Probabilistic Forecasting in Practice

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AMS Short Course on Probabilistic Forecasting

San Diego, CA

January 9, 2005

Operational Probabilities

BALTIMORE WASHINGTON INTERNATIONAL

KBWI GFS MOS GUIDANCE 11/19/2004 1200 UTC

DT	/NOV 19		/NOV 20								/NOV 21								/NOV 22		
HR	18	21	00	03	06	09	12	15	18	21	00	03	06	09	12	15	18	21	00	06	12
N/X							49				58				48				64		42
TMP	58	57	54	52	52	52	52	54	56	56	54	53	53	52	51	58	62	61	54	48	44
DPT	51	51	51	50	51	52	52	52	52	52	53	52	51	50	49	50	49	47	47	40	38
CLD	OV	OV	OV	OV	OV	OV	OV	OV	OV	OV	OV	OV	OV	BK	BK	BK	BK	BK	SC	FW	BK
WDR	36	06	09	09	08	09	09	11	13	13	17	00	28	29	29	31	30	30	30	31	31
WSP	01	02	01	01	02	03	04	03	02	02	01	00	02	02	04	07	09	07	04	05	05
P06			44		57		48		34		38		4		6		2		1	1	5
P12							63				40				10				2		5
Q06			1		1		1		1		1		0		0		0		0	0	0
Q12							1				0				0				0		0
T06			2/ 8		5/ 0		2/ 0		0/ 0		0/13		0/ 0		0/ 0		0/ 0		1/14		0/ 0
T12					5/ 8				2/ 0				1/14				0/ 0			1/15	
POZ	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
POS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
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	7	6	6	5	3	3	3	3	3	3	4	4	5	6	8	6	6	7	8	8	8
VIS	6	6	6	5	5	3	3	4	5	5	5	5	5	5	2	7	7	7	7	7	7
OBV	N	N	N	BR	BR	BR	BR	BR	BR	BR	BR	BR	BR	FG	FG	N	N	N	N	N	N

Covert Probabilities

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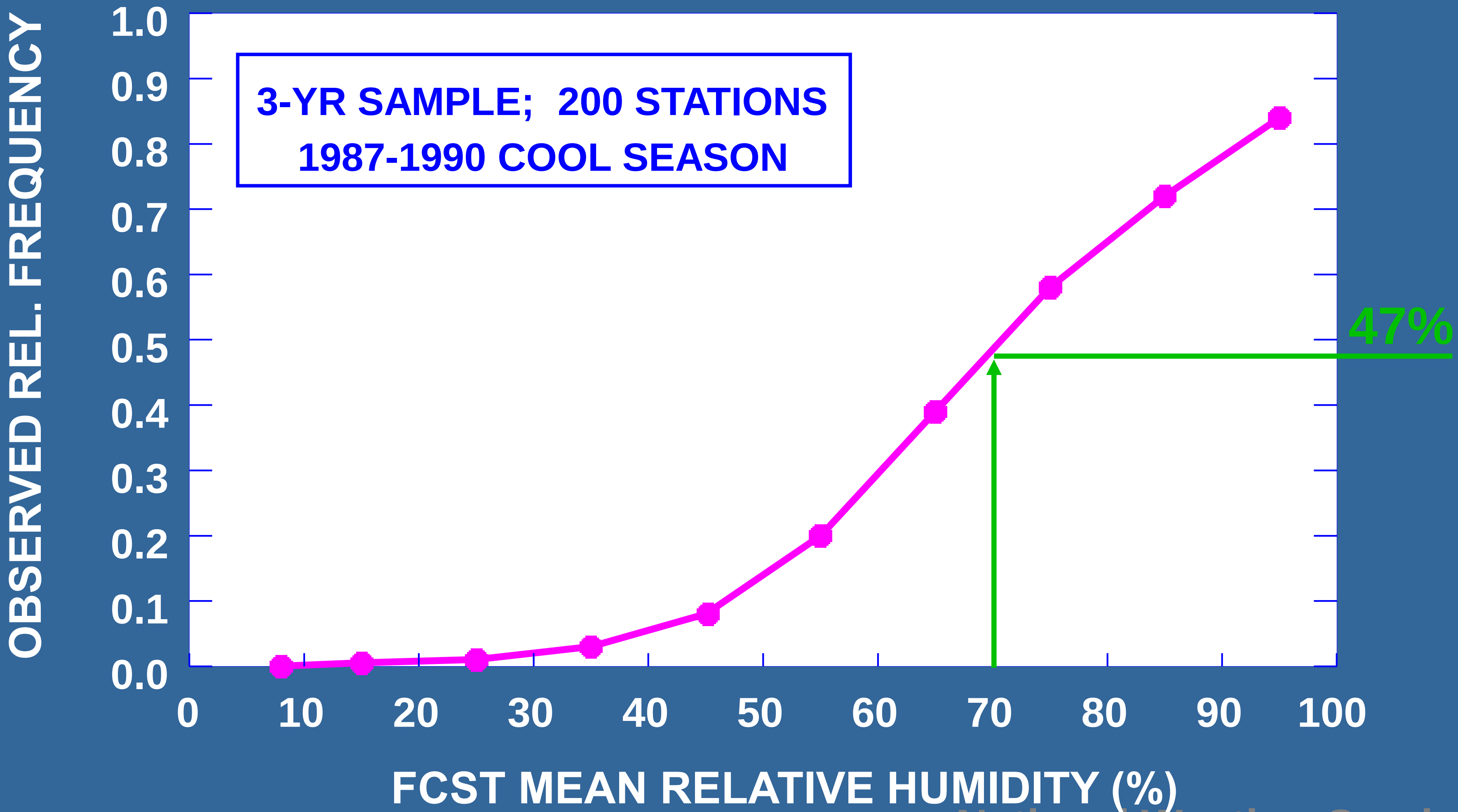
Q12							1				0				0				0		0
T06			2/ 8		5/ 0		2/ 0		0/ 0		0/13		0/ 0		0/ 0		0/ 0		1/14		0/ 0
T12					5/ 8				2/ 0				1/14				0/ 0			1/15	
POZ	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
POS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
TYP	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R
SNW							0								0						0
CIG	7	6	6	5	3	3	3	3	3	3	4	4	5	6	8	6	6	7	8	8	8
VIS	6	6	6	5	5	3	3	4	5	5	5	5	5	5	2	7	7	7	7	7	7
OBV	N	N	N	BR	BR	BR	BR	BR	BR	BR	BR	BR	BR	FG	FG	N	N	N	N	N	N

Outline

- Model Output Statistics (MOS)
  - *Definitions*
  - *Properties*
  - *Regression Estimation of Event Probabilities (REEP)*
- Predictand definitions
- Appropriate predictors
- Developmental considerations
- Application in an operational environment
- Sample forecasts
- Subjective probabilities

A SIMPLE STATISTICAL MODEL

Relative frequency of 12-24 h precipitation occurrence as a function of forecast relative humidity



Model Output Statistics (MOS)

Relates observations of the weather element to be predicted (predictand) to appropriate variables (predictors) via a statistical method

Predictors include:

- NWP model output
- Prior observations
- Geoclimatic data – terrain, normals, etc.

Current statistical method: multiple linear regression (forward selection)

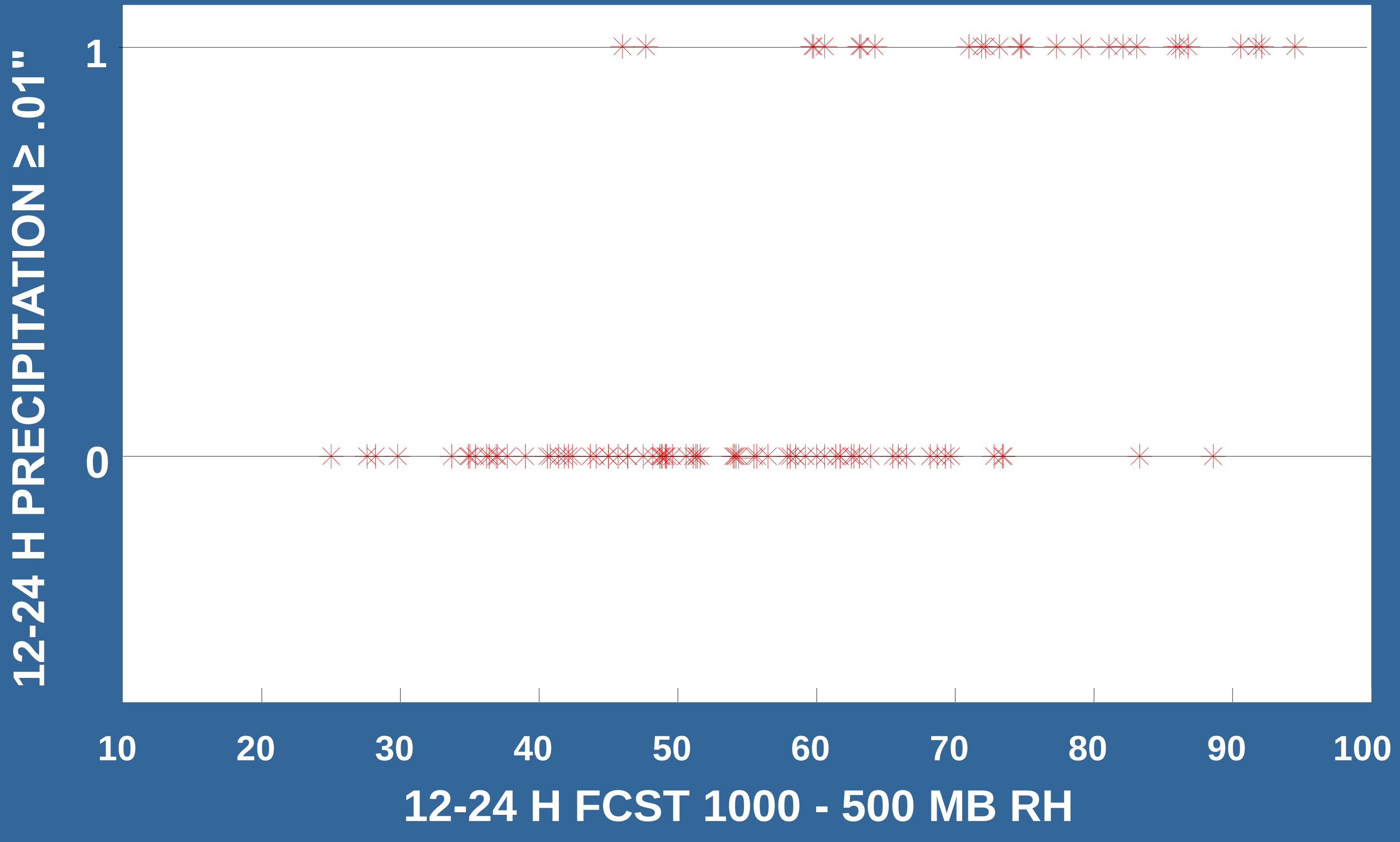
Properties of MOS Development

- Mathematically simple, yet powerful
- Models non-linearity through NWP variables and predictor transformations
- Uses record of observations at forecast points
- Applies equations to future run of similar forecast model
- Produces probability forecasts from a single run of the underlying NWP model
- Can use other mathematical methods such as logistic regression or neural networks

Regression Estimation of Event Probabilities (REEP)

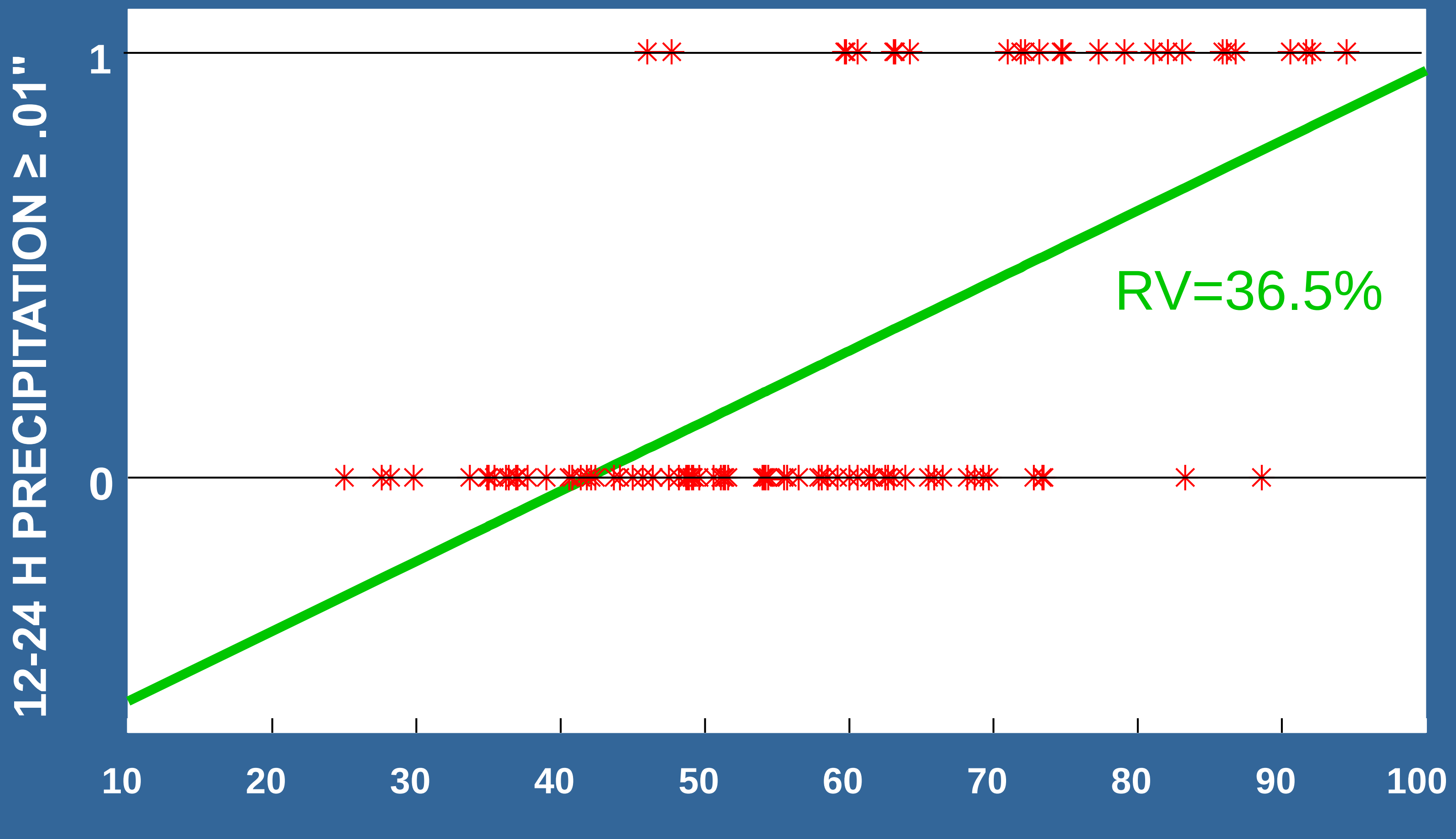
- Define the meteorological variable (predictand)
- Define the event in terms of categories of the predictand
- Transform predictand to a 0 (event does not occur) or a 1 (event occurs)
- Develop regression model relating predictand to predictors
- Interpret regression fit in terms of estimated relative frequencies, i.e., probabilities

Event Definition

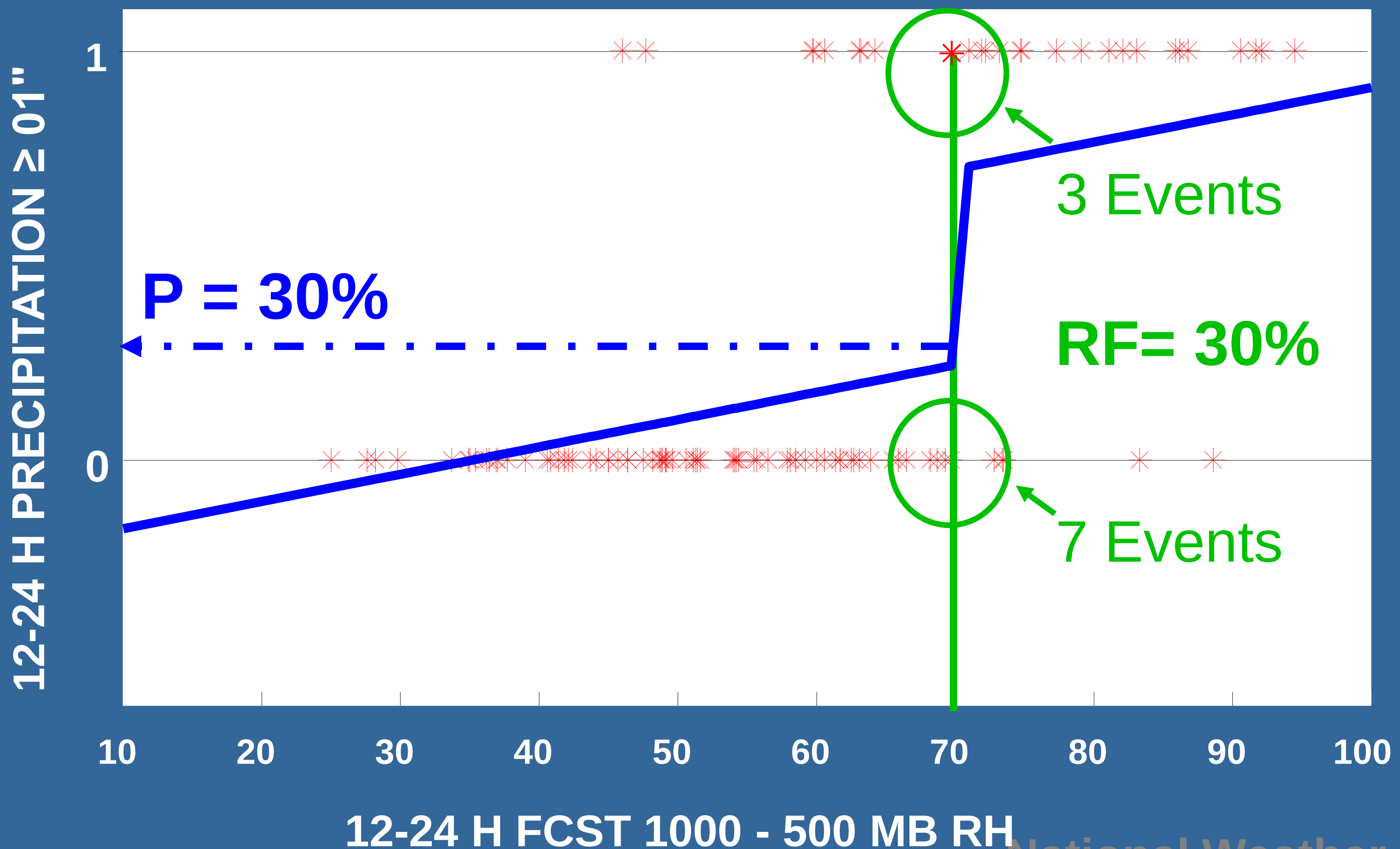


National Weather Service

Simple Linear Regression Fit



Regression Estimation of Event Probabilities



Properties of MOS Probabilities

- Unbiased –average of probabilities over a period of time equals long-term relative frequency of the event

- Reliable – conditionally ("piece-wise") unbiased over the range of probabilities

- Reflects predictability of event – range of probabilities narrows and approaches relative frequency of event as predictability decreases, with increasing projections or rare events

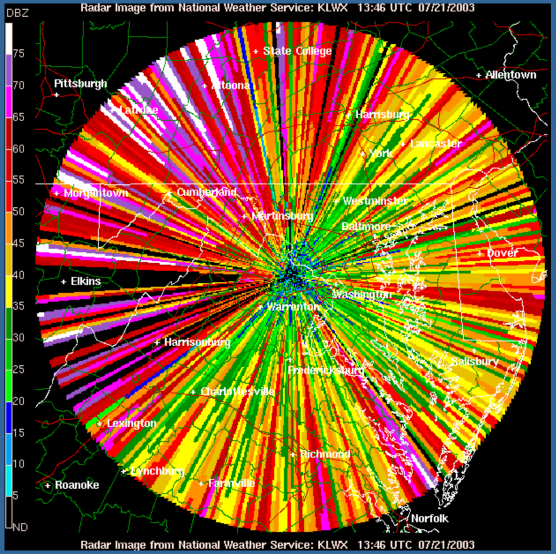
Probability Considerations

So, if the MOS probability represents the long-term relative frequency of the event, what is the event definition ???

- Meteorological element
- Characteristics of the observing system
- Point or areal extent
- Temporal resolution
- Categorical breakpoints
- Conditional on another event

Predictand Definitions

Suitable observations?



Appropriate Sensor?

Real ?

Good siting?

Snowfall Guidance
Dealing with Observational Systems

PORT HOPE, MI

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 KP58   GFSX MOS GUIDANCE   1/09/2004  0000 UTC
 FHR  24| 36  48| 60  72| 84  96|108 120|132 144|156 168|180 192
 FRI  09| SAT 10| SUN 11| MON 12| TUE 13| WED 14| THU 15| FRI 16 CLIMO
 X/N  10|  5  17| 14  33| 26  29| 13  15|  3   6|  2  11|  8  17 12 28
 TMP   8|  8  16| 20  31| 27  23| 15  12|  5   6|  4  10| 10  16
 DPT  -2|  1   3| 19  24| 22  15|  8   4|  1  -3| -6   1|  7   6
 CLD  OV| OV  OV| OV  OV| OV  OV| OV  PC| OV  OV| OV  OV| OV  OV
 WND  13|  8   7| 11  13| 13  12| 15  14| 13  12| 11  12| 12  11
 P12  12| 12  18| 49  75| 60  38| 46  28| 17  21| 28  25| 20  23999999
 P24    |     18|     75|     83|     51|     32|     38|     29   999
 Q12   0|  0   0|  1   1|  1   0|  1   0|  0   0|  0    |
 Q24    |      0|      1|      2|      1|      0|       |
 T12   2|  1   0|  1   1|  2   0|  0   0|  0   0|  0   0|  0   0
 T24    |  2    |  1    |  9    |  1    |  1    |  2    |  1
 PZP   0|  0   0|  0   0|  0   2|  0   0|  0   0|  0   1|  1   2
 PSN 100|100 100|100  99| 88  90|100 100| 99 100| 98  96| 96  95
 PRS   0|  0   0|  0   0| 12   9|  1   0|  1   1|  2   3|  2   1
 TYP   S|  S   S|  S   S|  S   S|  S   S|  S   S|  S   S|  S   S
 SNW    |      1|      2|      2|      2|       |       |
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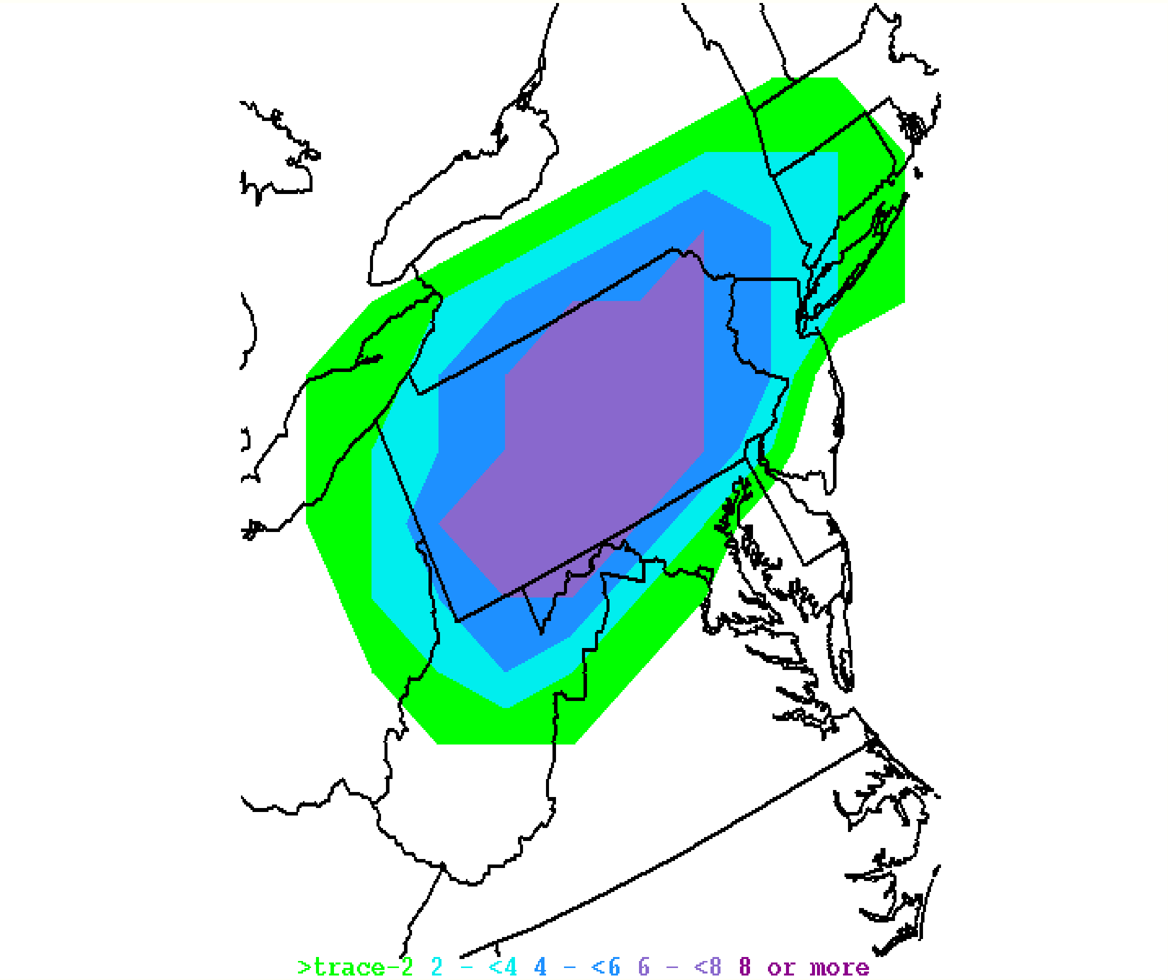
MOS Snowfall Guidance

Observations from Co-op Observer Network



Challenges of the Co-op Network

Station Selection:

- ***Some sites don’t report snowfall amount***
- ***Some sites open (or close) during the sample period***
- ***Some sites “move” either horizontally or vertically during the sample period***
- ***Some sites report neither accurately nor reliably***

More Challenges of the Co-op Network

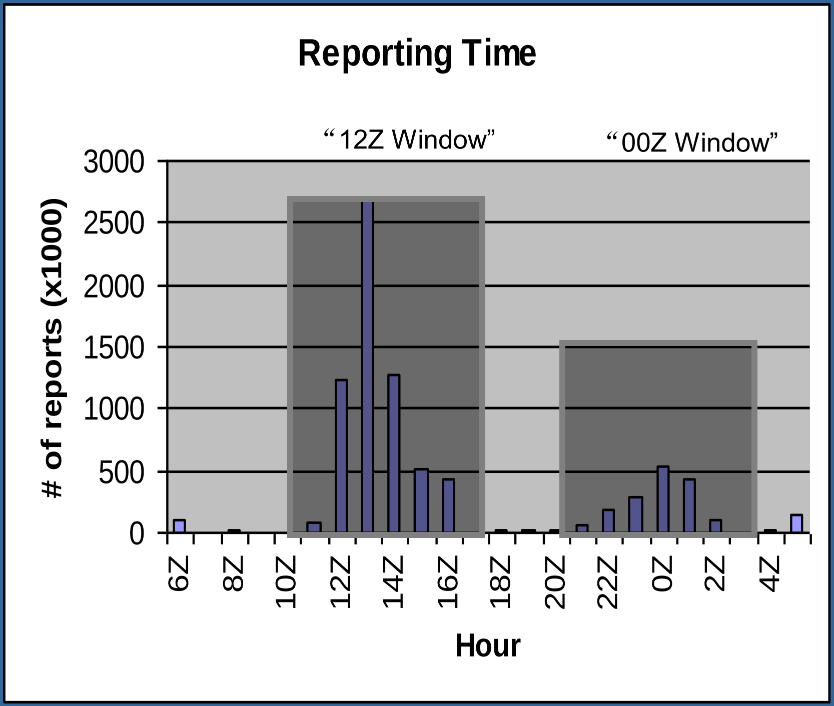
Station Reporting Time:

- ***Sites report once in a 24-hr period***
- ***Reporting times are site-specific and are in local time***
- ***Other hydrological elements are sometimes reported separately***
- ***Reporting times change at some sites during the sample period***

Strategy

Arrive at one "official" reporting time per site

Discard any site with multiple reporting times or multiple locations

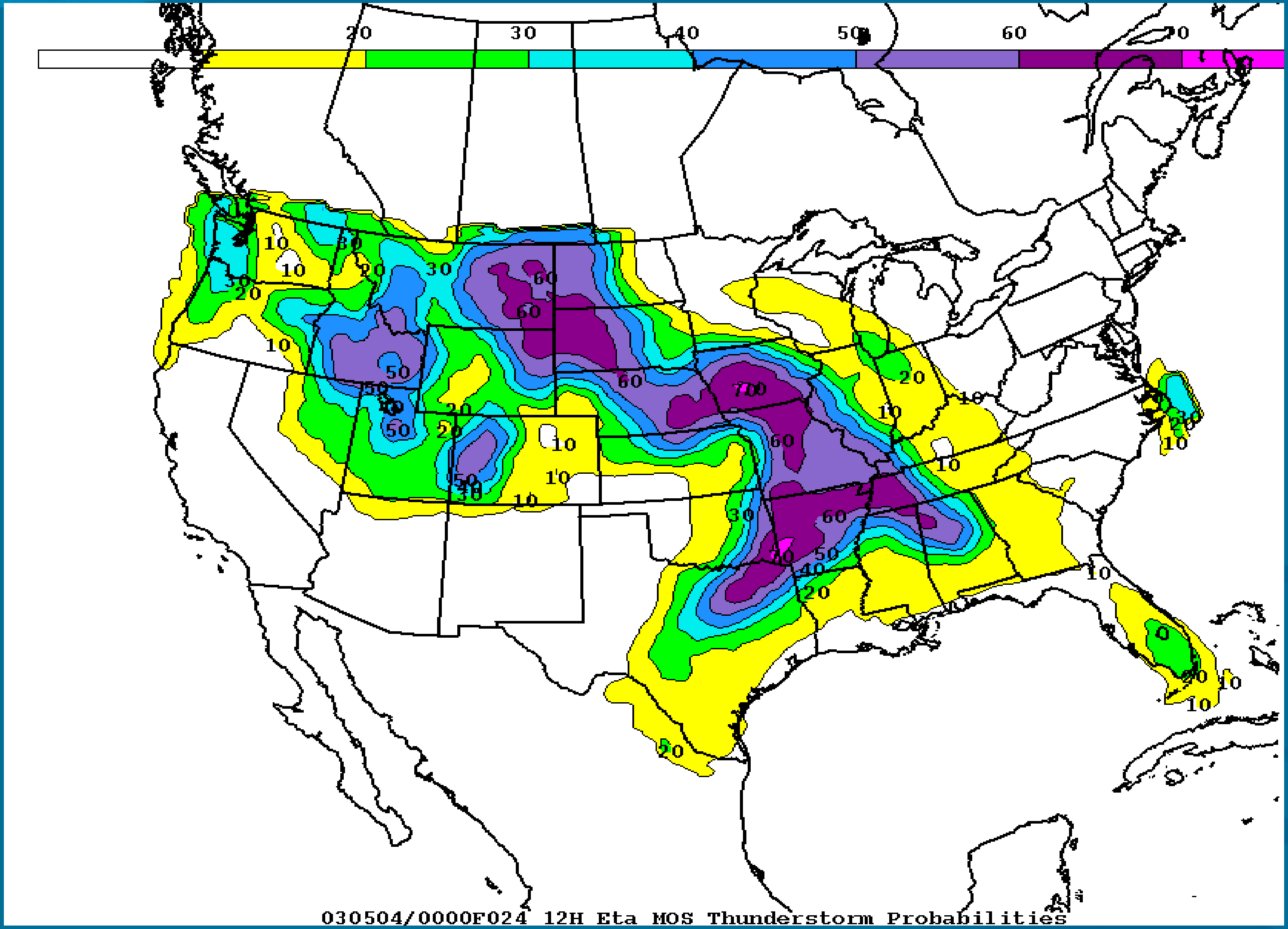


Two distinct "windows"

12Z: 11 – 17Z, 00Z: 21 – 3Z

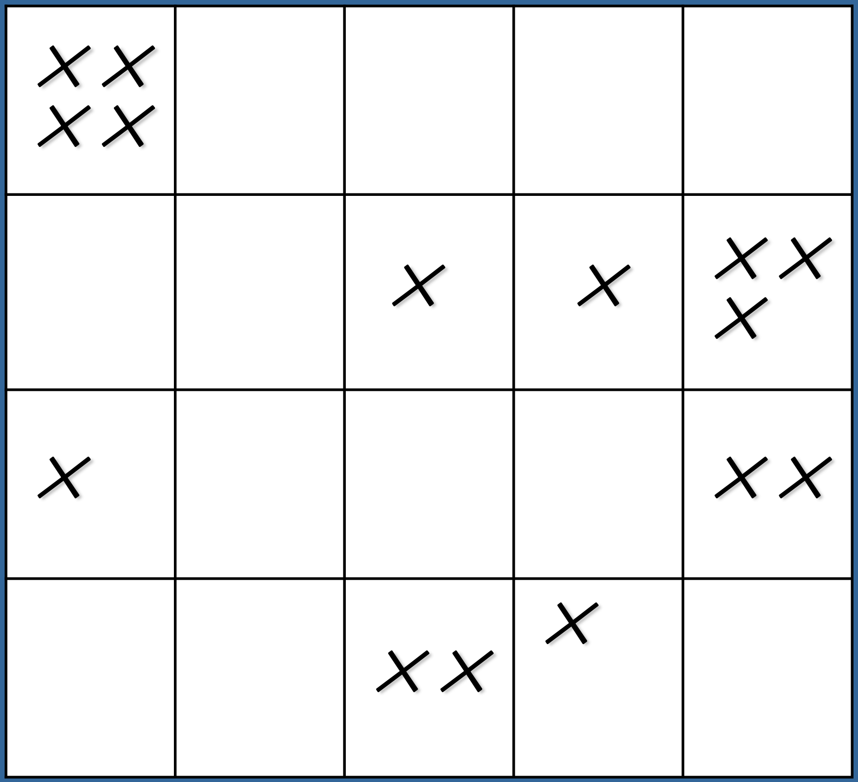
Discard any site outside the two windows

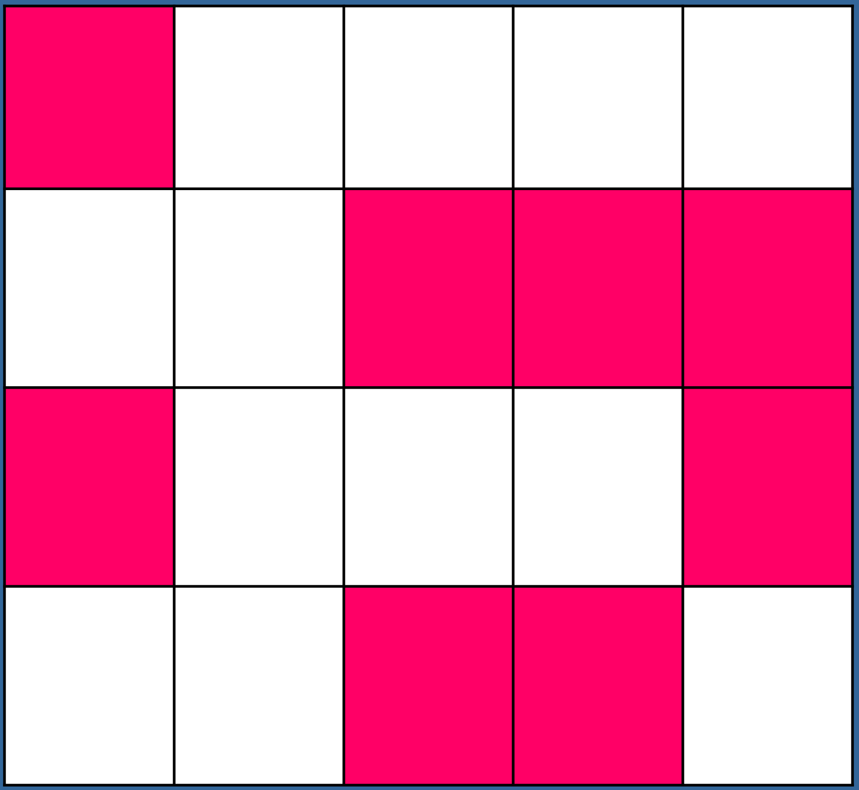
MOS Thunderstorm Probabilities -
Dealing with remote sensors



Creating Predictand Events

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





= thunderstorm

= no thunderstorm

What is "appropriate" for thunderstorms?

Time period?

1 hour

2 hours

3 hours

6 hours

12 hours

Grid size?

5 km

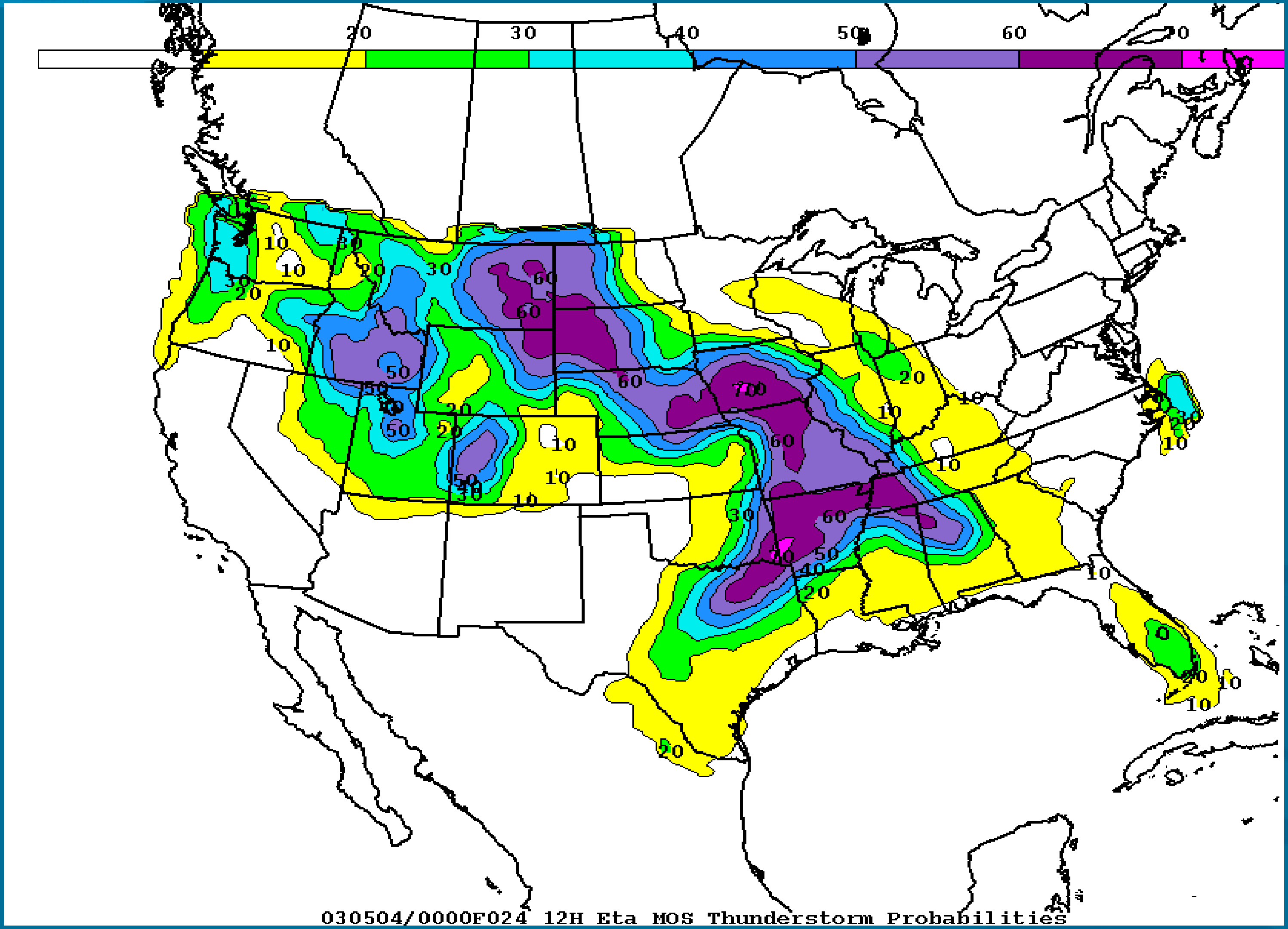
10 km

20 km

40 km

120 km

MOS Thunderstorm Probabilities - 12-h period, 40-km grid



Categorical Breakpoints
Define the event "Y" = 1 when …

Weather Element	Breakpoint
Prob. of Precip.	≥ .01 inches of liquid-equivalent
Thunderstorms	≥ 1 strike
Visibility (less than ½ mile)	< ½ mile
Sky cover (clear)	CLR/SKC

More Categorical Breakpoints

```
 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
...
CLD  CL BK BK BK OV OV OV OV OV OV OV OV OV OV OV OV OV BK CL CL CL
...
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
...
```

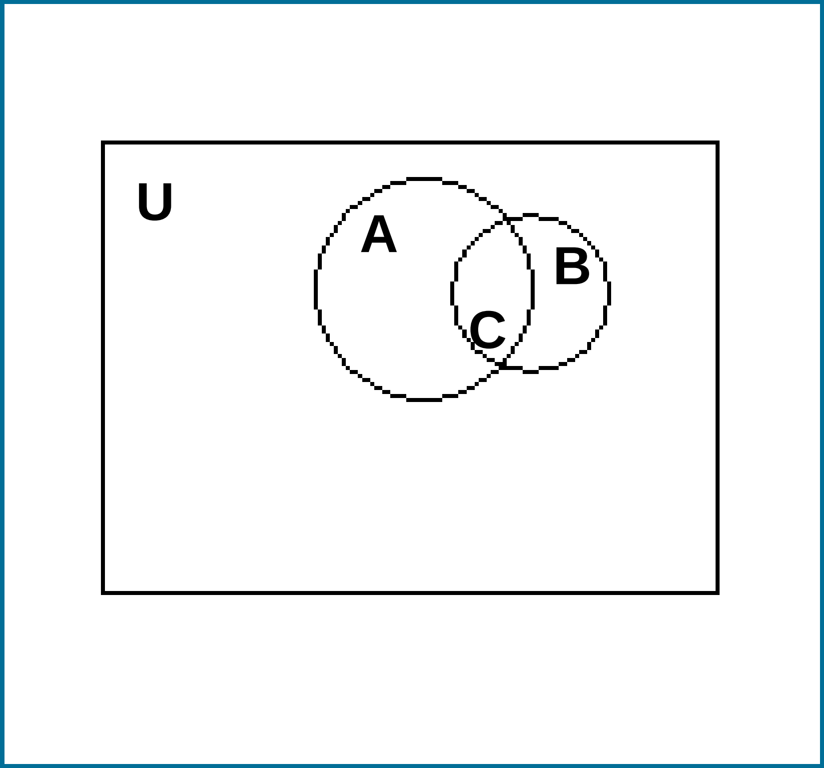
Ceiling Height

- Category 1: < 200 ft
- Category 2: 200 – 400 ft
- Category 3: 500 – 900 ft
- Category 4: 1000 – 1900 ft
- Category 5: 2000 – 3000 ft
- Category 6: 3100 – 6500 ft
- Category 7: 6600 – 12000 ft
- Category 8: > 12000 ft

Visibility

- Category 1: < 0.5 mi
- Category 2: 0.5 mi - < 1 mi
- Category 3: 1 - < 2 mi
- Category 4: 2 - < 3 mi
- Category 5: 3 – 5 mi
- Category 6: 6 mi
- Category 7: > 6 mi

Conditional Probabilities

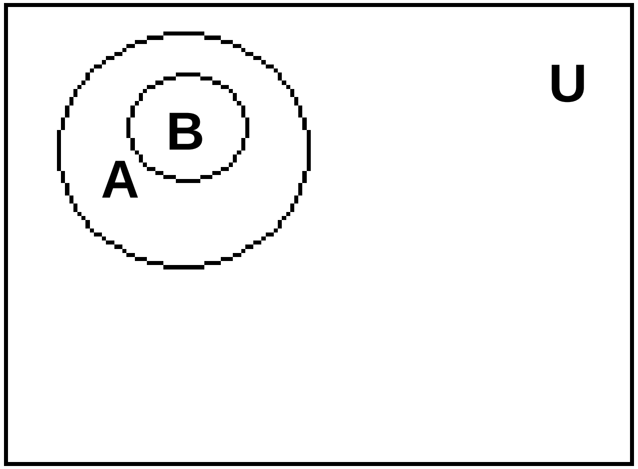


If event B is conditioned upon A occurring, then:

$$Prob(B/A)=Prob(A \cap B)/Prob(A)$$

or: $Prob(B/A)=Prob(C)/Prob(A)$

Conditional Event Probabilities



If event B is conditioned upon A occurring, then:

$Prob(B/A)=Prob(A \cap B)/Prob(A)$

or: $Prob(B/A)=Prob(B)/Prob(A)$

Examples:

If precipitation occurs, what is the probability that freezing rain will occur?

If precipitation occurs, what is the probability that 0.25 inches or more will occur?

Conditional Predictands

Precipitation type (condition: precipitation occurrence)

- freezing (FZDZ,FZRA,PL,mixtures)
- snow (SN or SG)
- liquid (RA,DZ,mixtures)

NOTE: exclusive and exhaustive

Precipitation amount (condition: $\geq$ 0.01 inches of precip.)

- $\geq$ 0.10 inches
- $\geq$ 0.25 inches
- $\geq$ 0.50 inches
- $\geq$ 1.00 inches
- $\geq$ 2.00 inches

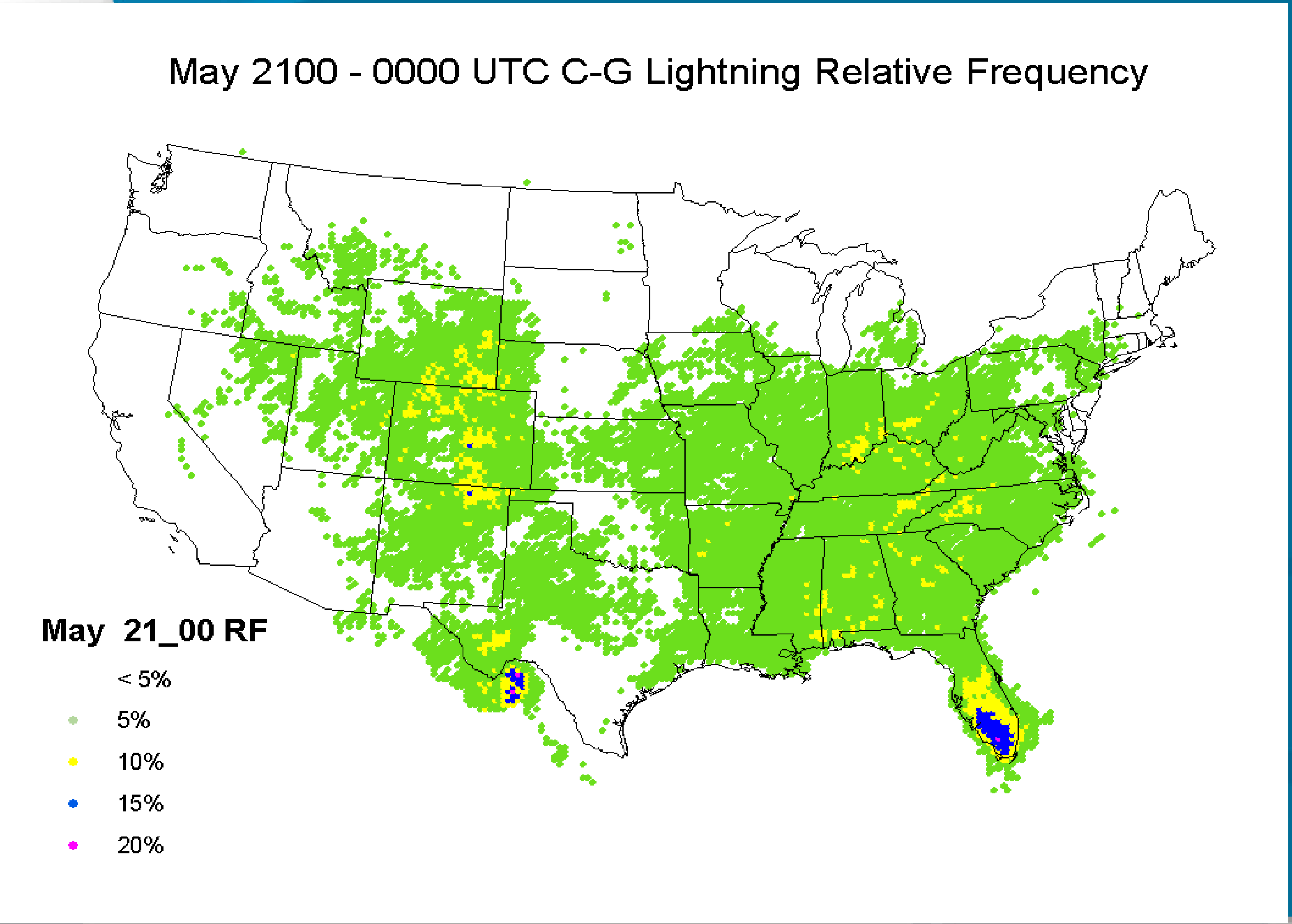
NOTE: not exclusive, but exhaustive

Appropriate Predictors

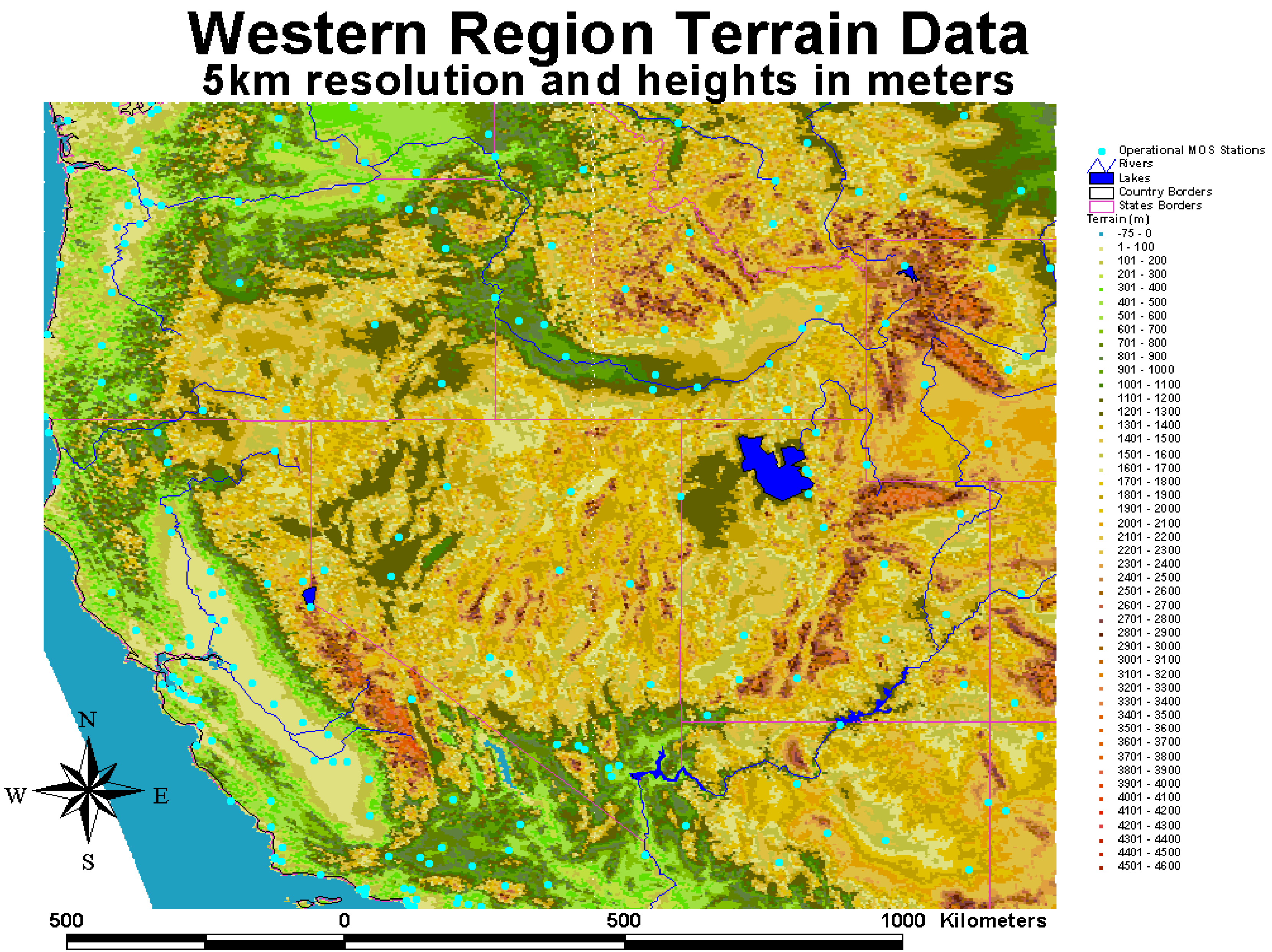
Predictor Considerations

- **Describe physical processes associated with event**
  - ***thunderstorms: CAPE, K-index, vertical velocity, etc.***
- **Avoid irrelevant variables**
  - ***thunderstorms: 1000-500 hPa thickness***
- **Use event relative frequencies or high-resolution geophysical variables (terrain) that contribute to local forcing of event**
- **Mimic forecaster thought process**
  - ***thunderstorms: interact relative frequency and K-index***
- **Provide non-linear transforms of predictors**

Relative Frequency Predictor



High-Resolution Terrain



Transform - Point Binary Predictor

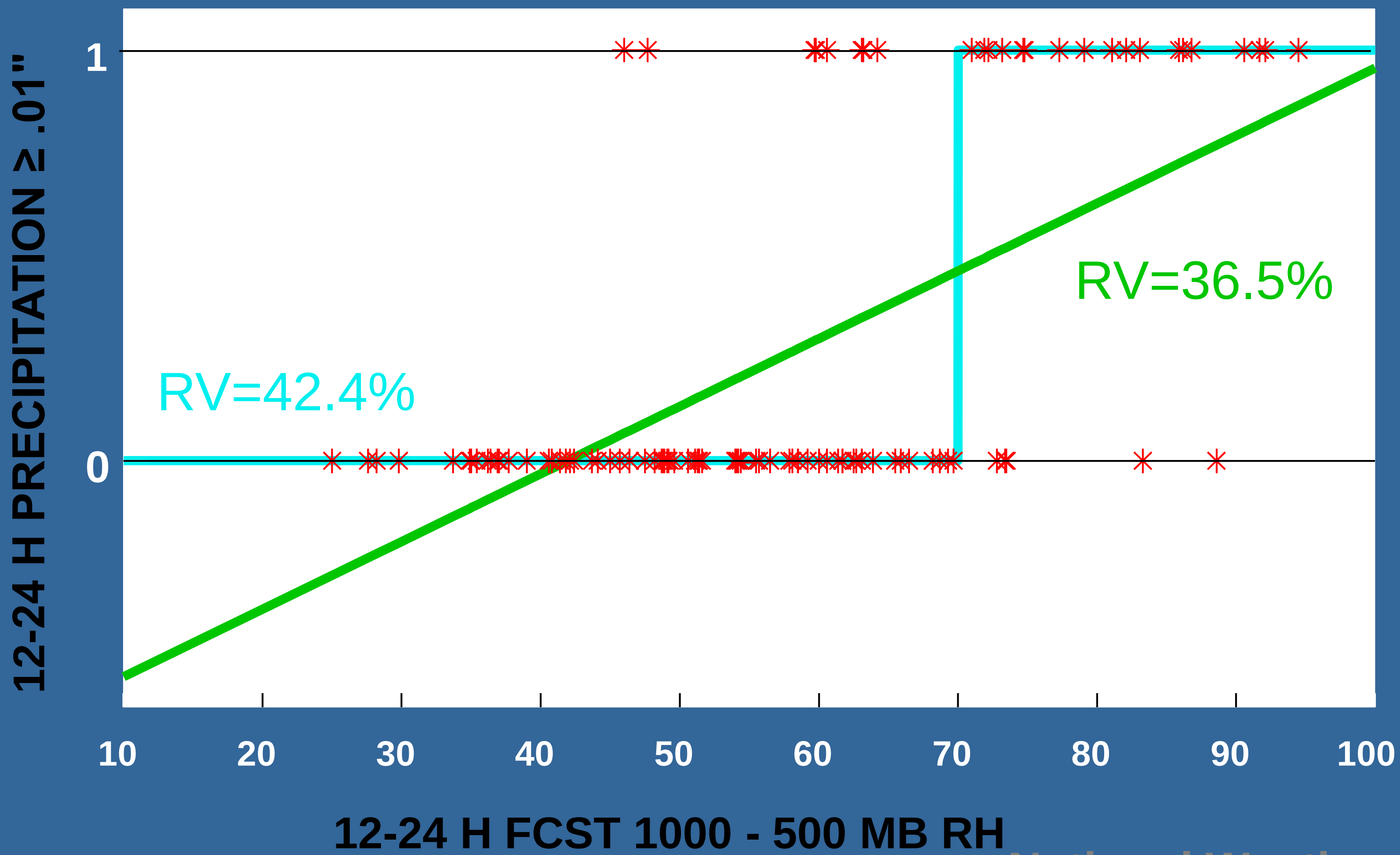
FCST 12-24 H MEAN RH PREDICTOR CUTOFF = 70%
INTERPOLATE; STATION RH ≥ 70% , SET BINARY = 1;
BINARY = 0, OTHERWISE

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

(71%) ● KCMH

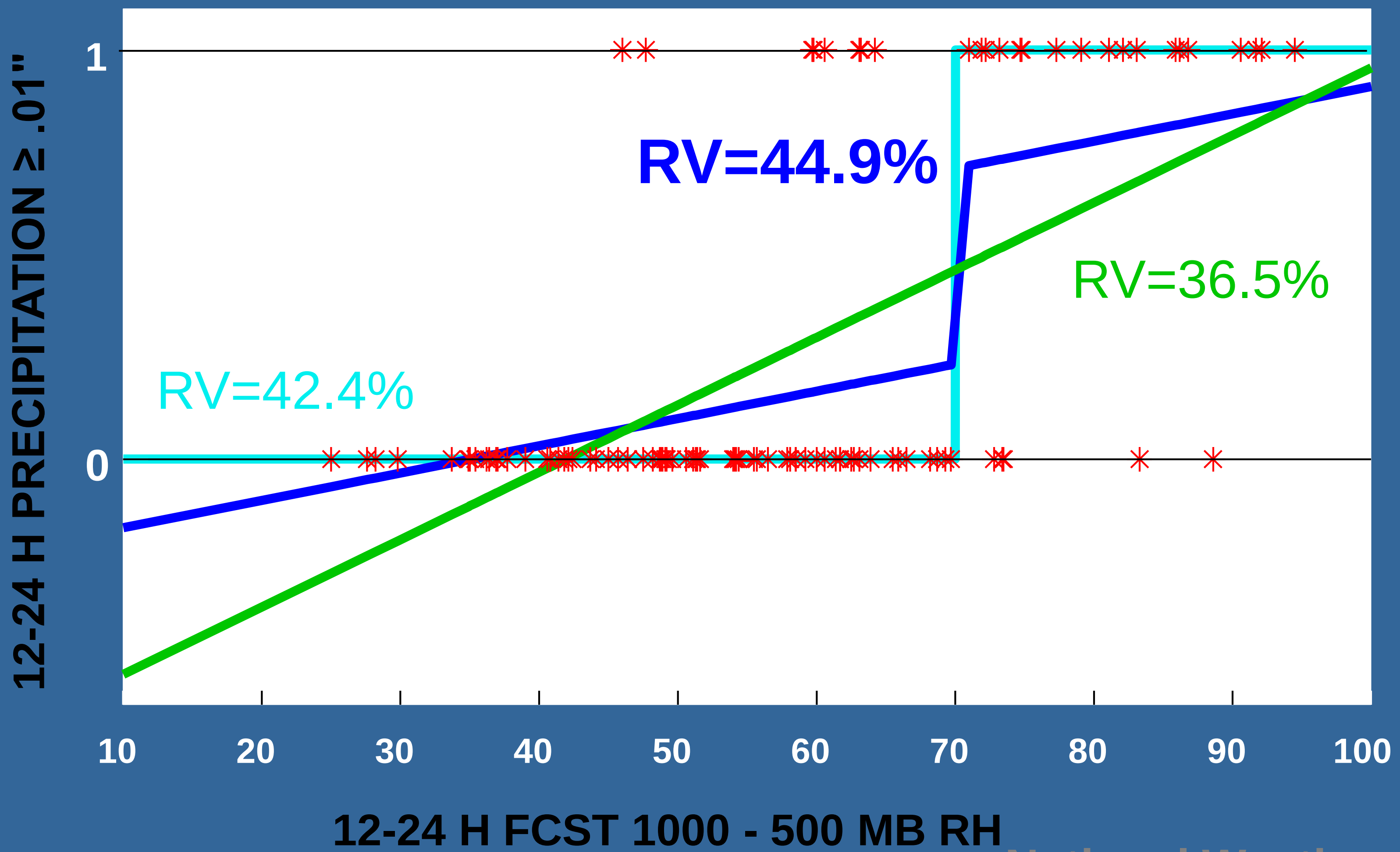
RH ≥70% ; BINARY AT KCMH = 1

Linear Regression – Point Binary Predictor Only



Linear Regression – Cont. & Point Binary Predictors

POP = -0.234 + (0.007∗RH) + (0.478∗BINARY RH (70%))



Transform - Grid Binary Predictor

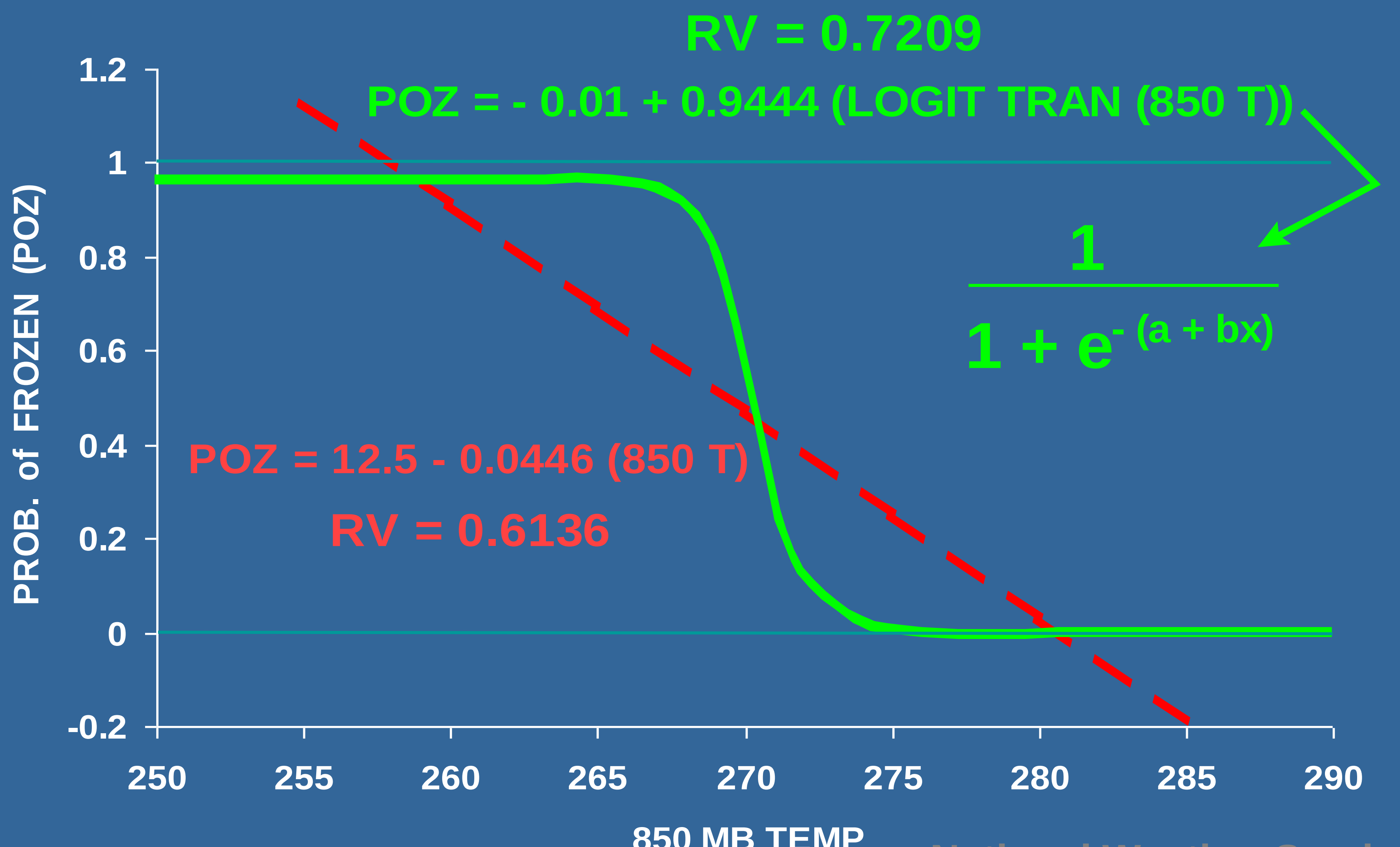
FCST 12-24 H MEAN RH PREDICTOR CUTOFF = 70%
WHERE RH > 70%, SET GRIDPOINT VALUE = 1; = 0, OTHERWISE;
INTERPOLATE TO STATION

1	1	1	1
1	1	1	1
	(.21) ● KCMH		
1	0	0	1
0	0	0	1

0 ≤ VALUE AT KCMH ≤ 1

Transform – Logit Fit

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



Developmental Considerations

Development in the Real World

Selection and quality control of the observational dataset

Precise definitions of predictand and conditioning (if any) events

Simultaneous development for related predictands

precipitation type:

freezing

snow

liquid

Note$_1$: exclusive and exhaustive

Note$_2$: sum of 3 probabilities should = 1

More Developmental Considerations

- **Choice of appropriate predictors**
- **Number of terms in the equation – selection criteria**
  - ***Multi-collinearity***
  - ***Overfit***
- **Stratification of developmental sample**
  - ***Forecast cycle***
  - ***Projection***
  - ***Season (cool, warm; winter; spring, summer, cool)***

Issues with the Developmental Sample

Size of sample

Representativeness of sample

Stability of sample

Frequency of event

- is event rare?

Pooling of data

- regionalized equations

- station specificity

Regionalized Probability Equations

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Q12							1				0				0				0		0
T06			2/ 8		5/ 0		2/ 0		0/ 0		0/13		0/ 0		0/ 0		0/ 0		1/14		0/ 0
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POS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
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	7	6	6	5	3	3	3	3	3	3	4	4	5	6	8	6	6	7	8	8	8
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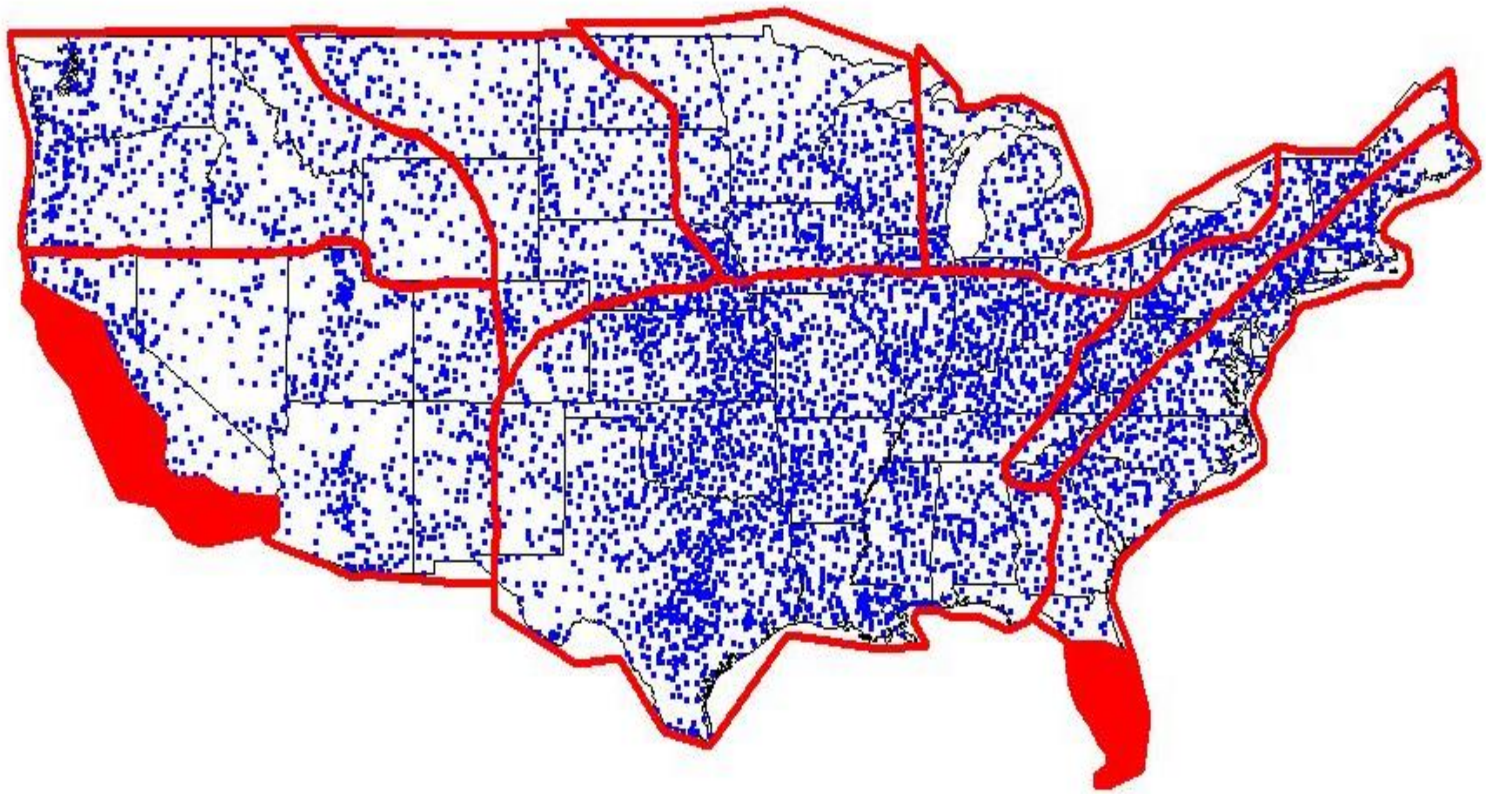
OBV	N	N	N	BR	BR	BR	BR	BR	BR	BR	BR	BR	BR	FG	FG	N	N	N	N	N	N

Regionalized Development – Snowfall Guidance



Operational 12-h PoP Equation
Mid-Atlantic, cool season, valid 12-24h after 00Z

$\text{Probability} = C_0 + C_1 * X_1 + C_2 * X_2 + \ldots$

All variables are grid binaries; mean RH is from 1000-700 hPa

Equation based on 11286 cases

Reduction of variance =.617

Term	Value	Var.	Proj.
C_0	.234		
C_1	.680	12h Prcp.	24
C_2	.221	Mean RH	12
C_3	-.230	500 VV	18
C_4	.210	Mean RH	18
C_5	-.109	K Index	18

Sample 12-h PoP Equation
BWI, cool season, valid 12-24h after 00Z

Probability = $C_0 + C_1 * X_1 + C_2 * X_2 + \ldots$

Variable is a grid binary; breakpoint of 0.05 inches

Equation based on 361 cases; 84 precip. events

Reduction of variance =.639

Term	Value	Var.	Proj.
C_0	.014		
C_1	.987	12h Prcp.	24

Operational Precip. Type Equations
Mid-Atlantic, valid 18h after 00Z

Probability = $C_0 + C_1 * X_1 + C_2 * X_2 + \ldots$

Note: Trans. Thk. Is a function of 1000-850 hPa thk.

Thk. Is a grid binary of the 1000-925 hPa thk.

Term	FZ	SN	RN	Var.	Proj.
C_0	.003	.252	.746		
C_1	-.032	.823	-.790	Trans. Thk.	18
C_2	.169	-.087	-.082	Vert. ZR	15
C_3	.643	-.080	-.563	ZR RFreq	18
C_4	.104	-.152	.048	Vert. ZR	21
C_5	-.009	-.248	.257	Thk.	18

Application in an Operational Environment

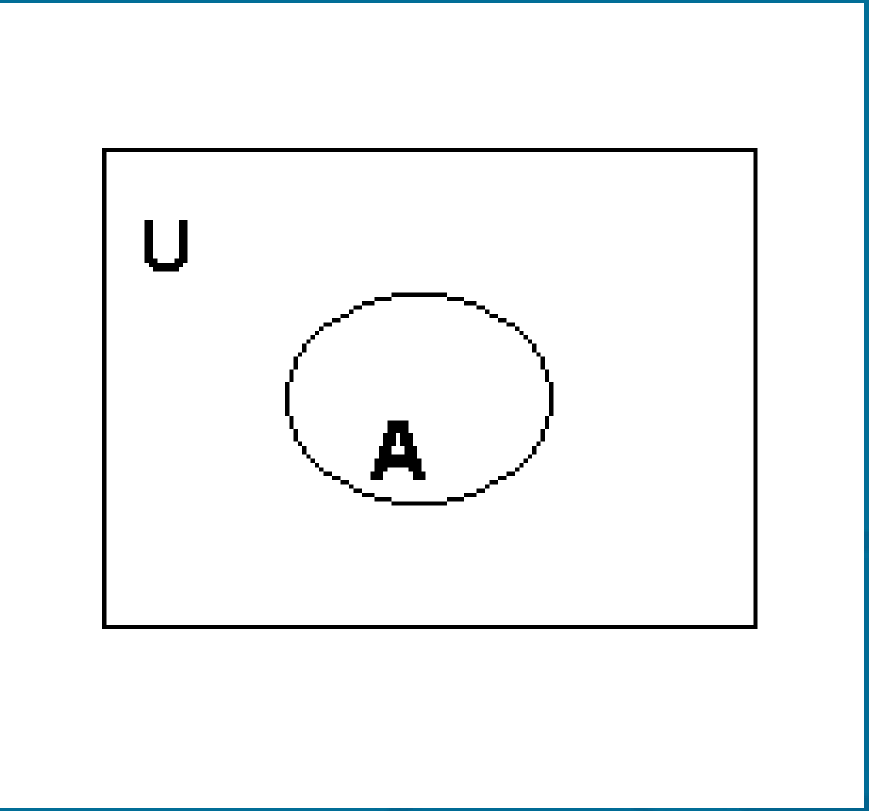
Truncating Probabilities

$0 \leq$ Prob (A) ≤ 1.0

Applied to PoP's and thunderstorm probabilities

If Prob(A) < 0, Prob_{adj} (A)=0

If Prob(A) > 1, Prob_{adj} (A)=1.



Normalizing Categorical Probabilities

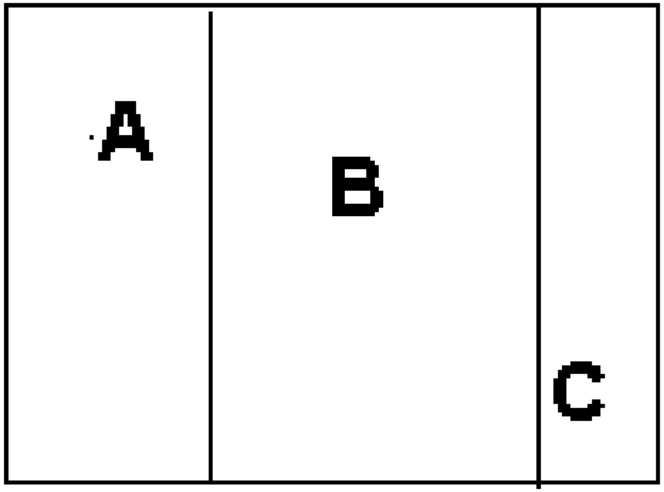
Sum of probabilities for exclusive and exhaustive categories must equal 1.0

If Prob (A) < 0, then sum of Prob (B) and Prob (C) = D, and is > 1.0.

Set: Prob_{adj} (A) = 0,

Prob_{adj} (B) = Prob (B) / D,

Prob_{adj} (C) = Prob (C) / D



Monotonic Categorical Probabilities

If event B is a subset of event A, then:

Prob (B) should be ≤ Prob (A).

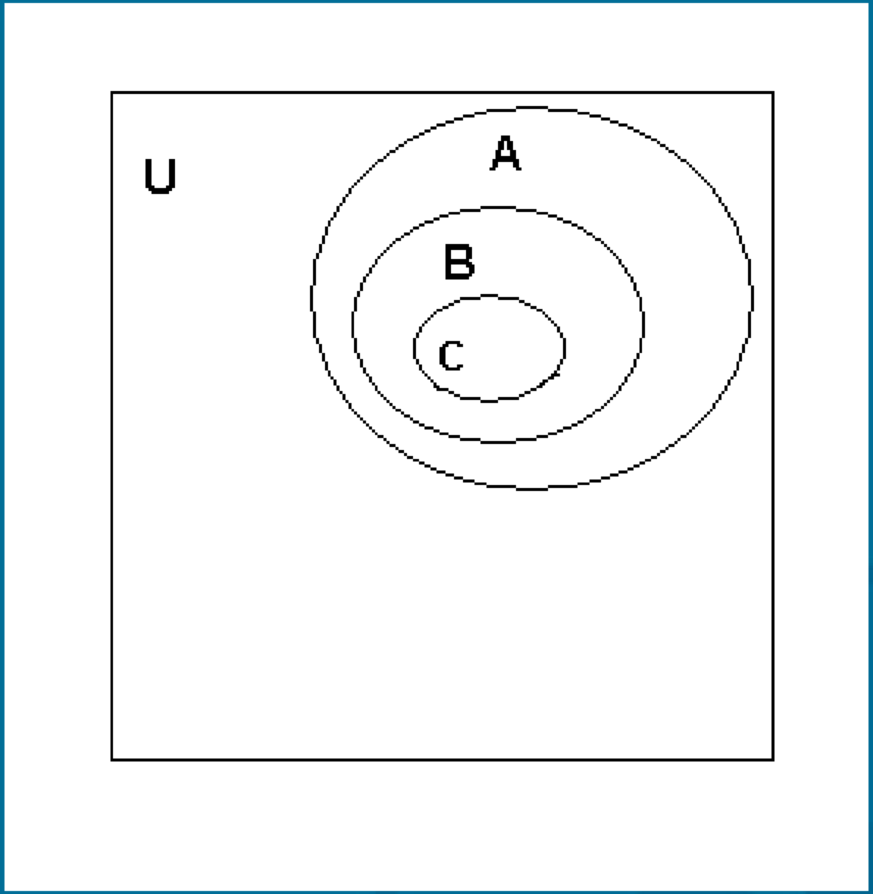
Example: B is ≥ 0.25 in; A is ≥ 0.10 in

Then, if Prob (B) > Prob (A)

set $Prob_{adj}$ (B) = Prob (A).

Now, if event C is a subset of event B, e.g., C is ≥ 0.50 in, and if Prob (C) > Prob (B),

set $Prob_{adj}$ (C) = Prob (B)



Unconditional Probabilities from Conditional

If event B is conditioned upon A occurring:

Prob(B/A)=Prob(B)/Prob(A)

Prob(B) = Prob(A) $\times$ Prob(B/A)

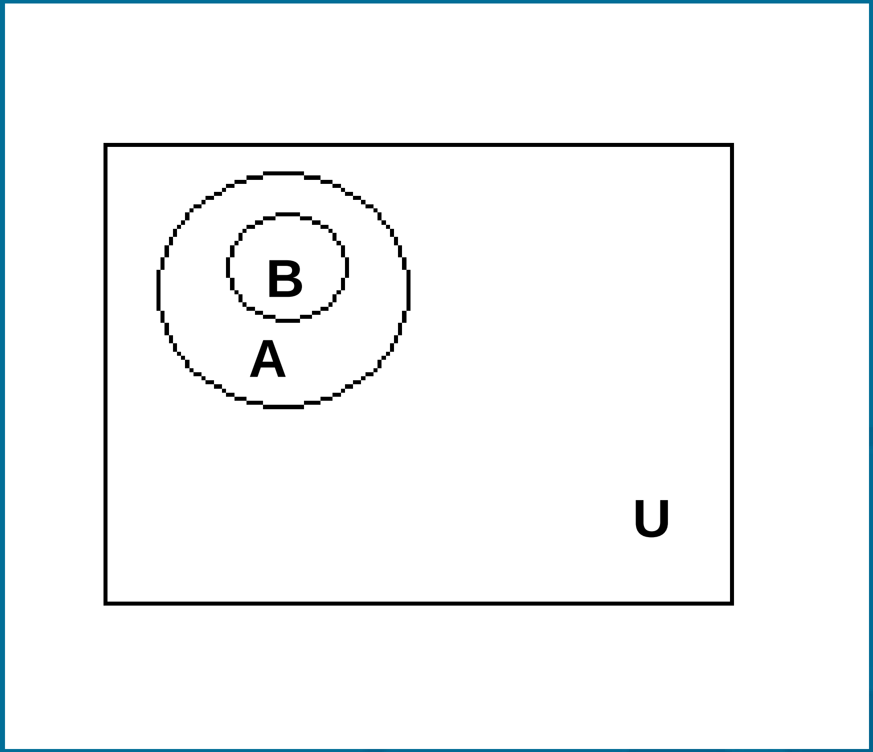
Example:

Let A = event of $\geq$ .01 in., and B = event of $\geq$ .25 in., then if:

Prob (A) = .70, and

Prob (B/A) = .35, then

Prob (B) = .70 $\times$ .35 = .245



Temporal Coherence of Probabilities

Event A is ≥ 0.01 in. occurring from 12Z-18Z

Event B is ≥ 0.01 in. occurring from 18Z-00Z

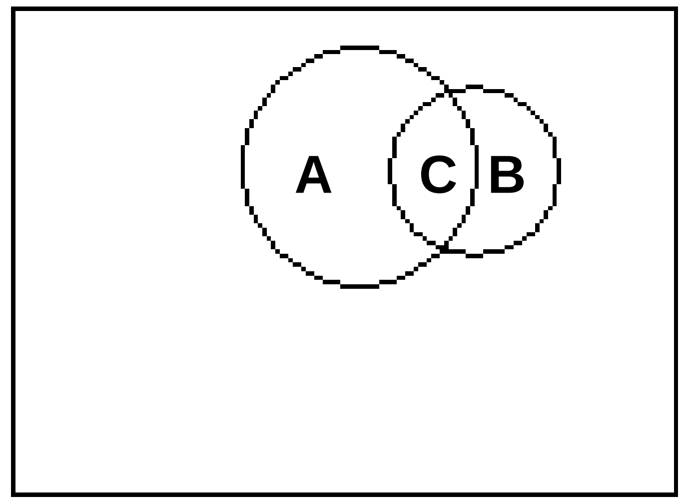
$A \cup B$ is ≥ 0.01 in. occurring from 12Z-00Z

Then $P(A \cup B) = P(A) + P(B) - P(A \cap B)$

Thus, $P(A \cup B)$ should be:

≤ P(A) + P(B) and

≥ maximum of P(A), P(B)



Temporal Coherence - Partially Enforced

Thus, P(A∪B) should be:

≤ P(A) + P(B) – coherence not checked

≥ maximum of P(A), P(B) – coherence checked

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SAN DIEGO
 KMYF   GFS MOS GUIDANCE   12/28/2004  1200 UTC
 DT /DEC  28/DEC  29                /DEC  30                /DEC  31
 HR   18 21 00 03 06 09 12 15 18 21 00 03 06 09 12 15 18 21 00 06 12
 …
 P06        79    71   100    68     5     6    14     9    16 21 28
 P12                   100          68          19          25    32
 Q06         4     3     5     2     0     0     0     0     0  0  1
 Q12                     5           2           0           0     0
 T06      9/ 0 30/ 2 22/ 4  9/ 0  0/ 0  0/ 0  0/ 0  0/ 0  1/ 0  0/ 0
 T12           47/ 3       29/ 4        0/ 0        0/ 0     3/ 0
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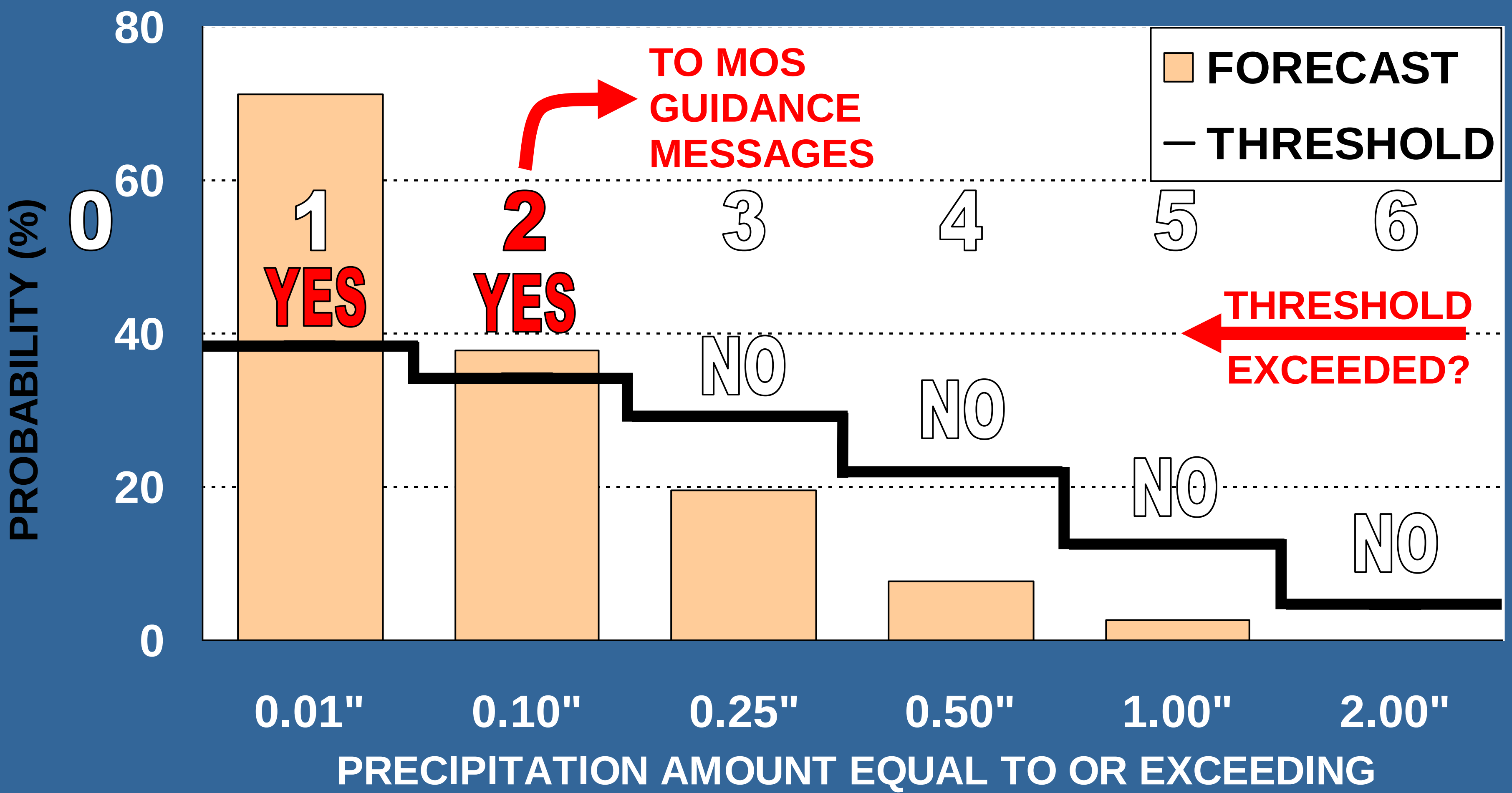
Other Possible Post-Processing

- Compute the expected value
  - used for estimating precipitation amount
- Fit probabilities with a distribution
  - Weibull distribution used to estimate median or other percentiles of precipitation amount
- Calculate time-interval probability from probabilities for two or more subintervals
- Estimate “best” category forecast
  - definition of “best” depends on the user
- Reconcile meteorological inconsistencies
  - difficult to do
  - inconsistencies minimized somewhat by use of NWP model in developmental and operational processes

MOS BEST CATEGORY SELECTION

Using QPF Probabilities as an Example



Meteorological Consistency

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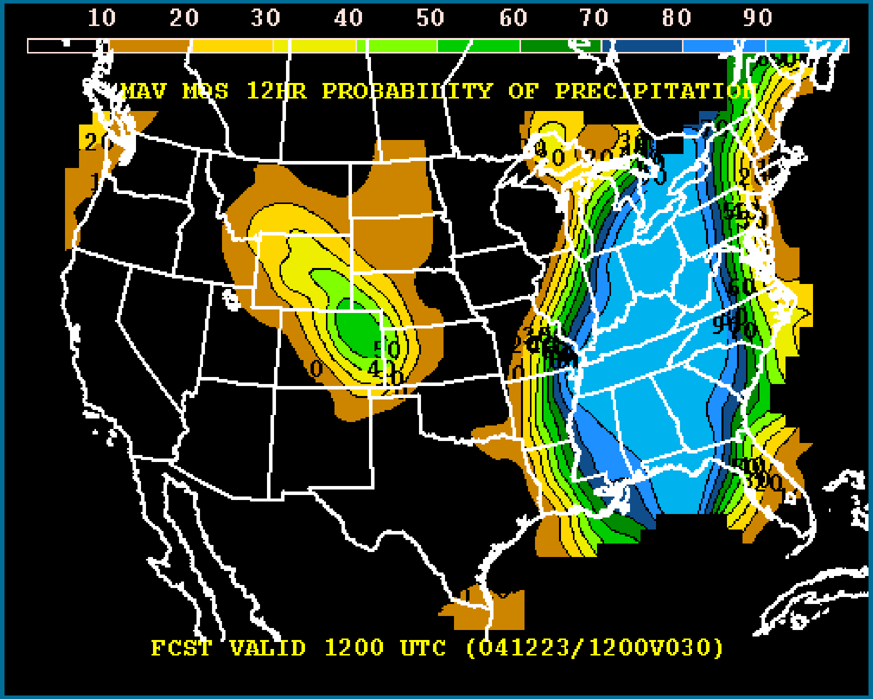
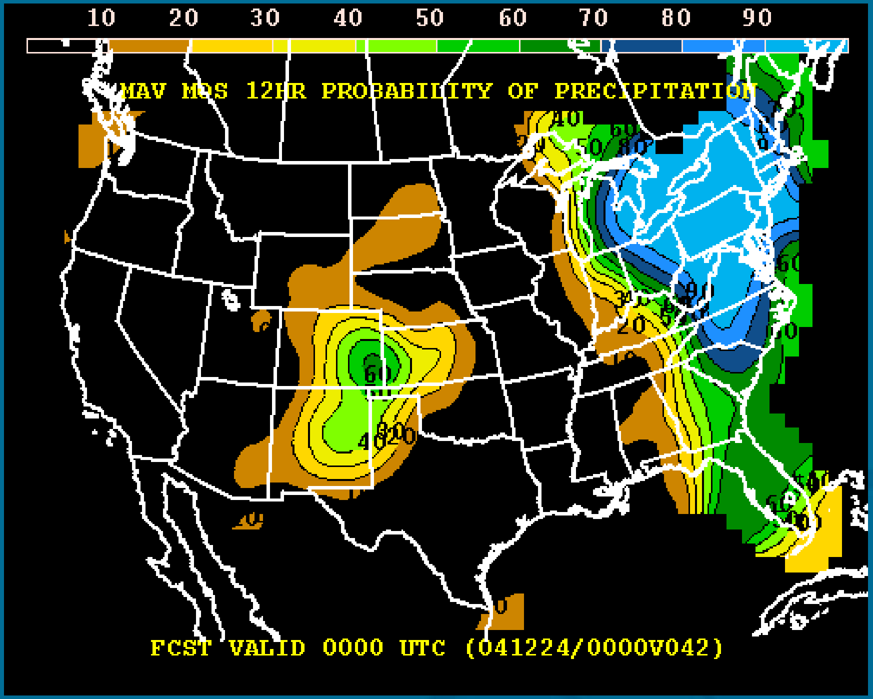
BALTIMORE WASHINGTON INTERNATIONAL
 KBWI    GFSX MOS GUIDANCE  12/29/2004  0000 UTC
 FHR   24| 36   48| 60   72| 84   96|108 120|132 144|156 168|180 192
 WED   29| THU 30| FRI 31| SAT 01| SUN 02| MON 03| TUE 04| WED 05 CLIMO
 X/N   53| 34   50| 36   57| 41   62| 37   56| 41   54| 34   46| 33   51 25 41
 TMP   45| 38   43| 40   51| 44   50| 40   49| 44   45| 36   39| 37   44
 DPT   33| 31   36| 38   44| 36   38| 37   42| 39   35| 29   29| 32   35
 CLD   PC| PC   PC| OV   OV| CL   CL| OV   OV| OV   OV| OV   OV| OV   OV
 …
 P12    3|  4    1| 20   28| 12    3|  9   36| 34   25| 25   23| 30   26 22 24
 P24     |      10|      31|      12|      36|      38|      36|      30    34
 Q12    0|  0    0|  0    0|  0    0|  0    1|  1    0|  0     |
 Q24     |       0|       0|       0|       0|       1|        |
 …
 PZP    4| 10   13|  9    7|  9    8| 10    8| 10    8| 21   22| 18   13
 PSN    0|  3    0|  0    0|  0    0|  0    0|  0    0|  0   11| 13    8
 PRS   12|  8    5|  0    0|  0    2|  0    0|  0    5|  5    6|  0    0
 TYP    R|  R    R|  R    R|  R    R|  R    R|  R    R|  R    Z|  R    R
 SNW     |       0|       0|       0|       0|       |        |
```

Some Sample Forecasts

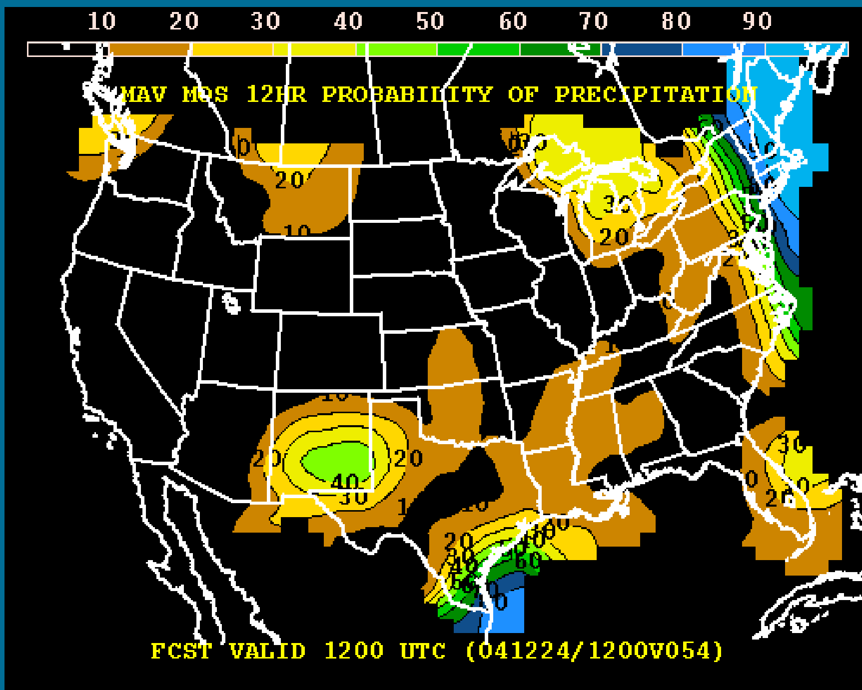
See http://www.nws.noaa.gov/tdl/synop/products.shtml

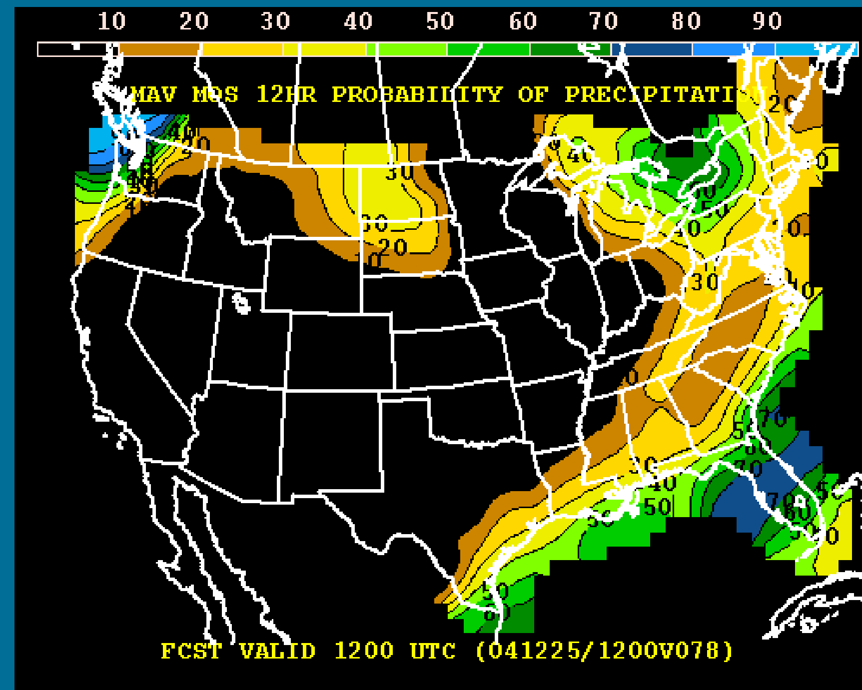
12-h PoPs, valid Dec. 23 & 24, 2004



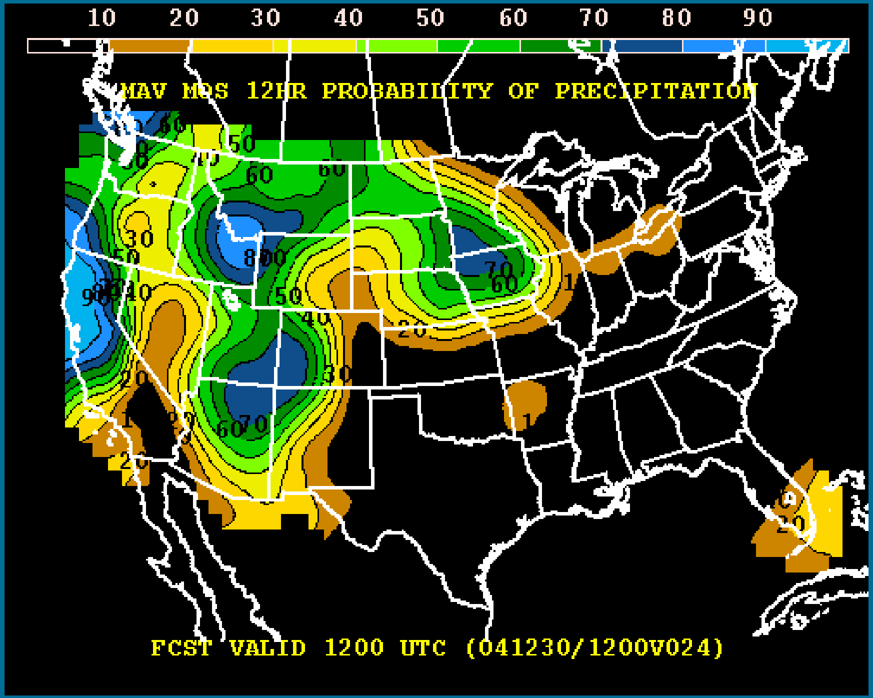


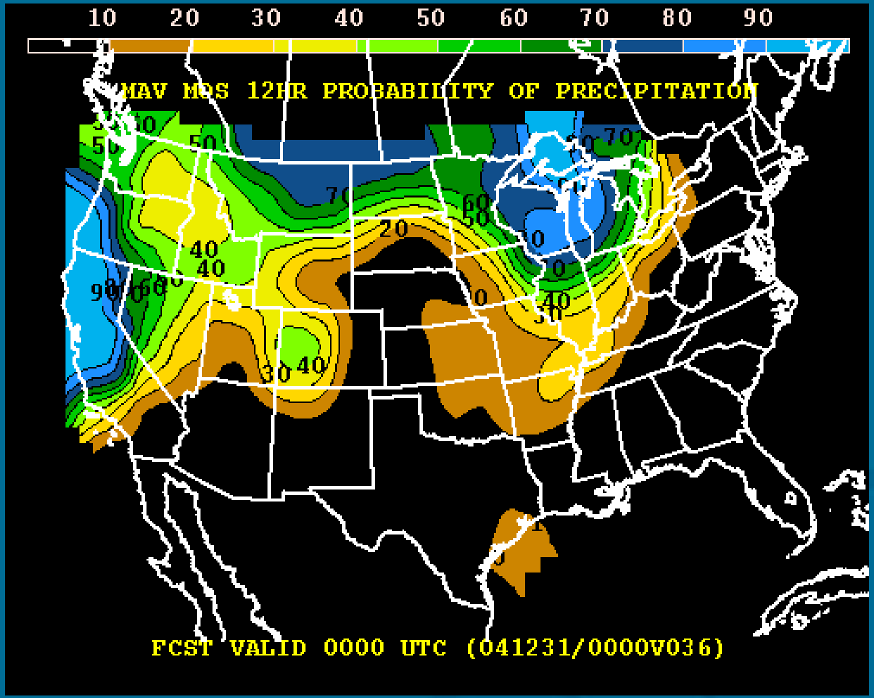
12-h PoPs, valid Dec. 24 & 25, 2004



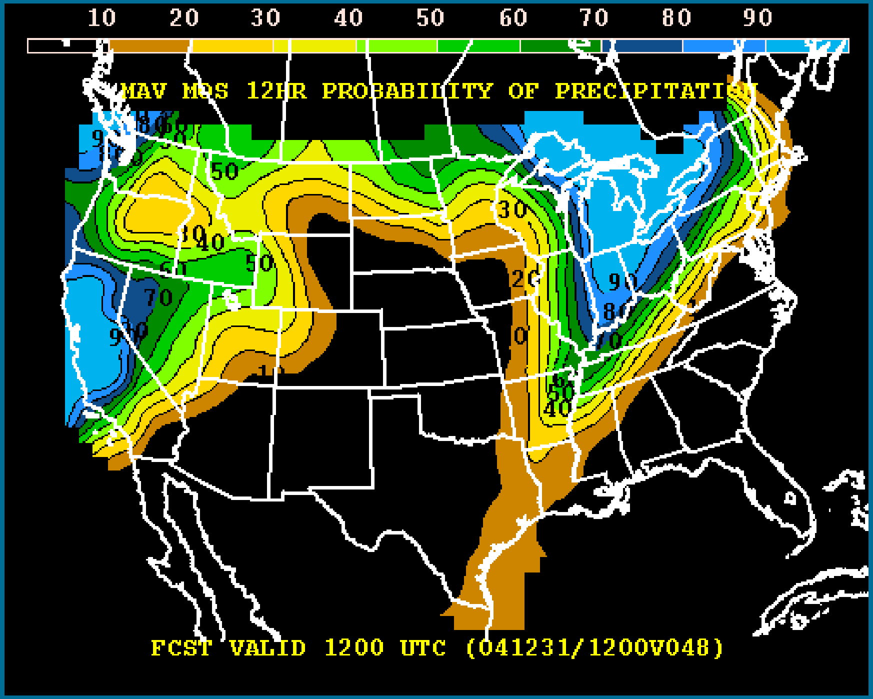


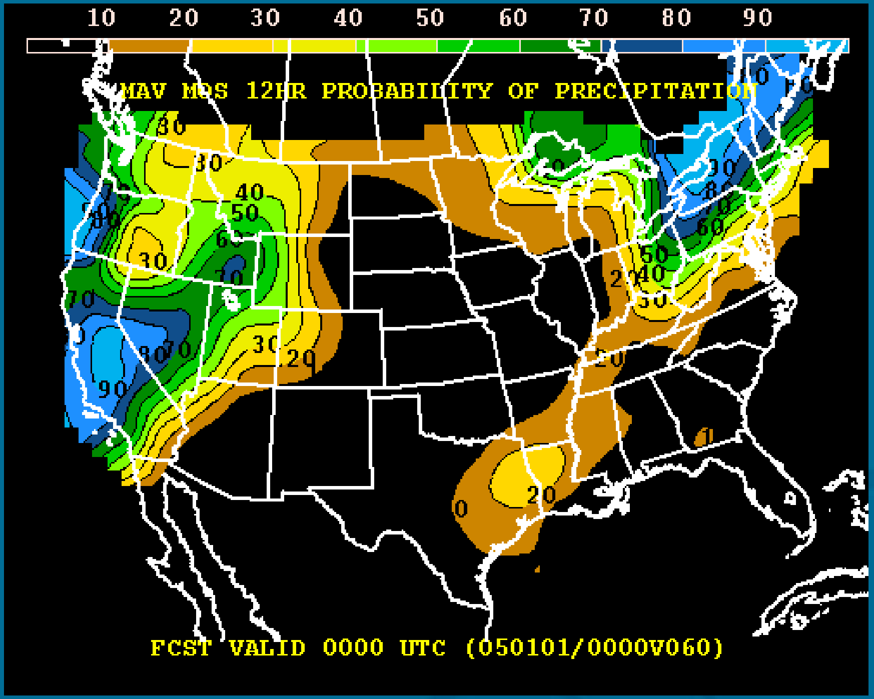
12-h PoPs, valid Dec. 30 & 31, 2004





12-h PoPs, valid New Year’s Eve 2004





Range in Probability

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KSAN   GFSX MOS GUIDANCE  12/31/2004  0000 UTC
 FHR  24| 36  48| 60  72| 84  96|108 120|132 144|156 168|180 192
 FRI  31| SAT 01| SUN 02| MON 03| TUE 04| WED 05| THU 06| FRI 07 CLIMO
 X/N  58| 50  61| 50  61| 50  59| 47  58| 48  58| 50  59| 47  64 48 66
 TMP  55| 51  59| 52  58| 52  56| 49  56| 50  55| 52  57| 49  61
 DPT  51| 46  50| 47  48| 46  46| 42  44| 42  50| 46  46| 40  45
 CLD  OV| OV  PC| PC  OV| OV  OV| PC  OV| OV  OV| OV  OV| PC  PC
 WND  14| 11   9|  7  12| 11  14| 12  11| 12  14| 12  12|  9  10
 P12  64| 13   9| 16  46| 93  61| 19  43| 47  58| 65  52| 32  15 15 15
 P24    |      18|     53|     94|     52|     65|     77|     32    23
 Q12   2|  0   0|  0   1|  3   3|  0   1|  1   3|  3    |
 Q24    |       0|      1|      4|      1|      3|       |
 T12   2|  0   0|  1   1|  6  14|  0   1|  8   8| 10  10|  4   1
 T24    |  2    |  1    |  6    | 14    |  9    | 17    | 10
```
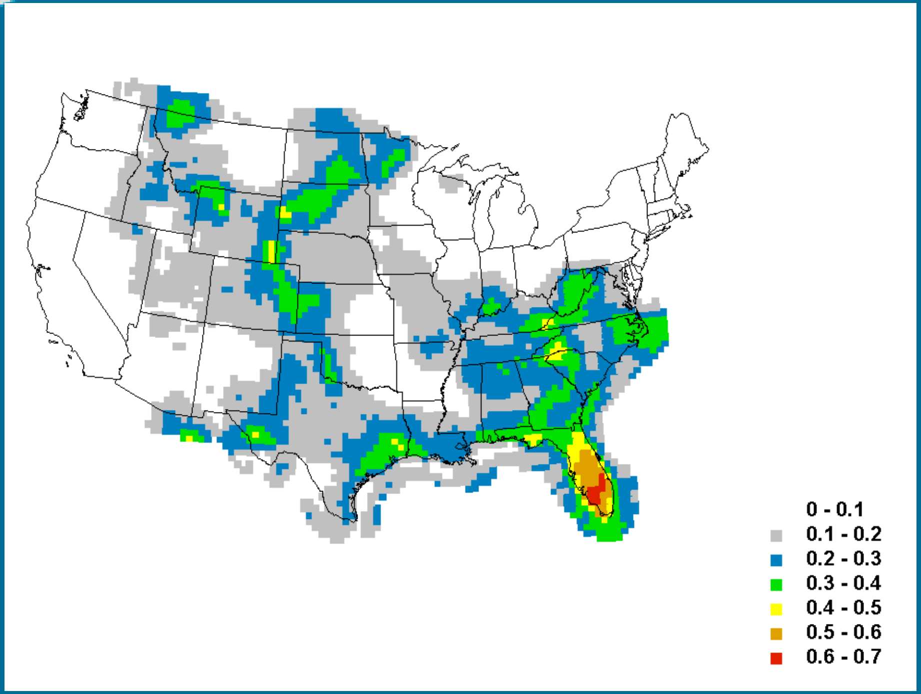
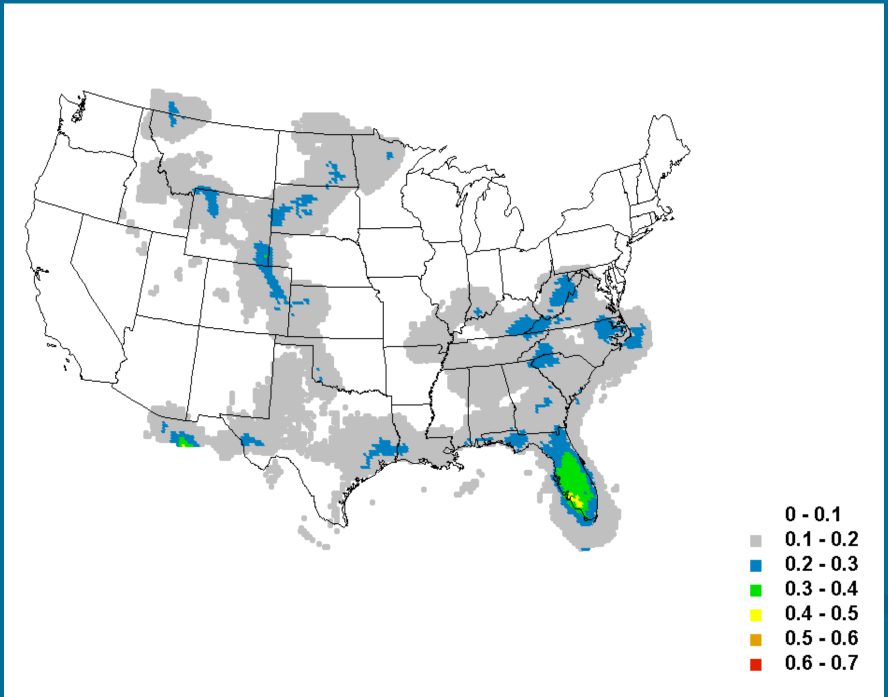

Grid Resolution Makes A Difference





21-24h forecast
40-km tstm prob.

21-24h forecast
20-km tstm prob.

Subjective Probabilities

Objective vs. Subjective PoP Forecasts Cool Season

(00/12Z cycles combined)