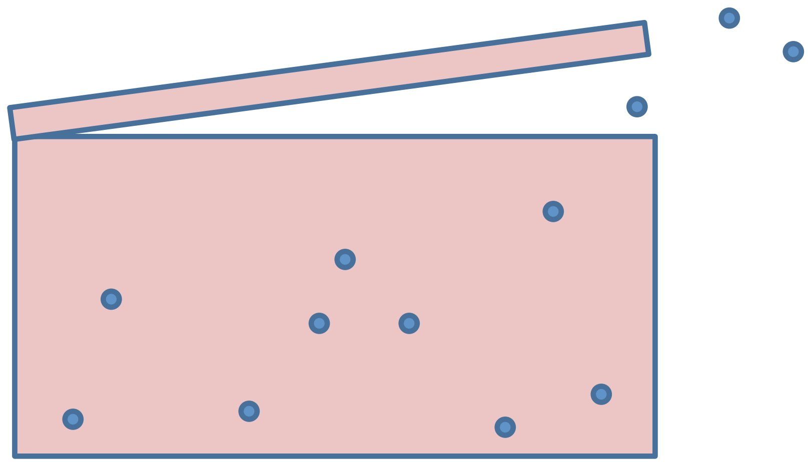
A Simple Conceptual Model for Winter $PM_{2.5}$ Episodes in Western Mountains and the Historical Record it Reveals

Yayi Dong, Rick Hardy, Brady Johnson - Idaho DEQ

A Conceptual Model

What Makes a $PM_{2.5}$ Episode?



What makes daily high PM2.5?

Inversion
High emissions
Low wind speeds
High humidity
High pressure system
Snow cover
Secondary aerosol production
Low temperature
Low mixing height
…………………………

What info needed for modeling?

Meteorological Modeling + Photochemical Grid Modeling

Concentration = (Emission (%, #, …) – Removal (#*,&…))/Volume

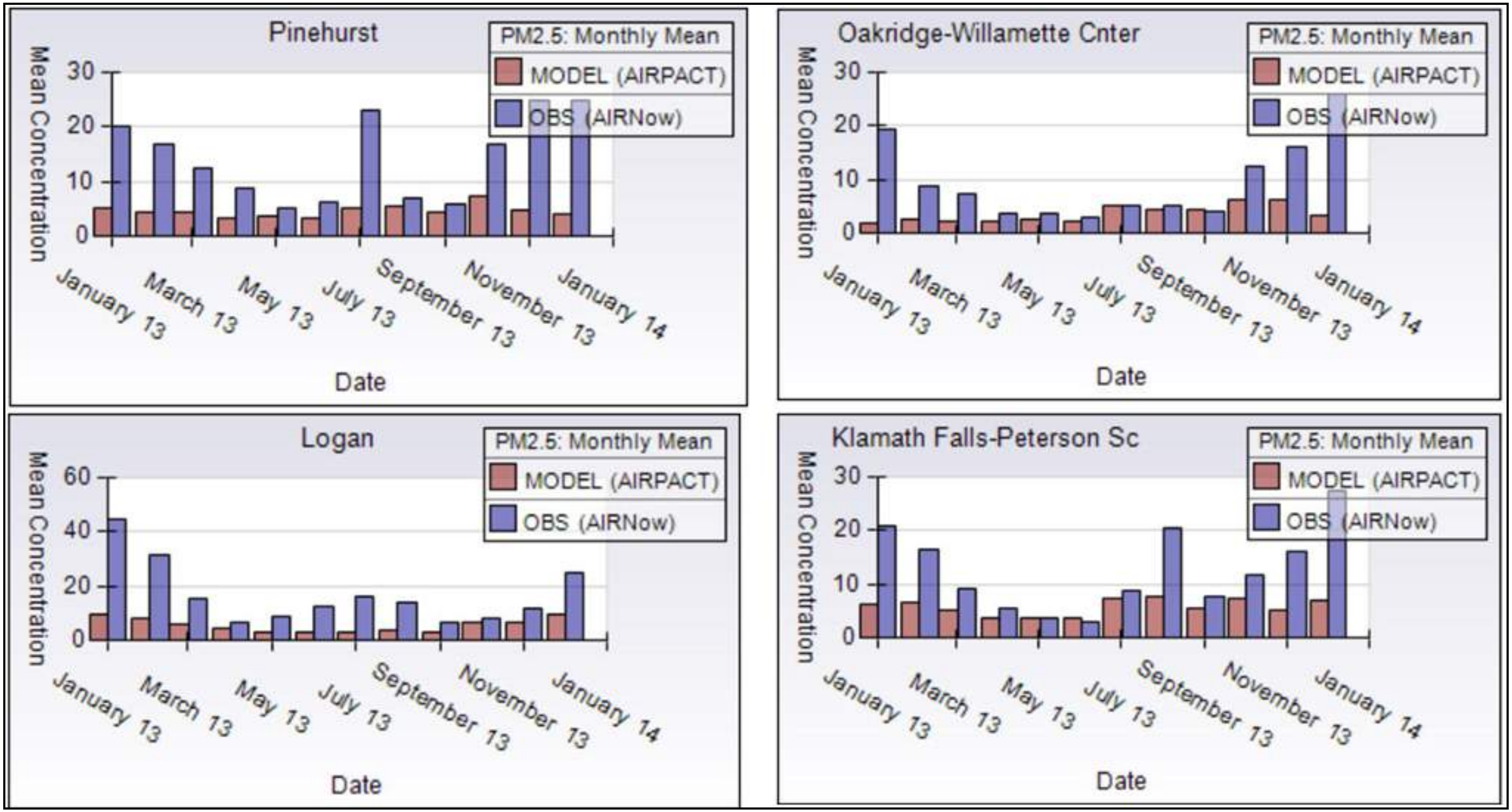
More parameters

or

Less parameters?

More Parameters are not always better;

AIRPACT performance in mountain valleys is extremely poor in winter, largely due to sub-grid terrain and failure to simulate cold air pools in WRF



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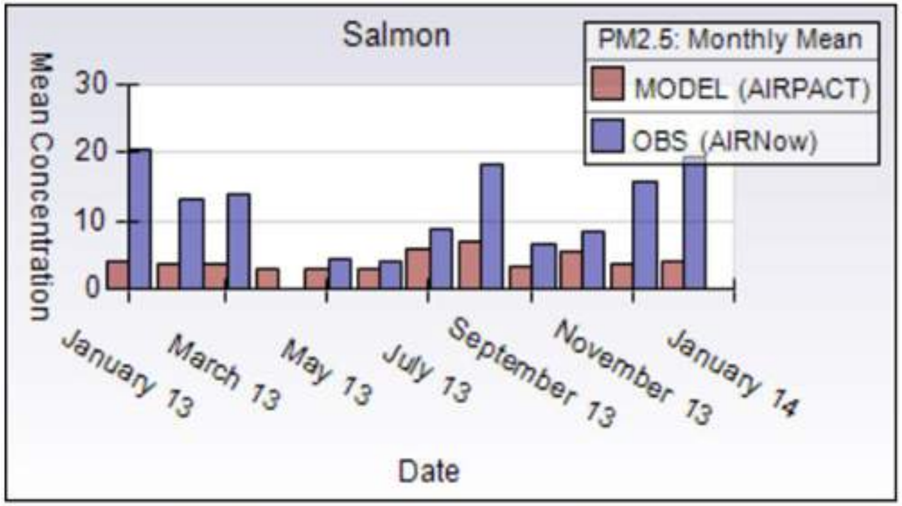
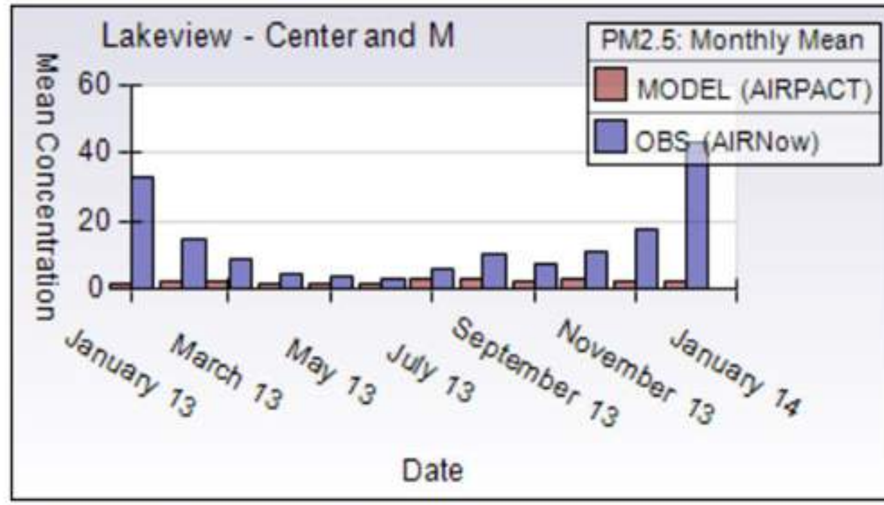
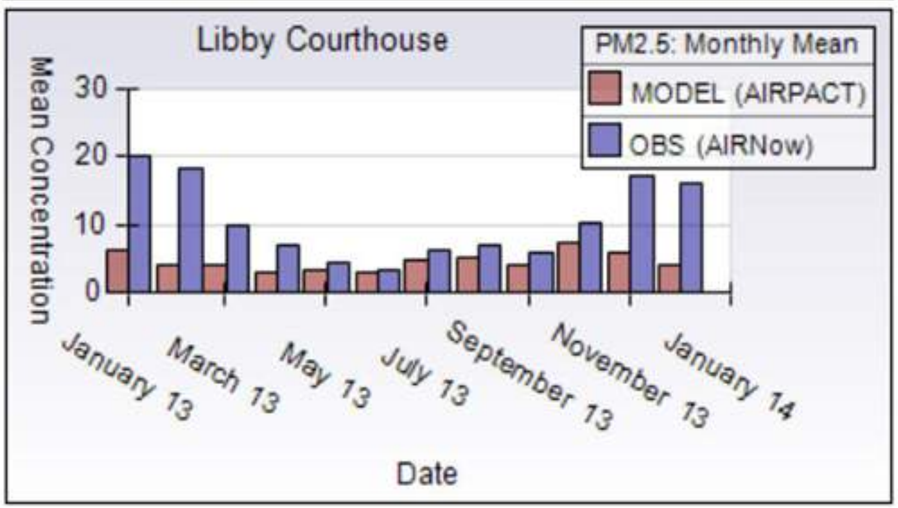
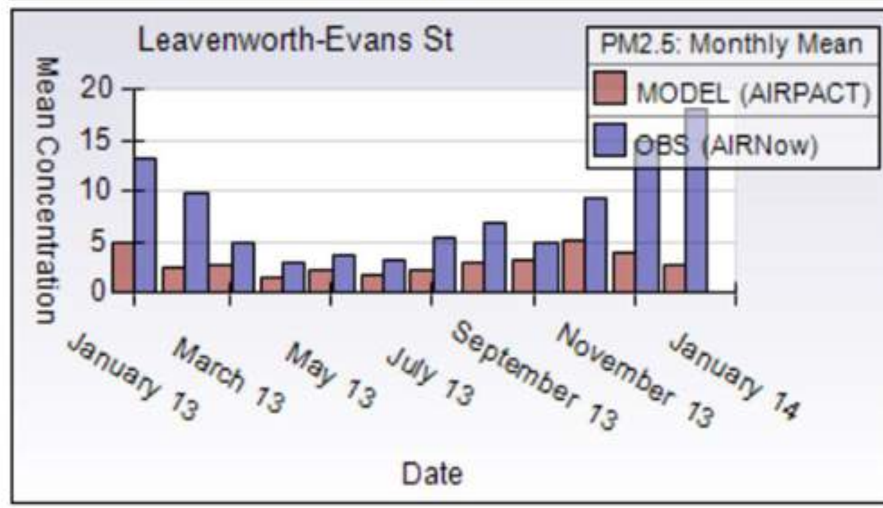








A choice of using less parameters

Concept of Deep Stable Layer (DSL)

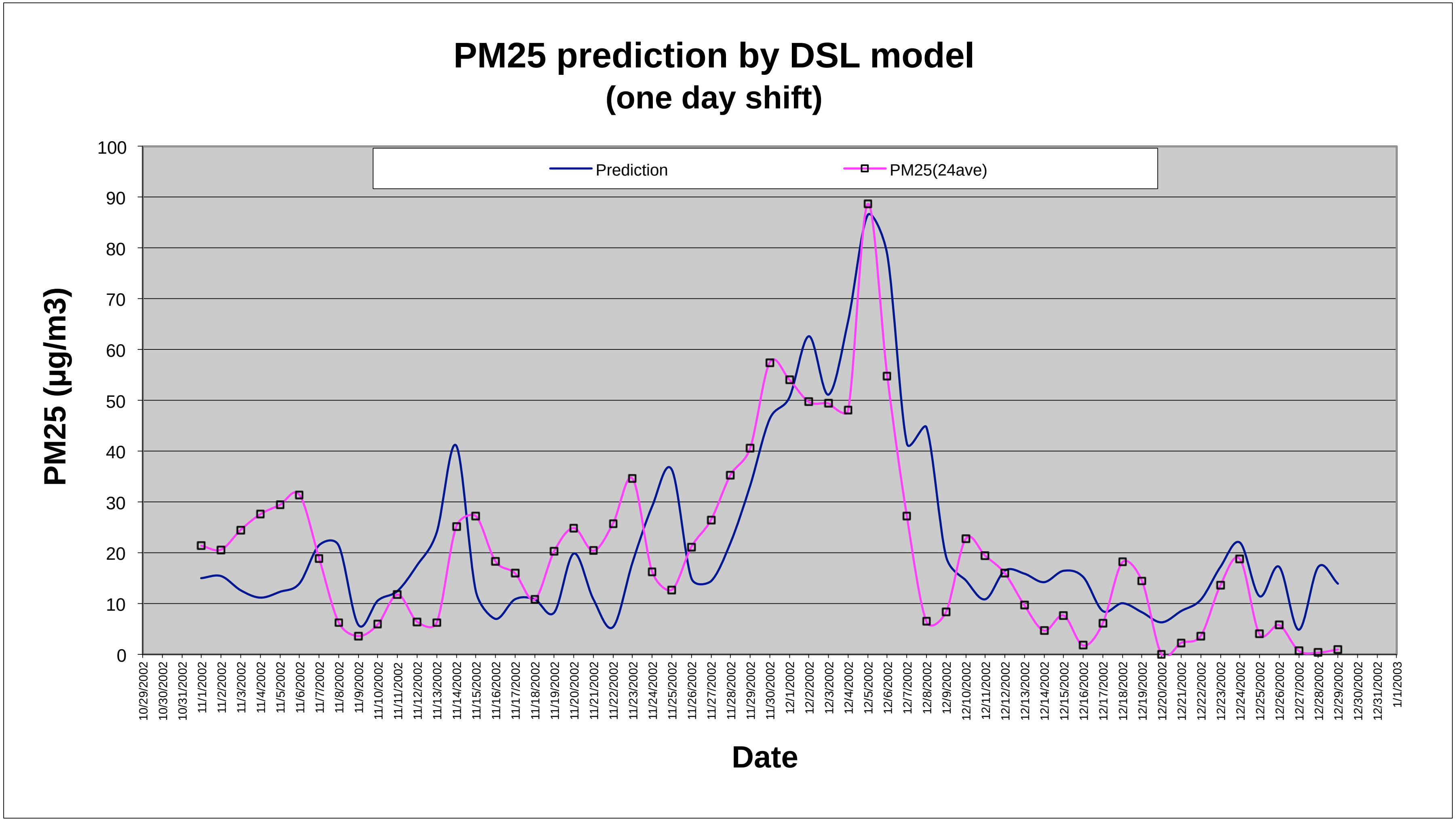
- DSL: The sum of all stable layers (lapse rate < 2.5°C/km) is more than 975m (65% of 1500m) within the lowest 1500m.
- DSL is a parameter reflecting strength of stability of the lower atmosphere.

From: (Wolyn and McKee, *Deep Stable Layers in the Intermountain Western United States*, Monthly Weather Review, v 117, 1989).

- In addition, when the Lower Stable Layer, LSL (<500m) remains stable in the afternoon sounding, PM levels accumulate at a consistent rate characteristic of each airshed and its emissions.

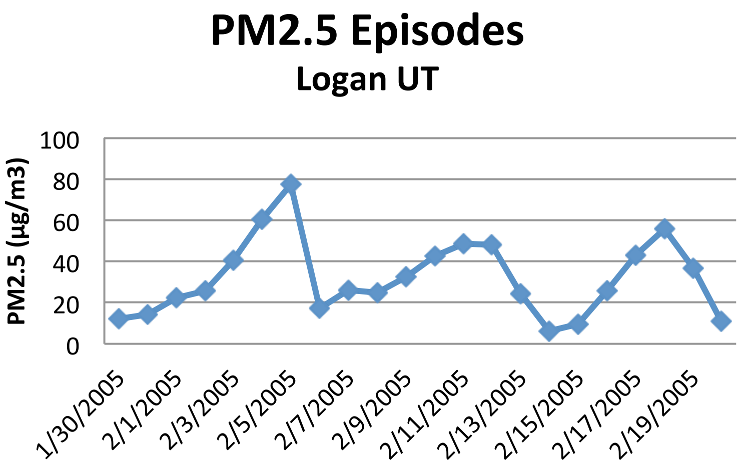
- .

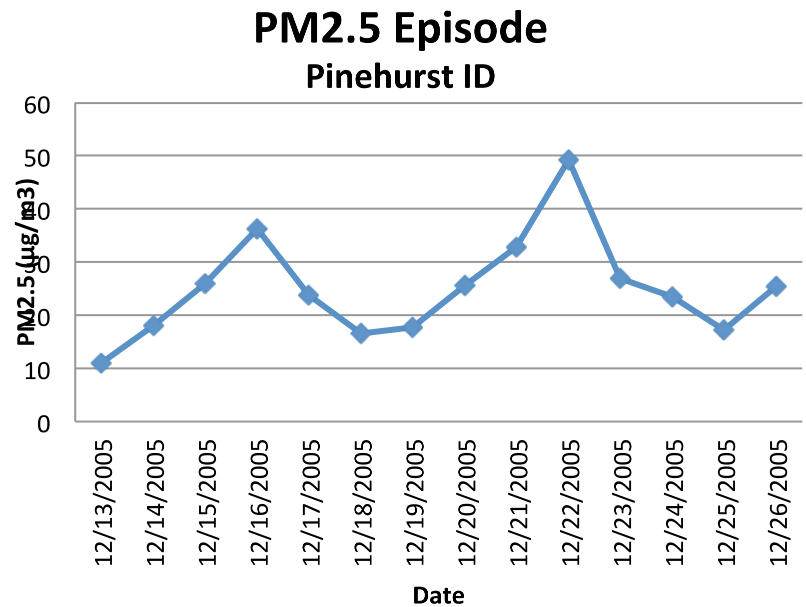
PM$_{2.5}$ Predicted using DSL

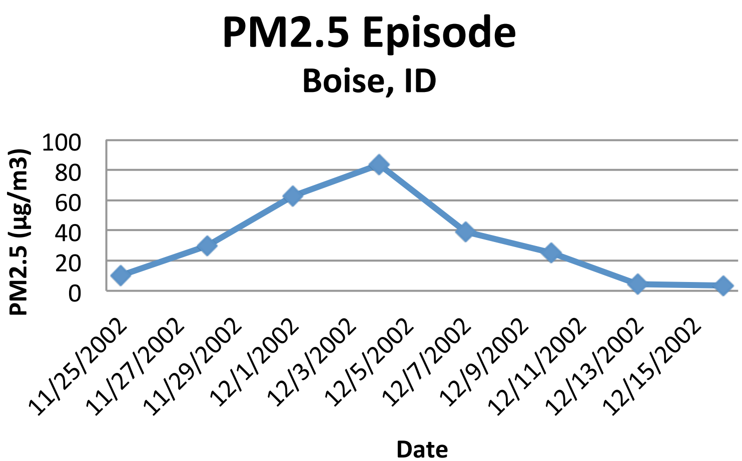


Observations

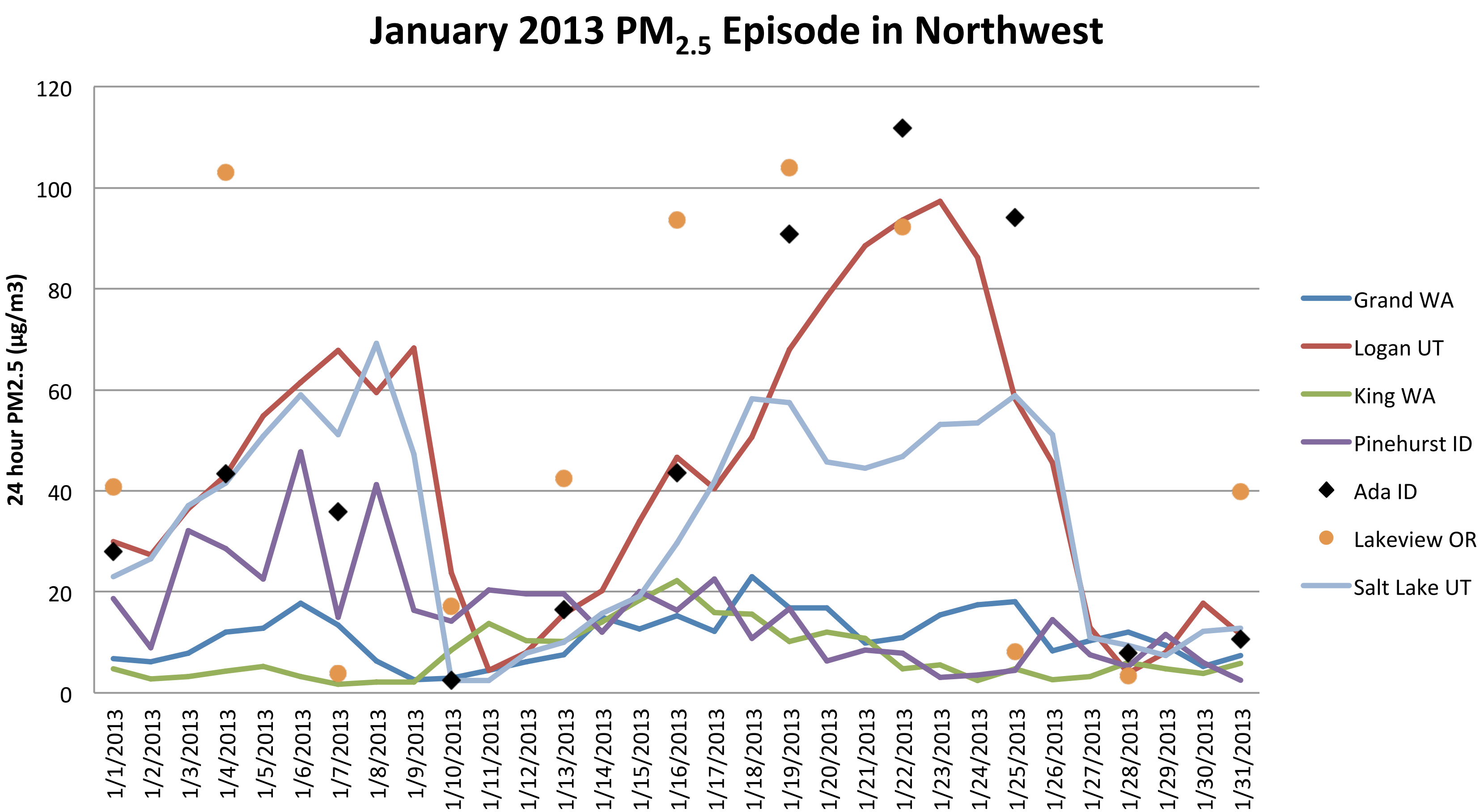
Linear increment of $PM_{2.5}$







2013 $PM_{2.5}$ Events were Regional



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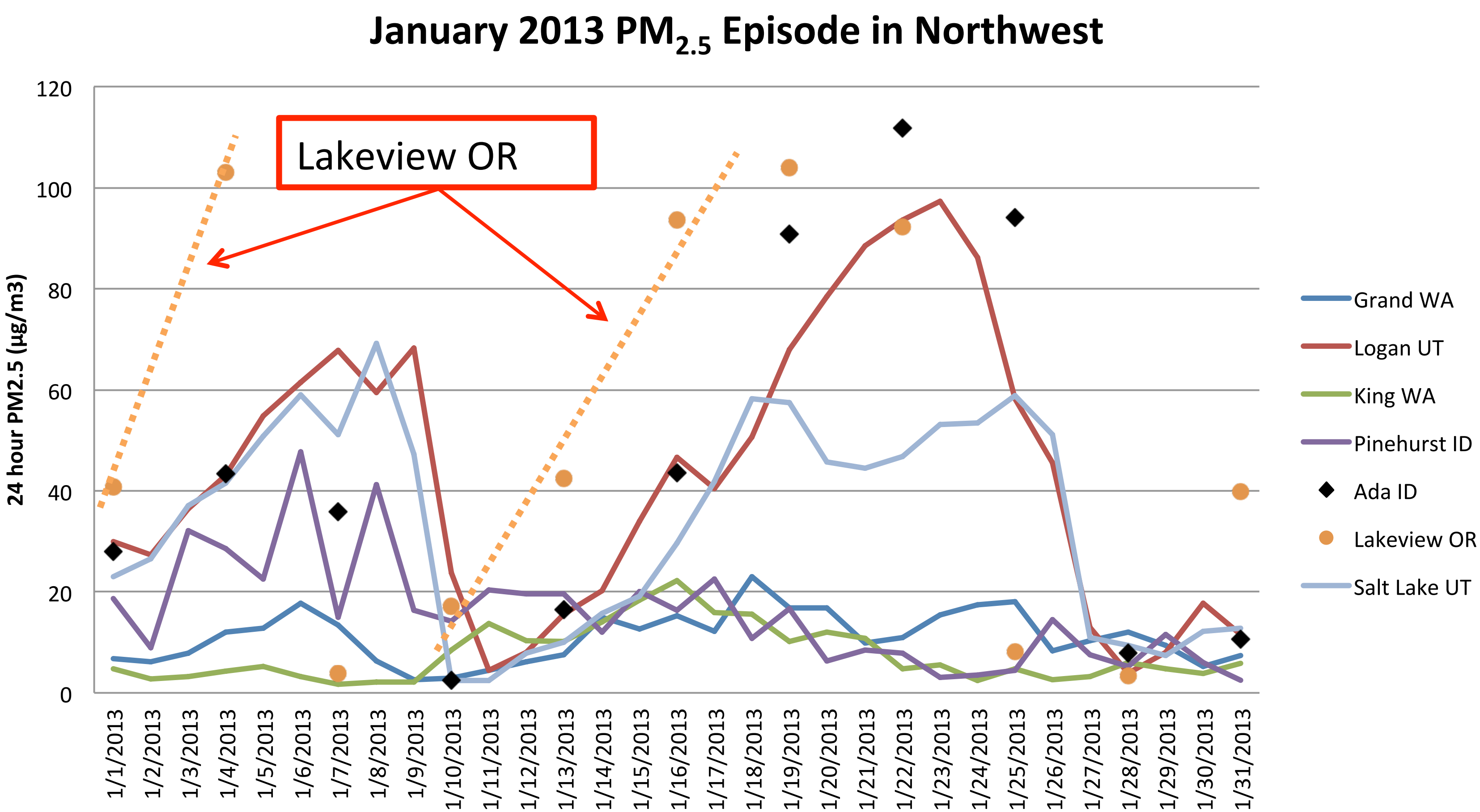

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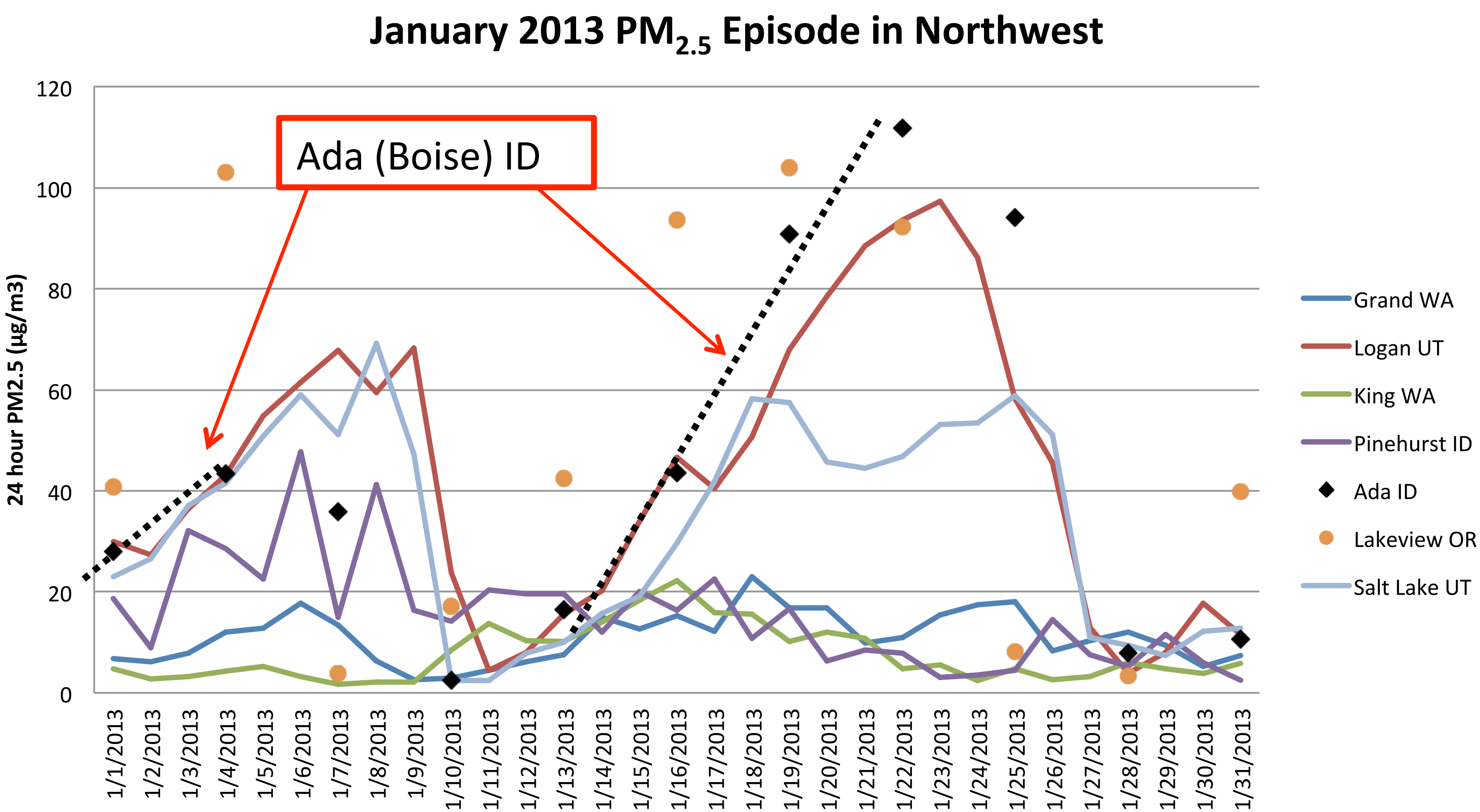

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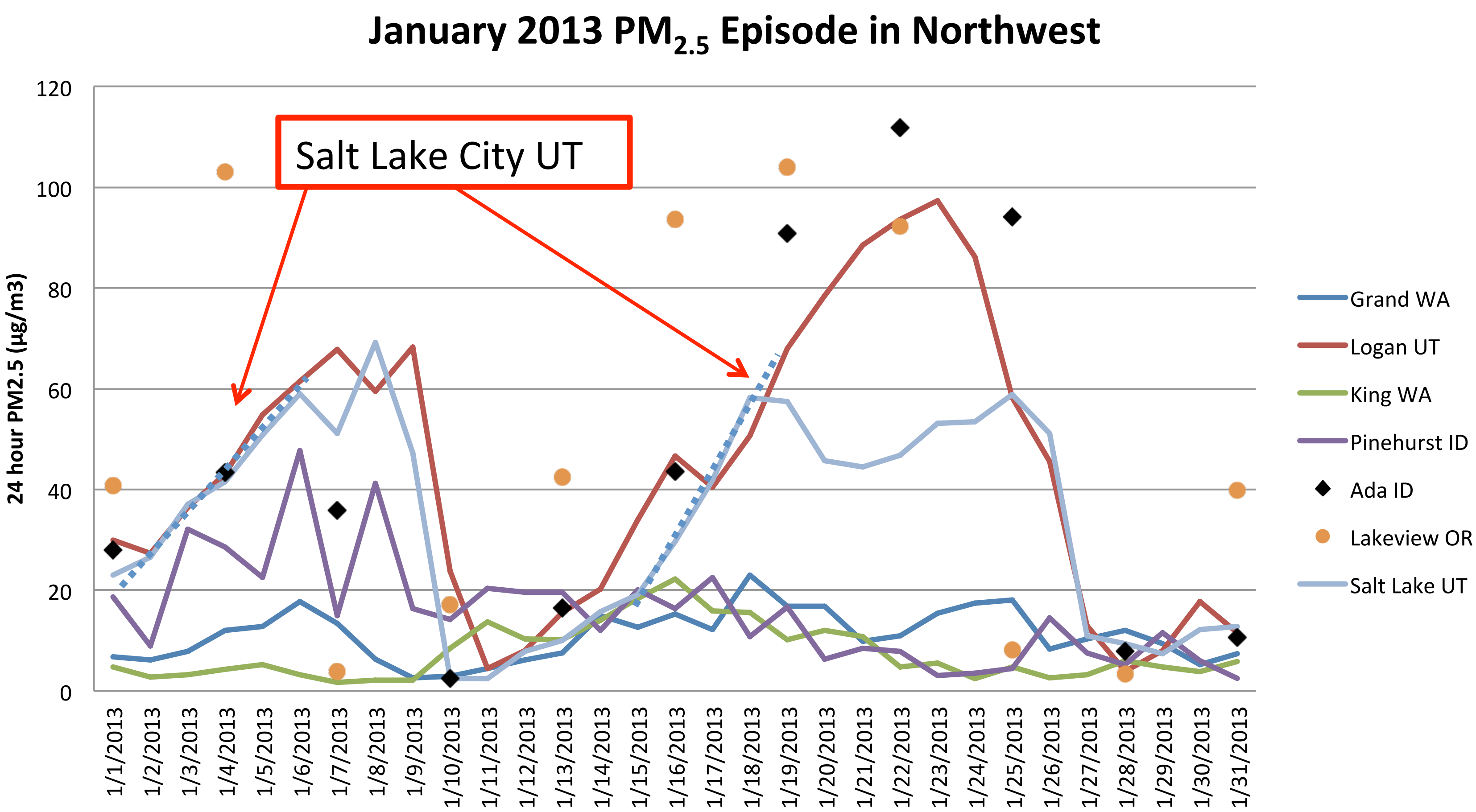
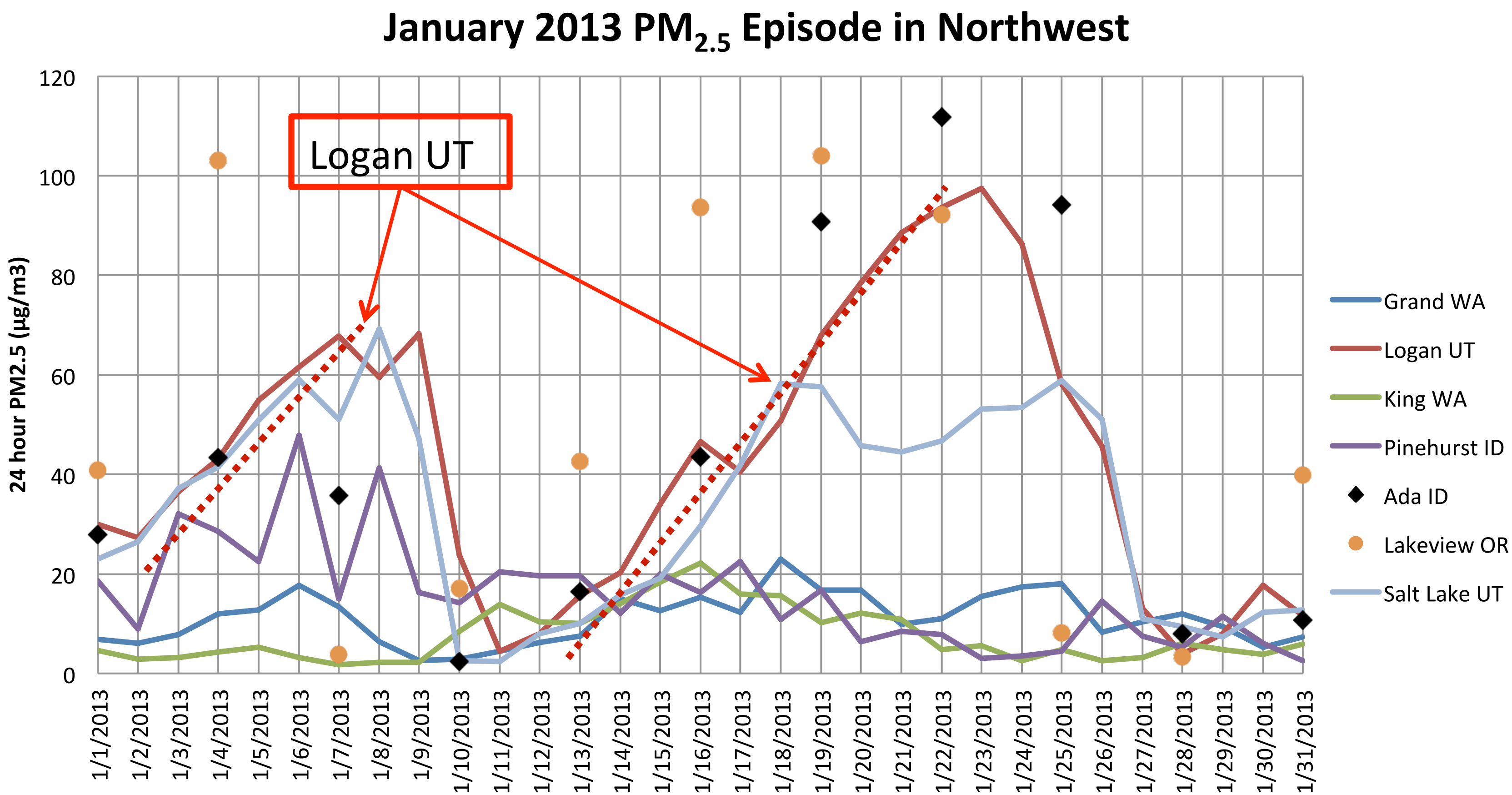
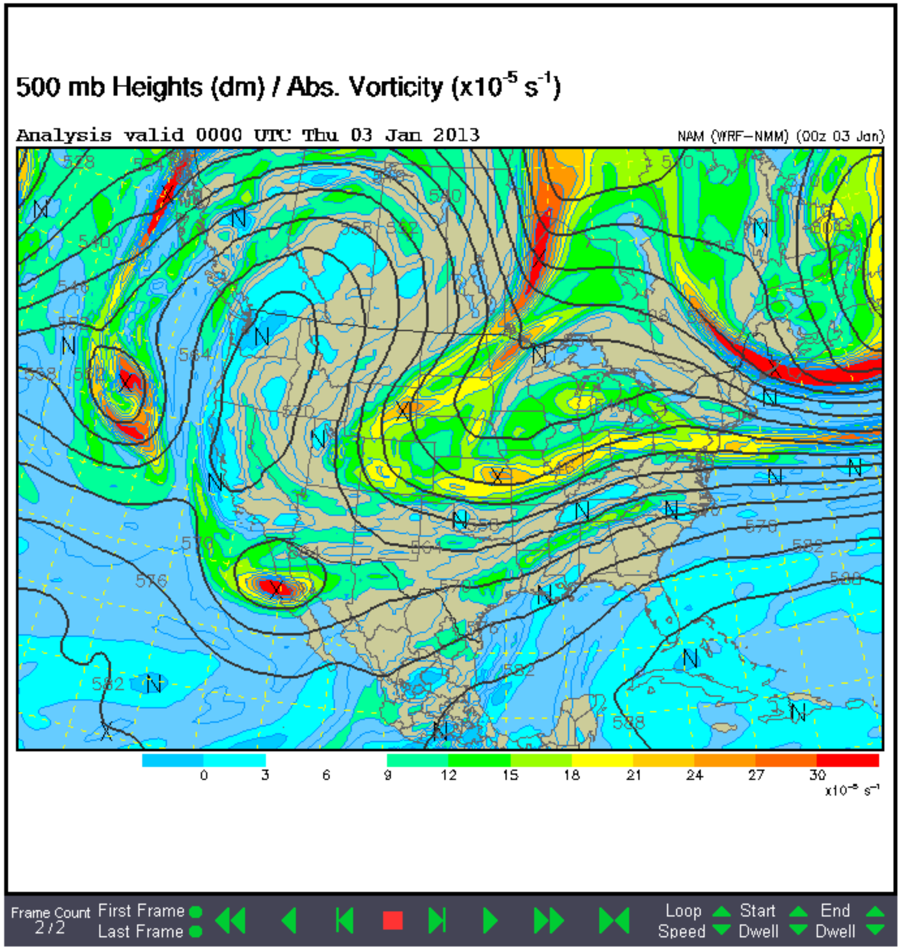


2013 $PM_{2.5}$ Events were Regional

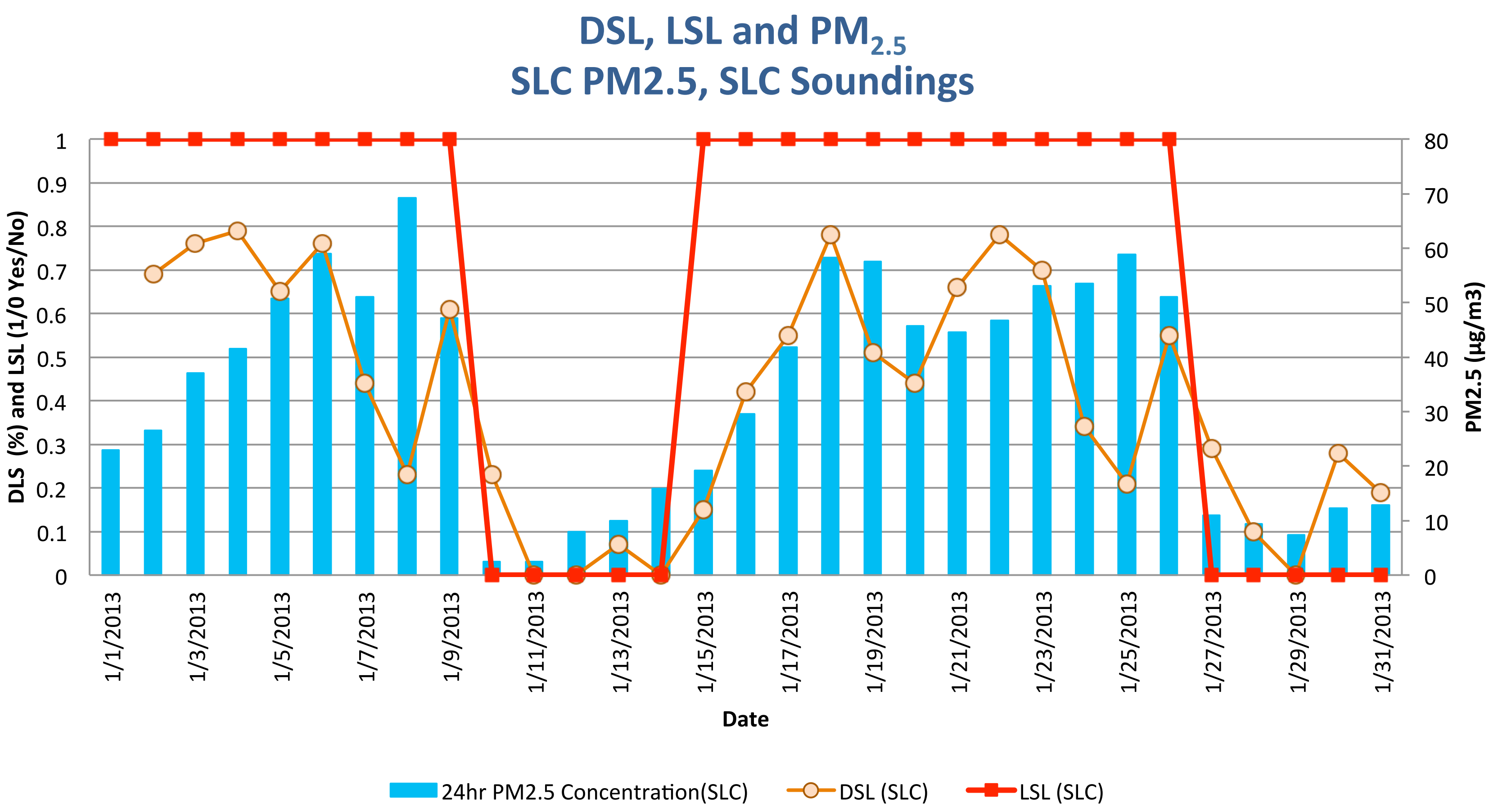
And increases are generally linear increments



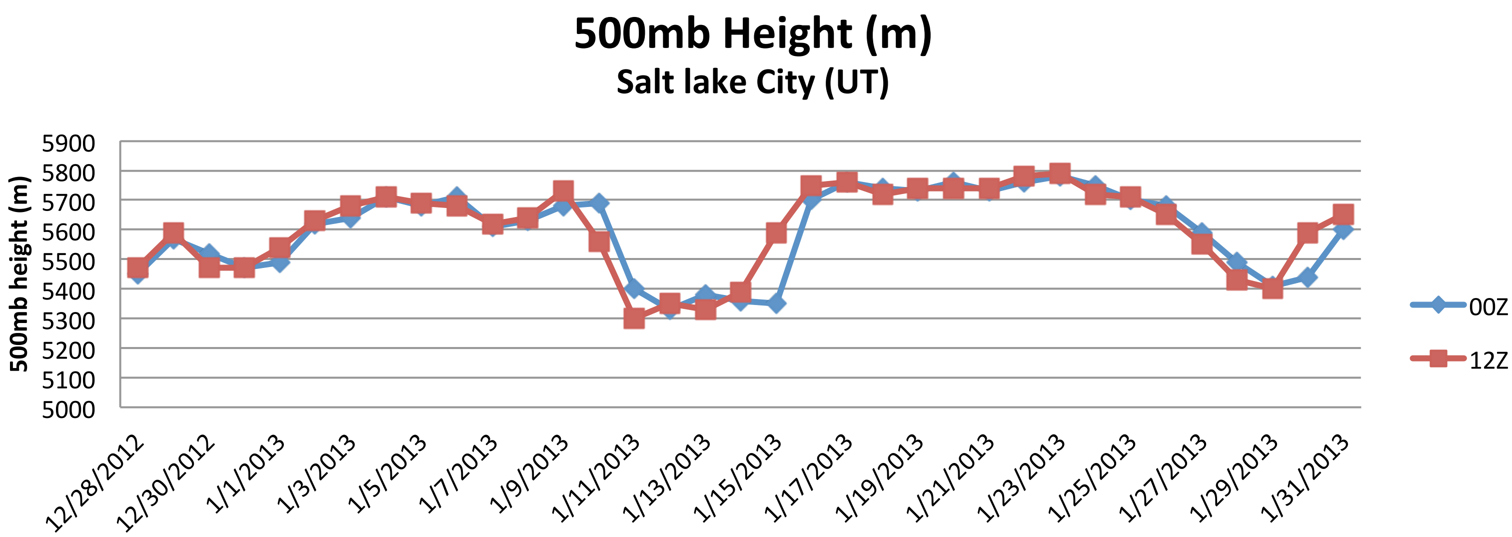
Weather System: High Pressure Ridge

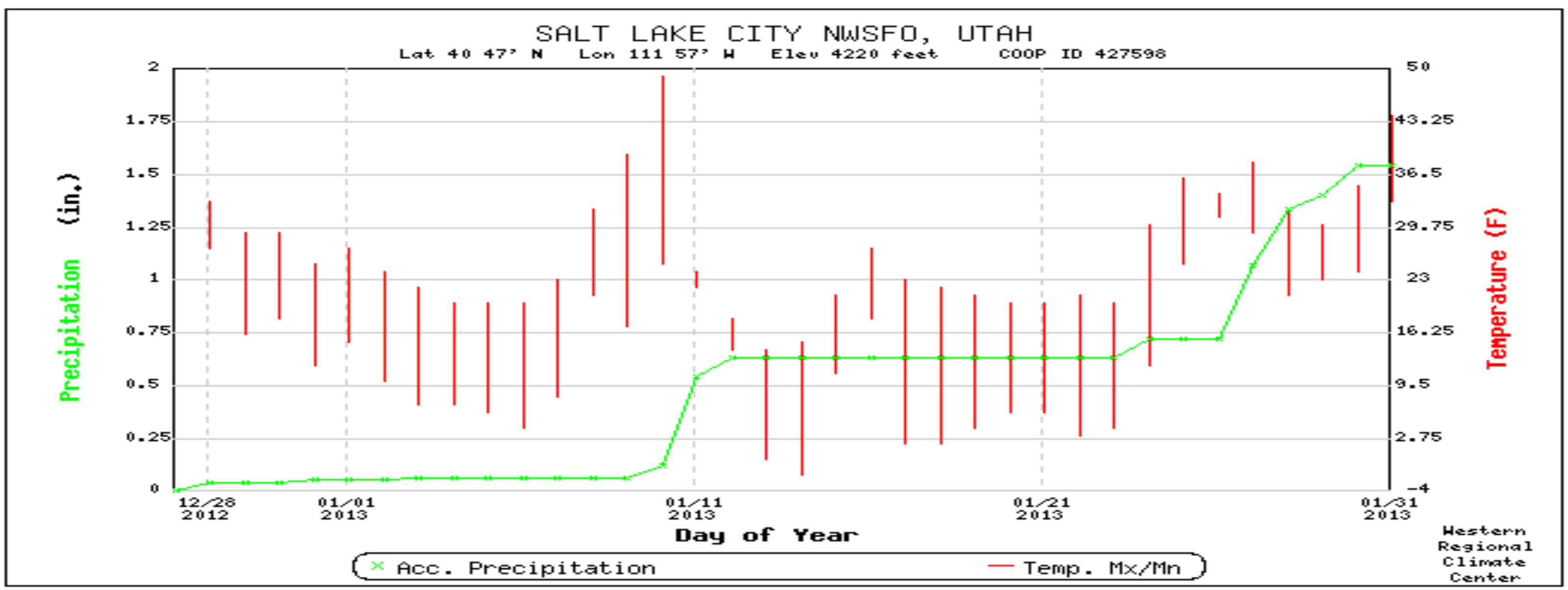


DSL, LSL and $PM_{2.5}$



Define Stagnation Events

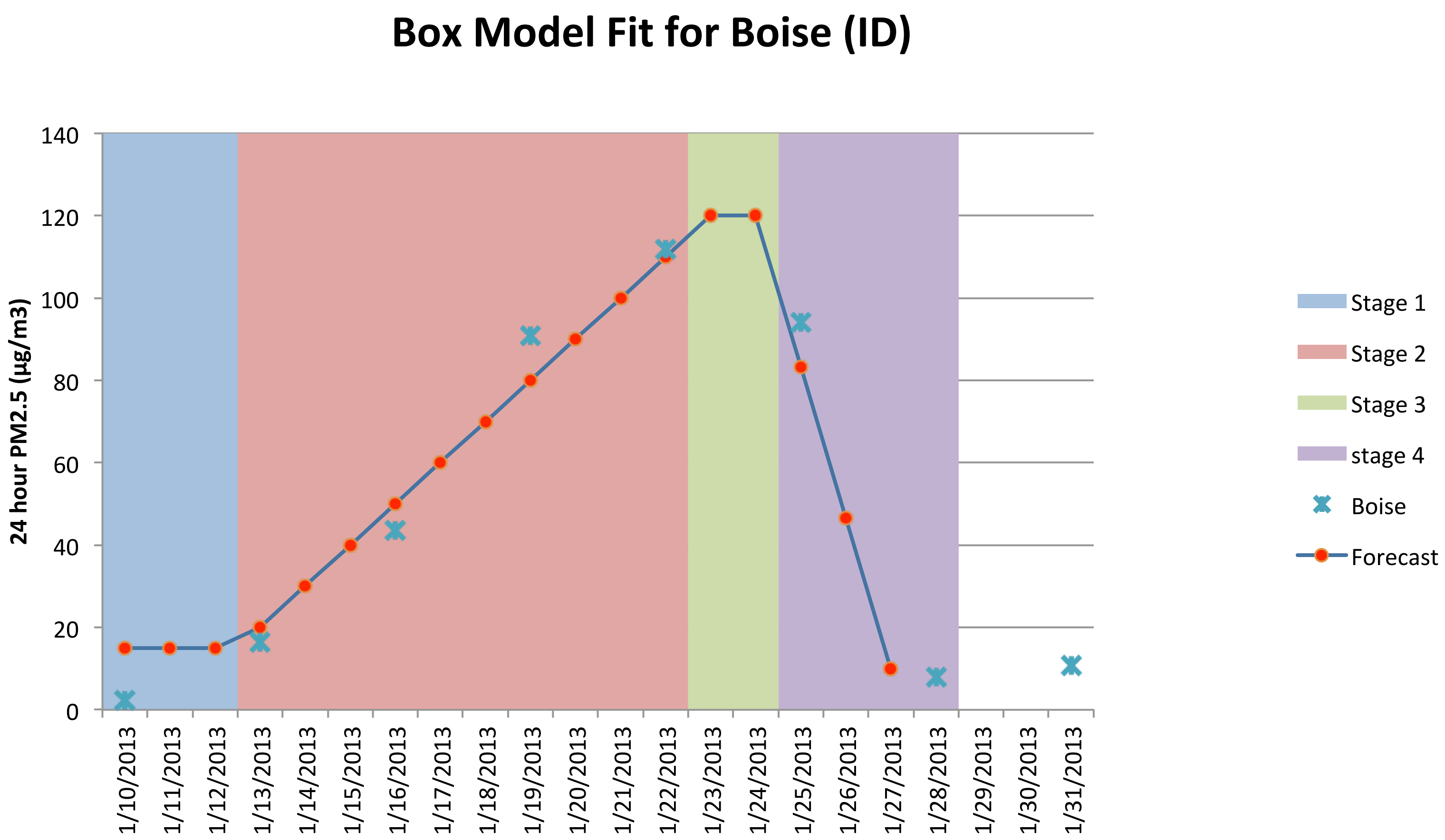




The four stages of a $PM_{2.5}$ episode

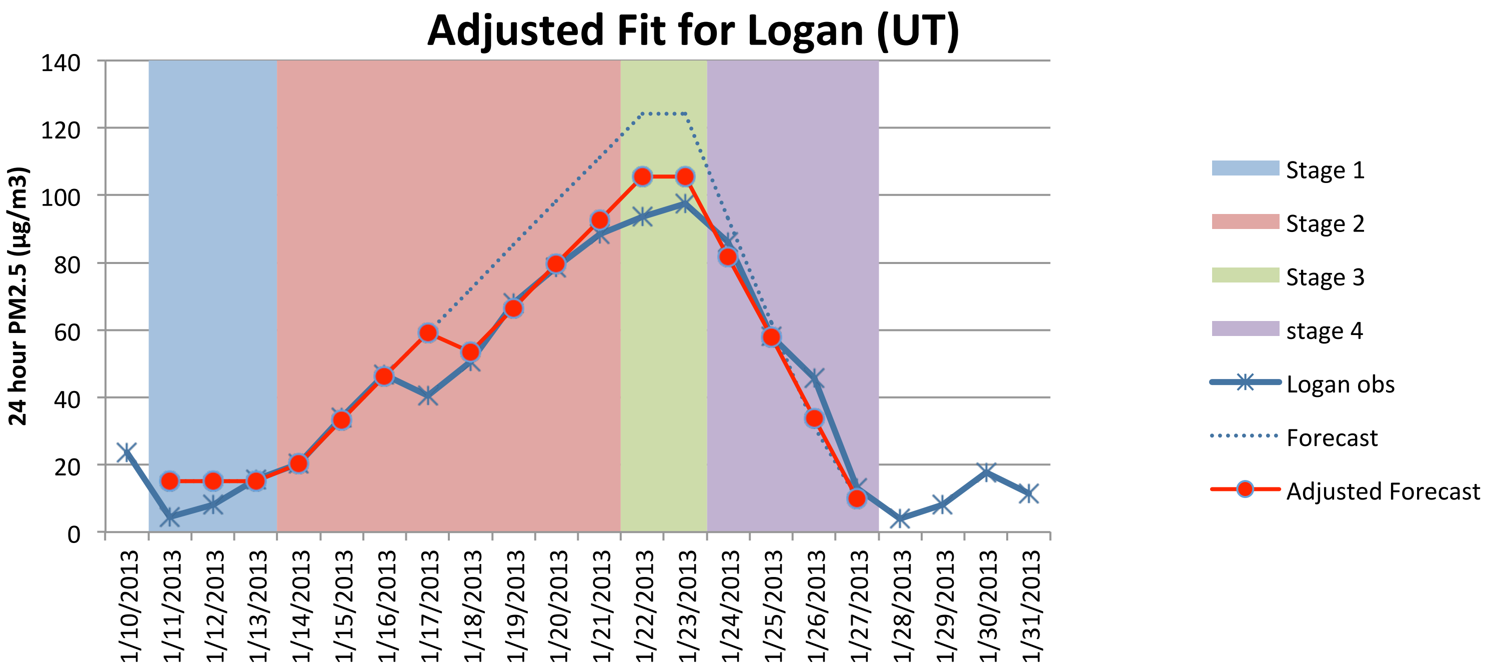
Observations	Stage 1	Stage 2	Stage 3	Stage 4	End
500mb Pressure height	below 5500m, starts to rise	**Often over 5700m, remains approx constant**	Starts to drop slowly	dropping until 5500m	Below 5500m
Surface Temperature	starts to drop	**Below freezing point, could be very cold, often snow**	Starts to rise	Continue rising	Higher
DSL*	Rising	**High**	Decreasing	Decreasing	None
LSL	No	**Yes**	Yes	yes	No
Precipitation	Decreasing or none	**No**	No	May increase	Maybe
PM2.5*	Start to rise, often below 20 µg/m3	**Rising**	High, reaches peak level	Decreasing fast	Low

For Boise (ID)



Box Model Fit for Boise (ID)
24 hour PM2.5 (µg/m3)
140
120
100
80
60
40
20
0
1/10/2013
1/11/2013
1/12/2013
1/13/2013
1/14/2013
1/15/2013
1/16/2013
1/17/2013
1/18/2013
1/19/2013
1/20/2013
1/21/2013
1/22/2013
1/23/2013
1/24/2013
1/25/2013
1/26/2013
1/27/2013
1/28/2013
1/29/2013
1/30/2013
1/31/2013
Stage 1
Stage 2
Stage 3
stage 4
Boise
Forecast

For Logan (UT)

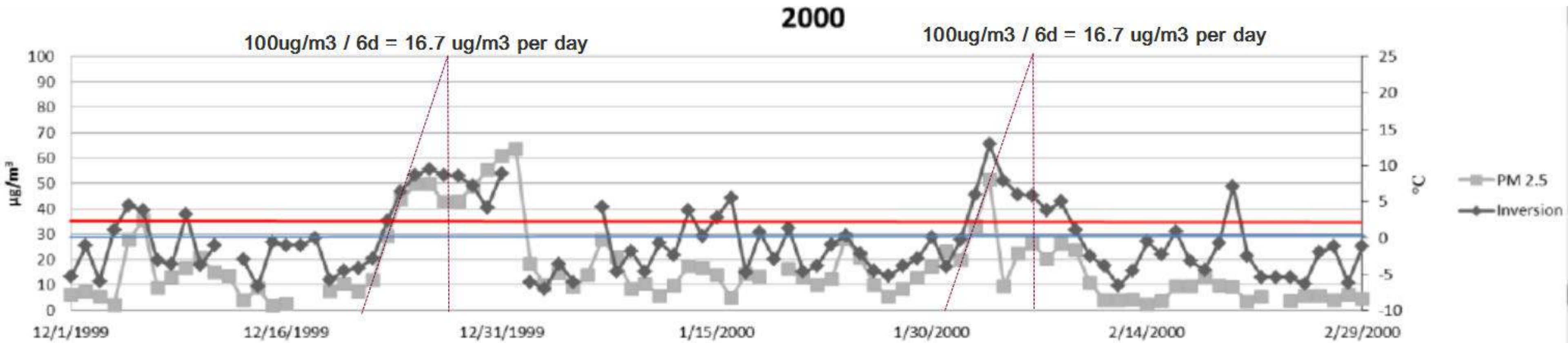


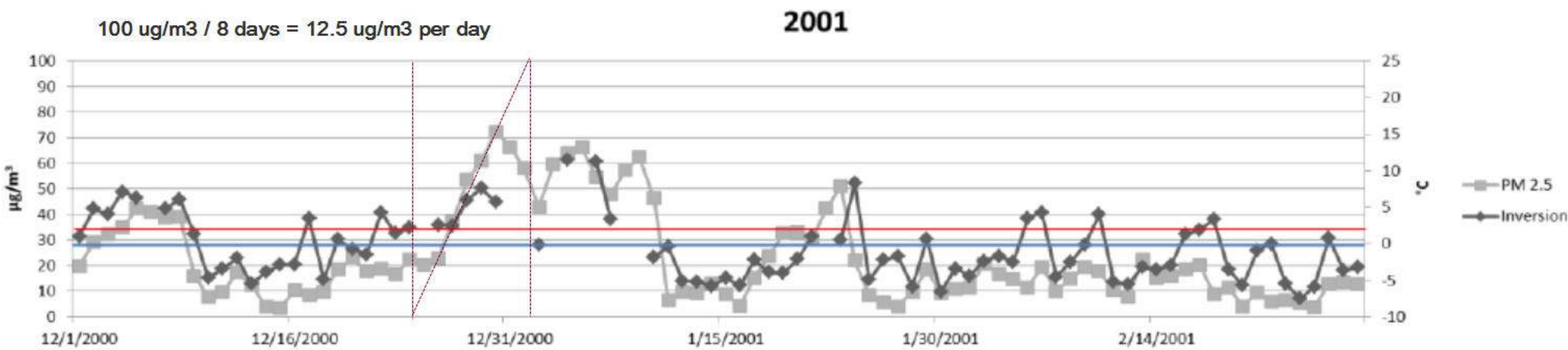
Adjusted Fit for Logan (UT)
24 hour PM2.5 (µg/m3)
0
20
40
60
80
100
120
140
1/10/2013
1/11/2013
1/12/2013
1/13/2013
1/14/2013
1/15/2013
1/16/2013
1/17/2013
1/18/2013
1/19/2013
1/20/2013
1/21/2013
1/22/2013
1/23/2013
1/24/2013
1/25/2013
1/26/2013
1/27/2013
1/28/2013
1/29/2013
1/30/2013
1/31/2013
Stage 1
Stage 2
Stage 3
stage 4
Logan obs
Forecast
Adjusted Forecast

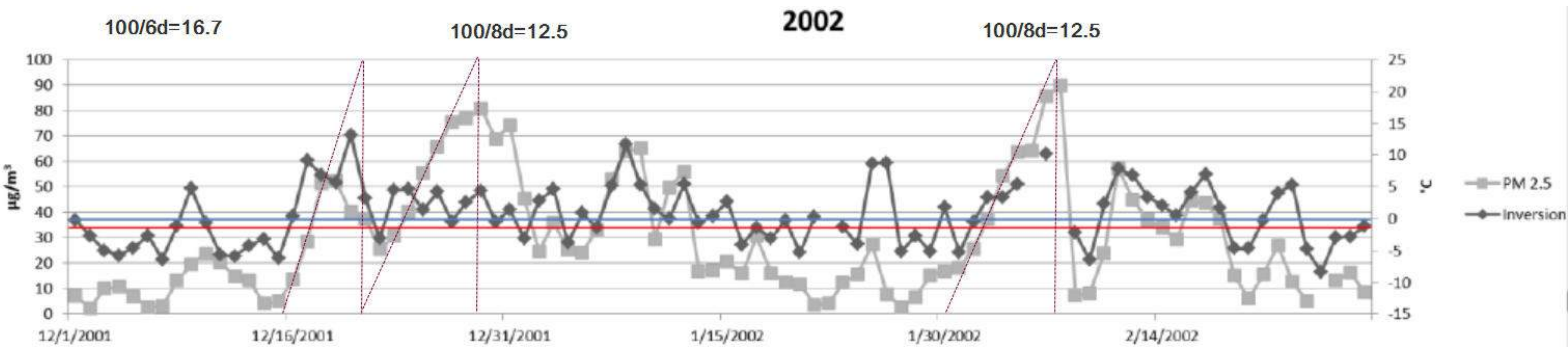
Estimated $PM_{2.5}$ daily rate of increase (24 hour average: µg/m^3 per day)

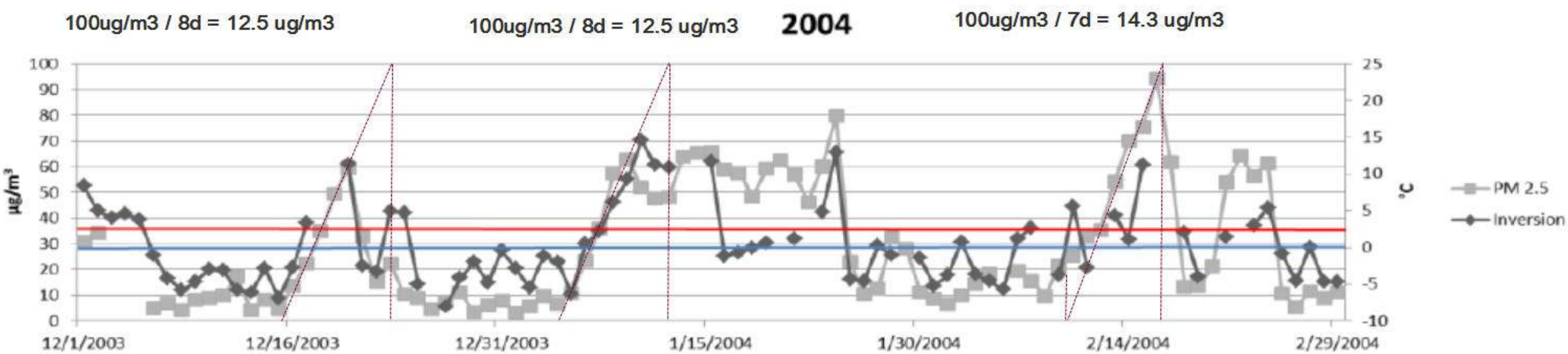
Site	Ada (ID)	Lemhi (ID)	Shoshone (ID)	Logan (UT)	Crook (OR)	Lakeview (OR)	Lane (OR)	Libby (MT)	SLC (UT)
Rate (µg/m3 per day)	10	12	11	13	8	15	12	11	10

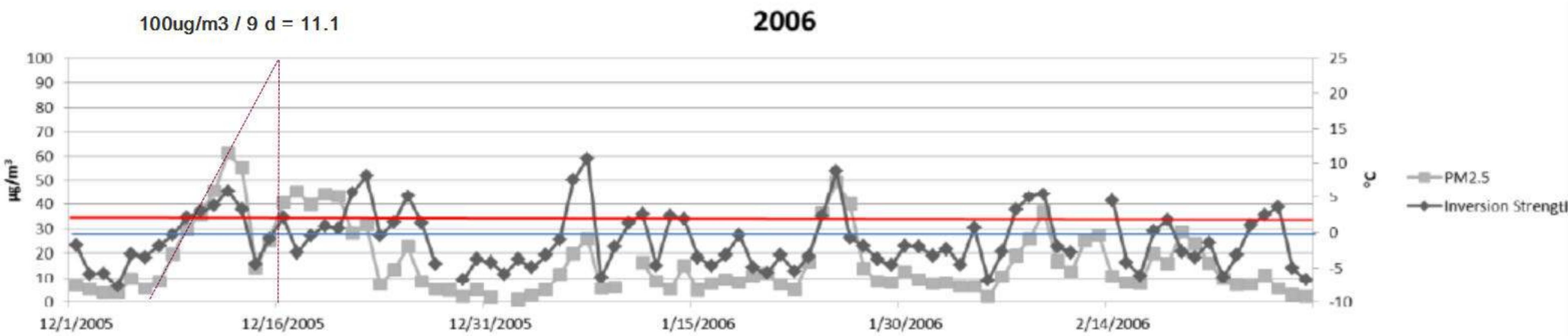
Logan trends in Daily accumulation rate (slope)



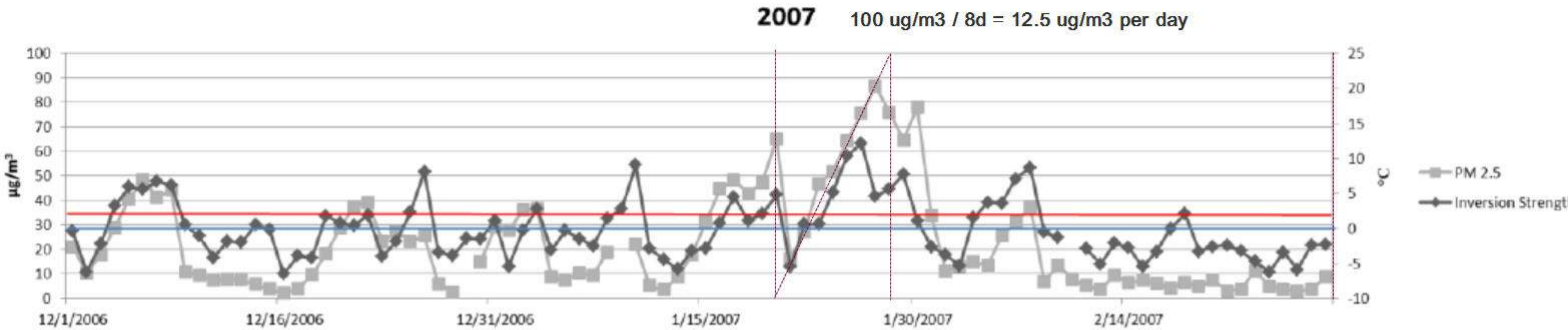



100/6d=16.7
100/8d=12.5
2002
100/8d=12.5
µg/m³
°C
PM 2.5
Inversion
12/1/2001
12/16/2001
12/31/2001
1/15/2002
1/30/2002
2/14/2002

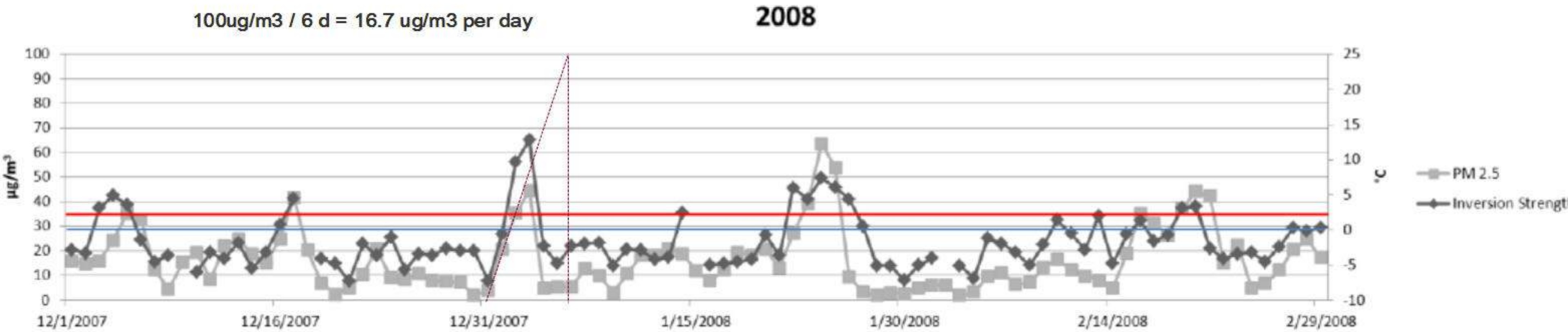

100ug/m3 / 8d = 12.5 ug/m3
100ug/m3 / 8d = 12.5 ug/m3
2004
100ug/m3 / 7d = 14.3 ug/m3
µg/m³
°C
PM 2.5
Inversion
12/1/2003
12/16/2003
12/31/2003
1/15/2004
1/30/2004
2/14/2004
2/29/2004



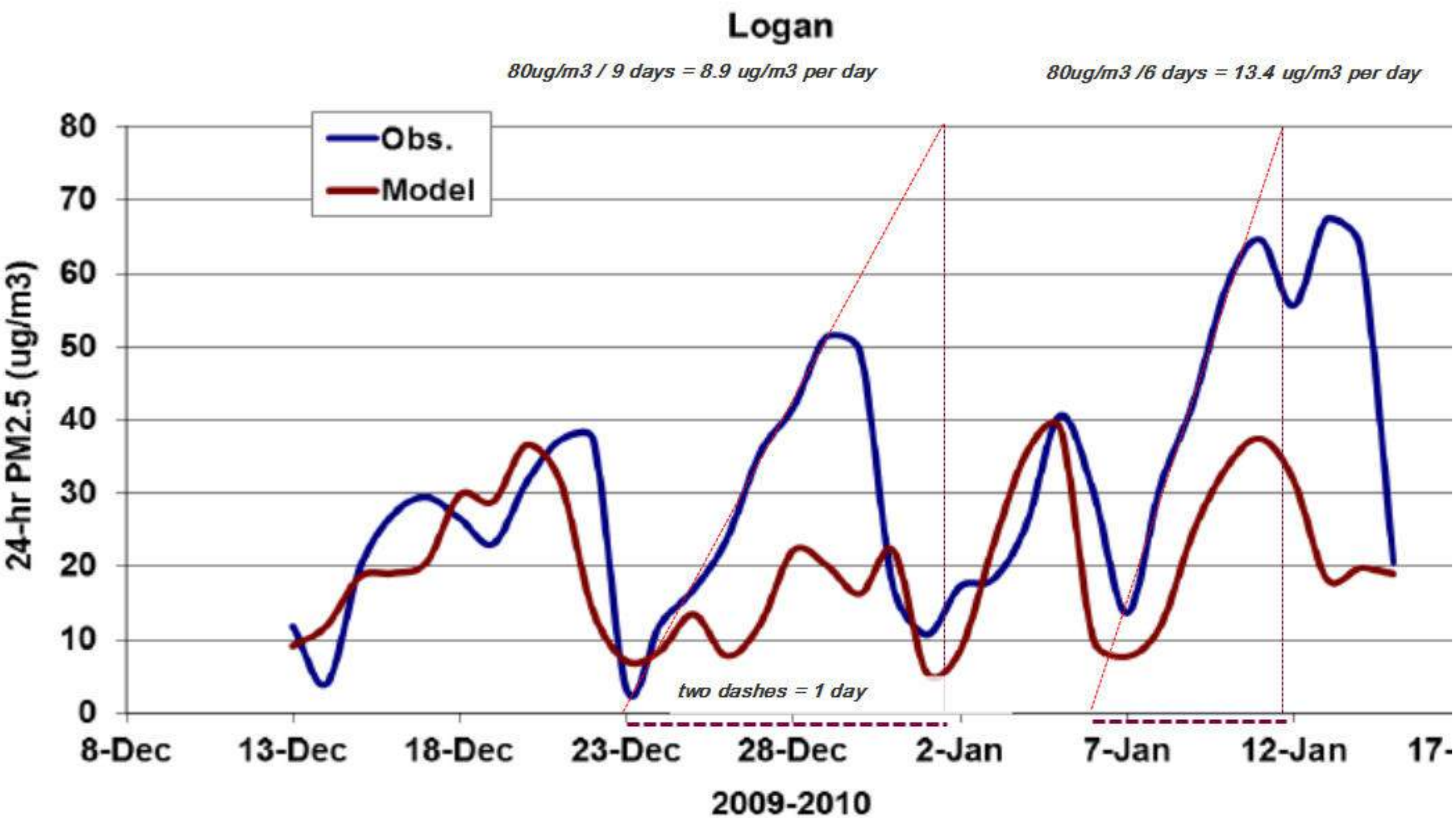
100ug/m3 / 9 d = 11.1
2006
μg/m³
°C
PM2.5
Inversion Strengt
12/1/2005
12/16/2005
12/31/2005
1/15/2006
1/30/2006
2/14/2006



2007
100 ug/m3 / 8d = 12.5 ug/m3 per day
μg/m³
°C
PM 2.5
Inversion Strengt
12/1/2006
12/16/2006
12/31/2006
1/15/2007
1/30/2007
2/14/2007

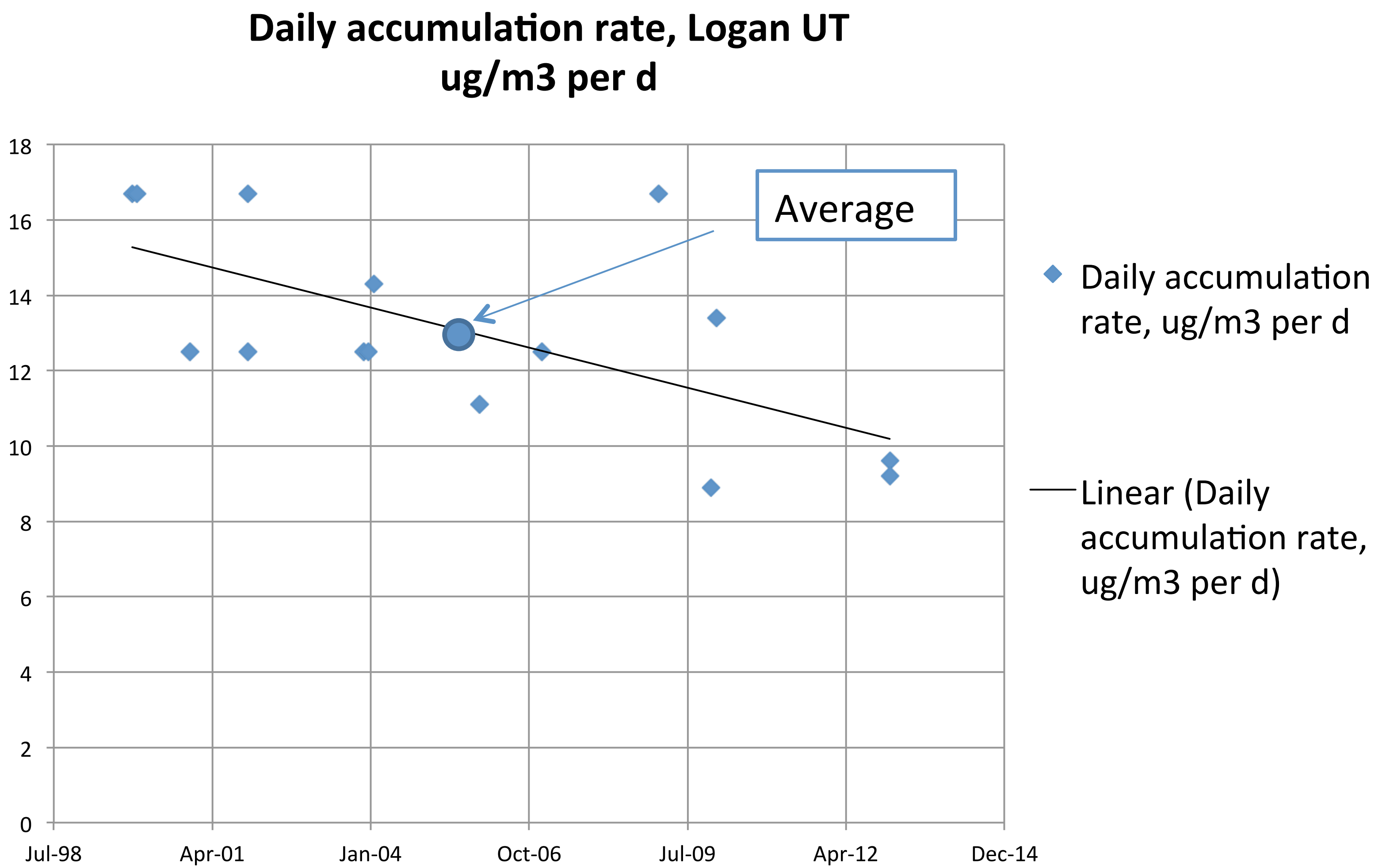


100ug/m3 / 6 d = 16.7 ug/m3 per day
2008
µg/m³
°C
PM 2.5
Inversion Strengt
12/1/2007
12/16/2007
12/31/2007
1/15/2008
1/30/2008
2/14/2008
2/29/2008

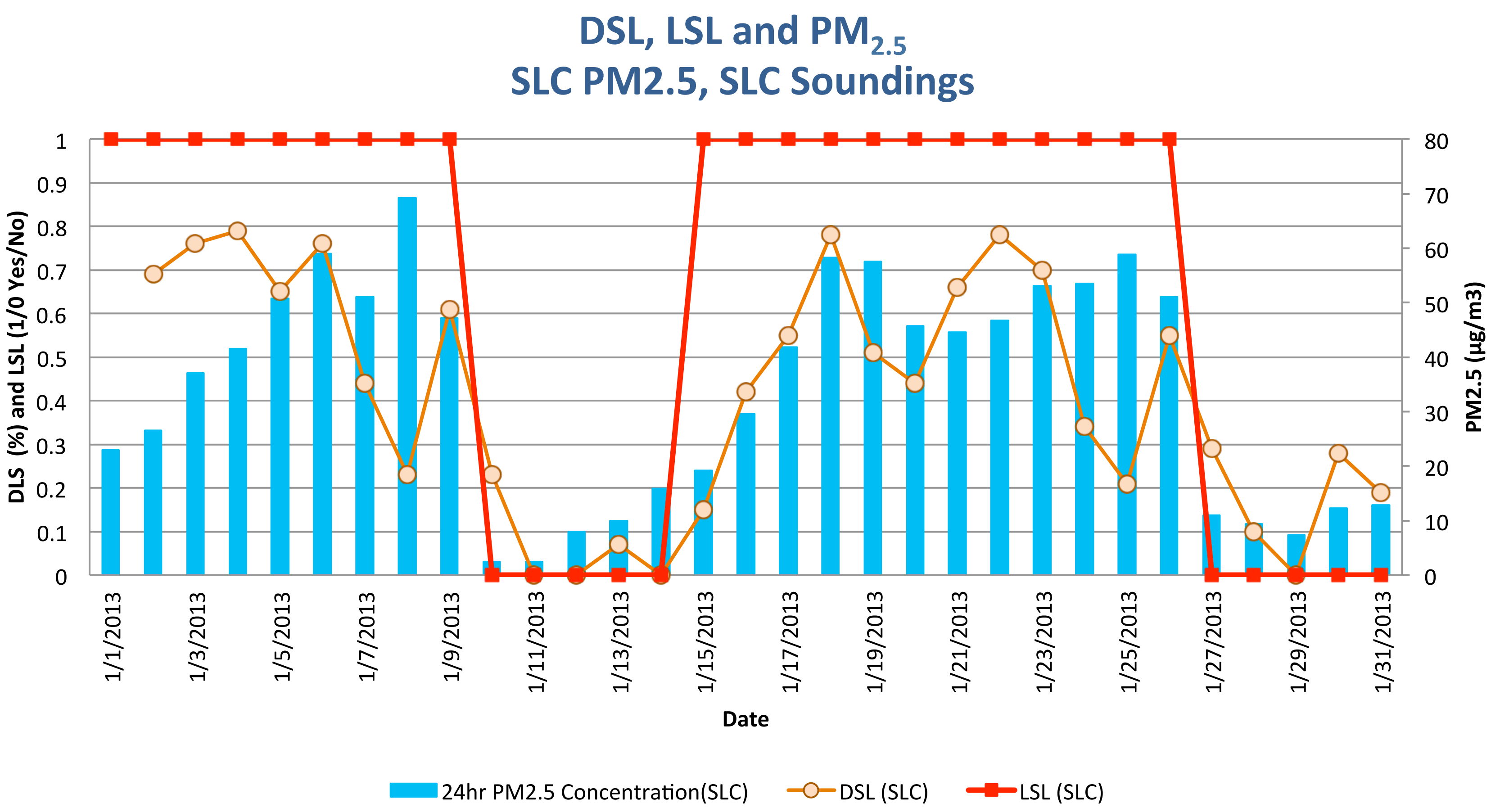


Logan
80ug/m3 / 9 days = 8.9 ug/m3 per day
80ug/m3 /6 days = 13.4 ug/m3 per day
Obs.
Model
24-hr PM2.5 (ug/m3)
two dashes = 1 day
8-Dec
13-Dec
18-Dec
23-Dec
28-Dec
2-Jan
7-Jan
12-Jan
17-
2009-2010

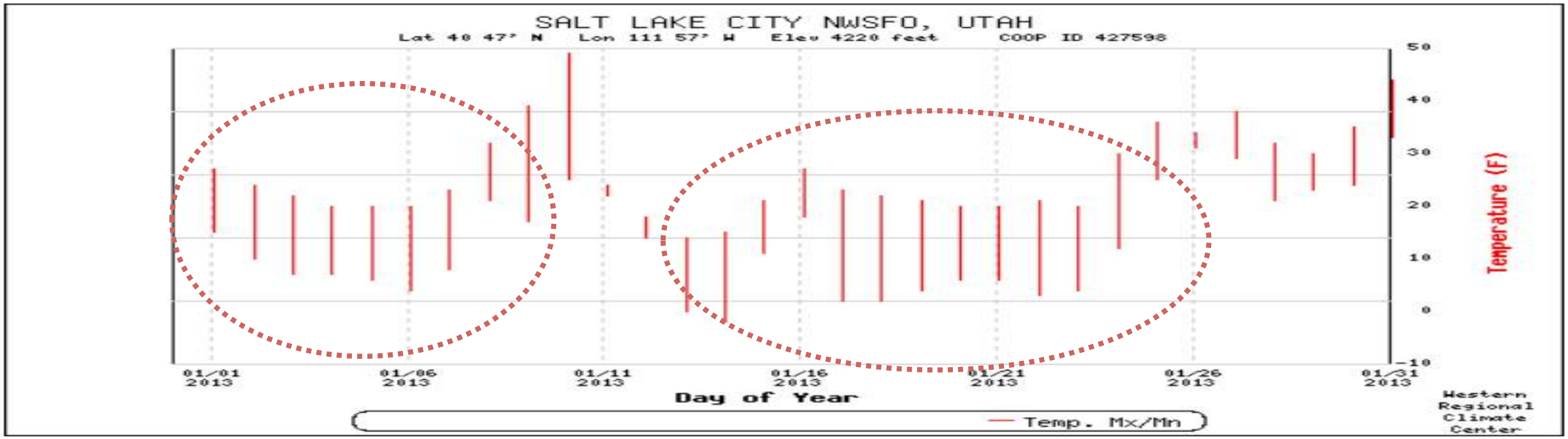
Slopes from Logan 1999 – 2013 Charts (Utah DAQ): Suggests emissions are decreasing

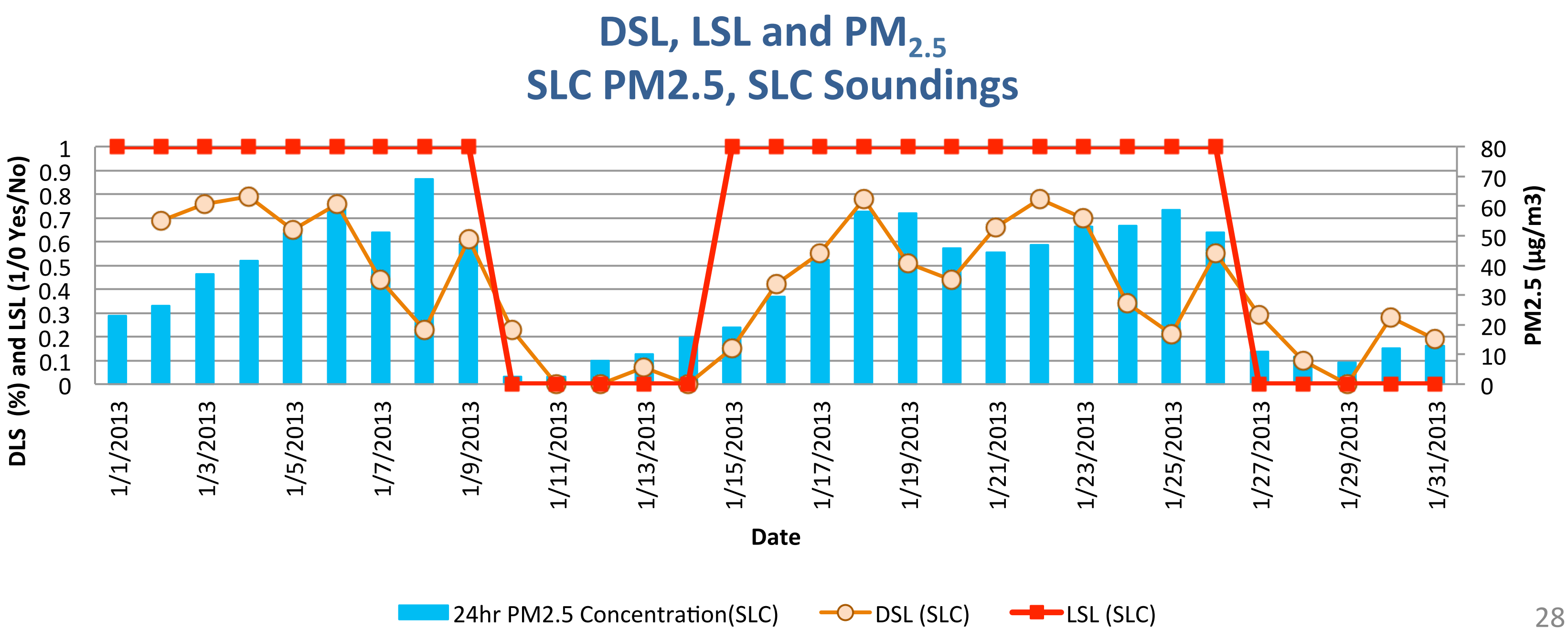


DSL, LSL and $PM_{2.5}$



Key Point from Conceptual Model: Inversion Severity & Max Concentration =f(# of days with cold air pool)





Part 1 Summary: Conceptual Model

- Severe $PM_{2.5}$ events are often regional phenomenon caused by persistent high pressure systems.
- Daily $PM_{2.5}$ increment (slope) appears to be constant
- The highest $PM_{2.5}$ levels depend on both the daily $PM_{2.5}$ increment AND length of the episode.
- Can aid in forecasting multiday $PM_{2.5}$ episodes.
- Can be used to identify and compare historical episodes.
  - **= f(number of days that DSL/CAP persists)**
  - **Therefore monthly average is a good indicator of CAPs**

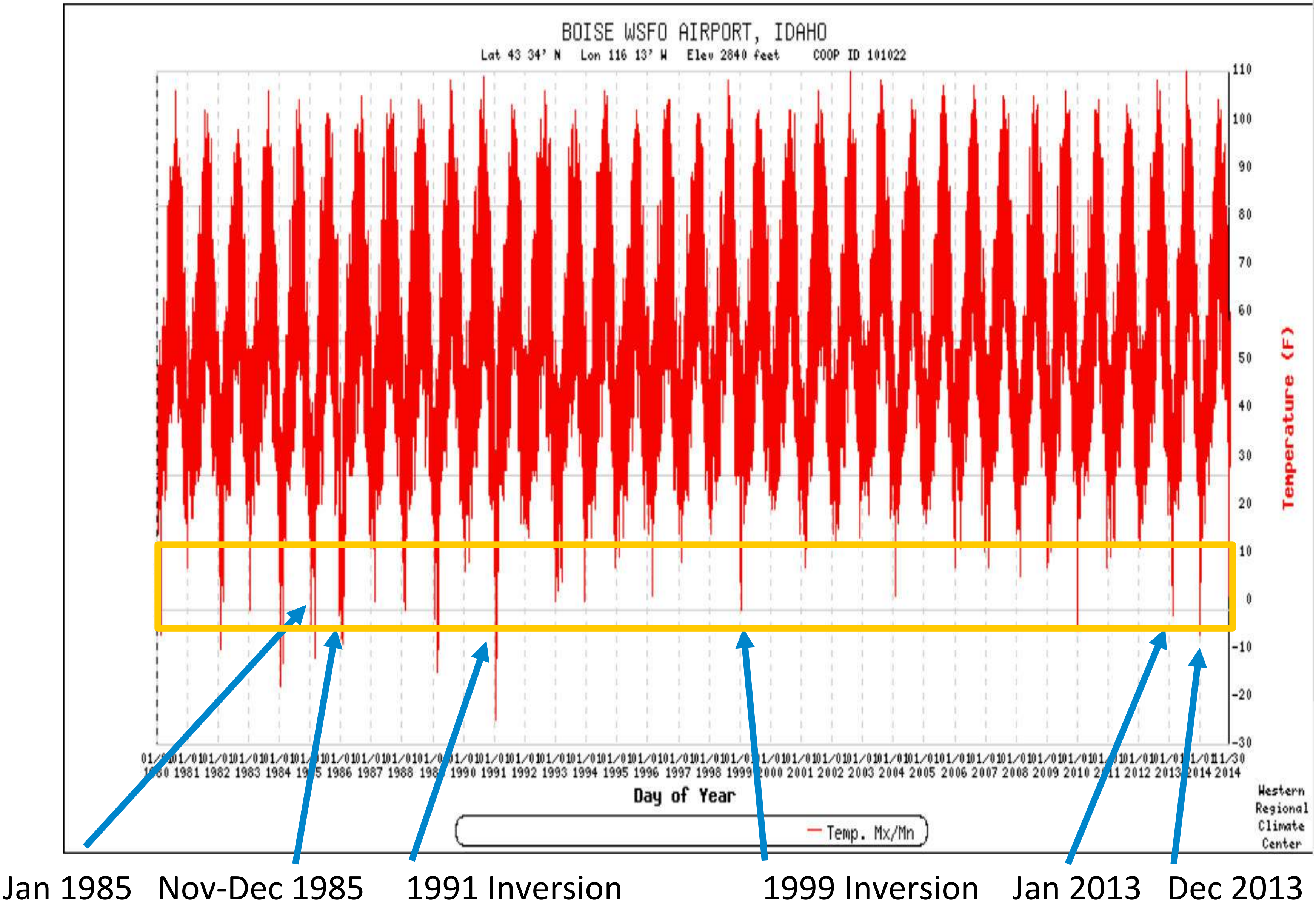
Part 2 Looking at historical record

- Based on Yayi Dong's DSL/LSL Conceptual Model, can we use temperature records to identify historical CAP inversions?

- Can we assess the severity of the 2013 inversions (in January, November, December)

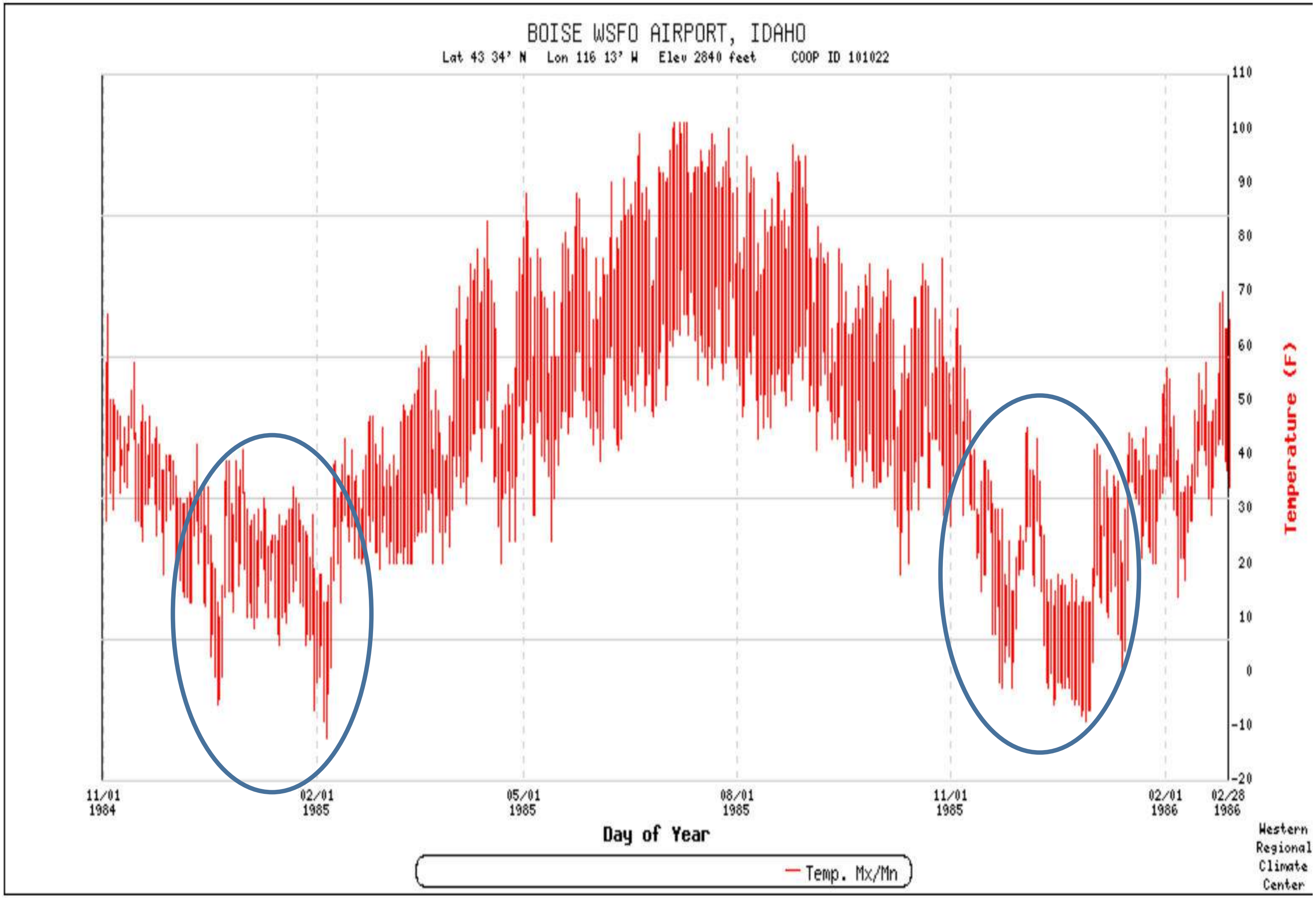
Summary-Of-the-Day Graph

From Western Regional Climate Center
http://www.wrcc.dri.edu/

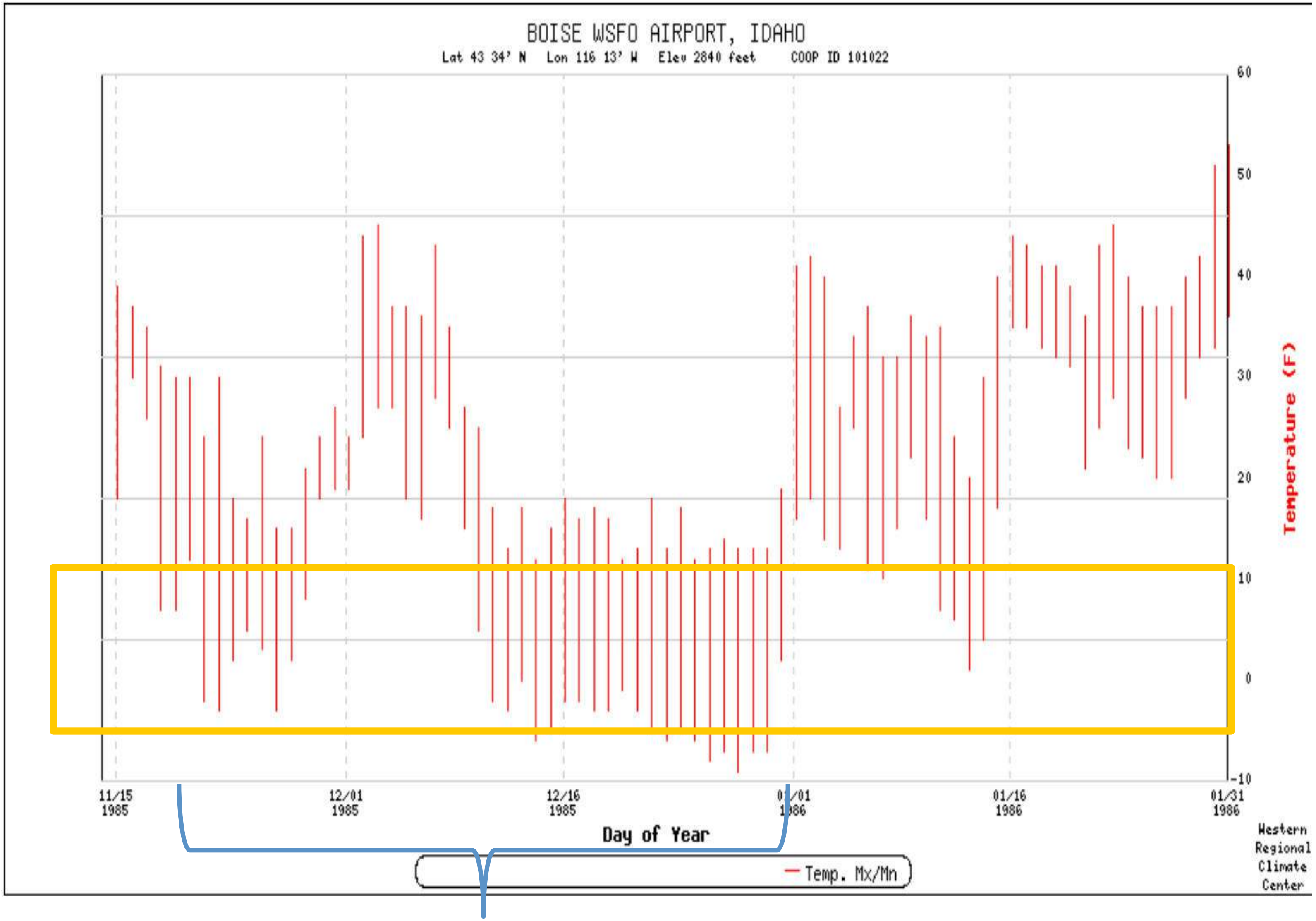


Summary-Of-the-Day Graph

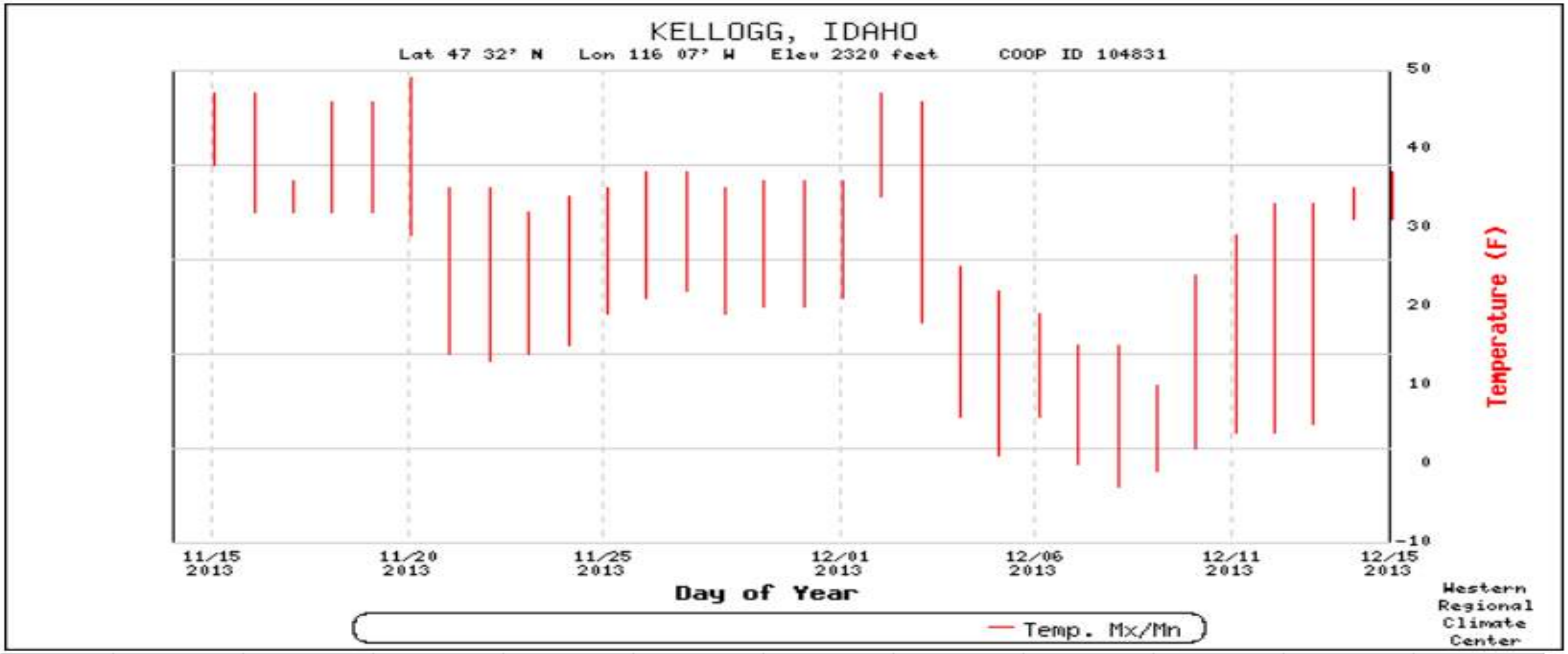
Jan 1985 and Nov-Dec 1985

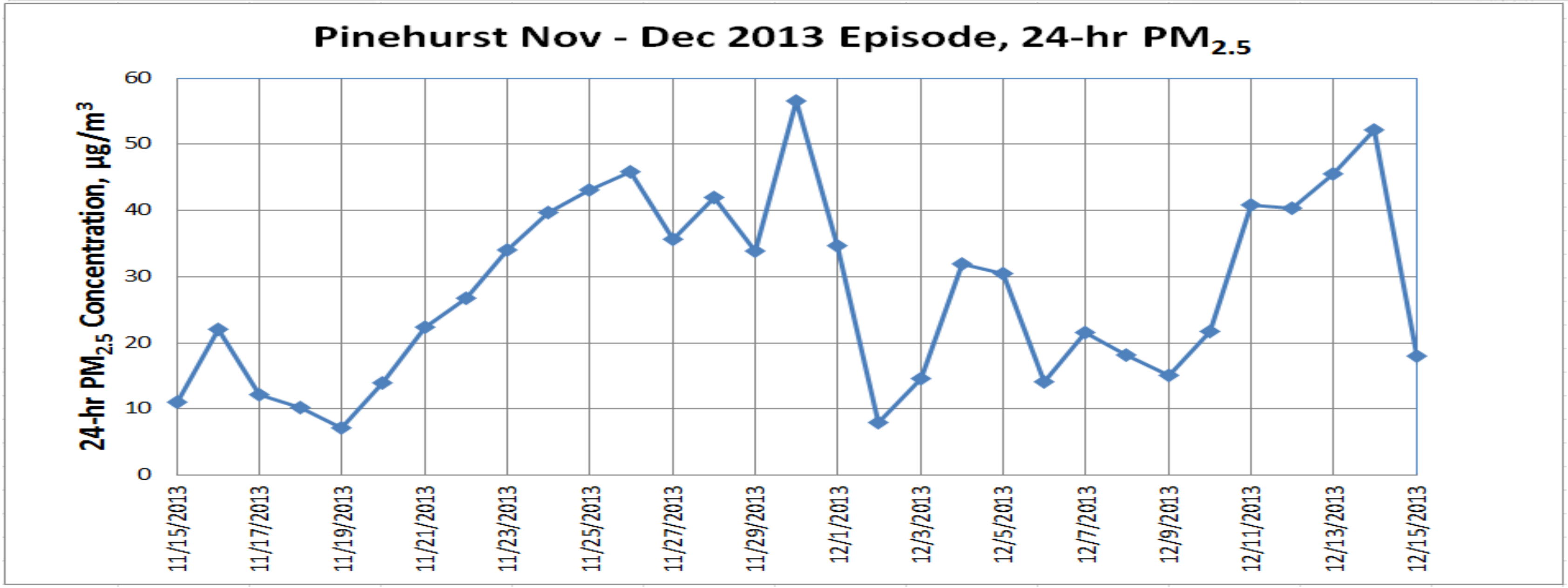


Summary-Of-the-Day Graph Nov-Dec 1985



5 – 6 week inversion in Nov-Dec 1985


KELLOGG, IDAHO
Lat 47 32' N Lon 116 07' W Elev 2320 feet COOP ID 104831
Temperature (F)
Day of Year
11/15 2013
11/20 2013
11/25 2013
12/01 2013
12/06 2013
12/11 2013
12/15 2013
Temp. Mx/Mn
Western Regional Climate Center


Pinehurst Nov - Dec 2013 Episode, 24-hr PM2.5
24-hr PM2.5 Concentration, µg/m3
11/15/2013
11/17/2013
11/19/2013
11/21/2013
11/23/2013
11/25/2013
11/27/2013
11/29/2013
12/1/2013
12/3/2013
12/5/2013
12/7/2013
12/9/2013
12/11/2013
12/13/2013
12/15/2013

Summary of Day Monthly Average Temp
(easy to obtain for entire Period of Record from WRCC)

SOD Monthly Summary

STATION NUMBER 101022 ELEMENT : DAILY MEAN TEMPERATU65.00 QUANTITY : MONTHLY AVERAGE
STATION : BOISE WSFO AIRPORT
FROM DATA WITH UNITS: DEGREES F
*** Note *** Provisional Data *** After Year/Month 201411
a = 1 day missing, b = 2 days missing, c = 3 days, ..etc..,
z = 26 or more days missing, A = Accumulations present
Long-term means based on columns; thus, the monthly row may not
sum (or average) to the long-term annual value.

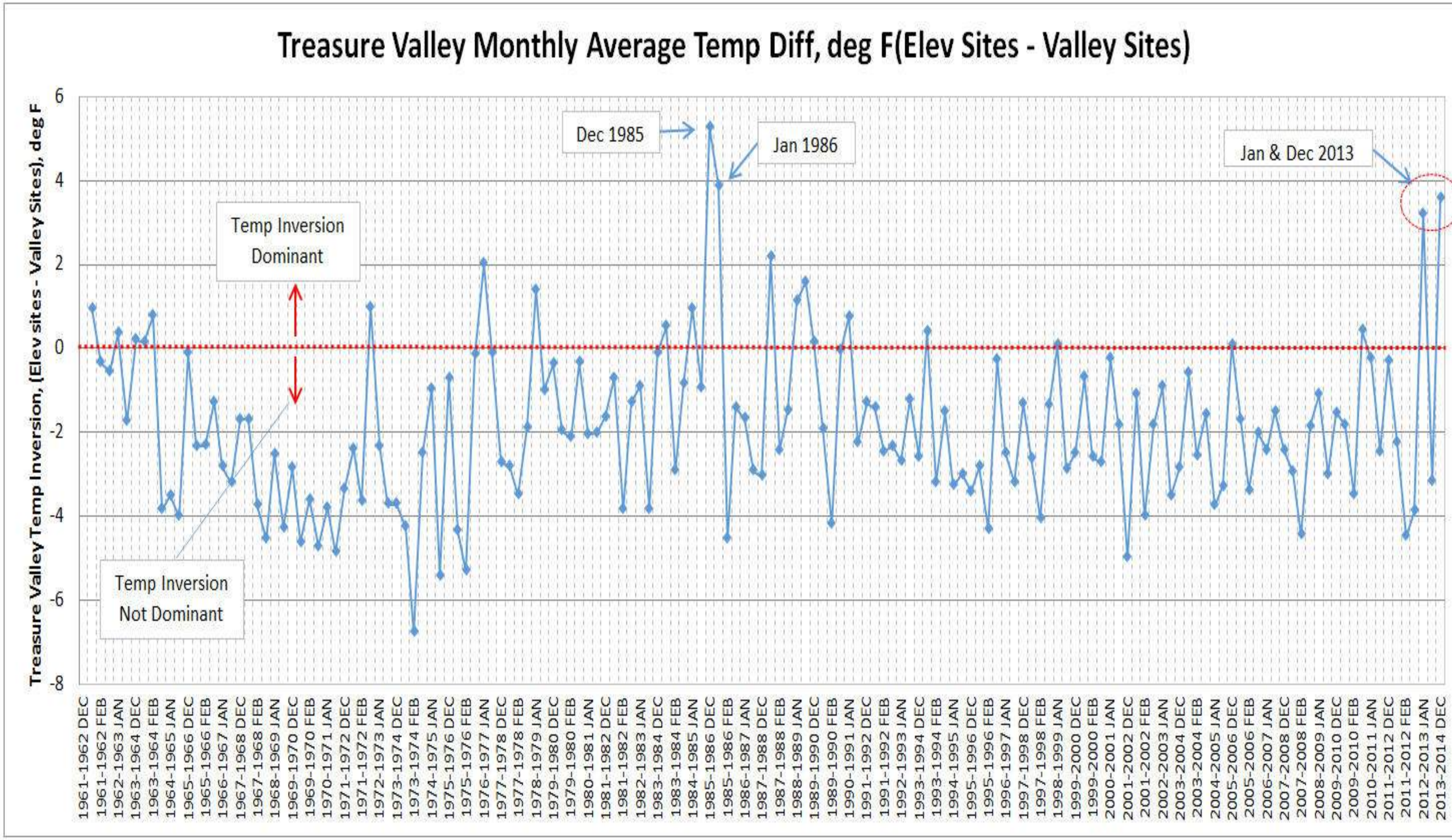
MAXIMUM ALLOWABLE NUMBER OF MISSING DAYS : 5

YEAR(S)	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANN
1940	33.03	38.91	45.58	50.07	61.29	69.58	74.89	74.18	63.13	54.32	35.50	35.26	52.98
1941	33.23	39.46	45.42	50.10	58.45	62.90	75.45	70.90	57.90	50.92	42.07	34.98	51.82
1942	20.56	31.54	40.26	51.77	52.97	60.77	75.66	72.90	63.20	52.52	39.68	33.45	49.61
1943	28.16	35.93	39.92	54.02	54.00	61.63	73.29	70.90	66.62	53.90	40.07	32.84	50.94
1944	25.03	34.05	38.32	48.88	58.58	60.75	72.26	70.69	63.73	57.97	38.68	29.05	49.83
1945	32.13	37.59	40.03	46.03	56.65	61.13	74.87	73.42	59.93	55.24	39.65	30.79	50.62
1946	29.03	33.77	43.76	51.85	57.66	65.37	74.89	73.26	61.02	45.13	37.73	36.21	50.81
1947	23.27	38.05	44.89	49.35	62.24	61.75	75.08	72.21	62.85	55.15	36.12	31.34	51.02

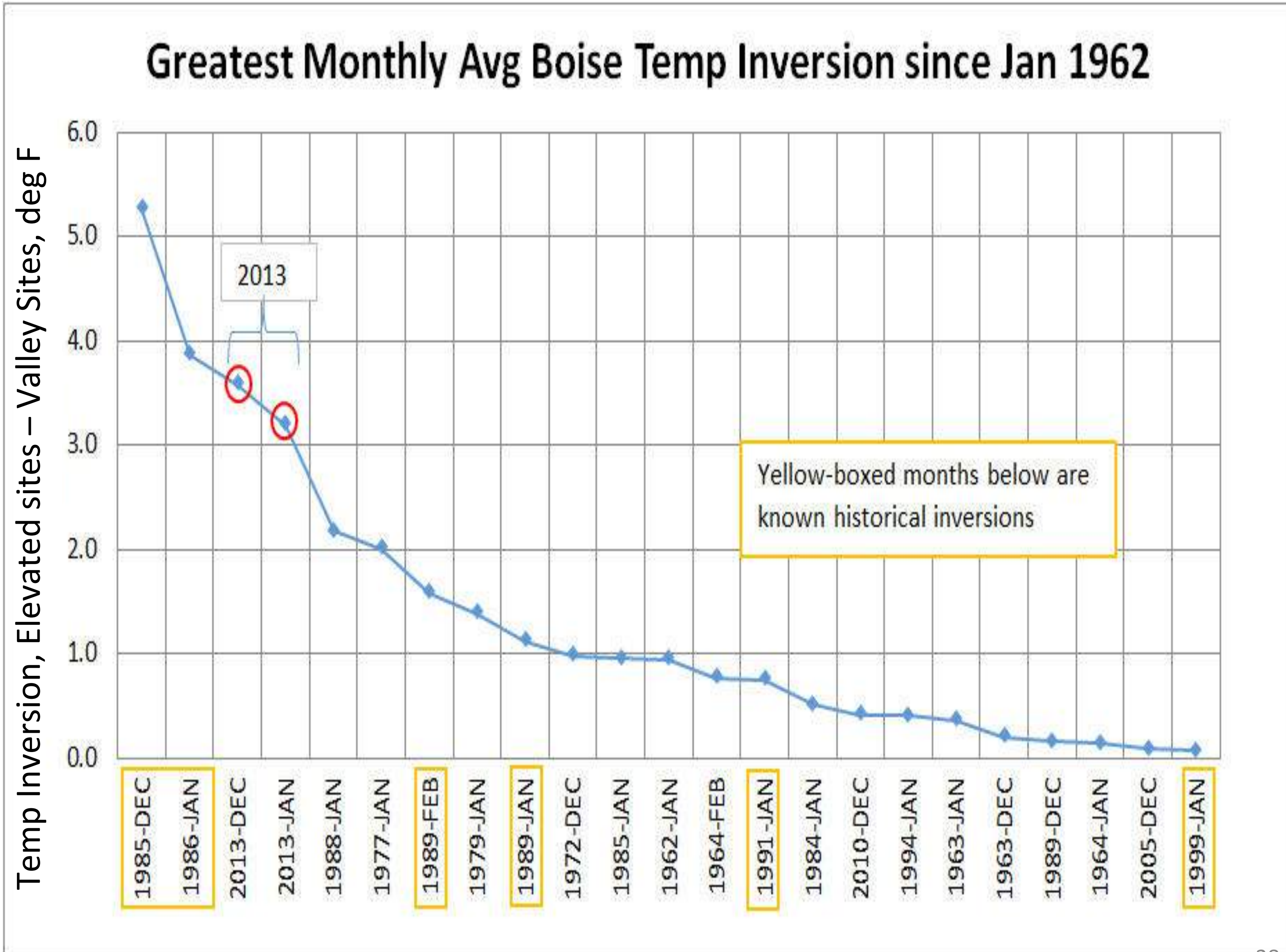
Inversion ΔT indicator can be estimated by (Average of Valley Sites Monthly Average Temp) – (Average of Elevated Sites Monthly Average) Temp

Type	Station Name	Elev
Valley	NAMPA SUGAR FACTORY	2470
Valley	DEER FLAT DAM	2511
Valley	BOISE WSFO AIRPORT	2846
Elevated	REYNOLDS	3928
Elevated	ARROWROCK DAM	3265

This results in an arbitrary, but historically consistent relative indication of inversion conditions. Requires sites with complete record back to 1960s.



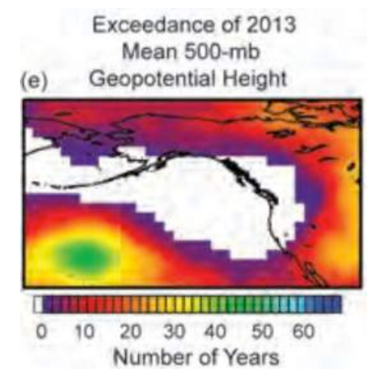
Treasure Valley Monthly Average Temp Diff, deg F(Elev Sites - Valley Sites)
Treasure Valley Temp Inversion, (Elev sites - Valley Sites), deg F
Dec 1985
Jan 1986
Jan & Dec 2013
Temp Inversion Dominant
Temp Inversion Not Dominant



Greatest Monthly Avg Boise Temp Inversion since Jan 1962
Temp Inversion, Elevated sites – Valley Sites, deg F
6.0
5.0
4.0
3.0
2.0
1.0
0.0
2013
Yellow-boxed months below are known historical inversions
1985-DEC
1986-JAN
2013-DEC
2013-JAN
1988-JAN
1977-JAN
1989-FEB
1979-JAN
1989-JAN
1972-DEC
1985-JAN
1962-JAN
1964-FEB
1991-JAN
1984-JAN
2010-DEC
1994-JAN
1963-JAN
1963-DEC
1989-DEC
1964-JAN
2005-DEC
1999-JAN

The 2013 event high pressure ridge in historical context.

The California drought occurred in tandem with a highly persistent region of positive geopotential height (GPH) anomalies over the northeastern Pacific Ocean (Fig. 2.1e,h), nicknamed the "Ridiculously Resilient Ridge" in the public discourse. . .

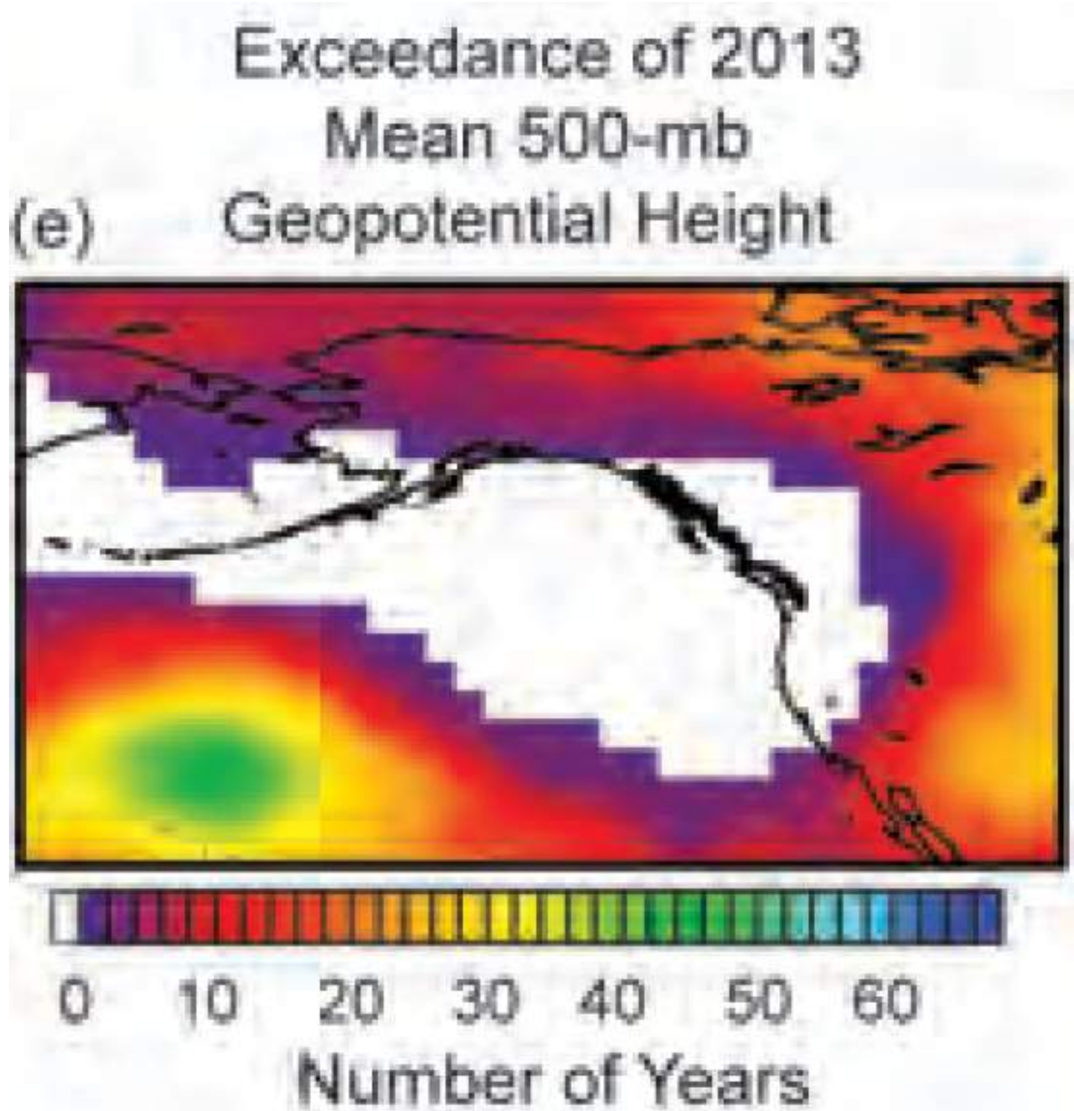


. . .We find that a vast geographic region centered in the Gulf of Alaska experienced 500-mb GPH anomalies that exceeded all previous values (Fig. 2.1e) in the 66-year NCEP1 reanalysis (Kalnay et al. 1996).

Swain, Daniel L. and Coauthors, 2014: *The extraordinary California Drought of 2013/2014: Character, Context, and the Role of Climate Change*, [in "Explaining Extremes of 2013 from a Climate Perspective"]. *Bull. Amer. Meteor. Soc.*, **95** (9), S3–S7.

The RRR

(e) Number of Jan–Dec periods during 1948–2012 in which 500-mb GPH were higher than the Jan–Dec 2013 value



Swain, Daniel L. and Coauthors, *The extraordinary California Drought of 2013/2014: Character, Context, and the Role of Climate Change*, [in "Explaining Extremes of 2013 from a Climate Perspective"]. *Bull. Amer. Meteor. Soc.*, **95** (9), S3–S7.

Part 2 Summary

- Yayi Dong's simple conceptual model can be useful for forecasting multi-day inversion concentrations in mountain valleys.
- It can also be used with simple temperature analysis to explore historical inversion episodes.
- Based on temperature records Jan and Dec 2013 were the worst inversion since the 1985 event for Boise.

Part 3 Historical PM trends and extreme events (Boise Example)

- Is the PM record consistent with the climatology?
(i.e. do the severe inversions lead to extreme PM levels?)
- Was January 2013 part of a trend or an outlier?

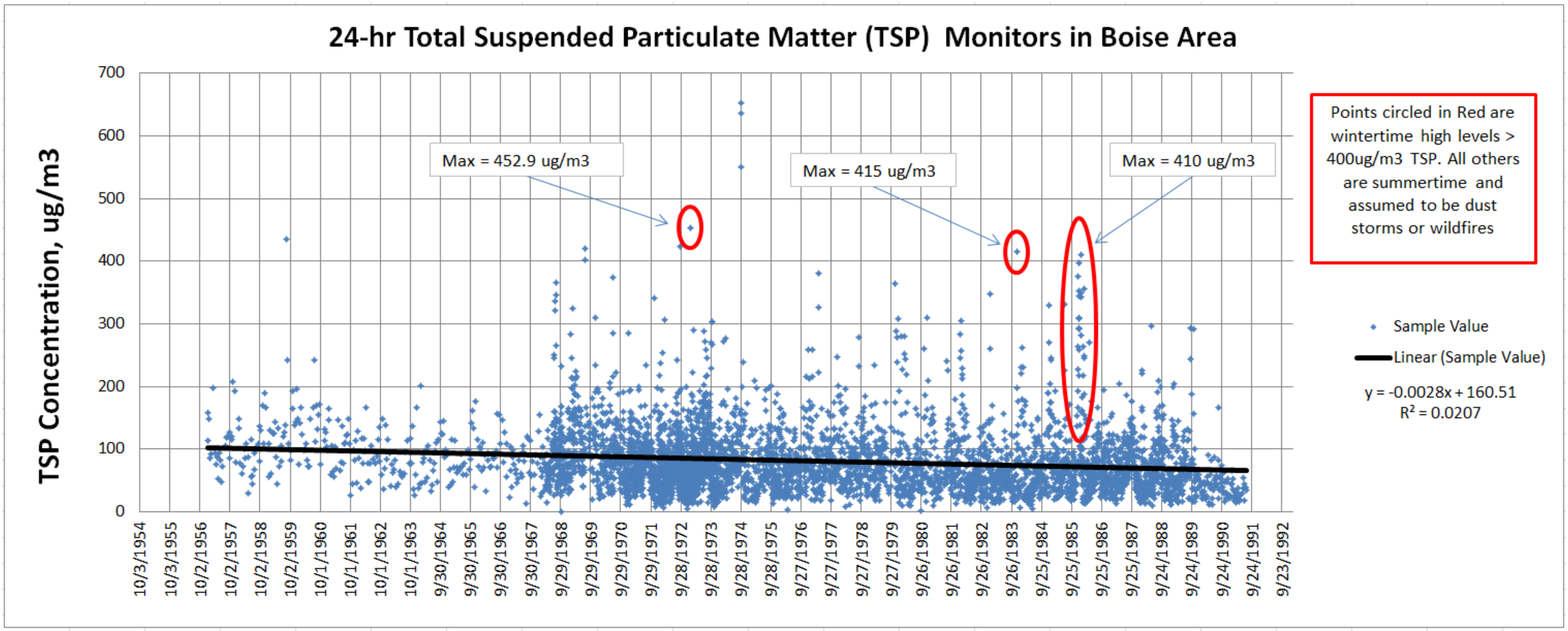
Part 3 Historical PM trends and outliers (Boise Exammple)

Do historic PM trends and extremes corroborate these inversion patterns?

- 1956 – 1990: TSP = Total Suspended Particulate Matter < ~30 µm
- 1988 – 2014: PM_{10} = Particulate matter less than 10 µm
- 1998 – 2014: $PM_{2.5}$ = Particulate matter less than 2.5 µm

Historic **TSP** levels indicate the greatest cluster of high days in the early monitoring history (almost 60 years) are in December 1985.

This is consistent with the temperature inversion record!



PM_{10} Trend during Winters, 1988 – 2014

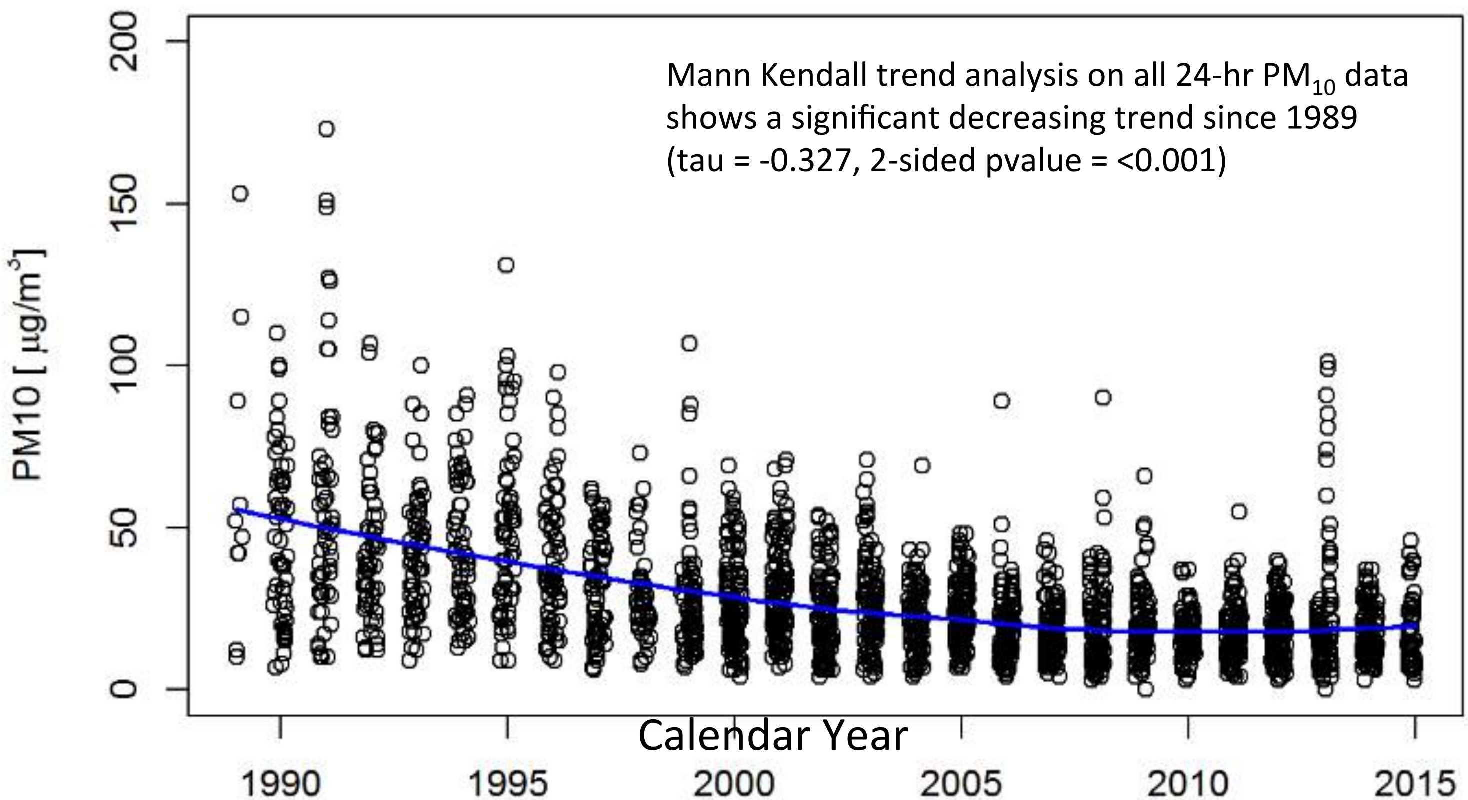
1)PM_{10} is examined first since it has a longer period of record than $PM_{2.5}$

2)Only Winter months are examined.

a) The PM problem is strictly a winter inversion issue.
b) This avoids the complication of Wildfire and most dust Exceptional Events.
c) One concurred wintertime Exceptional Event is removed (a dust storm from Nevada playas occurring Feb 15 & 16, 2011).

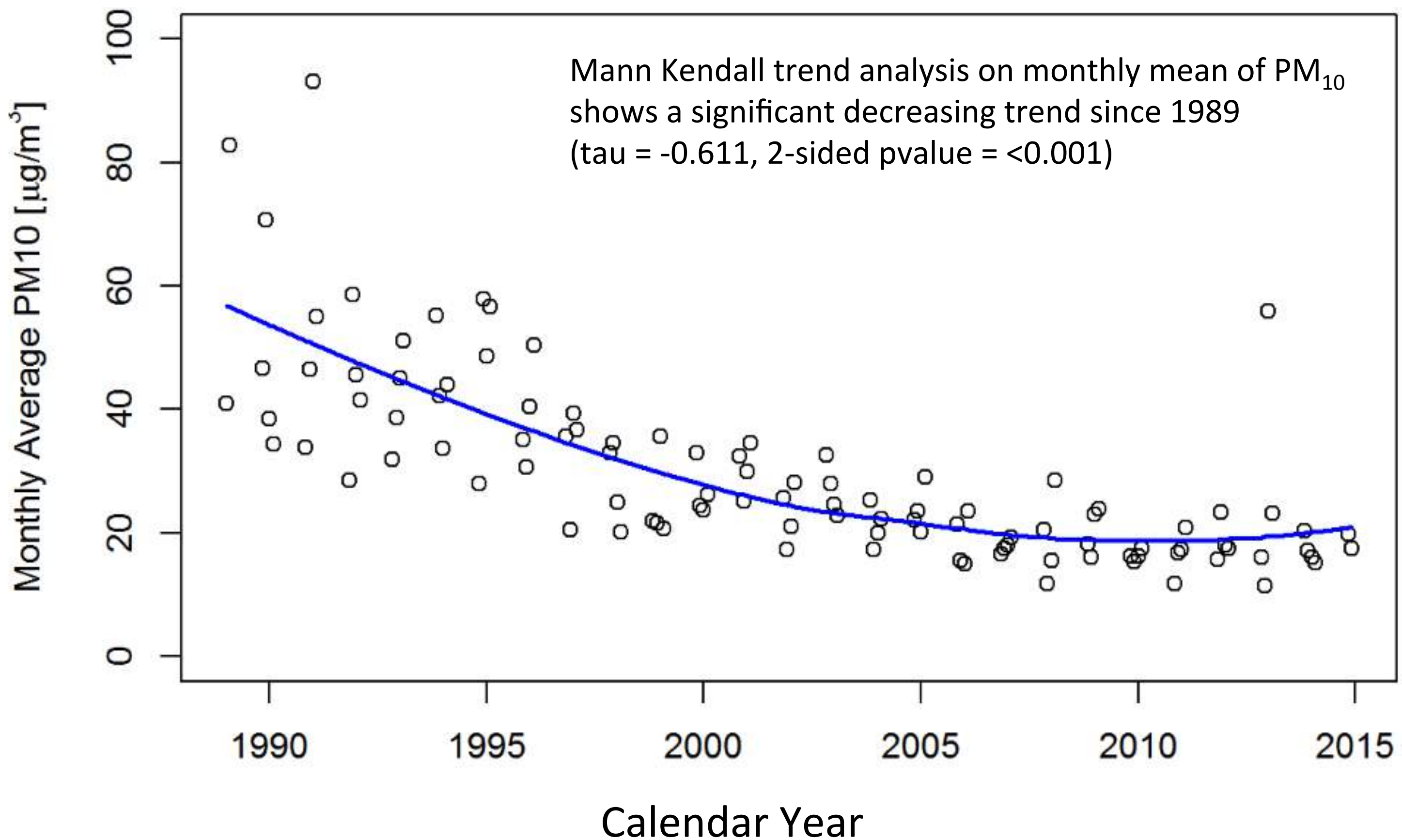
PM_{10} Winter **Daily** PM_{10} (NDJF) at Boise Fire Station

LOESS Trend Line 1988-2014: Significantly Decreasing Trend



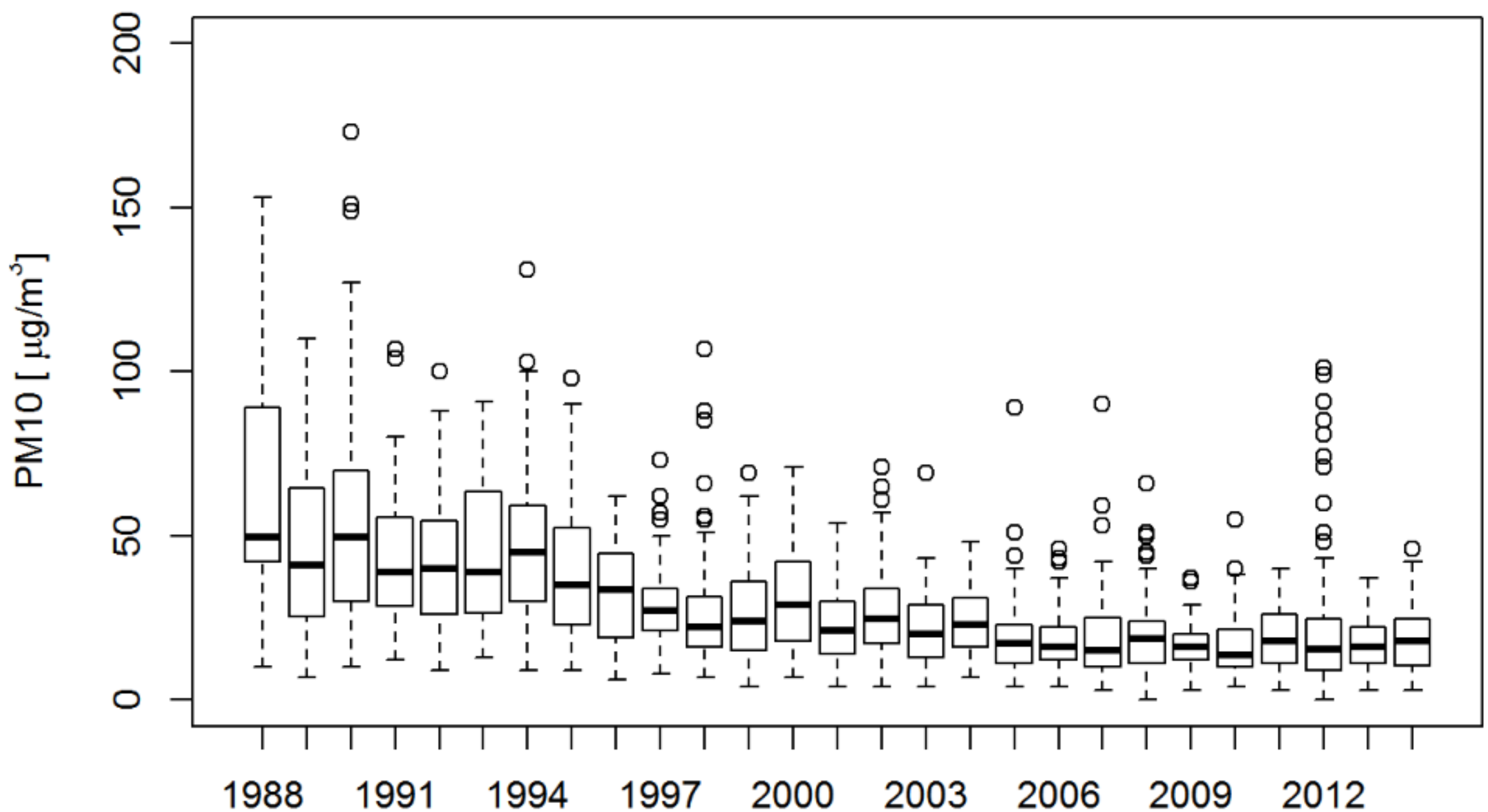
PM_{10} **Monthly** Averages (NDJF) at Boise Fire Station

LOESS Trend Line 1988-2014



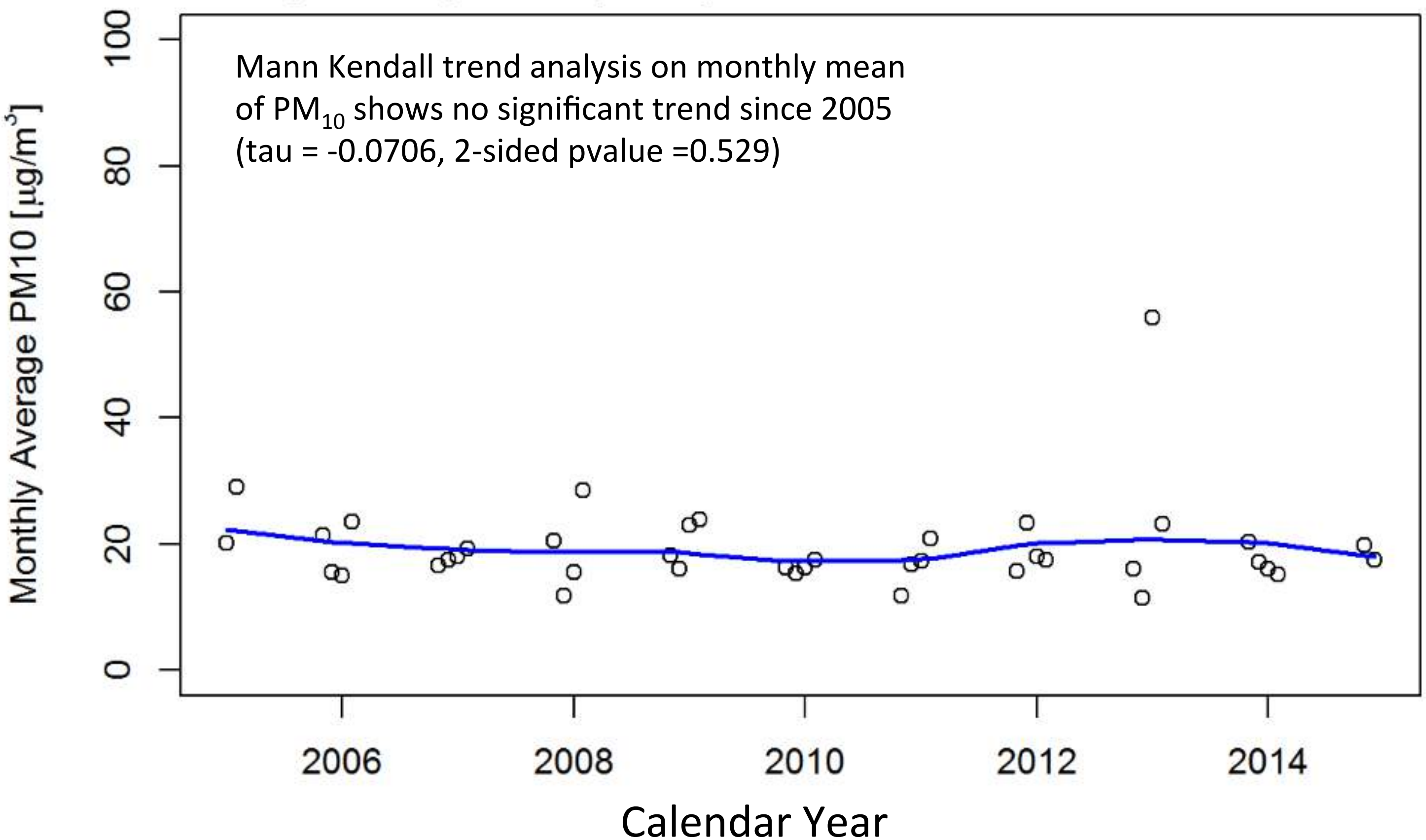
Histograms by Water-Year for NDJF

(25% & 75% quartile bars, "Error Bars" = 1.5 x Inner Quartile Range)

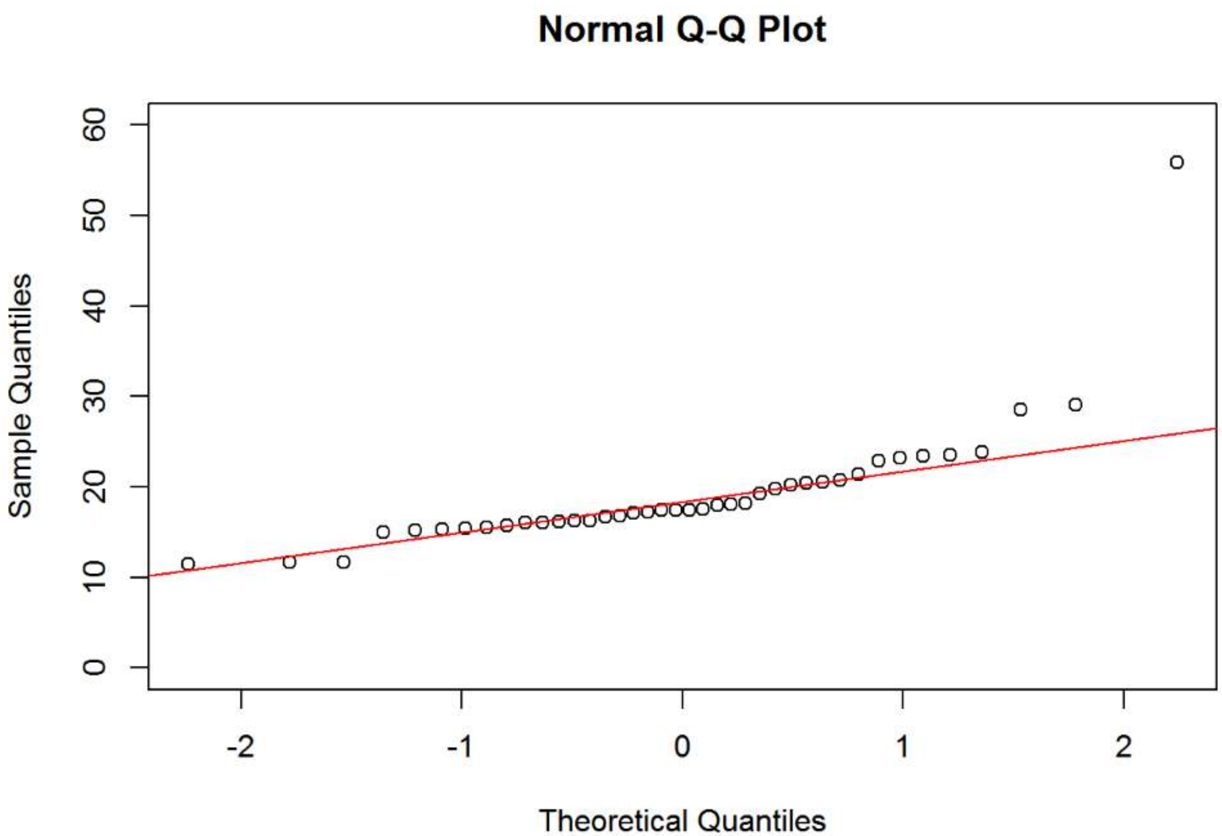


Years are "water years" or the year in which the winter starts.

Monthly Avg PM_{10} (NDJF): No Trend in Last 10 years

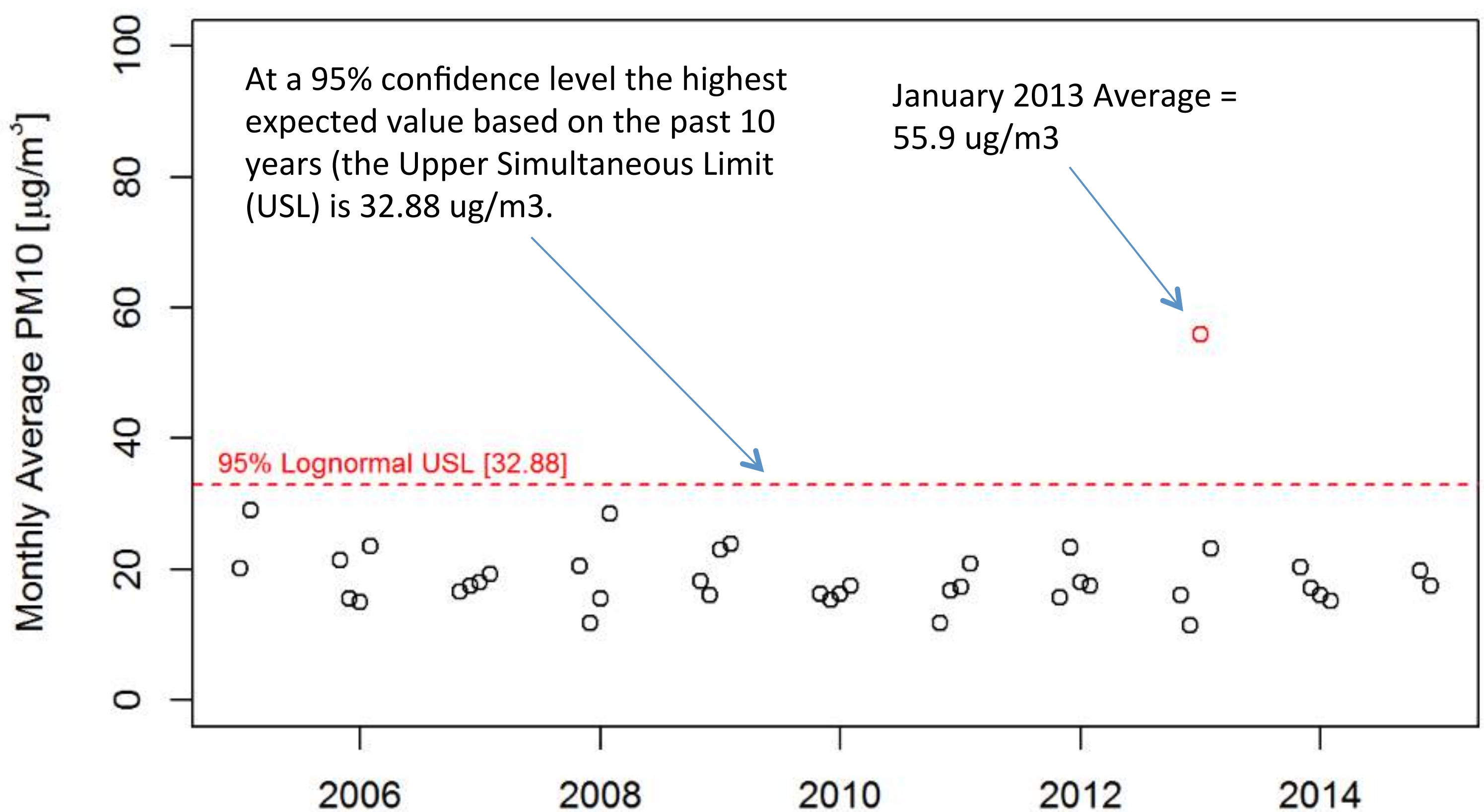


January 2013 Average Appears to be an Outlier but this plot assumes normality; the data are not normal.

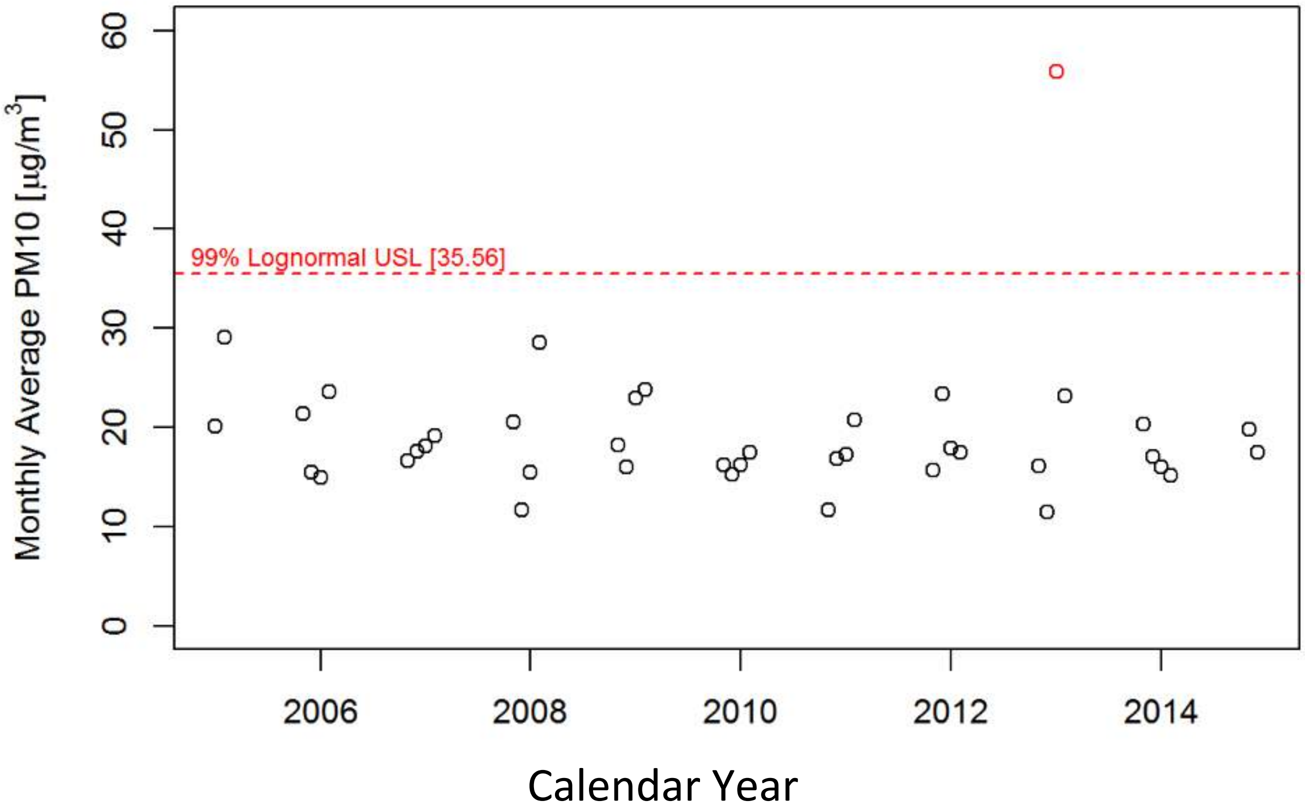


Grubb's test on the lognormal data supports classifying the January 2013 observation as a statistical outlier (p-value = <0.001).

January 2013 Average PM_{10} is well outside the expected population of values observed over the past 10 years

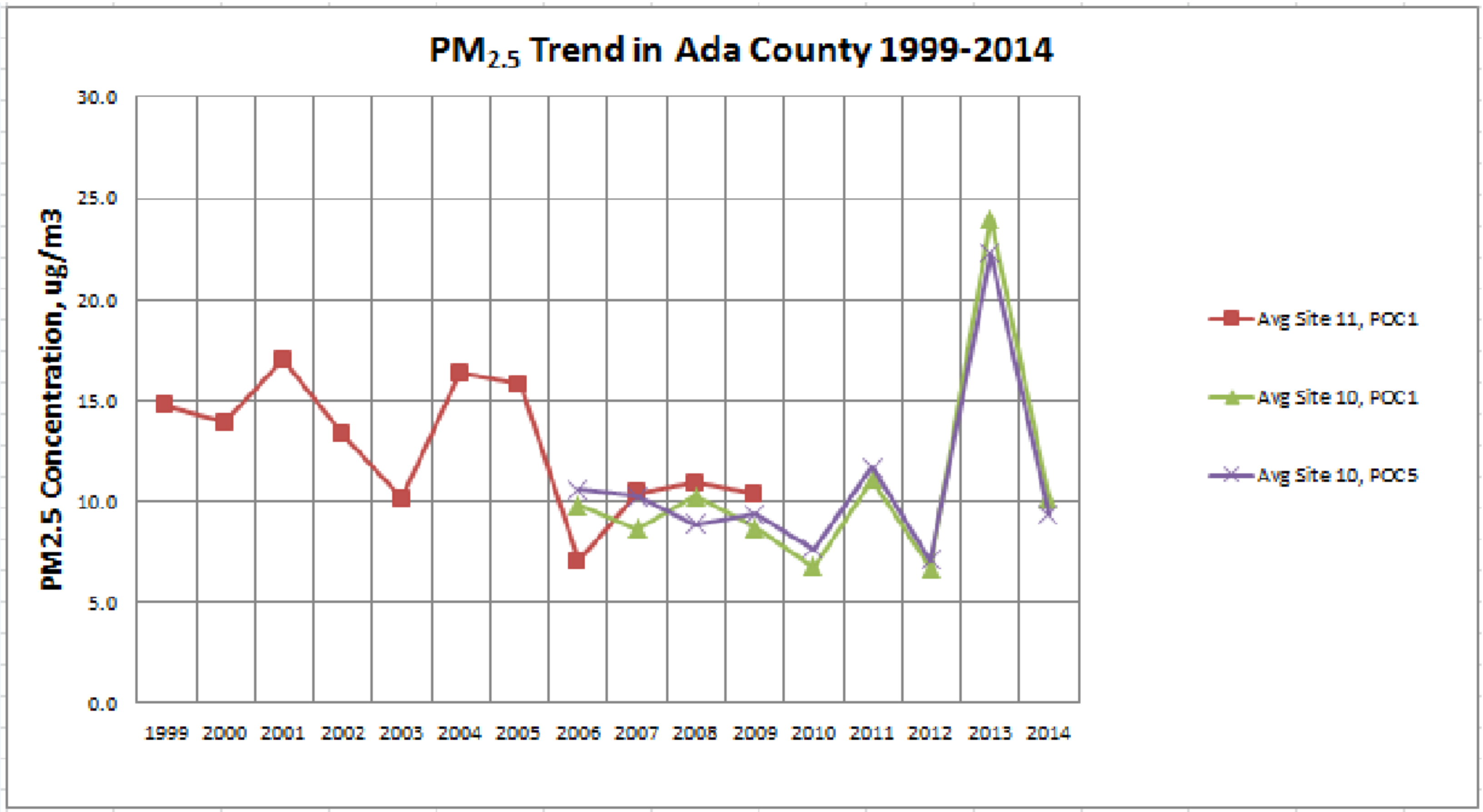


It is still well outside the expected PM_{10} population at a 99% confidence level



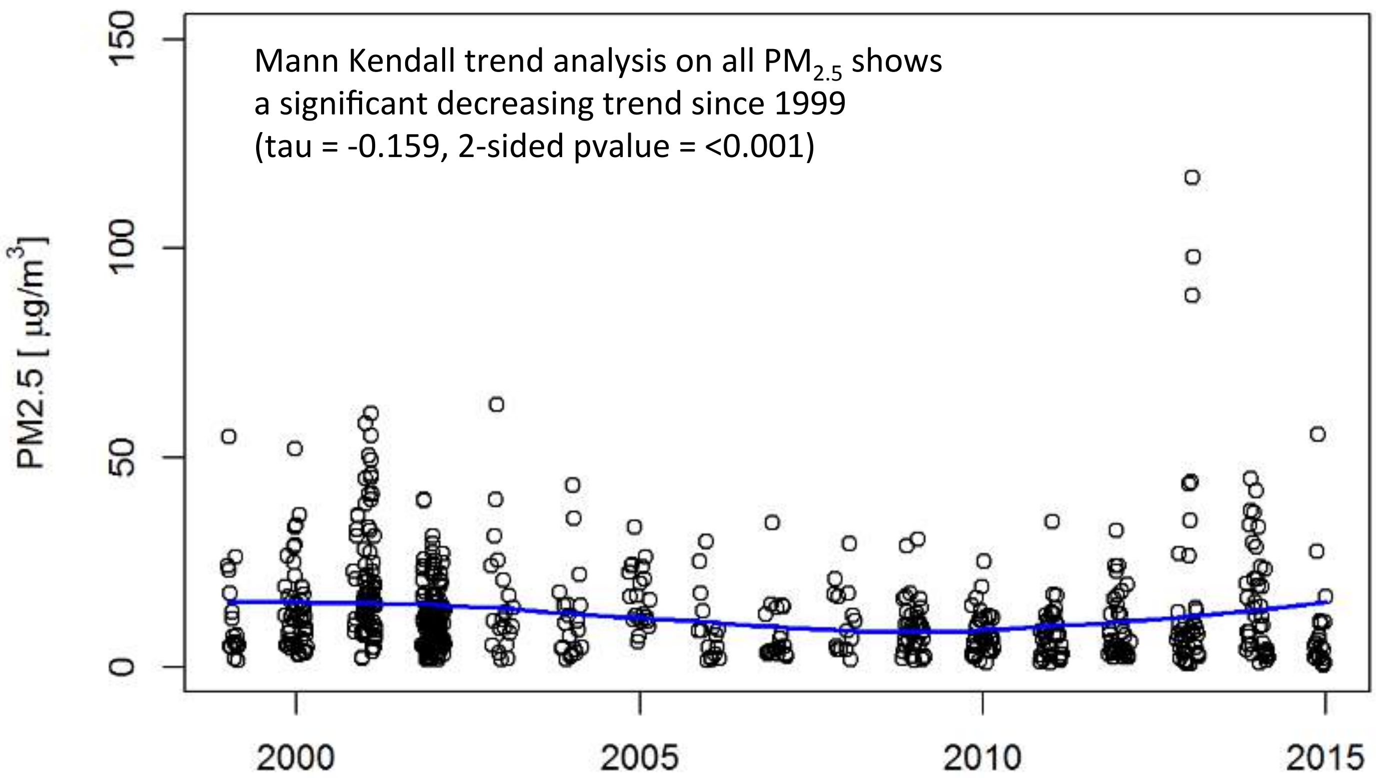
Now look at trends and outliers for $PM_{2.5}$

Boise Sites Mt. View School (Site 11) 1998-2005; St. Lukes (Site 10) 2006-2014



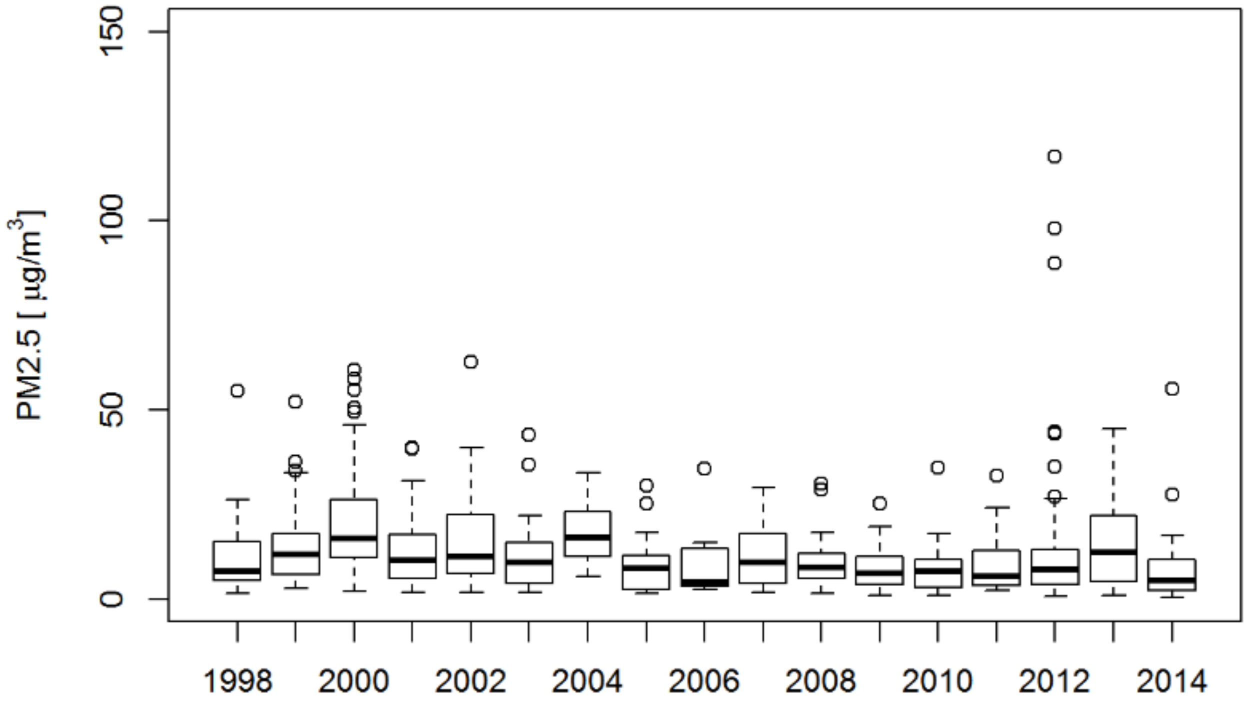
$PM_{2.5}$ Winter Daily Values at Mt. View & St. Luke's

LOESS Trend Line for Mt. View School (1998-2005) & St. Lukes (2006-2014)



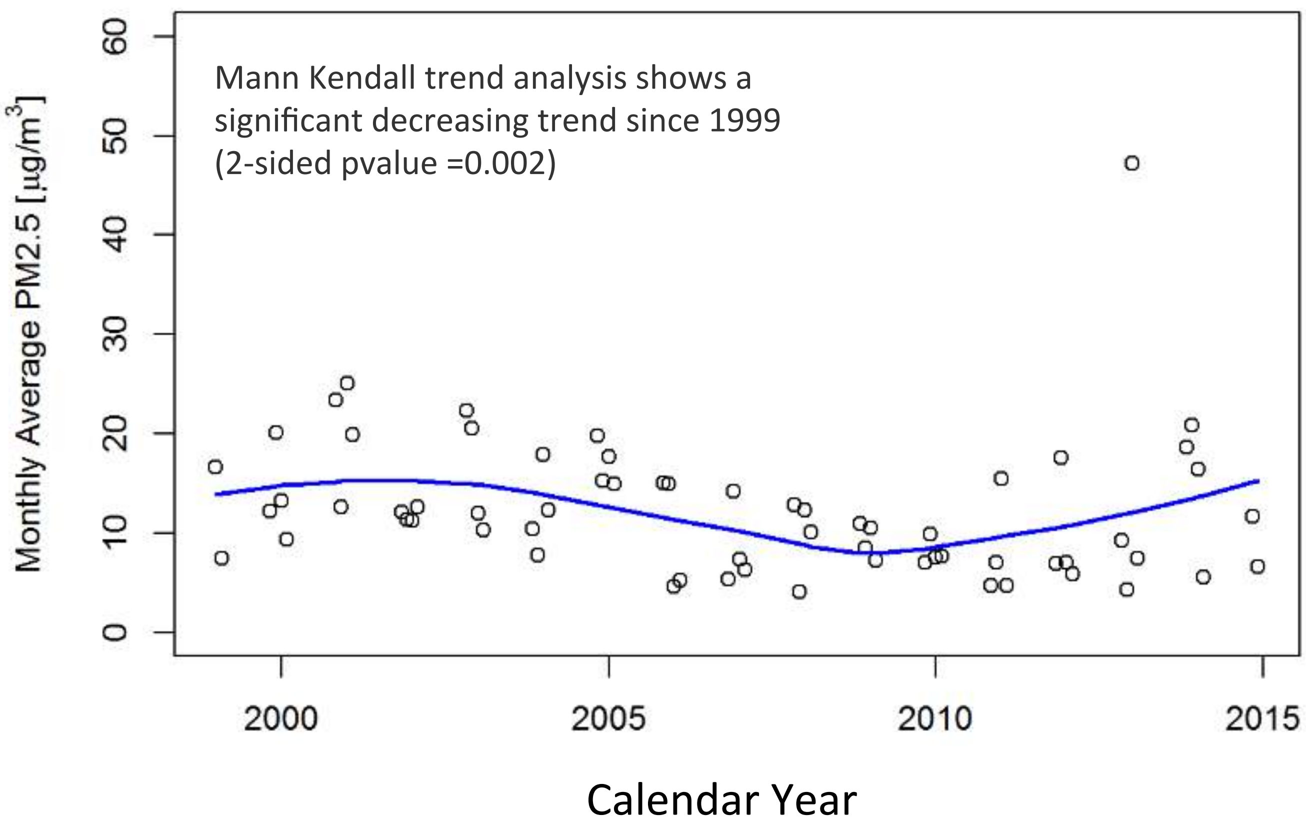
Histograms of Daily $PM_{2.5}$ (NDJF) at 2 Boise Sites

Mt. View 1998-2005, St. Lukes 2006-2014

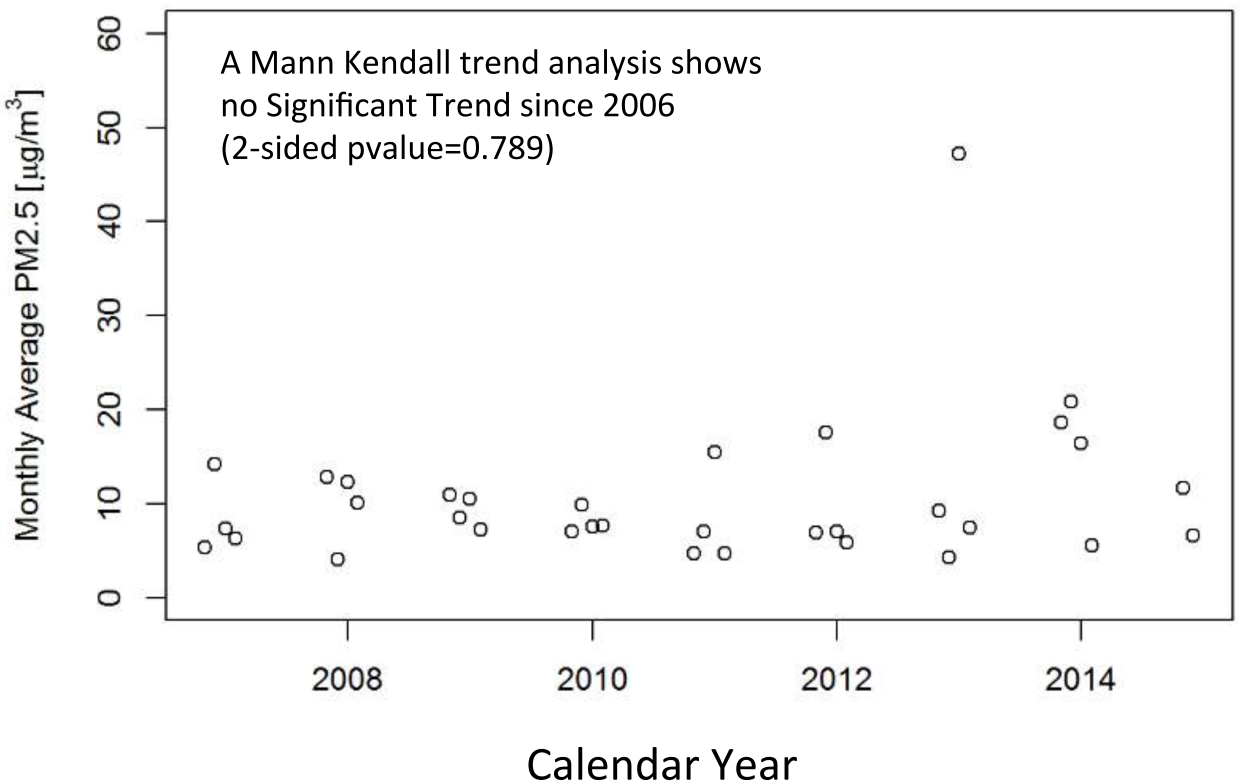


Years are “water years”, the year in which the winter starts.

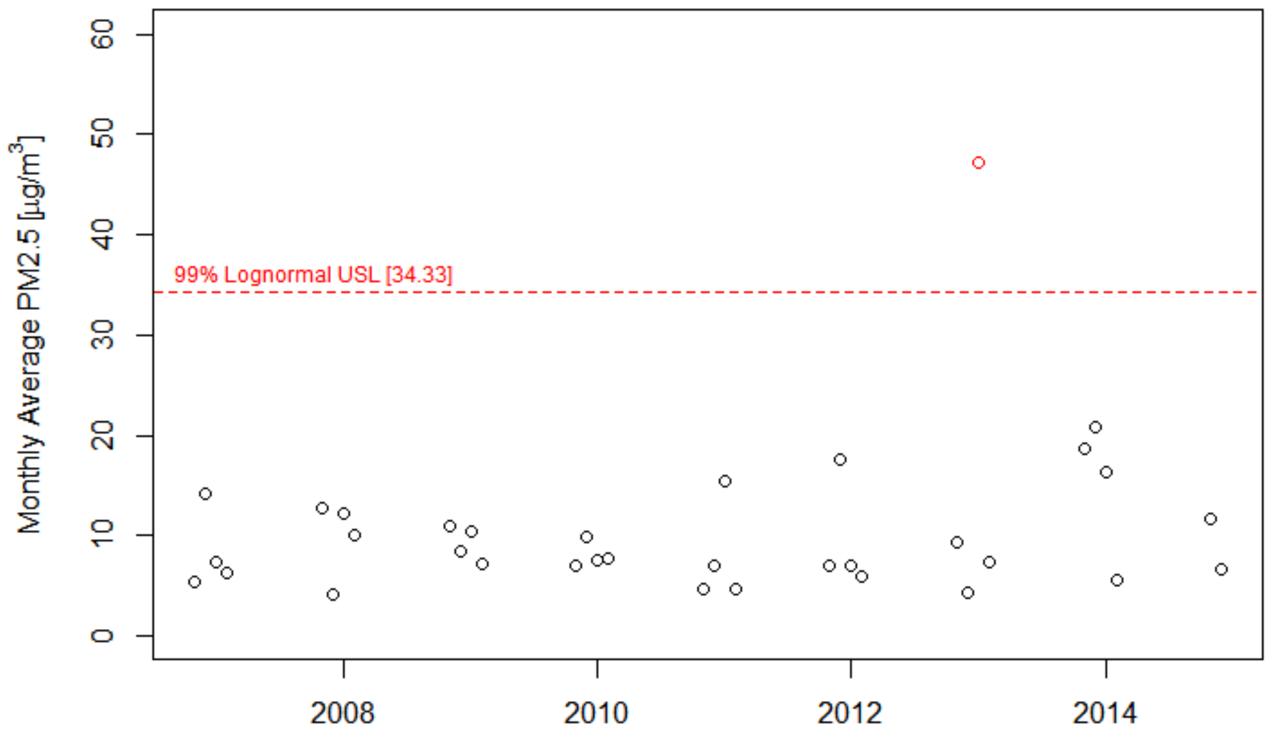
Winter Monthly Averages (NDJF) for both sites show a decreasing trend since 1999



St. Luke's Meridian Winter Monthly $PM_{2.5}$ (NDJF) 2006 - 2014



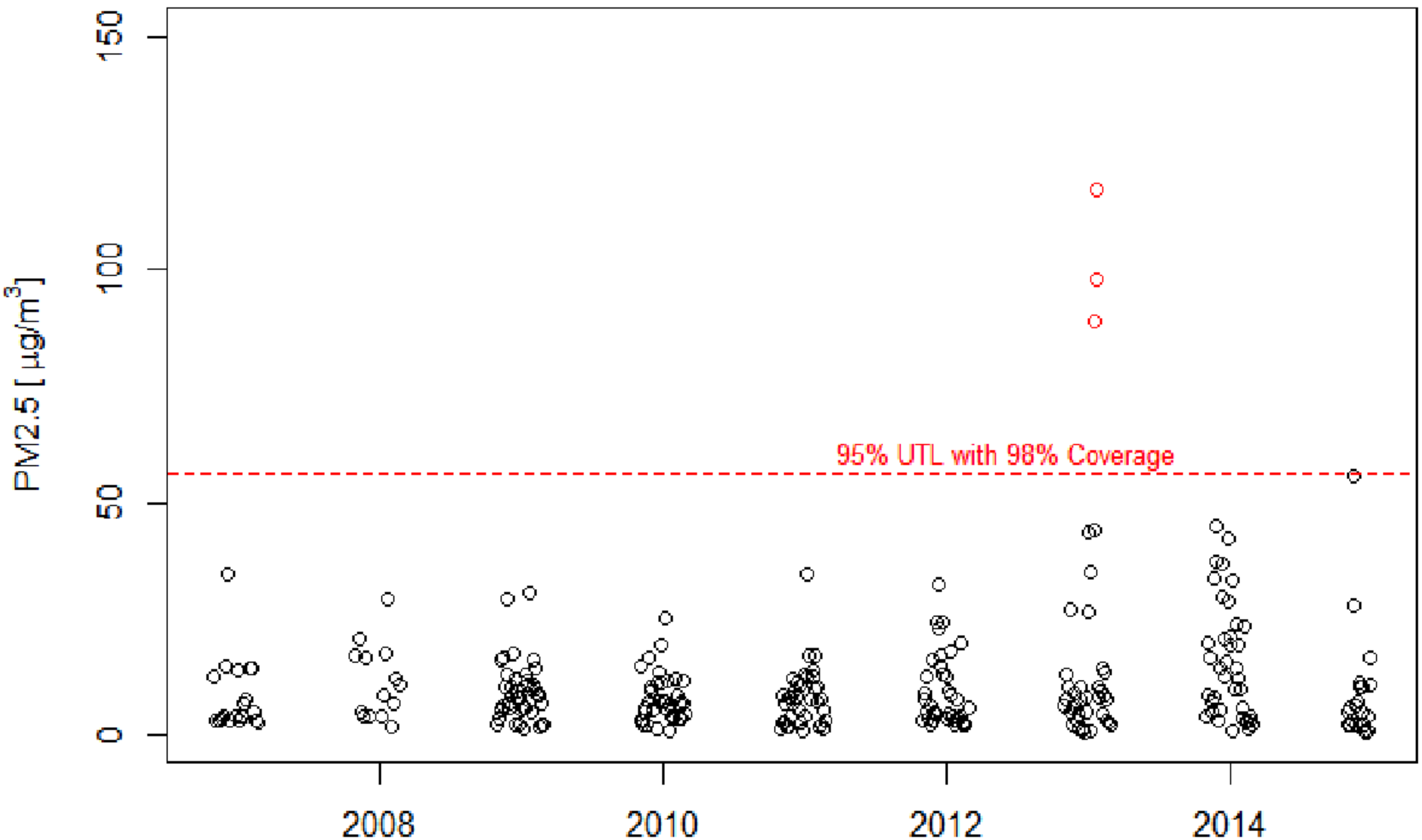
Data is lognormal. At 99% confidence, the January 2013 average $PM_{2.5}$ value is outside the expected population of values observed over the past 9 years.



Calendar Year

But the Standard is a 24-hr Standard based on the 98th percentile value- Not monthly averages

At a 95% confidence level based on 2006-2014 daily $PM_{2.5}$ values 98% of values will be below 56 µg/m³, the Upper Tolerance Limit. In the past 9 years only 3 values in January 2013 exceeded this level.



Conclusions

- A simple conceptual DSL/LSL model can capture Cold Air Pool inversions in Mountain Valleys.
  - A good tool for forecasting multi-day inversions
  - A good tool for retrospective analysis of historical inversions
  - Rate of increase during DSL/LSL events may reflect emissions trends
- It suggests number of inversion days per month is a good (~linear) surrogate for increasing episode severity.
  - Monthly average temperature varies with # days inversion
- Monthly average temps are a readily available tool with a long historical record.
- Elevated minus valley Monthly Average Temps are a useful indicator of inversion presence & persistence.

Conclusions - continued

- The Boise 1985 inversion was the worst inversion period on record and the PM records are in general agreement.
- The January 2013 inversion and November- December inversions were the second most severe on record for Boise.
- The *Ridiculously Resilient Ridge* that caused the worst California drought in a century also caused the persistent inversion conditions throughout the Northwest in 2013 in Jan, Nov & Dec.
- Such extreme episodes, while not EEs should not be considered to influence background concentrations for NSR modeling (certainly for minor sources where states have leeway).
- Some consideration in attainment milestones/designations should perhaps be weighed to account for such extreme conditions.

Discussion?