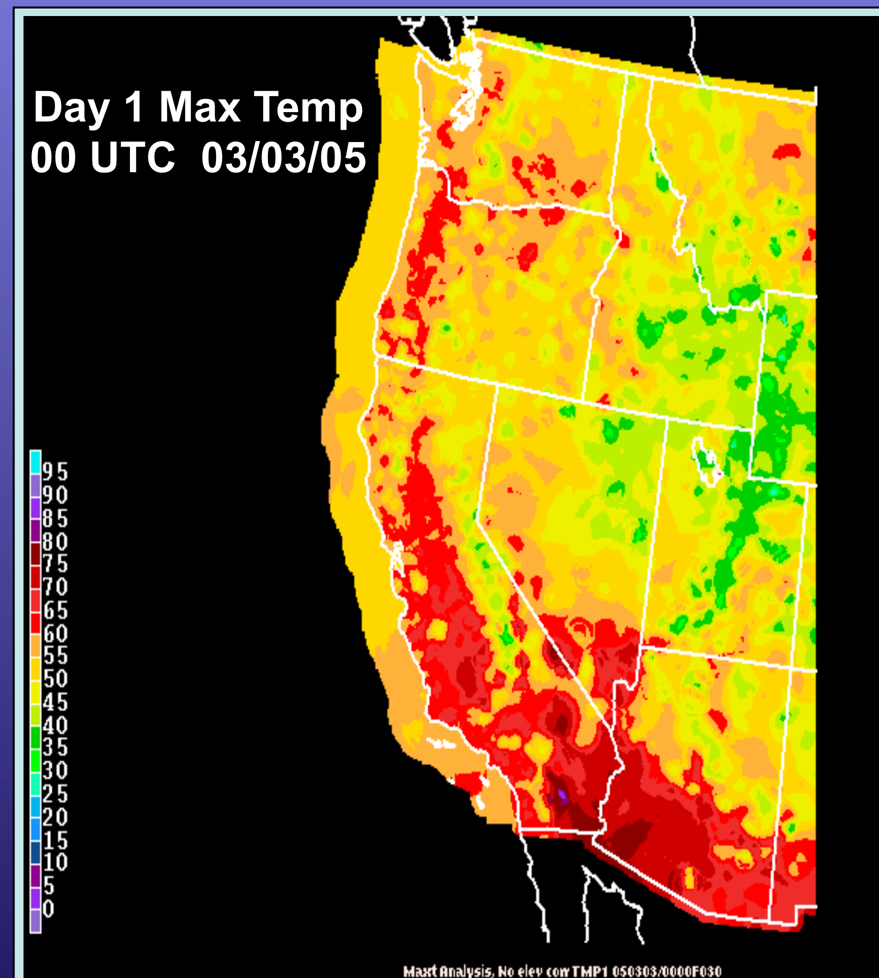
5-km Land Cover

Gridded MOS Concept - Step 1

"Blending" first guess and high-density station forecasts



First guess field from Generalized Operator Equation or other source



First guess + guidance at all available sites

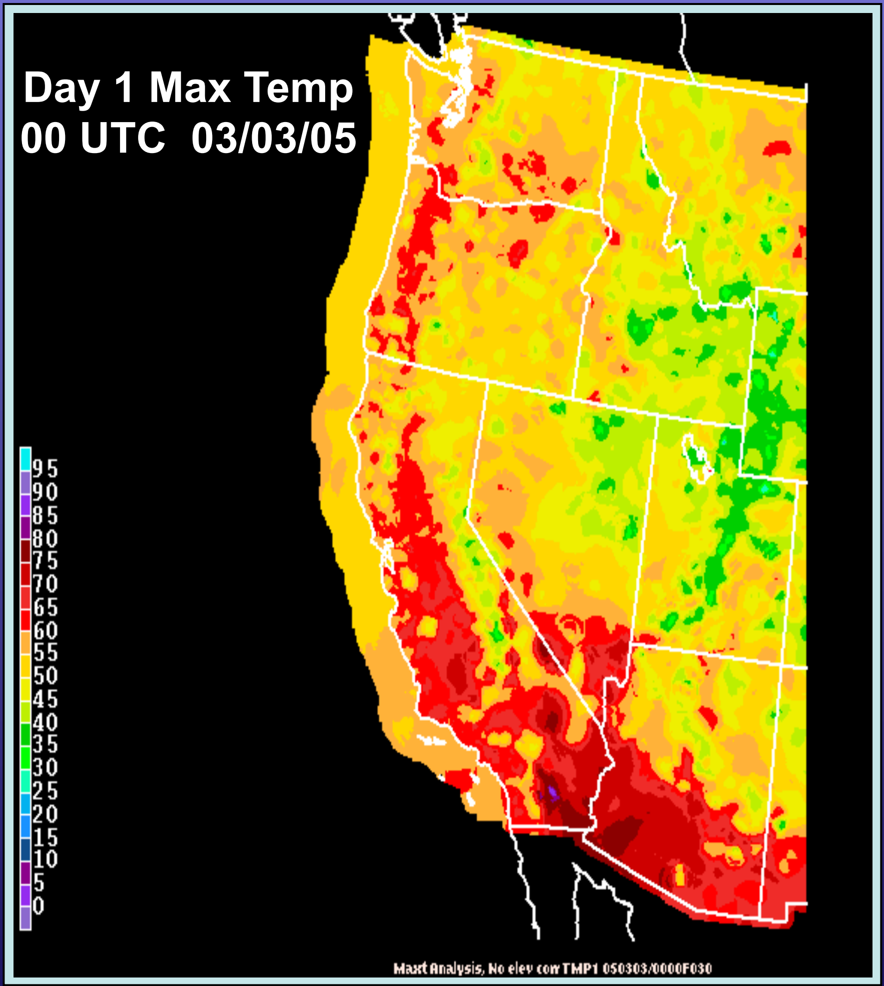
Developing the "First Guess" Field

Some options

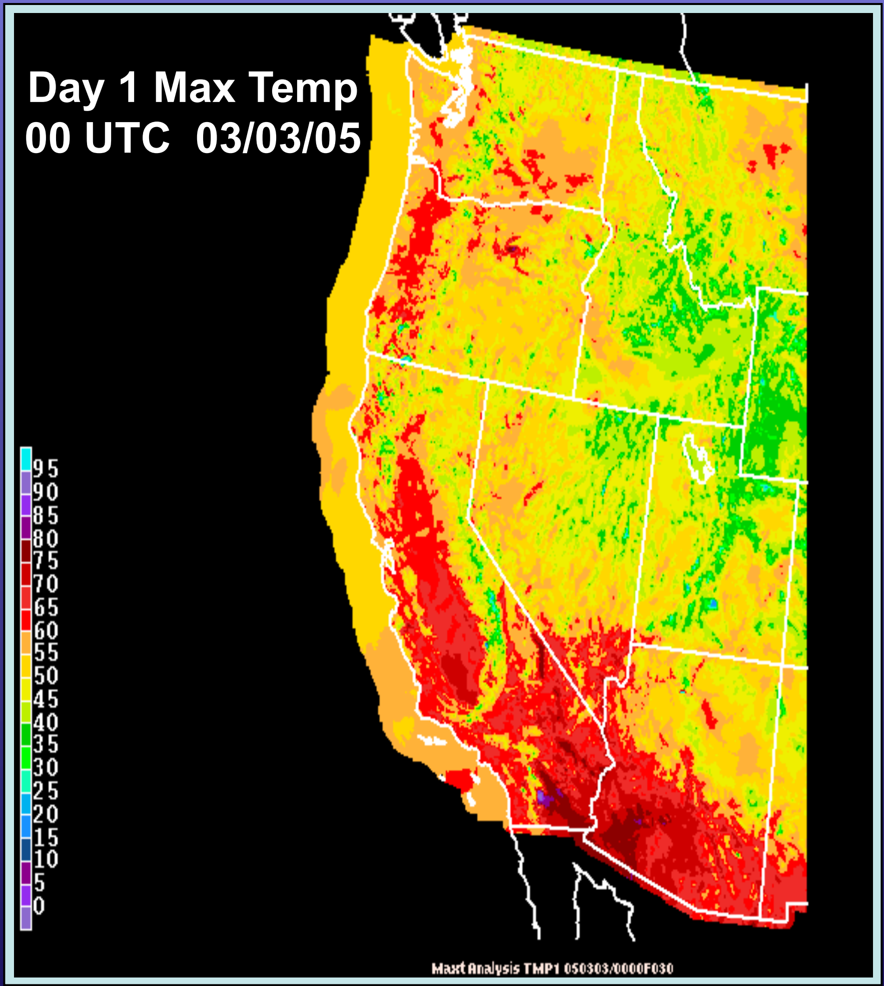
- Generalized operator equation (GOE)
  - Pool observations regionally
  - Develop equations for all elements, projections
  - Apply equations at all grid points within region
- Use average field value at all stations
- Use other user-specified constant
- Use NWP model forecast

Gridded MOS Concept - Step 2

Add further detail to analysis with high-resolution geophysical data and "smart" interpolation



First guess + guidance at all available sites



First guess + station forecasts + terrain

GMOS Analysis

Basic Methodology (Glahn, et al. 2009, WaF)

- **Method of successive corrections ("BCDG")**

  Bergthorssen and Doos (1955); Cressman (1959);
  Glahn (1985, LAMP vertical adjustment)

- **Elevation ("lapse rate") adjustment**

  Inferred from forecasts at different elevations
  Calculations done "on the fly" from station data
  Can vary by specific element, synoptic situation

- **Land/water gridpoints treated differently**

GMOS Analysis

Other Features

- Special, terrain-following smoother
- ROI can be adjusted to account for variations in density of observed data
- Nudging can be performed to help preserve nearby station data
- Parameters can be adjusted individually for each weather element

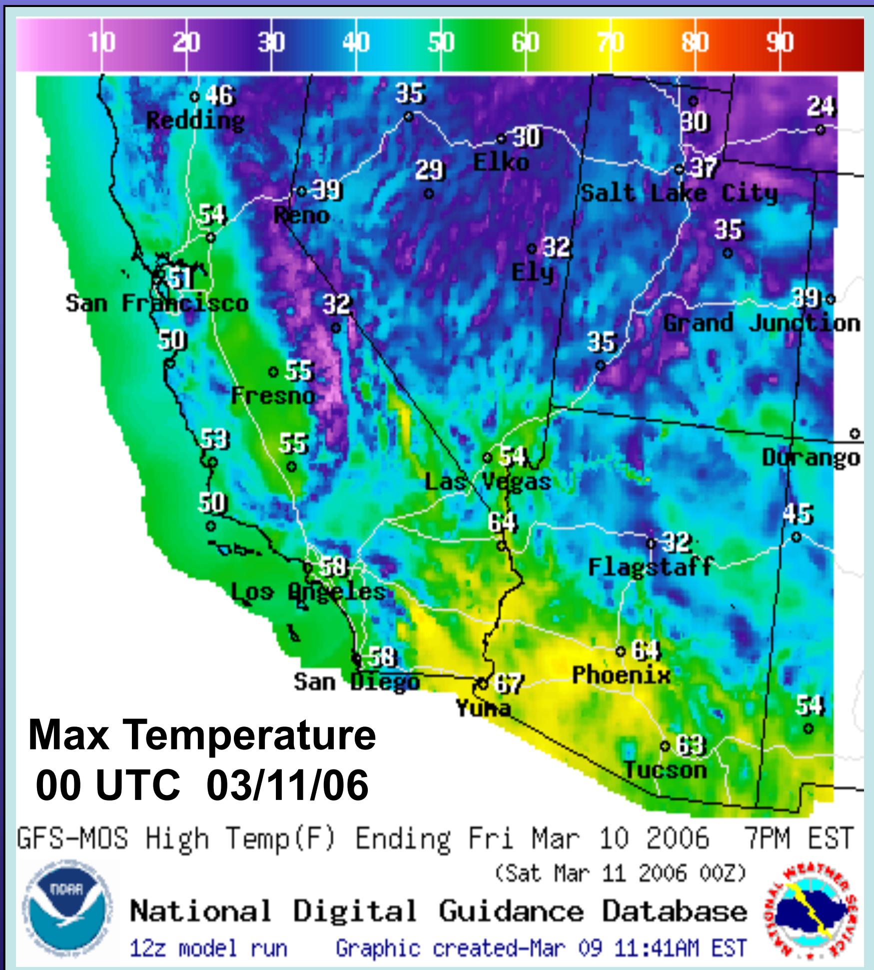
GMOS Analysis

Some Issues

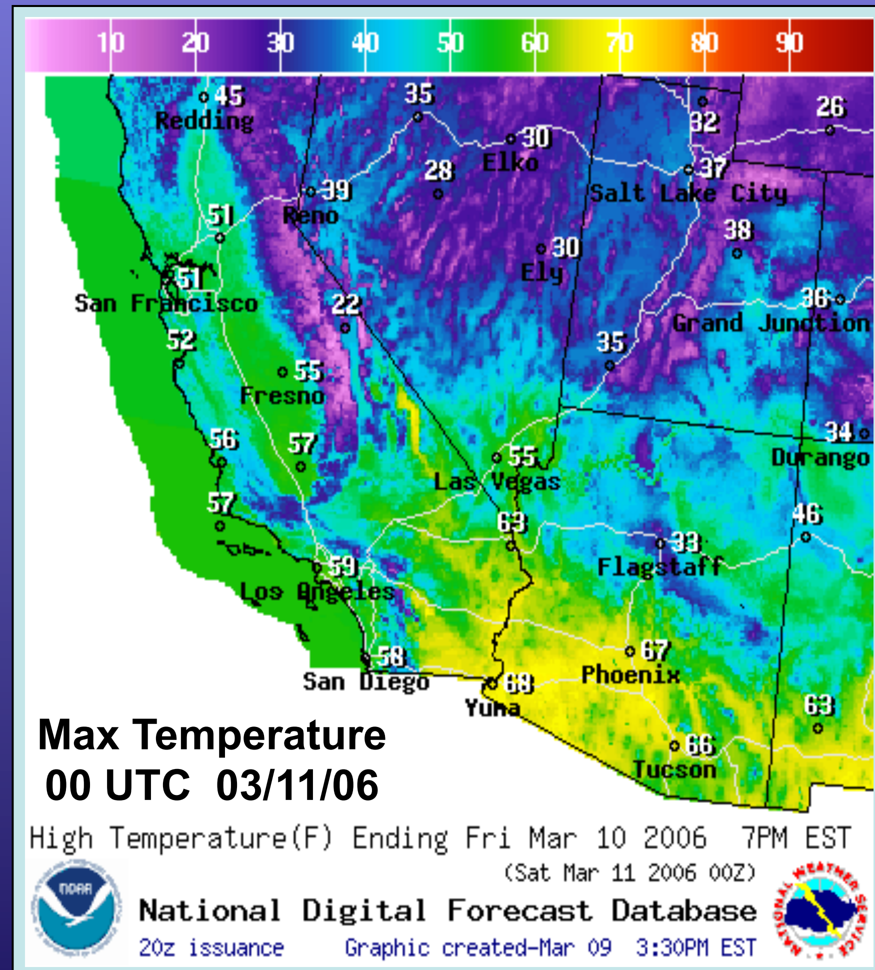
- Not optimized for all weather elements and synoptic situations
  - Need situation specific, dynamic models?
- May not capture localized variations in vertical structure
  - Vertical adjustment uses several station “neighbors”
- May have problems in data-sparse regions over flat terrain
  - Defaults to pure Cressman analysis with small ROI
  - Can result in some “bulls-eye” features

NDGD vs. NDFD

Which is "better"?



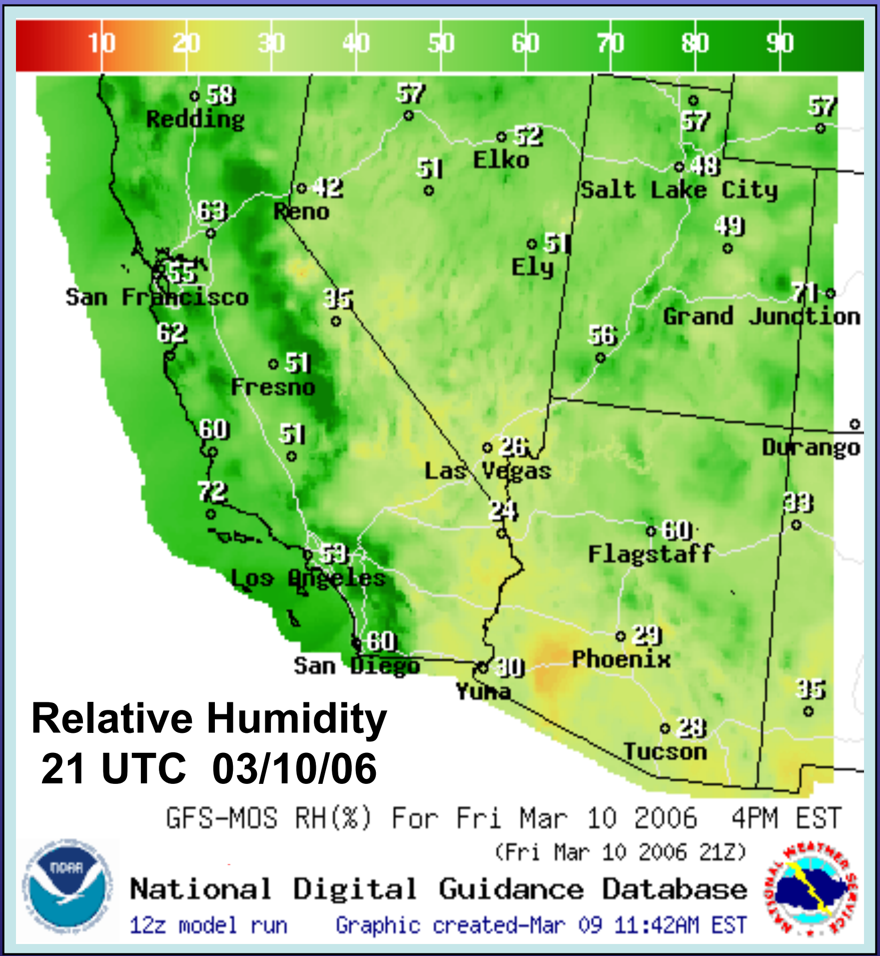
NDGD Max T

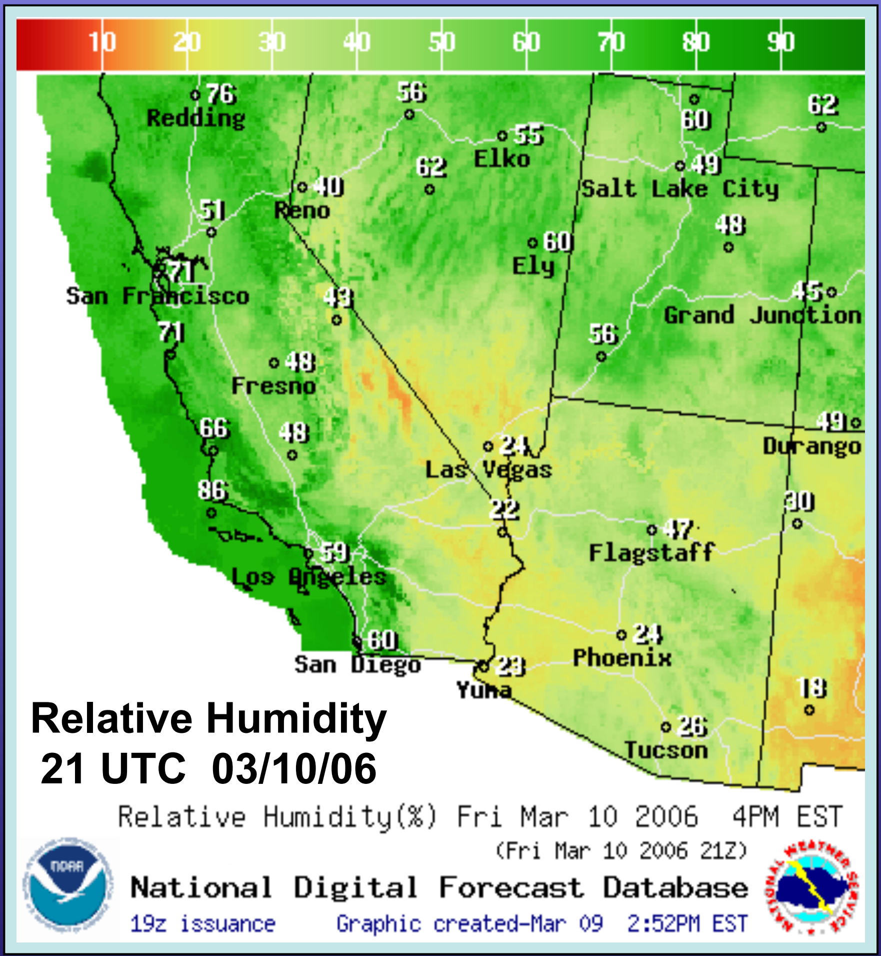


NDFD Max T

NDGD vs. NDFD

Which is "better"?





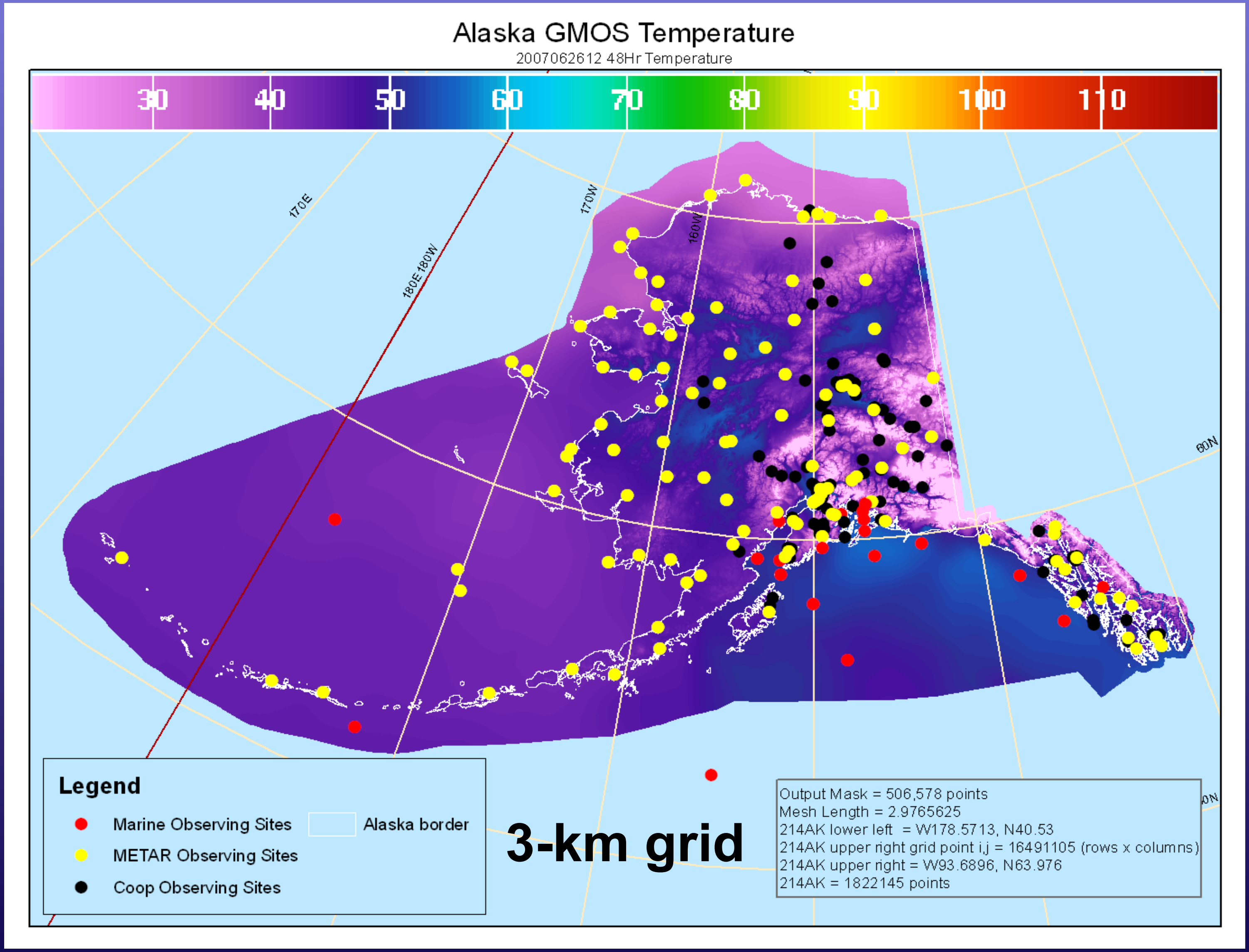
NDGD RH **NDFD RH**

Fewer obs available to analysis = less detail in GMOS

Forecasters adding detail: Which is "better"? More accurate?

AK GMOS Temps & Observing Sites

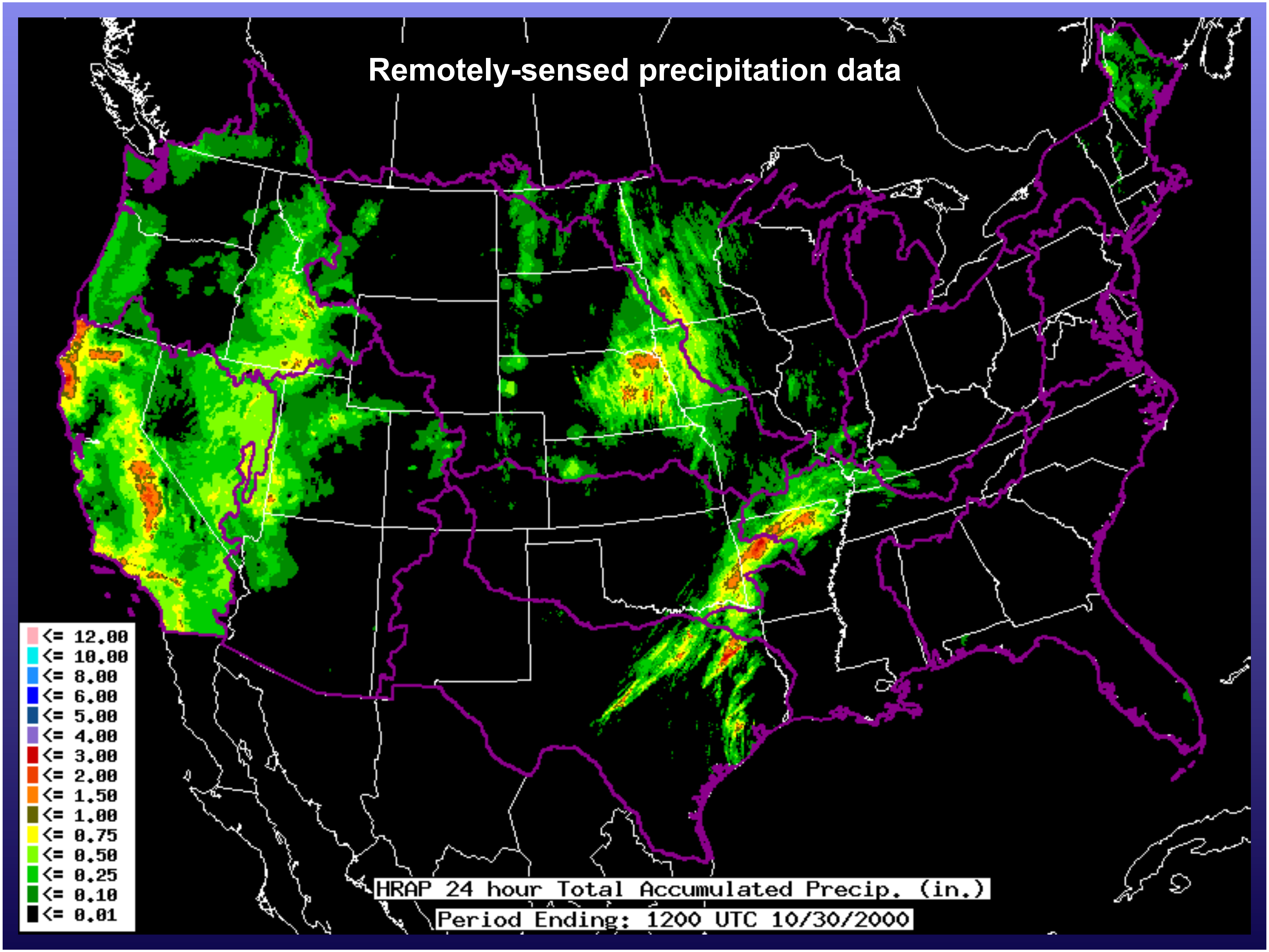
Even fewer obs available – Yikes!



The Future of MOS

"Enhanced-Resolution", Gridded MOS Systems

- **"MOS at any point" (e.g. GMOS)**
  - Support NWS digital forecast database
    - 2.5 km - 5 km resolution
  - Equations valid ***away*** from observing sites
  - Emphasis on high-density surface networks
  - Use high-resolution geophysical data
- **"True" gridded MOS**
  - Observations and forecasts valid on fine grid
  - Use remotely-sensed predictand data
    - e.g. WSR-88D QPE, Satellite clouds, NLDN



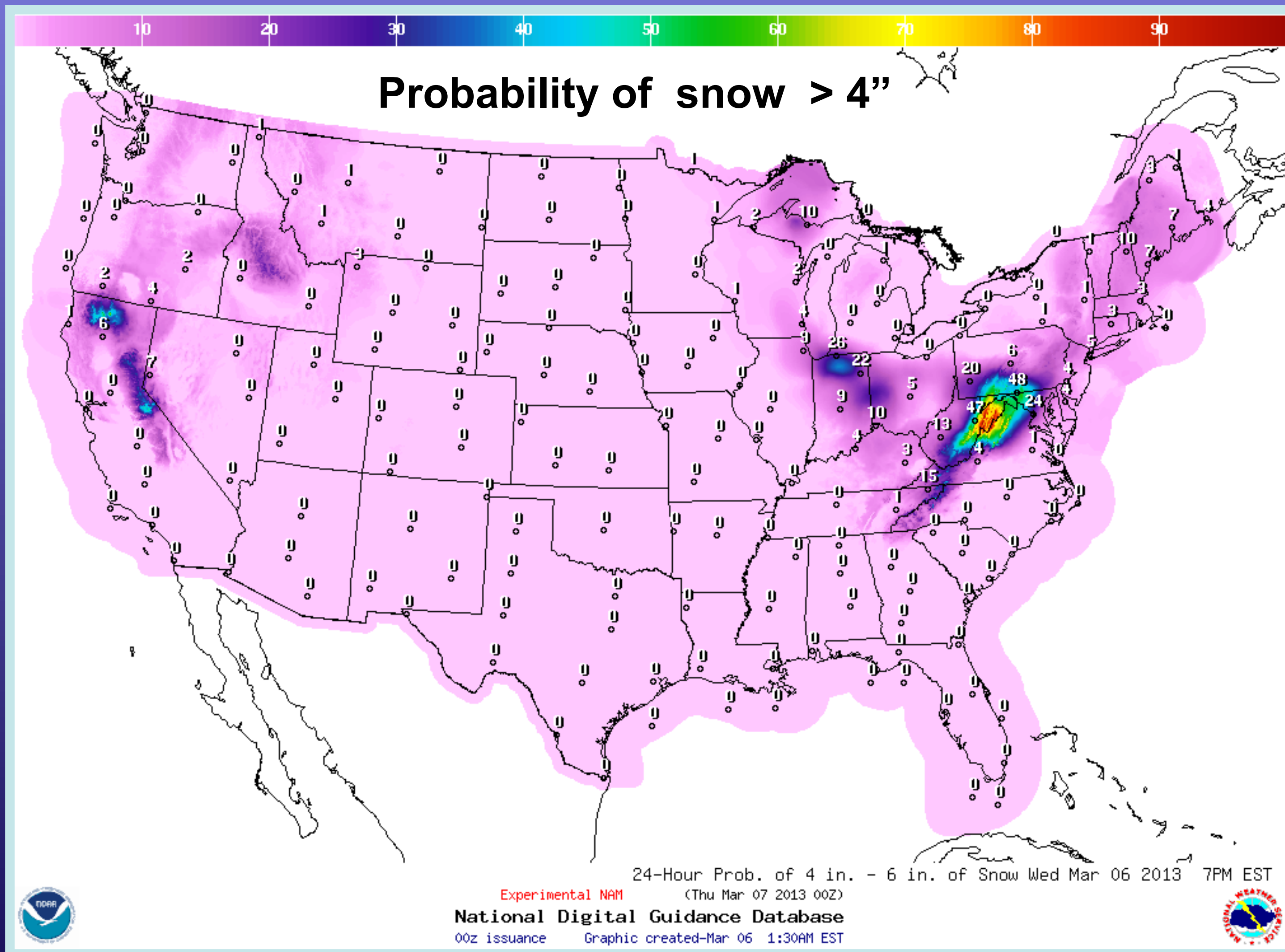
Remotely-sensed precipitation data
<= 12.00
<= 10.00
<= 8.00
<= 6.00
<= 5.00
<= 4.00
<= 3.00
<= 2.00
<= 1.50
<= 1.00
<= 0.75
<= 0.50
<= 0.25
<= 0.10
<= 0.01
HRAP 24 hour Total Accumulated Precip. (in.)
Period Ending: 1200 UTC 10/30/2000

The Future of MOS

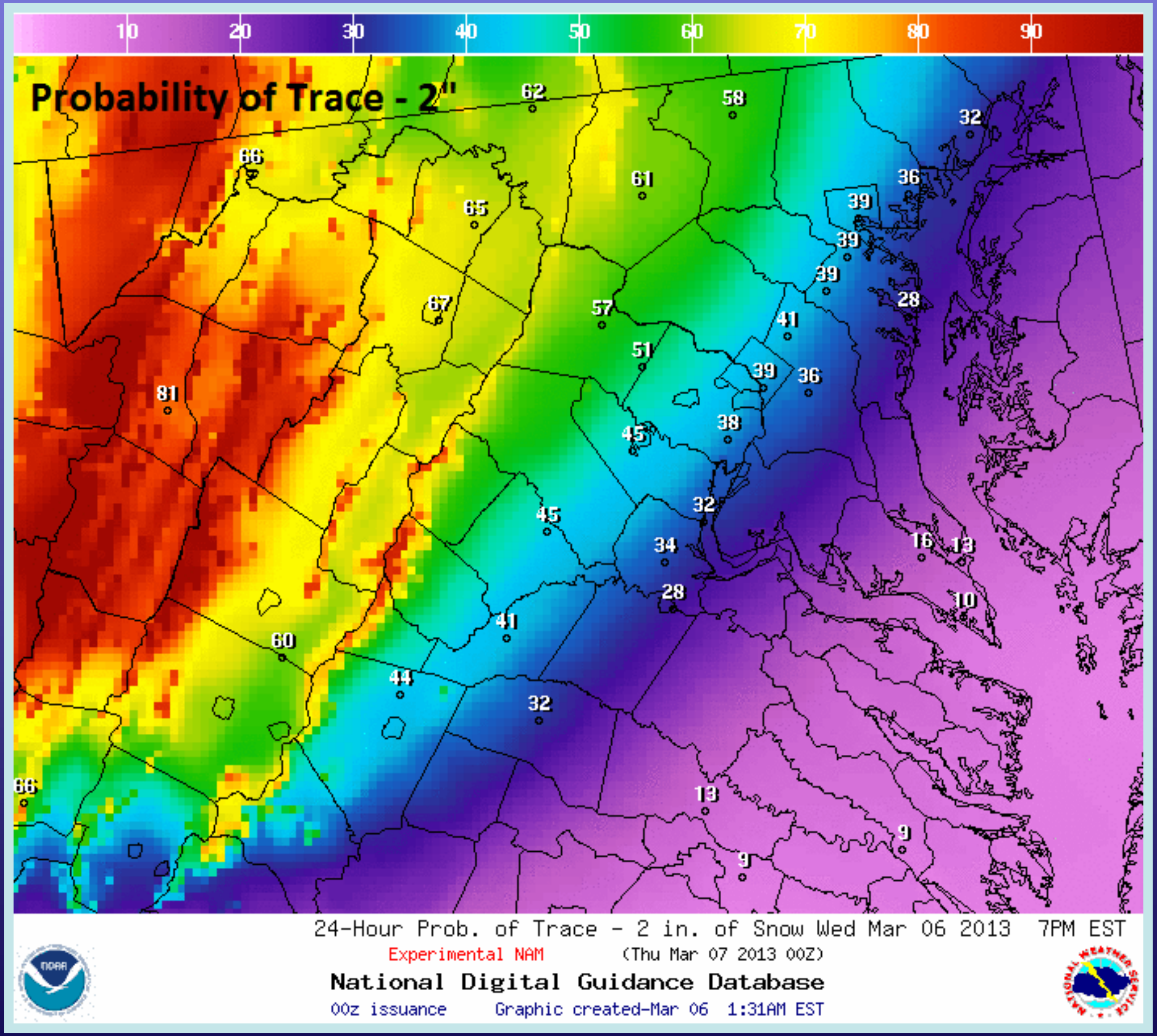
Gridded MOS: Where do we go from here?

- **Additions to current CONUS GMOS system**
  - “Predominant” weather grid
  - NAM-based companion system (short-range)
  - Probabilistic and/or ensemble-based products

NAM gridded snow amount probability

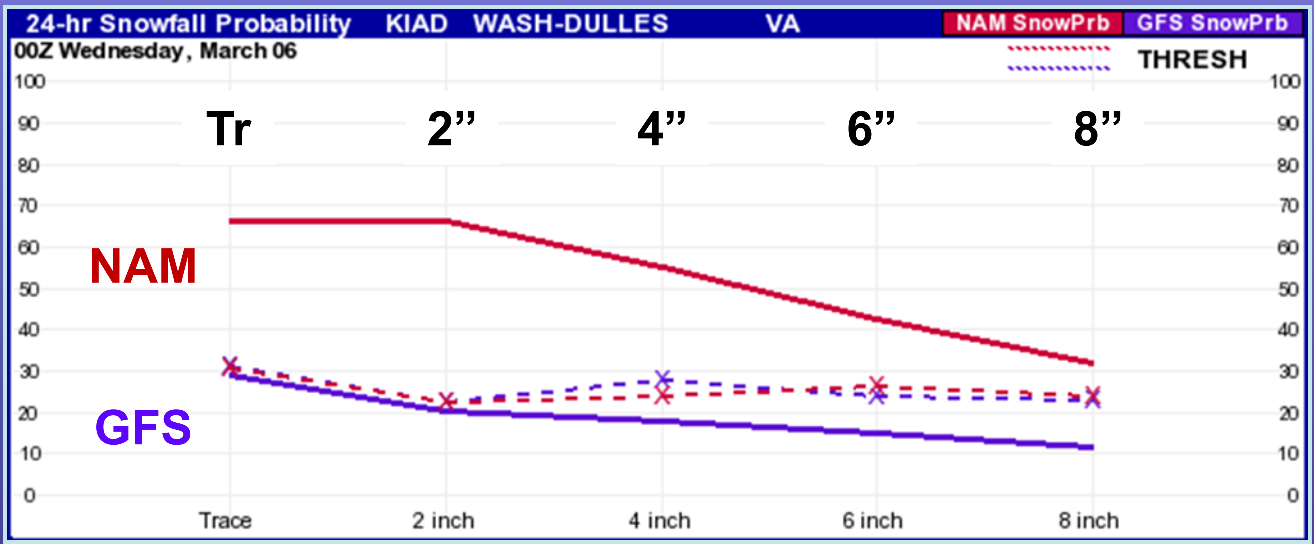


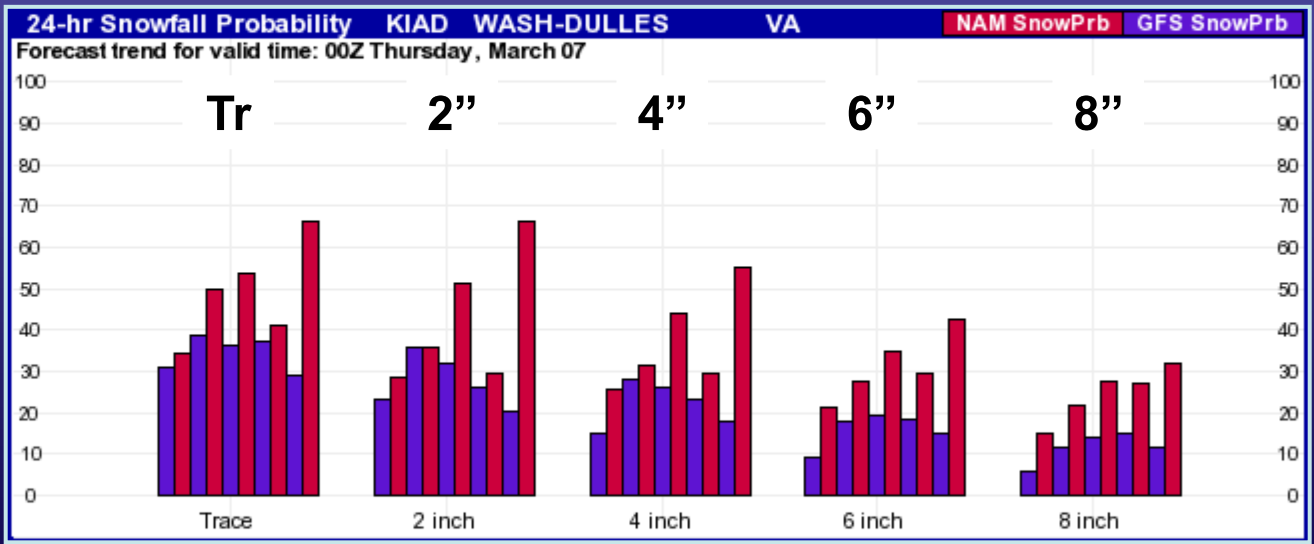
NAM gridded snow amount probability



GFS/NAM MOS 24-h snow amount probabilities

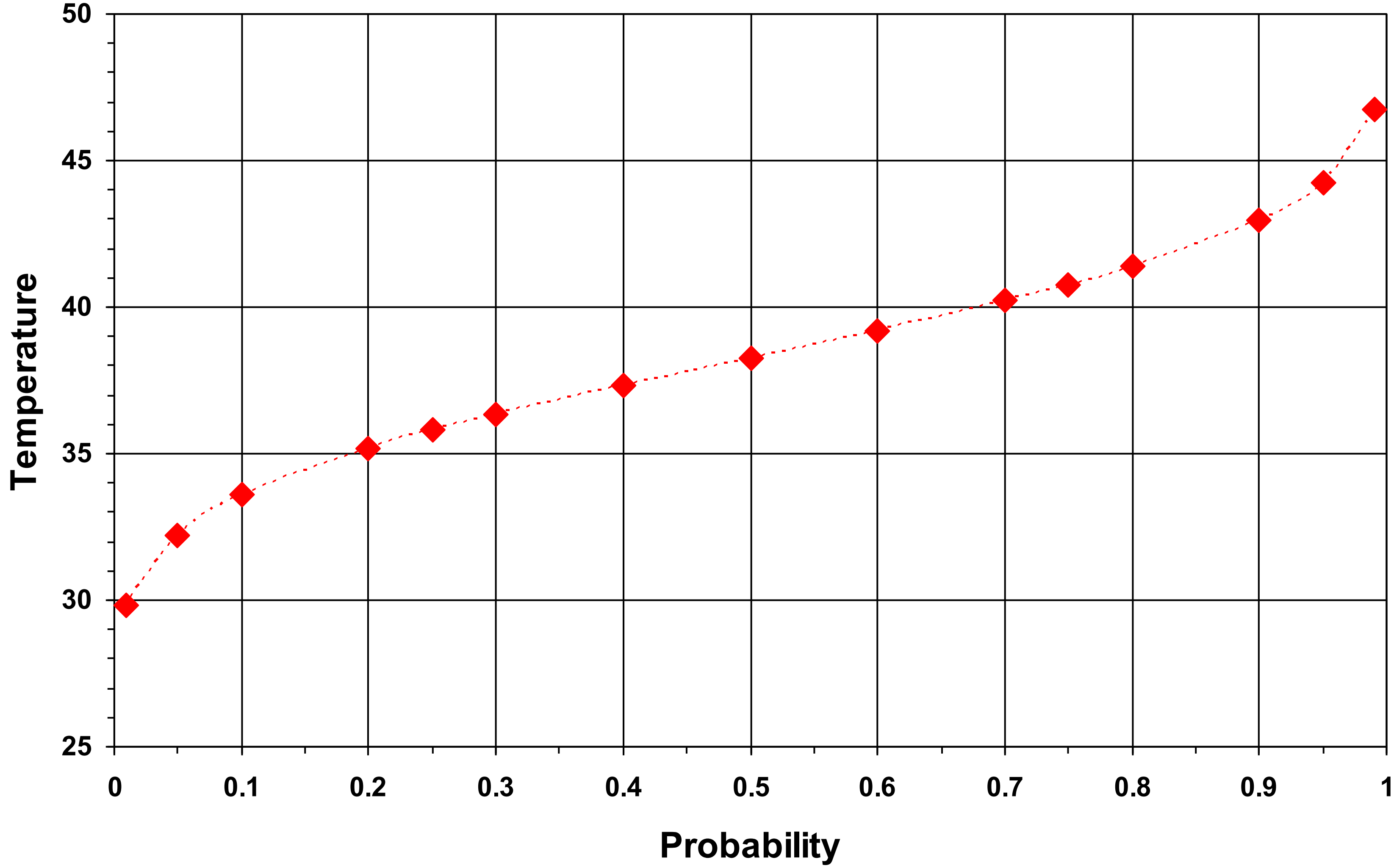
KIAD 00 UTC, 3/06/13





Sample Forecast as Quantile Function (CDF)

(72-h Temp KBWI 12/14/2004)



The Future of MOS

Gridded MOS: Where do we go from here?

- **Additions to current CONUS GMOS system**
  - "Predominant" weather grid
  - NAM-based companion system (short-range)
  - Probabilistic and/or ensemble-based products

- **Expand GMOS for AK / HI; add other OCONUS**
  - AK: Increase grid extent; improve marine winds
  - Hawaii: add QPF, Sky Cover
  - Puerto Rico

- **Improve GMOS interpolation procedures**

The Future of MOS

Gridded MOS: Where do we go from here?

- **Increase utilization of mesonet data**
  - Investigate MADIS archive (NCO/TOC/ESRL)
  - ~20,000 additional sites?

- **Incorporate remotely-sensed data where possible**
  - SCP augmented clouds / WSR-88D QPF (in use)
  - NSSL MRMS (Multi-radar, Multi-sensor) dataset?
  - New lightning datasets: Global, "Total" (CC & CG)

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Glahn, H.R., and D. Lowry, 1972: The use of model output statistics in objective weather forecasting, JAM, 11, 1203 - 1211.

Carter, G.M., et al., 1989: Statistical forecasts based on the NMC’s NWP System, Wea. & Forecasting, 4, 401 - 412.

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Glahn, H.R., et al., 2009: The Gridding of MOS., Wea. & Forecasting, 24, 520 – 529.