

Valley Cold Pools, Snow Cover, and Speciated PM_{2.5} in Western US Cities

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Reference Green et al, 2015, J. Appl. Meteor. Climatol., 54, 1191-1201. June 2015.

Background/Motivation

- Western U.S. valleys experience valley cold-air pools in winter with elevated pollution levels (e.g. Chen et al., 2012; Reeves and Stensrud, 2009; Silcox et al 2012; Whiteman et al., 2014)
- **Inversion strength** (difference between surface and high elevation temperatures) or **“heat deficit”** (heat necessary to dry adiabatically mix a layer of air) **can be related to PM_{2.5} concentrations**
- Enhanced ammonium nitrate during snow cover and strong inversions in Reno, NV was found on days with PM_{2.5} exceedances (Chen et al., 2012)

Chen, L.-W.A.; Watson, J.G.; Chow, J.C.; Green, M.C.; Inouye, D.; Dick, K. (2012). Wintertime particulate pollution episodes in an urban valley of the western U.S.: A case study. *Atmos. Chem. Phys.*, **12**(21):10051-10064. <http://www.atmos-chem-phys.net/12/10051/2012/acp-12-10051-2012.pdf>.

Reeves, H.D.; **Stensrud, D.J.** (2009). Synoptic-scale flow and valley cold pool evolution in the western United States. *Weather and Forecasting*, **24**(6):1625-1643.

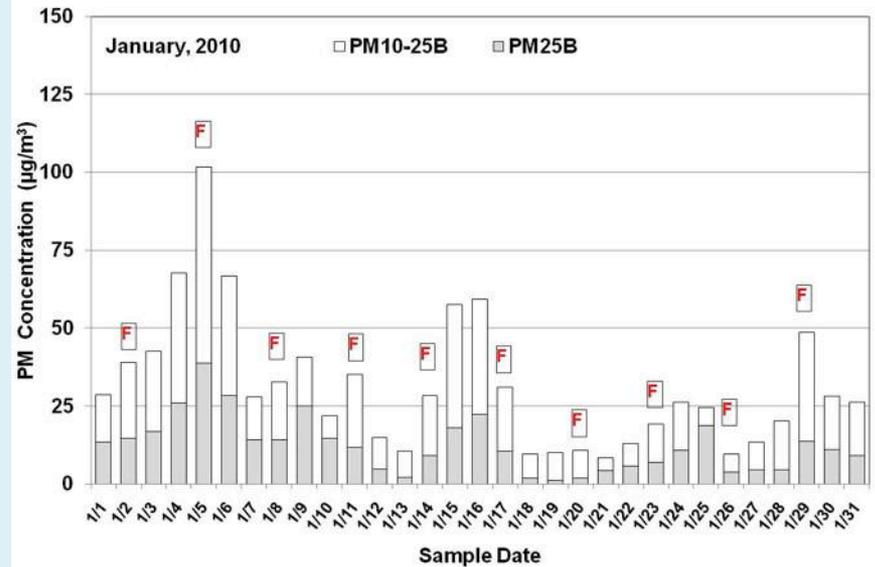
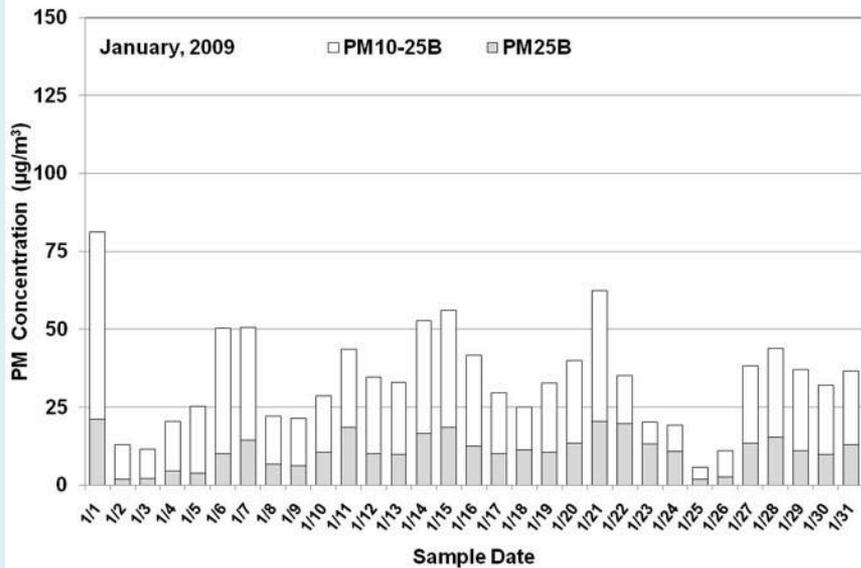
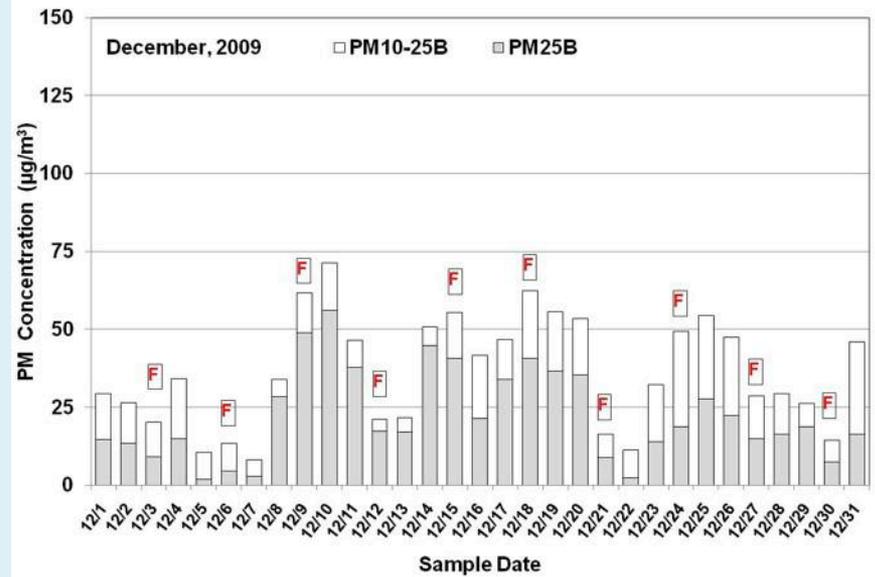
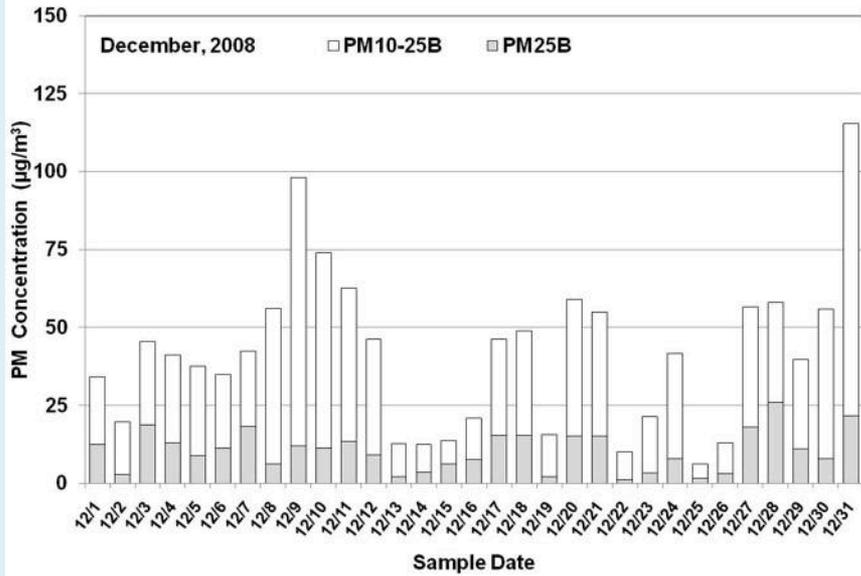
Silcox, G.D.; Kelly, K.E.; Crosman, E.T.; Whiteman, C.D.; Allen, B.L. (2012). Wintertime PM_{2.5} concentrations during persistent, multi-day cold-air pools in a mountain valley. *Atmos. Environ.*, **46**:17-24. .

Whiteman, C.D.; Hoch, S.W.; Horel, J.D.; Charland, A. (2014). Relationship between particulate air pollution and meteorological variables in Utah's Salt Lake Valley. *Atmos. Environ.*, **94**(0):742-753.

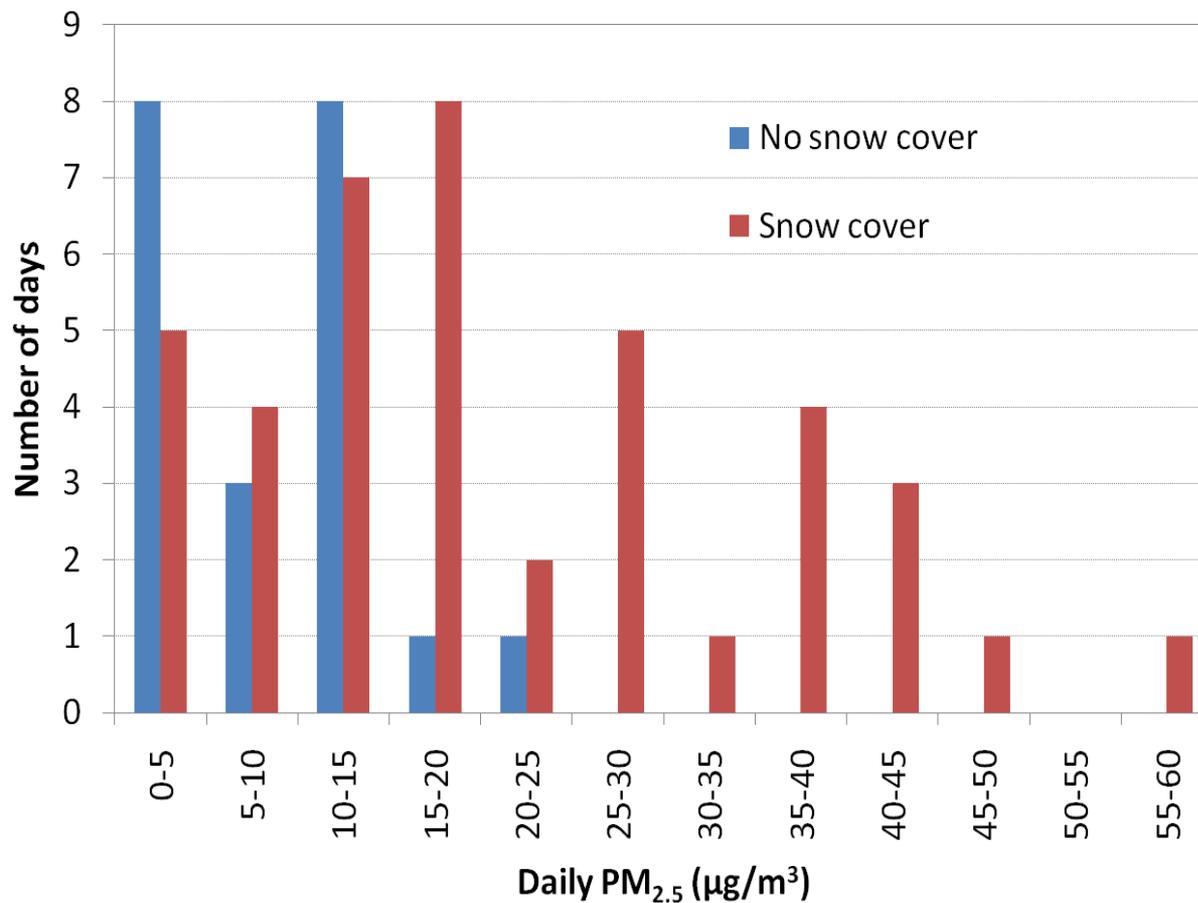
Objectives

- Investigate the relationship between $PM_{2.5}$ NAAQS exceedances and cold-air pools in Western U.S. valleys (e.g., Salt Lake City, Reno, Boise, Spokane, and Missoula)
- Examine trends in winter $PM_{2.5}$ with and without normalizing by yearly variations in atmospheric stability

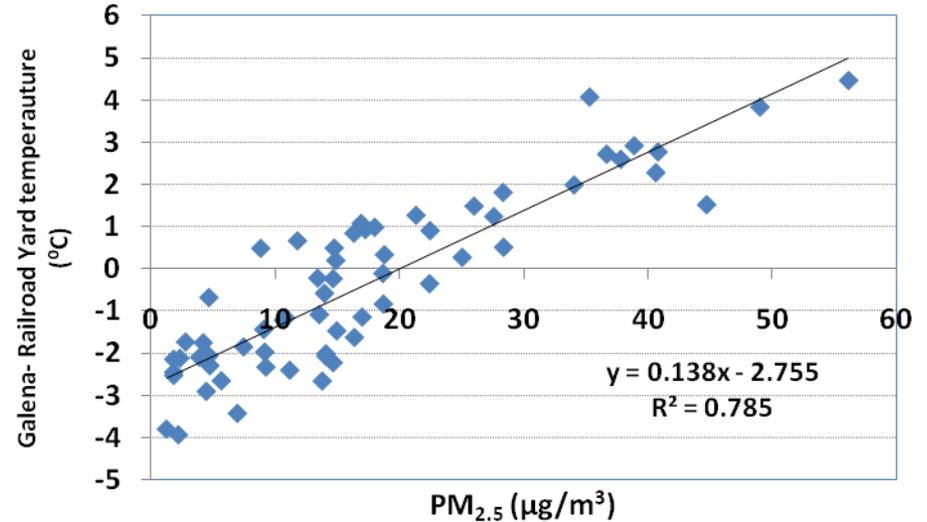
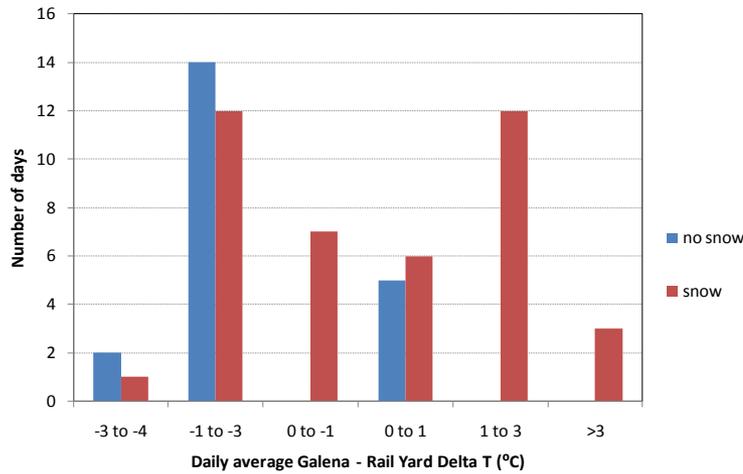
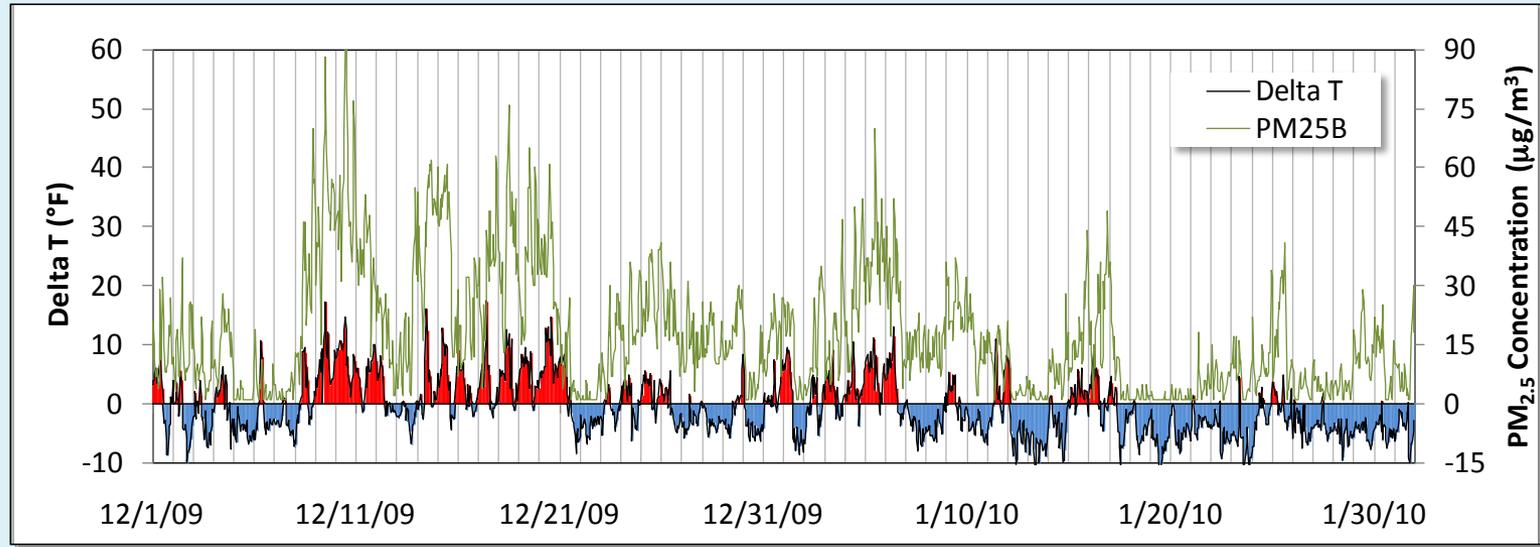
Daily PM₁₀ and PM_{2.5} (BAM) showed more PM_{10-2.5} during 2008/09 than 2009/10 at the Reno, NV compliance site



The highest PM concentrations corresponded with snow cover (Reno December 2009-January 2010) 9 days $>35 \mu\text{g}/\text{m}^3$, all with snow cover



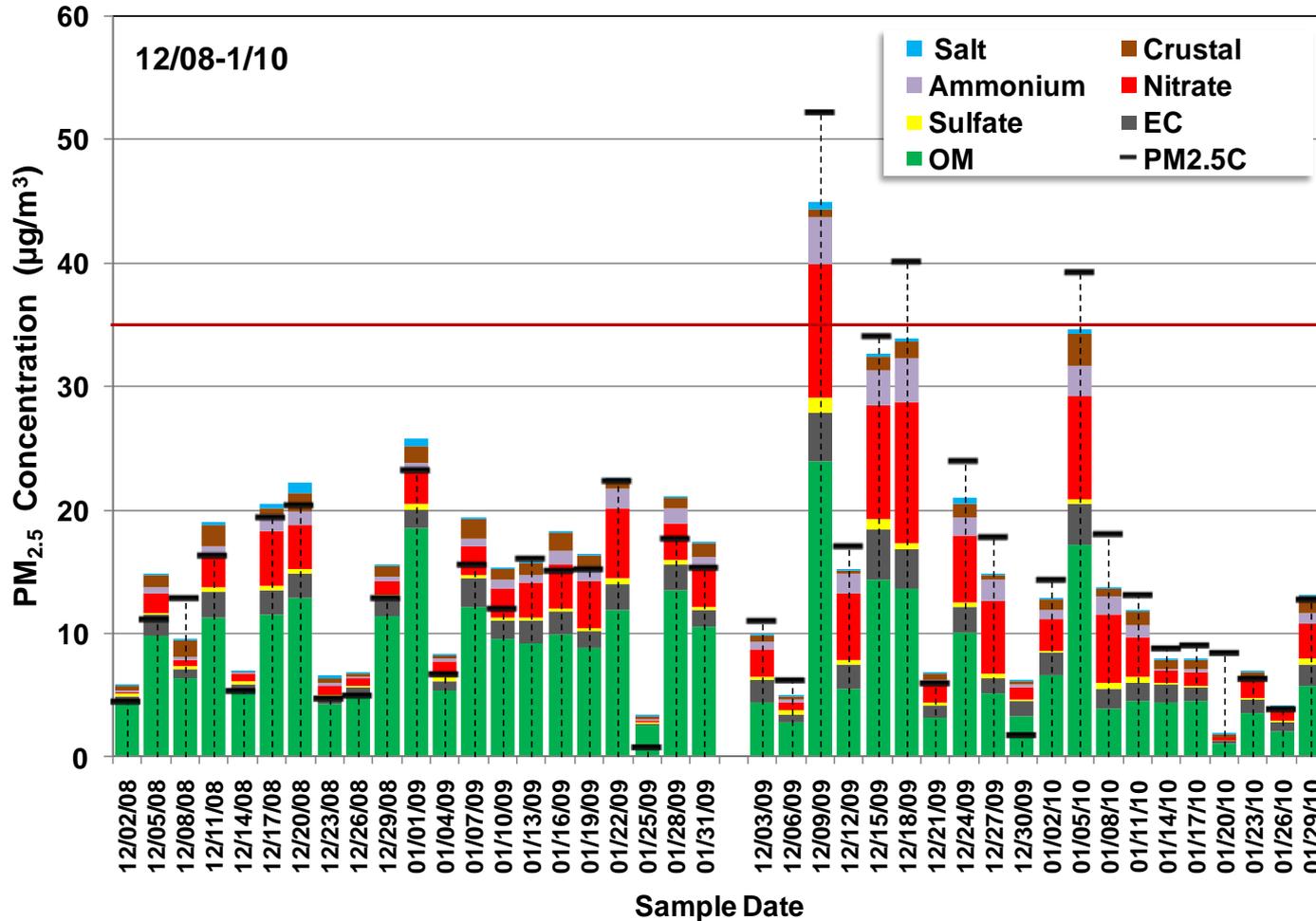
Snow cover resulted in more intense and prolonged surface inversions that trapped pollutants



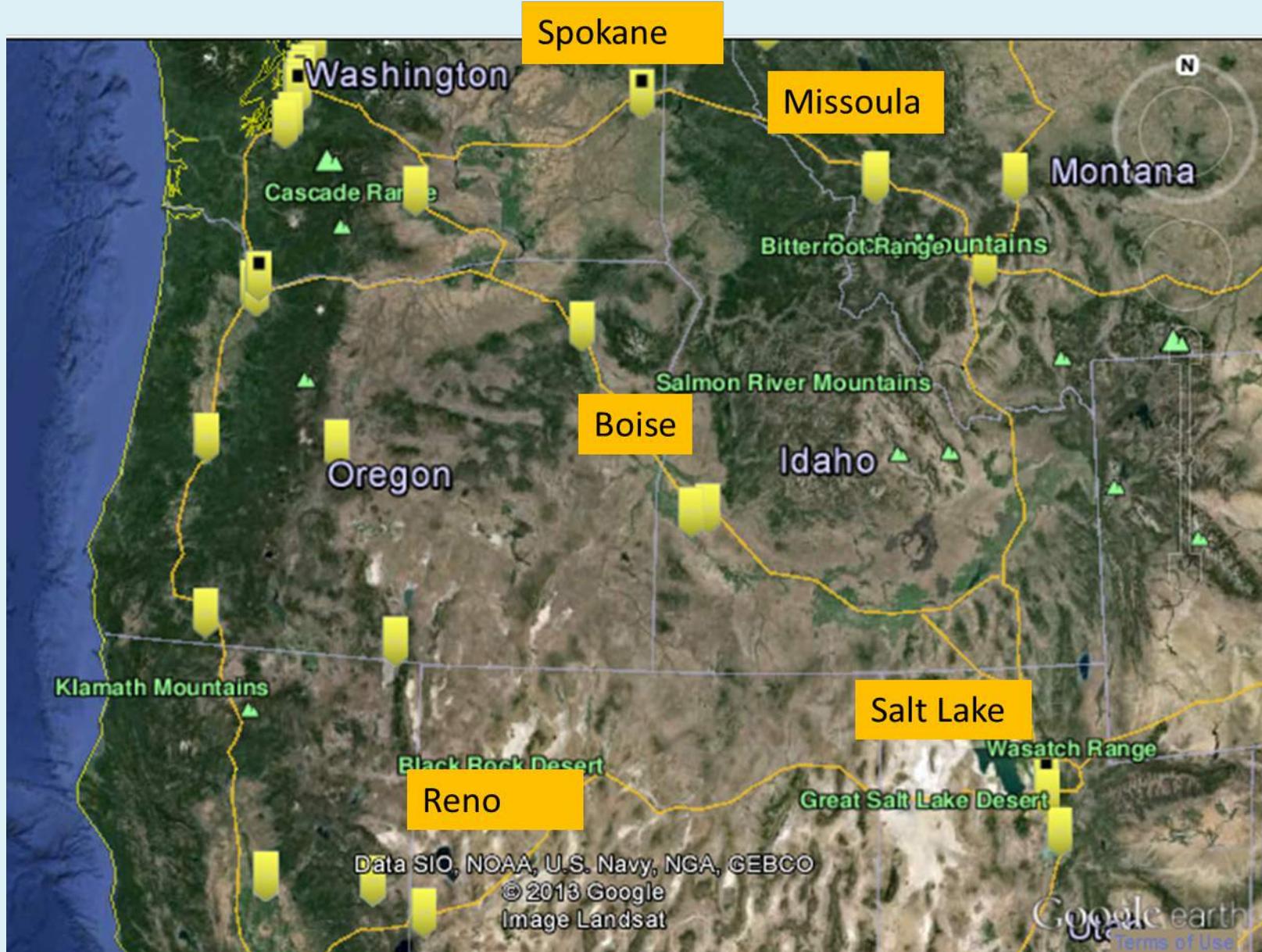
The major PM_{2.5} components during both seasons were carbon, ammonium, and nitrate, BUT

the biggest difference between winter 2008/2009 and 29/2010 was due to nitrate and unmeasured mass.

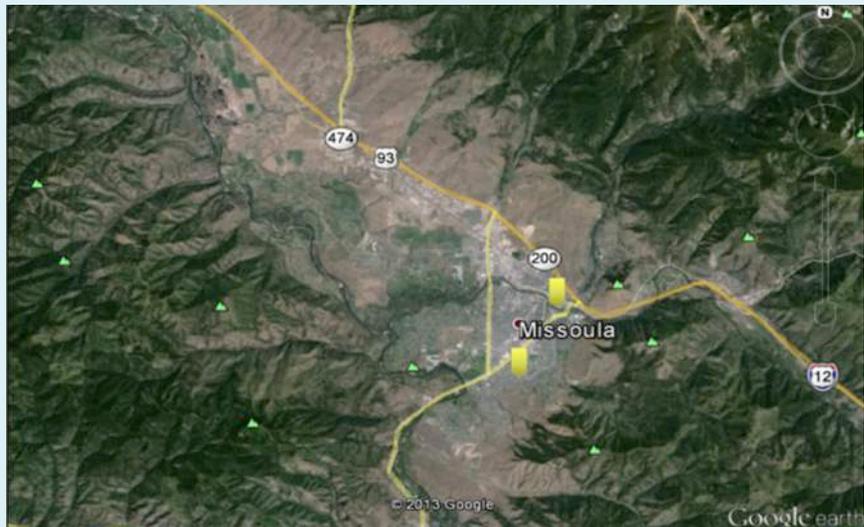
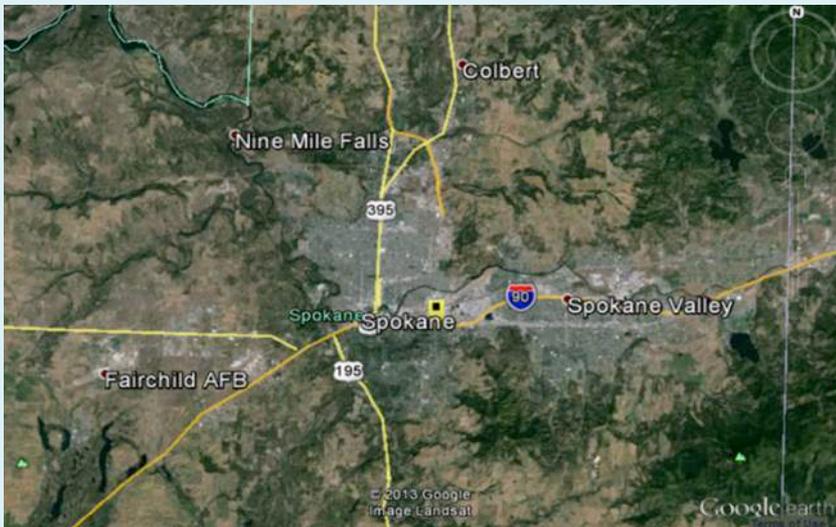
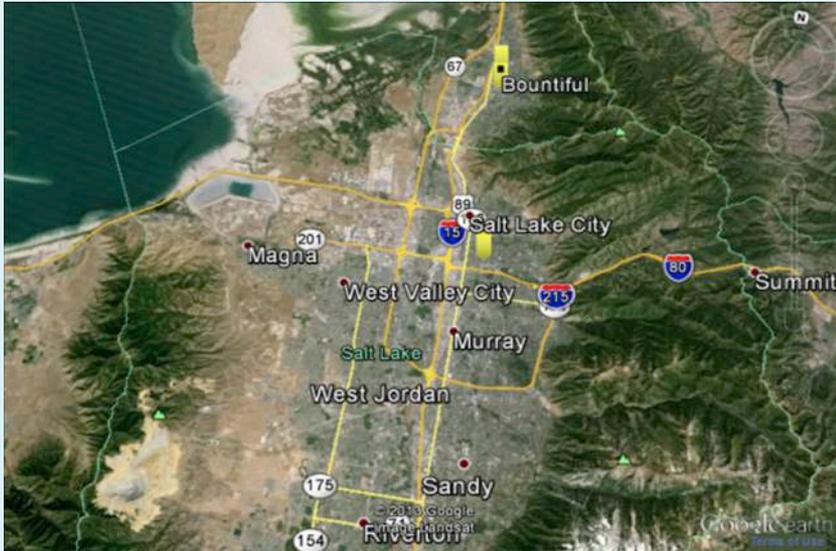
Lower temperatures and higher humidity favors ammonium nitrate formation



Question: How might the Reno findings apply to other valleys in the intermountain west that experience cold pools?



Topographic features of valley cities that may enhance cold-air pools



Methodology

- Investigate winter months (i.e., November-February) during the years of 2000-2013
- Characterize heat deficit (H) by inversion strength (for Salt Lake City, Reno, Boise, Spokane, and Missoula) or temperature differences between valley and ridge (i.e., Delta T for Missoula)
- Calculate daily average heat deficit (Whiteman et al., 1999) from 0Z and 12Z radiosonde observations at surface and ridge height.

$$H = C_p \int_0^h \rho(z) (\theta_h - \theta(z)) dz \text{ J/m}^2$$

Where C_p : specific heat; $\rho(z)$: air density; θ_h and $\theta(z)$: potential temperatures at ridge height (h) and height z

Radiosonde surface and ridge elevations used to calculate stability parameter (heat deficit)

Location	Surface height (m)	Top ridge height (m)	Layer thickness (m)
Salt Lake City	1288	2439	1151
Reno ^a	1342	2134	792
Boise	860	1829	969
Spokane	723	1829	1106
Missoula ^b	975	2410	1435

^aReno Airport used for lowest layer; radiosonde released at NWS office ~ 150 m above Reno Airport

^bMissoula has no radiosonde, used Airport for low level and ridgeline location for upper level

PM_{2.5} and Meteorological Data

- Daily PM_{2.5} mass from U.S. EPA Airdata site –<http://www.epa.gov/airdata/>
- **Speciated PM_{2.5} from Chemical Speciation Network (CSN) (every third and sixth day, in Airdata)**
- Daily snow depth (0700 LST) at airport (NOAA, 2014)

PM_{2.5} sampling sites included for data analysis

CBSA *	Site name	Latitude	Longitude	Elevation	Date range**	AQS ID
Salt Lake City	Hawthorne	40.73639	-111.87222	1306m	1/1/00-12/31/13 2/9/00-2/27/13	49-035-3006
Reno	Reno3	39.525082	-119.807717	1341m	1/1/00-12/31/13 11/3/01-2/27/13	32-031-0016
Boise	St. Luke's Meridian	43.600699	-116.347853	826m	11/1/06-2/27/13 11/1/06-2/27/13	16-001-0010
Boise	Northwest Nazerene College	43.562401	-116.562401	757m	11/2/00- 2/20/08 11/3/01-2/28/06	16-027-0004
Spokane	Spokane- Ferry St.	47.660743	-117.358121	590m	1/1/00-2/27/09 1/4/05-1/1/09	53-063-0016
Spokane	Spokane- Augusta Avenue	47.672482	-117.364852	585m	11/3/09-2/27/13	53-063-0021
Missoula	MSLA Health Dept.	46.874912	-113.995253	975m	1/1/00-2/26/11 1/24/03-12/30/09	30-063-0031
Missoula	MSLA Boyd Park	46.842181	-114.021499	975m	1/4/00-2/28/02, 11/15/08-11/30/13 2/24/01-2/28/02	30-063-0031

* Core based statistical area

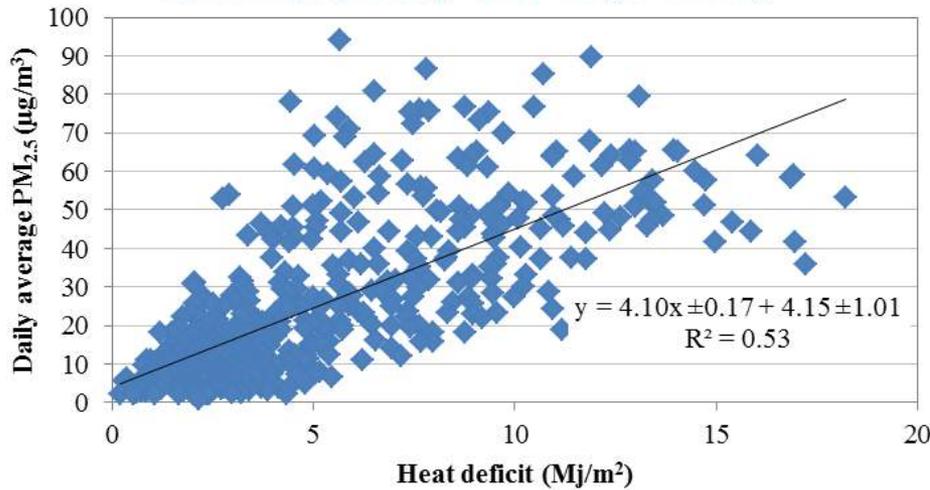
** Dates in purple are for PM_{2.5} mass only; dates in green are for CSN speciated data.

Data Analysis

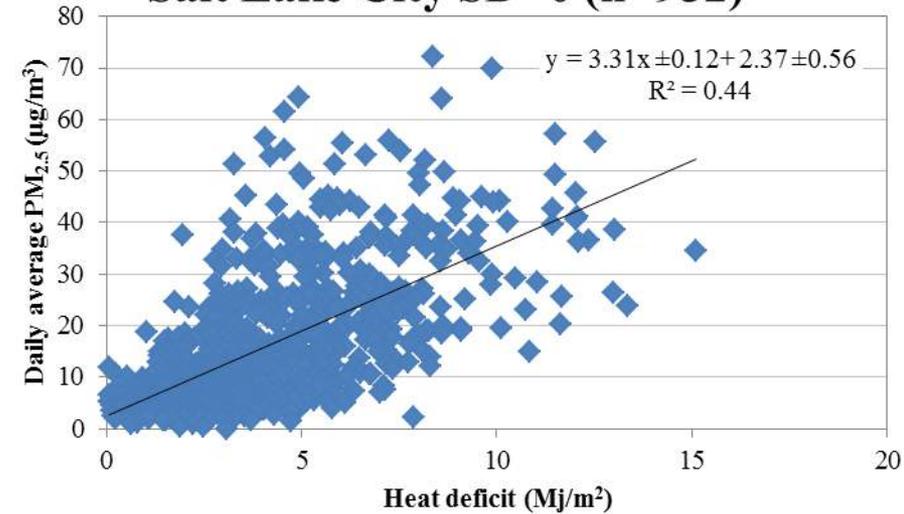
- Examine $PM_{2.5}$ vs. heat deficit (or Delta T), stratified by days with snow depth over 2.5 cm ($SD>0$) and without snow cover ($SD=0$).
- Used IMPROVE equation ($OM=1.4OC$; Watson, 2002) to evaluate $PM_{2.5}$ mass closure by major components
- Compared contributions to $PM_{2.5}$ by major components (i.e., sulfate, nitrate, OM, elemental carbon, geological, and salt) for days with and without snow cover

Reasonable relationships found between $PM_{2.5}$ and heat deficit for Salt Lake City and Reno (most high $PM_{2.5}$ days have snow depth [SD>0])

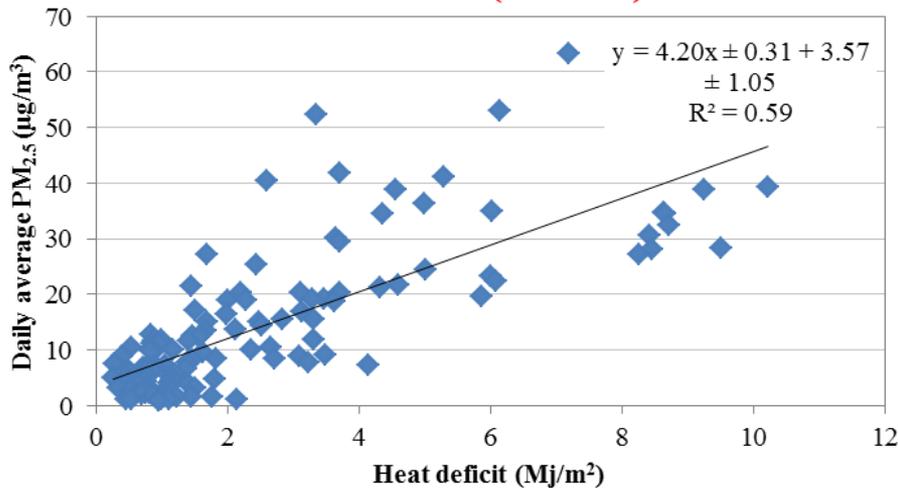
Salt Lake City SD>0 (n=539)



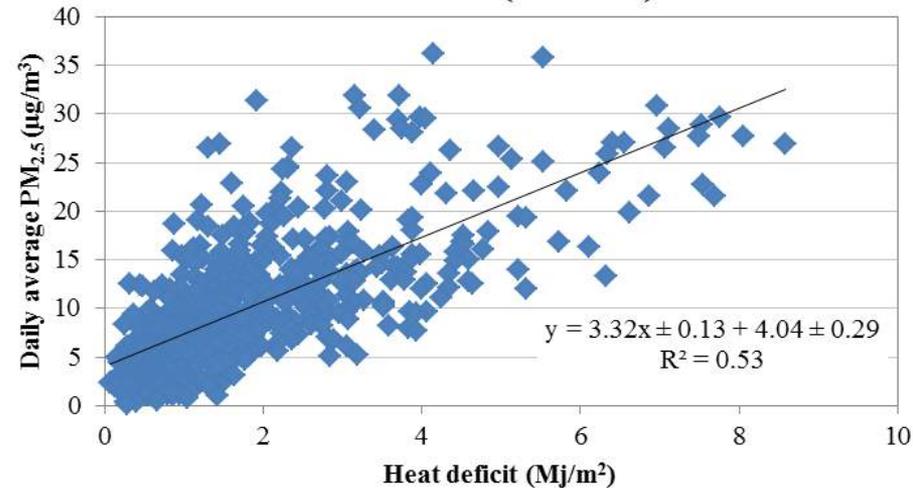
Salt Lake City SD=0 (n=952)



Reno SD>0 (n=128)

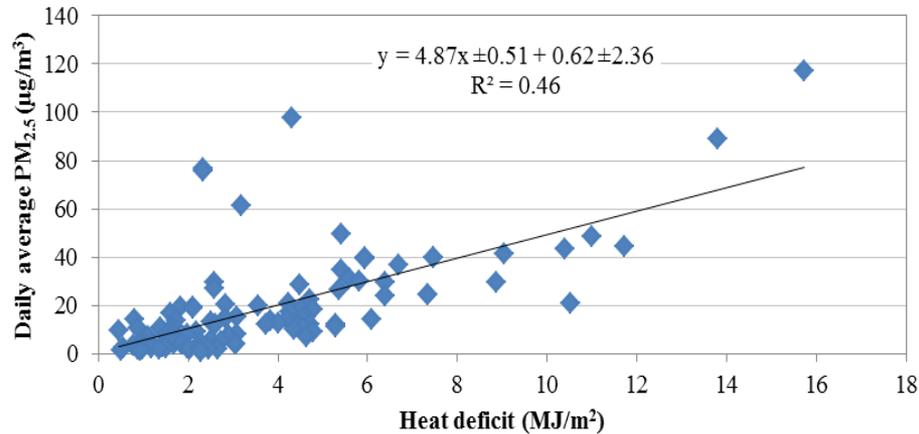


Reno SD=0 (n=628)

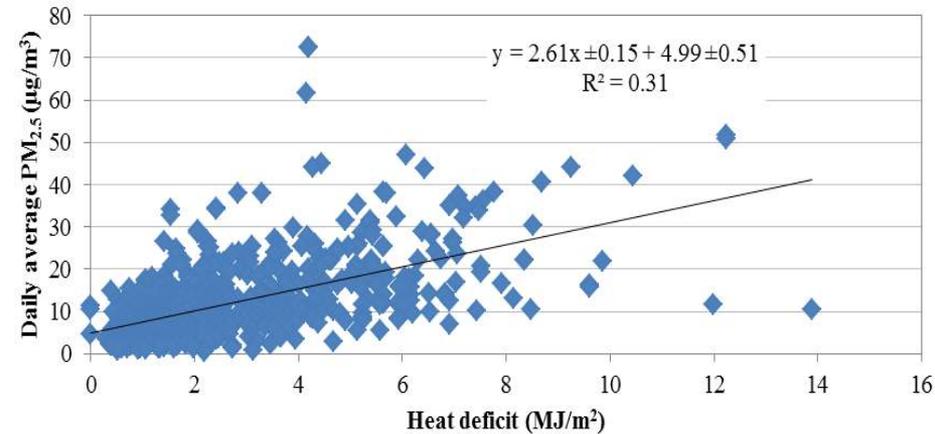


High PM_{2.5} days at Boise and Missoula found on snow cover days (SD>0)

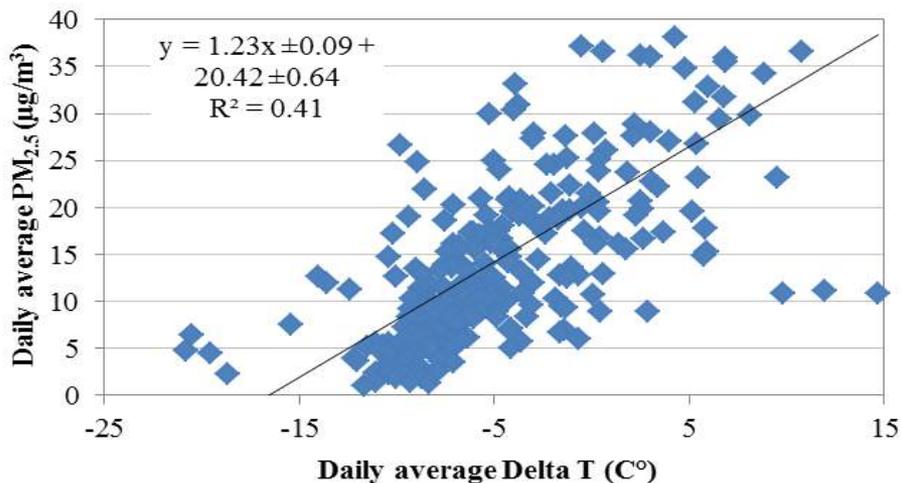
Boise Nazerene & Meridian SD>0 (n=111)



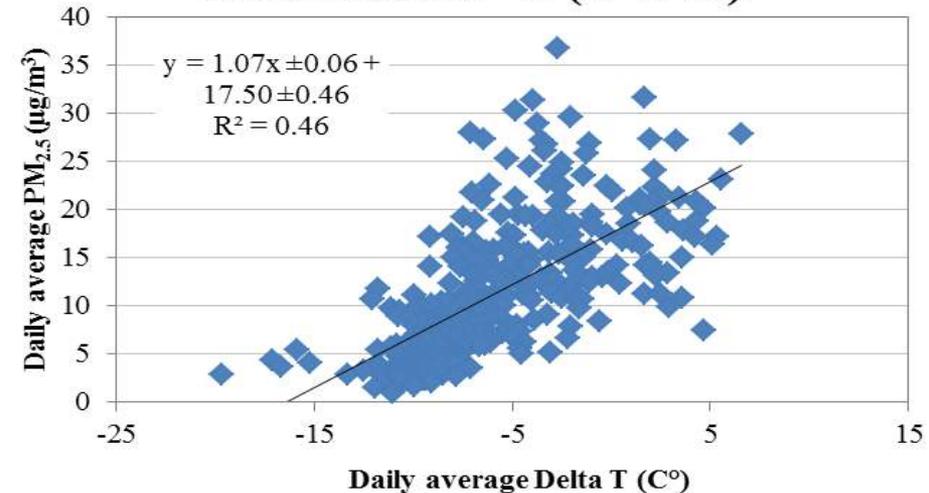
Boise Nazerene & Meridian SD=0 (n=687)



Missoula SD>0 (n=442)

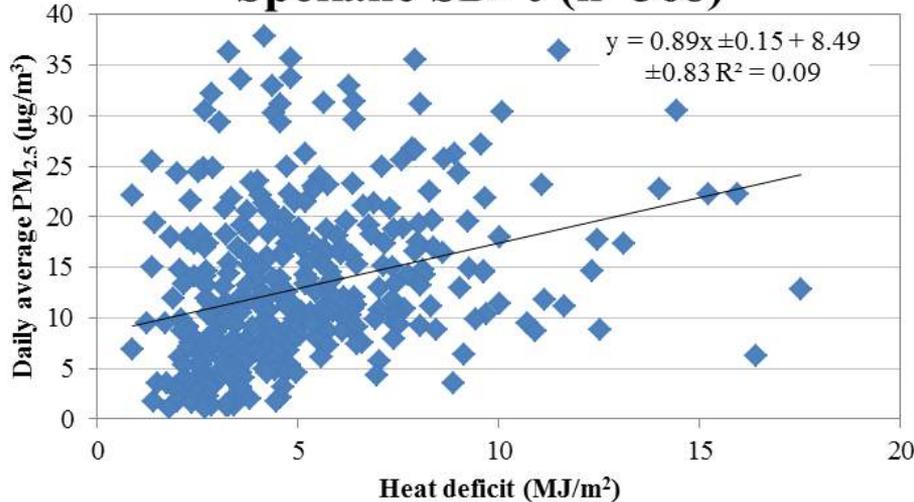


Missoula SD=0 (n=546)

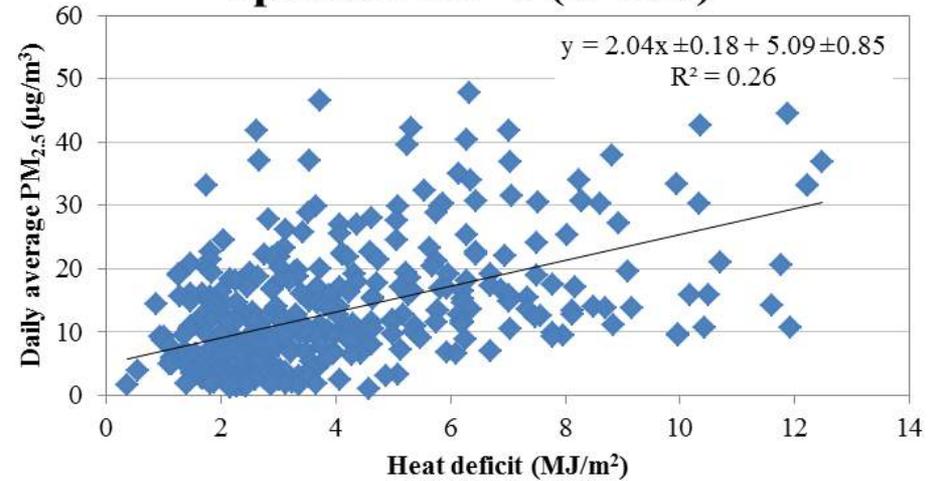


Not much relationship found between PM_{2.5} and heat deficit in Spokane

Spokane SD>0 (n=368)

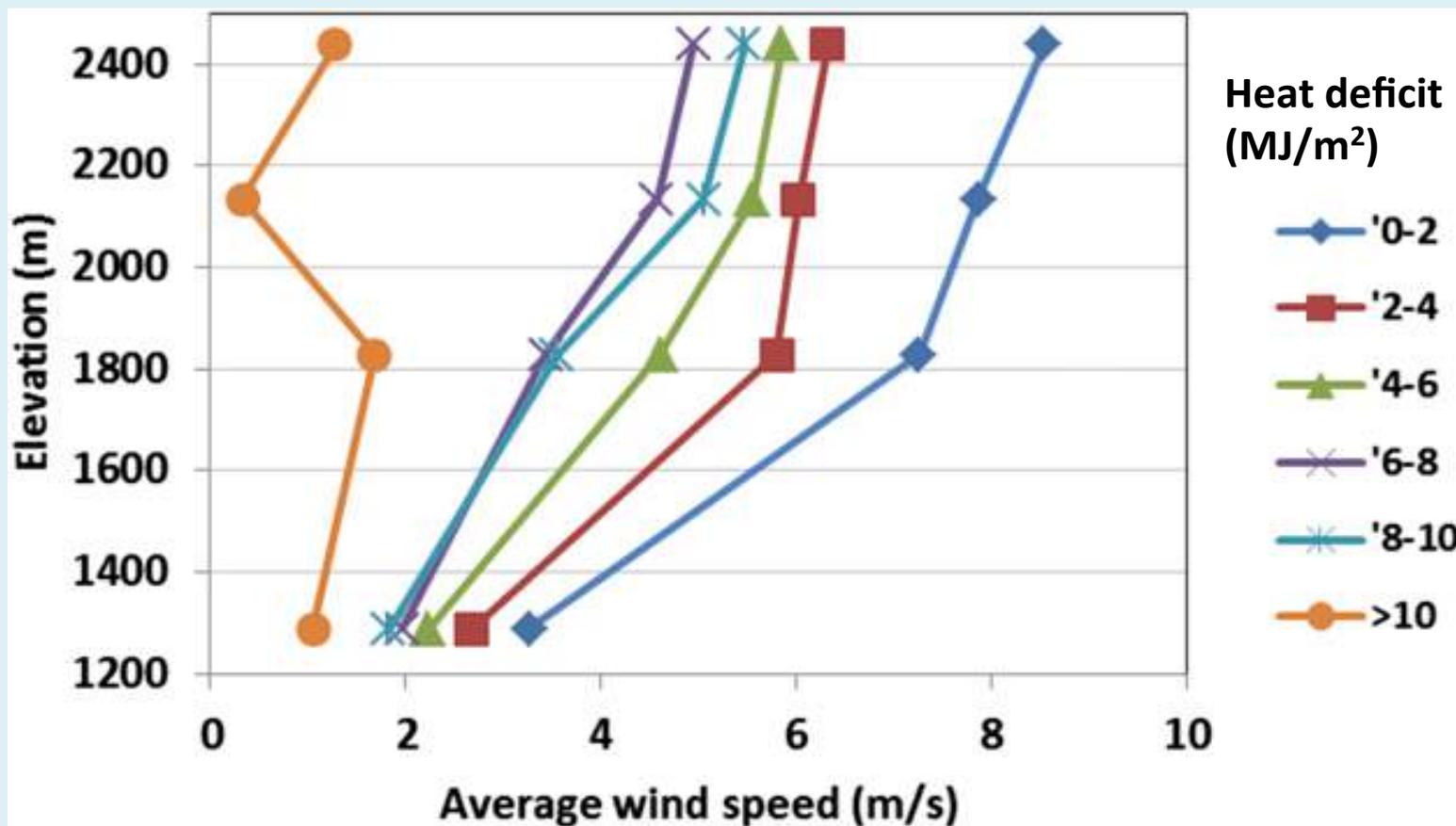


Spokane SD=0 (n=378)

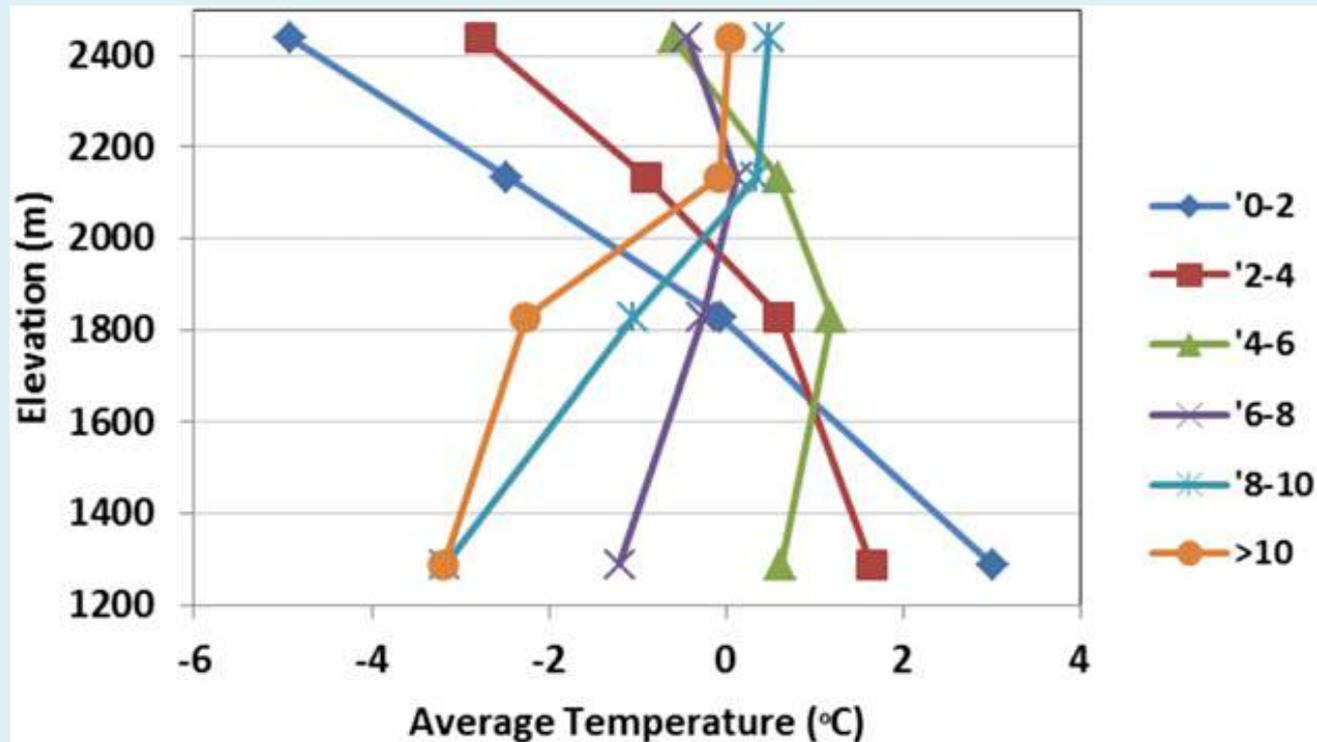


- High PM_{2.5} on days without snow cover; this may be attributed to the Spokane radiosonde site being 13 km away and 135 m higher than the air quality stations

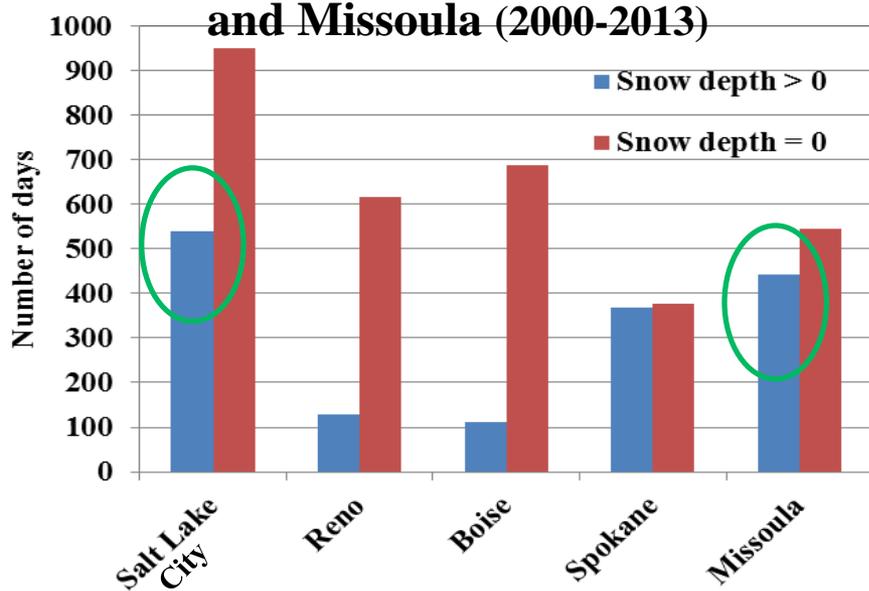
Lower wind speed is associated with higher heat deficit, providing less along-wind dispersion (Salt Lake City, UT)



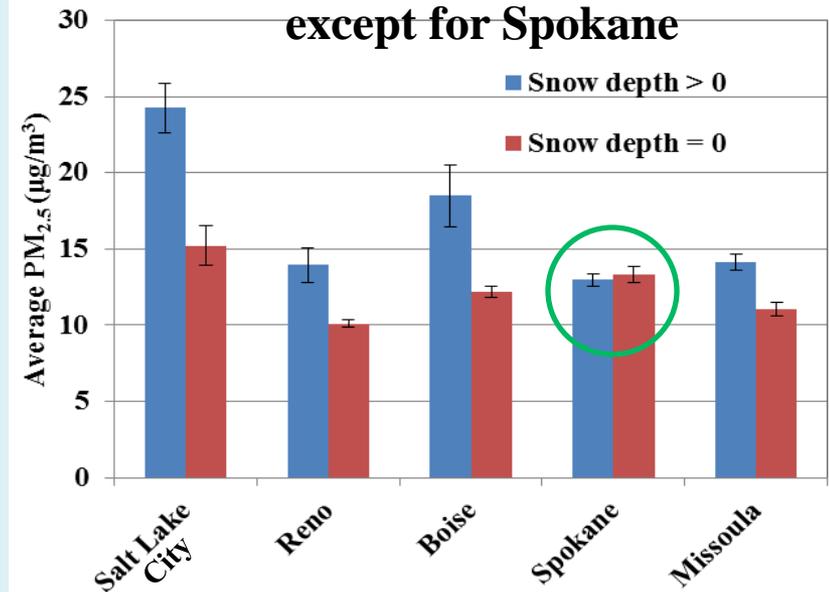
For heat-deficit $<4\text{MJ/m}^2$, temperature increases from the surface to 600 m AGL (Salt Lake City)



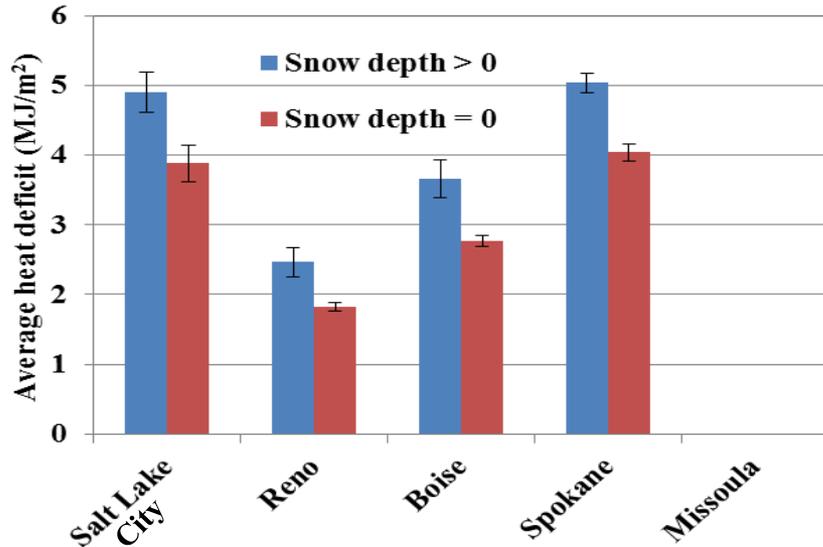
More Snow Cover Days in Salt Lake City and Missoula (2000-2013)



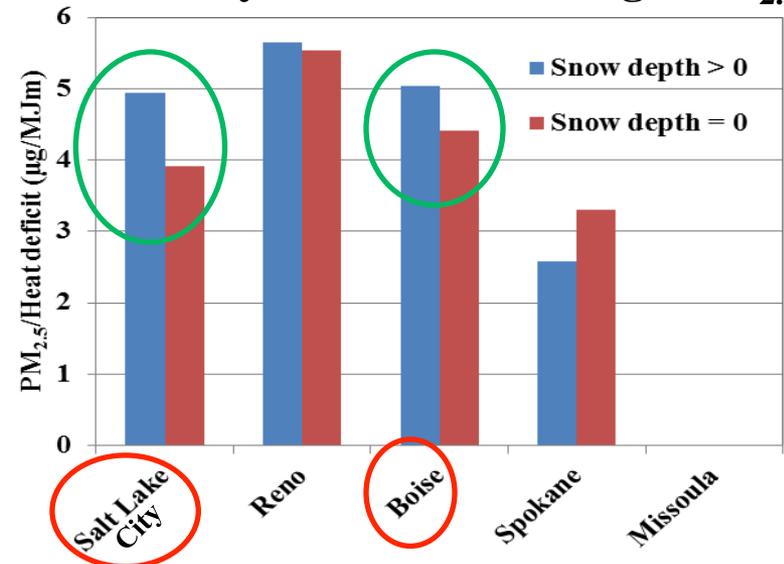
High PM_{2.5} on Snow Cover Days except for Spokane



High Heat Deficit on Snow Cover Days



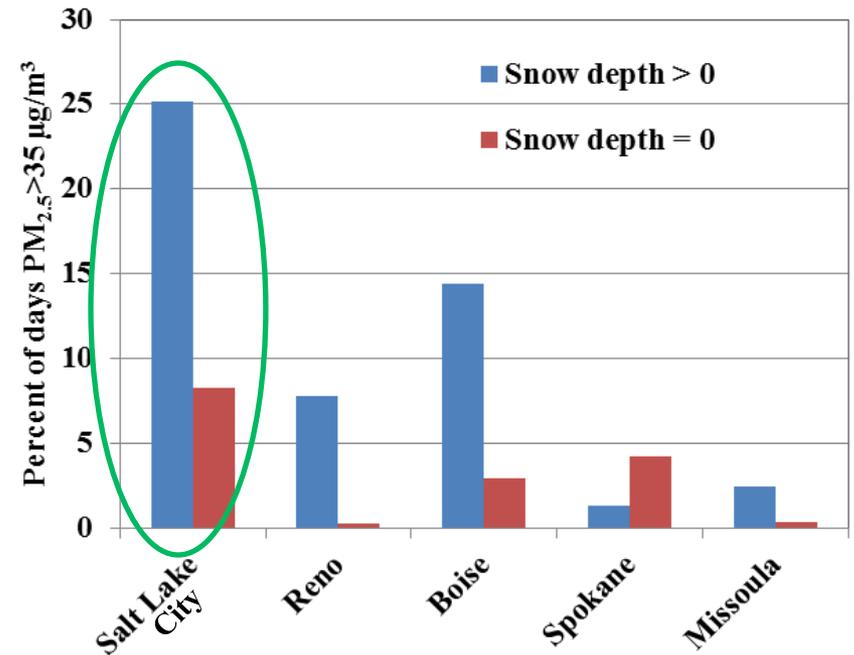
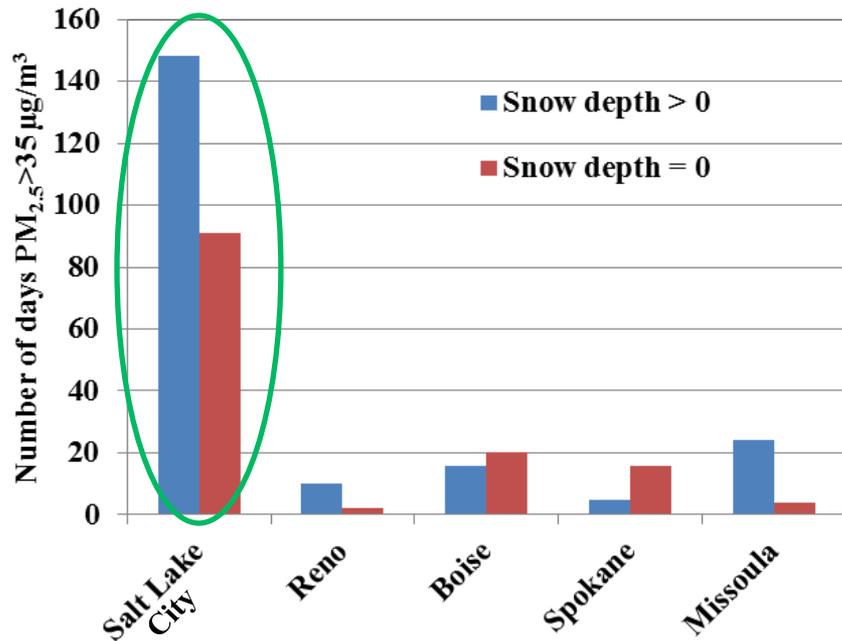
High PM_{2.5} to heat deficit ratio implies factors other than stability contributed to high PM_{2.5}



Normalizing PM_{2.5} by heat deficit control for variations in stability.

Snow cover days are more likely to exceed the NAAQS^a (except for Spokane)

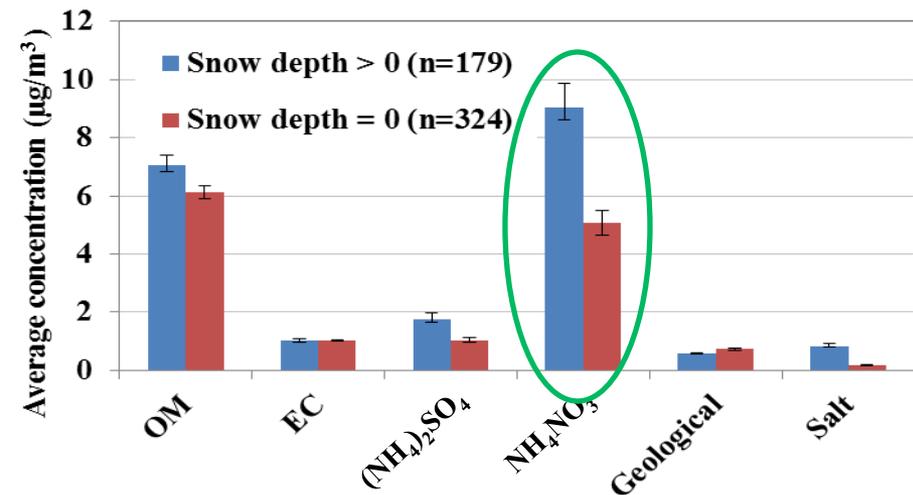
- Higher 24NAAQS exceedances found in Salt Lake City



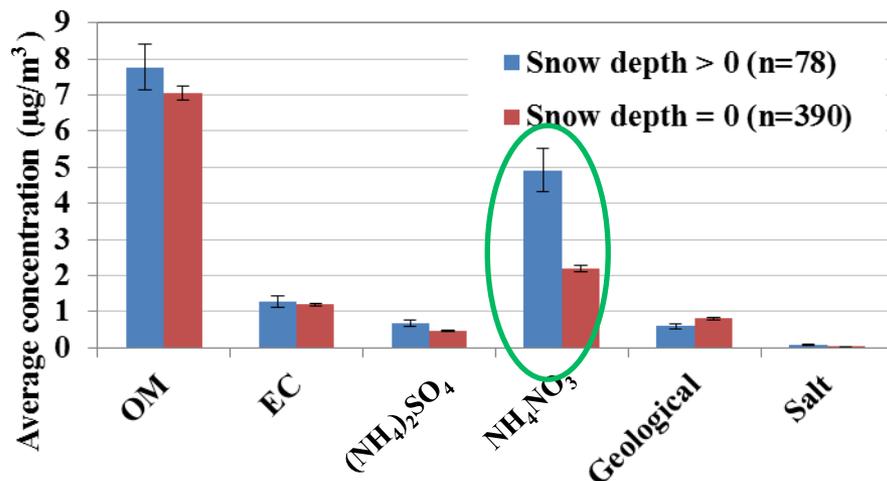
^a National Ambient Air Quality Standard for 24-hour PM_{2.5} is 35 µg/m³

Enhanced NH_4NO_3 on snow cover days accounts for most of the increases in $\text{PM}_{2.5}$

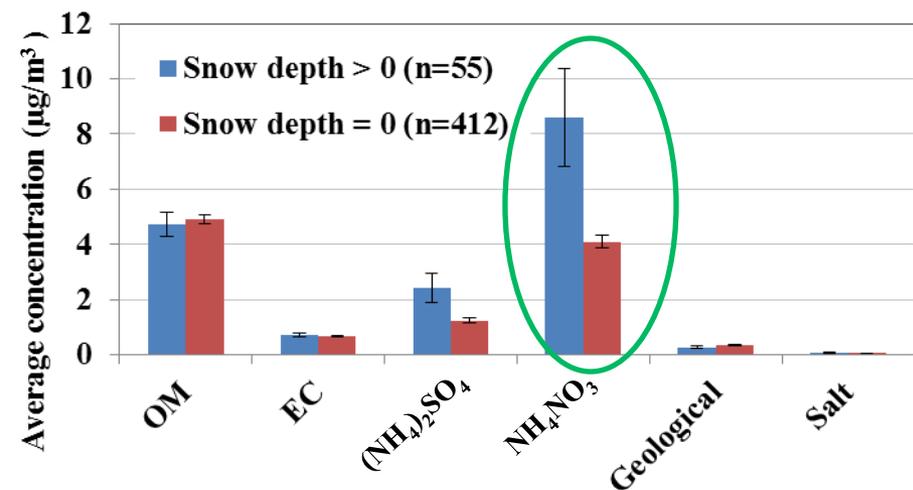
Salt Lake City



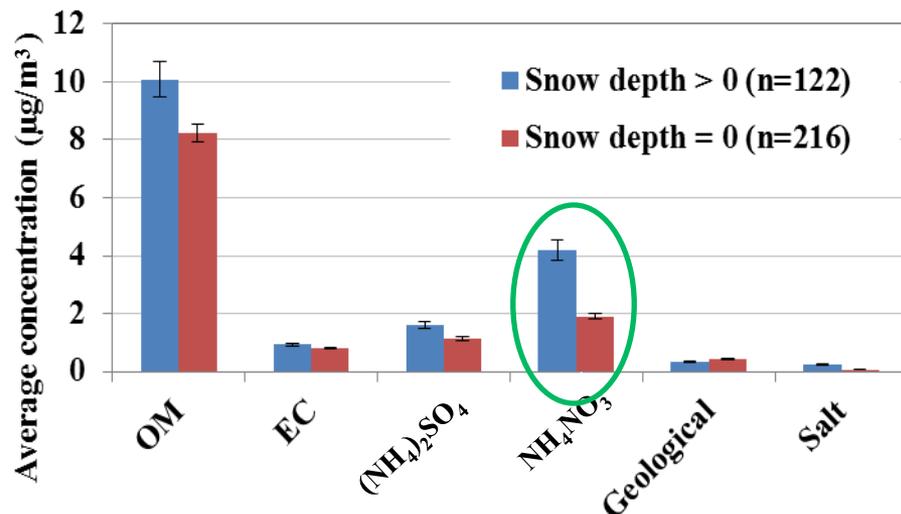
Reno



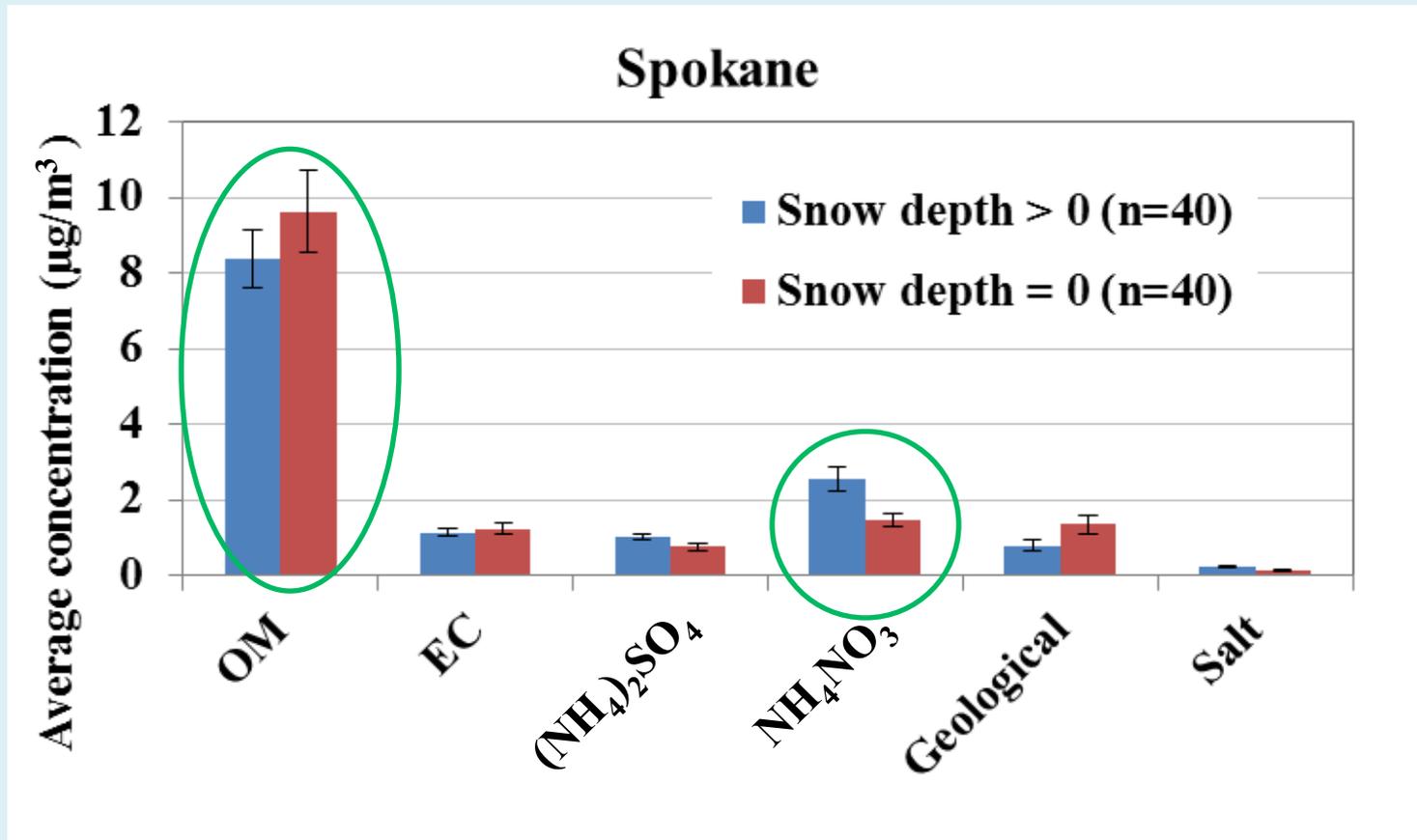
Boise



Missoula

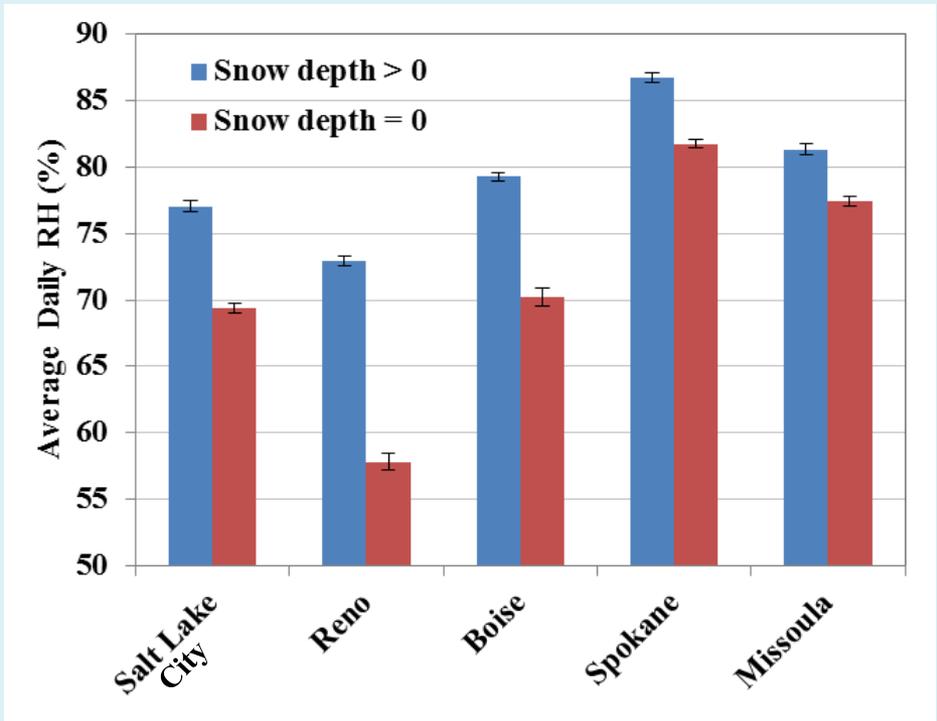
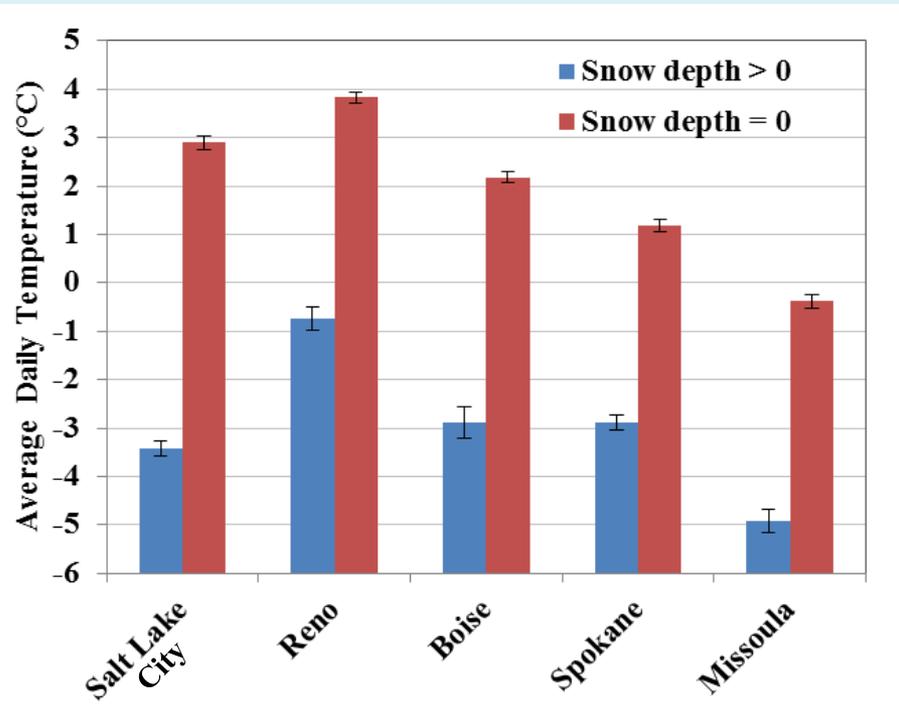


In Spokane, enhanced NH_4NO_3 on snow cover days were offset by reduced organic mass (OM)

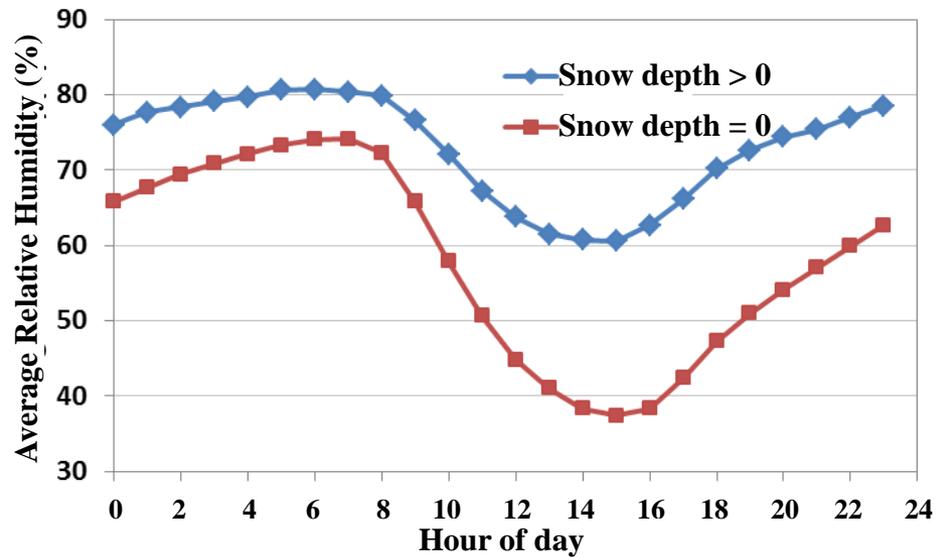
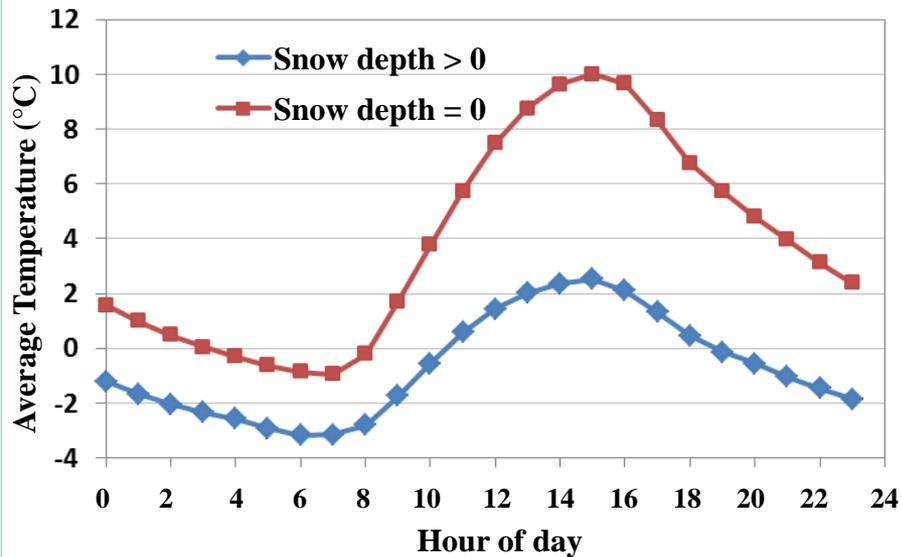


- $\text{OM} = 1.4\text{OC}$

Snow cover days are colder with higher RH than no snow cover days (meteorological conditions favor the formation in and retention of NH_4NO_3)

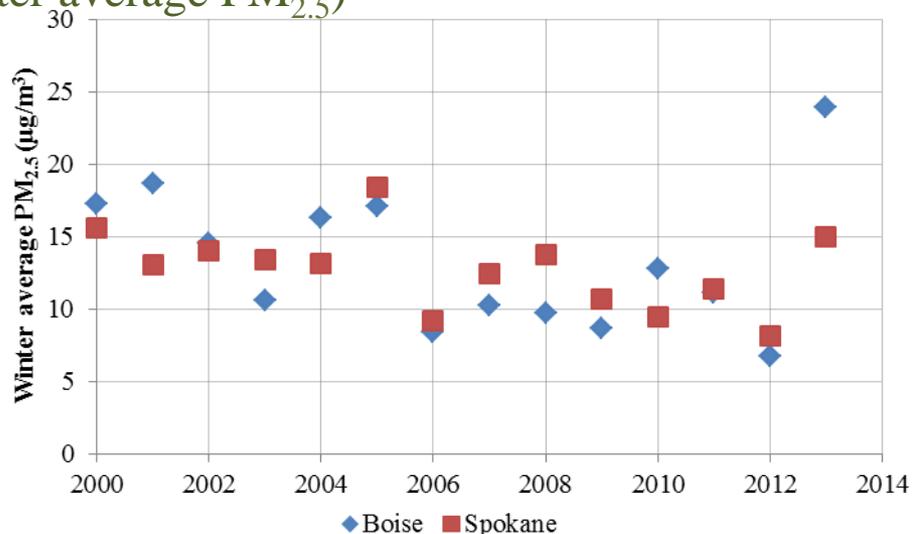
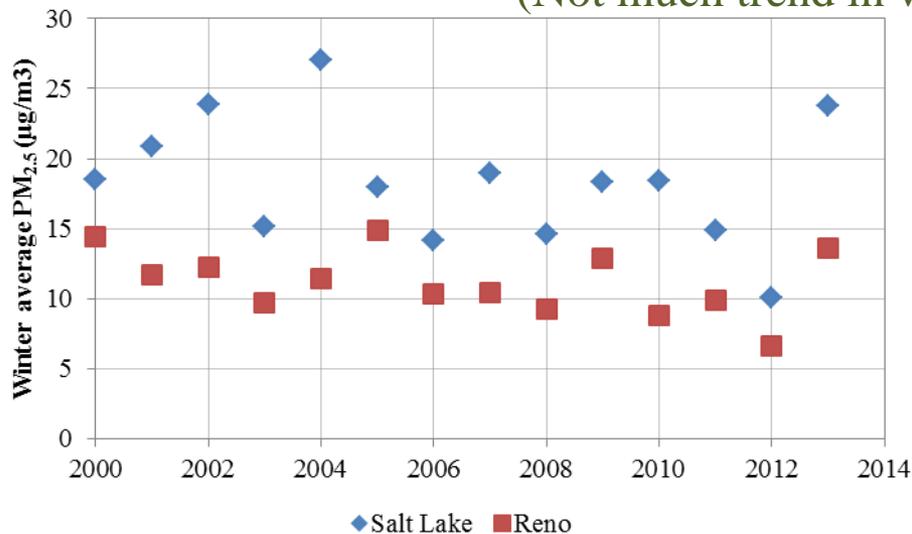


Strong afternoon warming on no snow cover days and lower RH (<40%) enhanced NH_4NO_3 volatilization (Reno, NV)

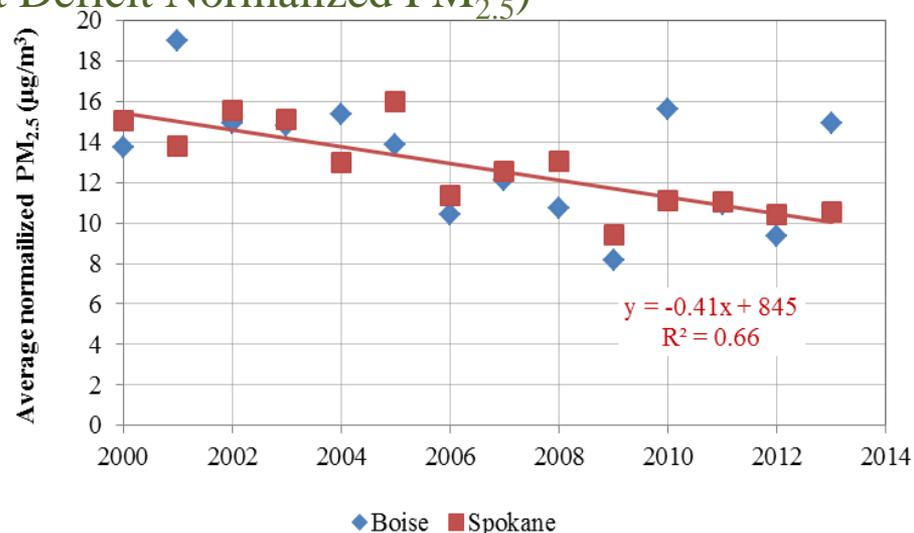
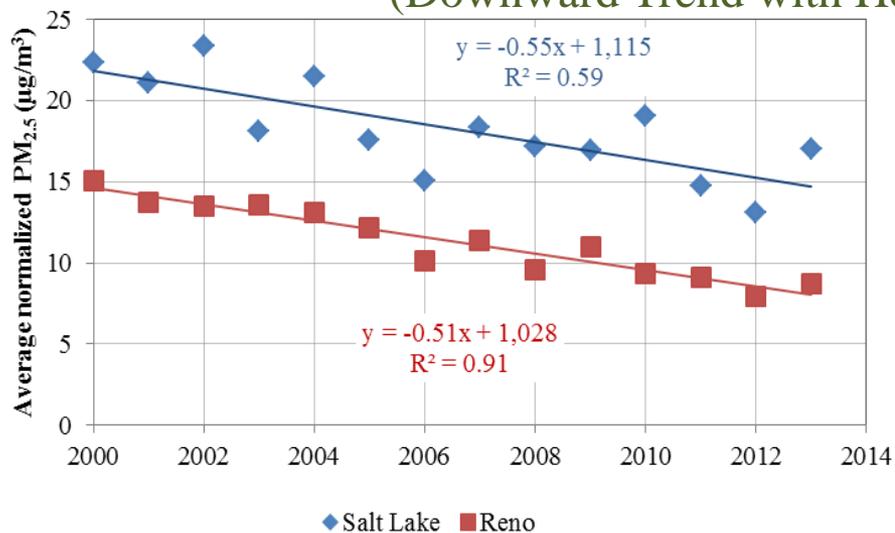


Much of the annual variations in average PM_{2.5} are explained by variations in average heat deficit (except for Boise)

(Not much trend in winter average PM_{2.5})

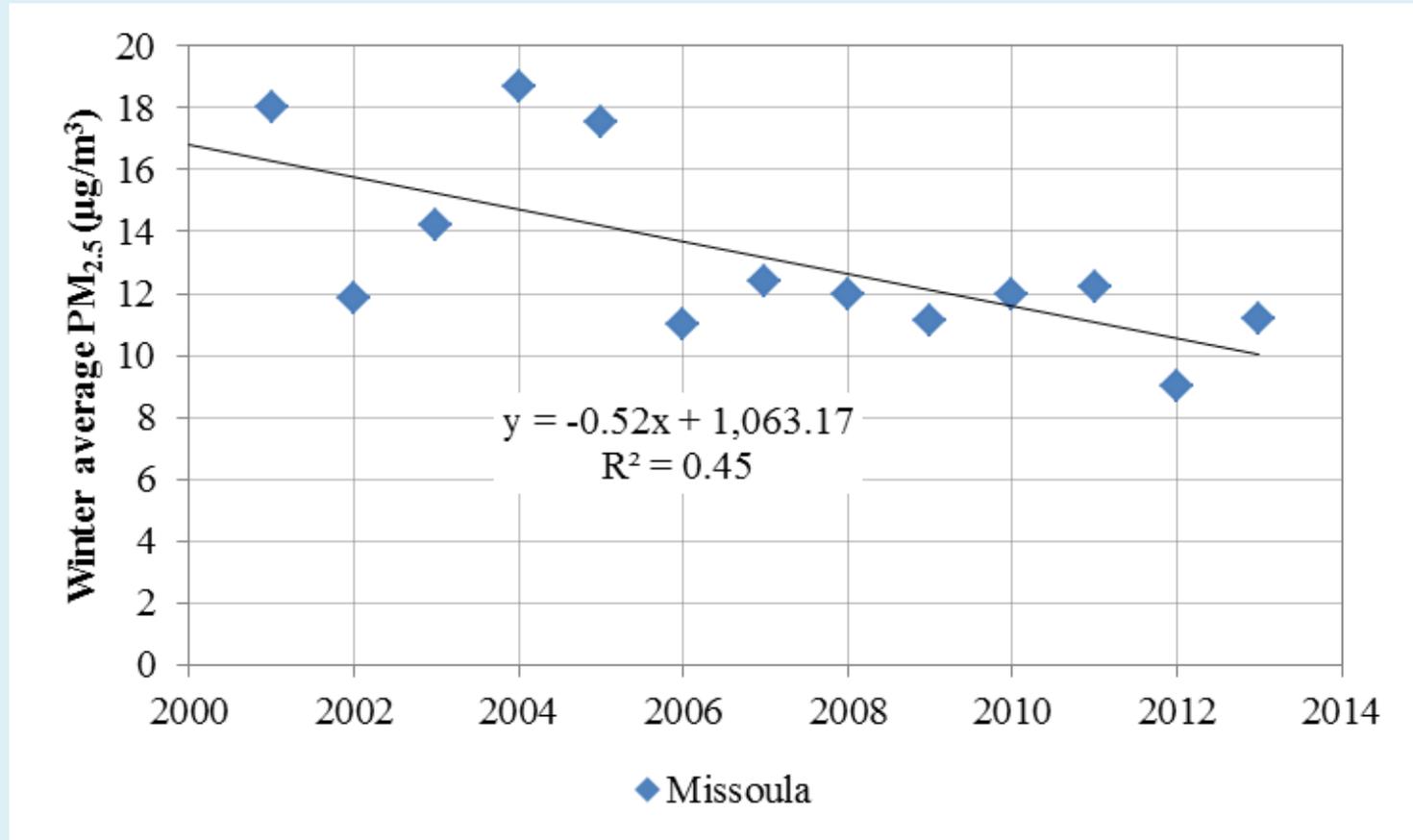


(Downward Trend with Heat Deficit Normalized PM_{2.5})



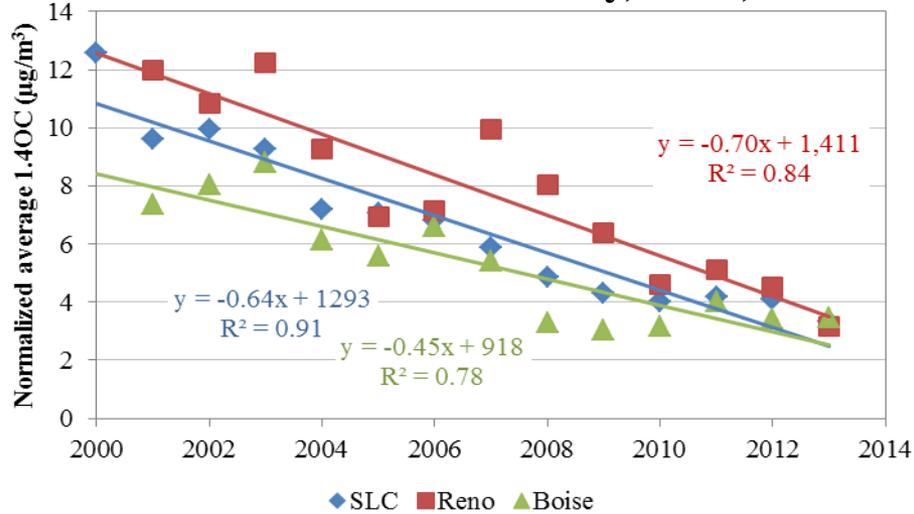
Sensitivity of PM_{2.5} to heat deficit shows a general decline (possible effects of emission reductions?)

Downward PM_{2.5} is also found for Missoula

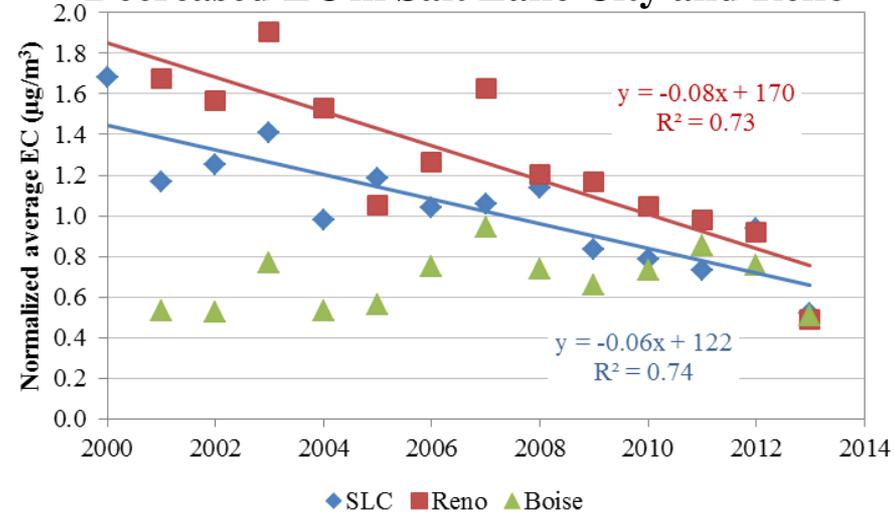


General downward trend on major PM_{2.5} components found in Salt Lake

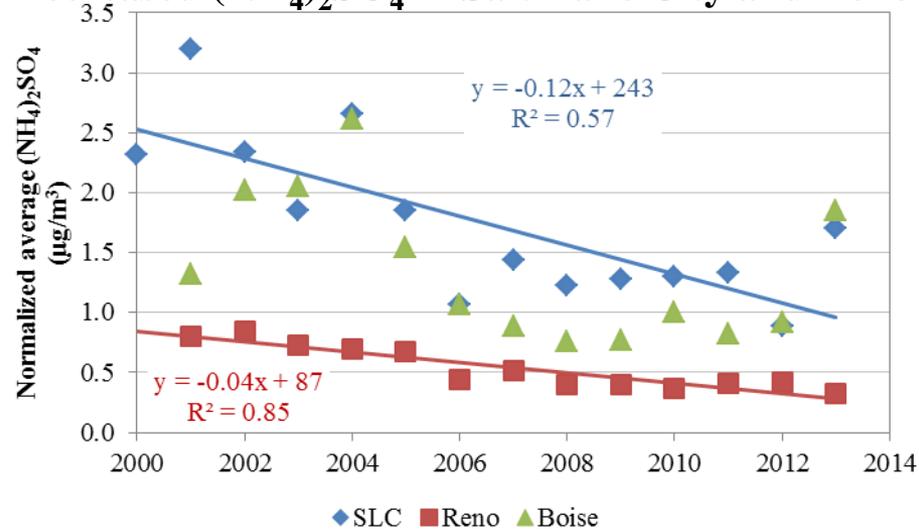
Decreased OM in Salt Lake City, Reno, and Boise



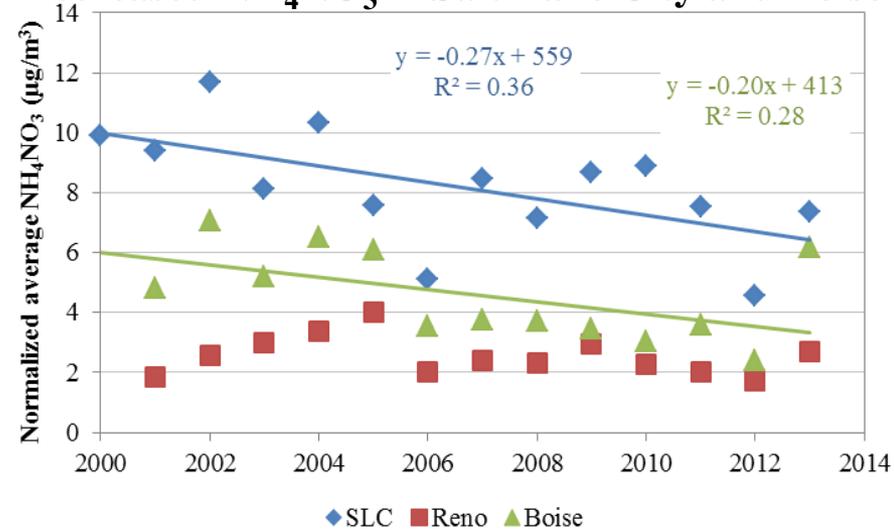
Decreased EC in Salt Lake City and Reno



Decreased (NH₄)₂SO₄ in Salt Lake City and Reno

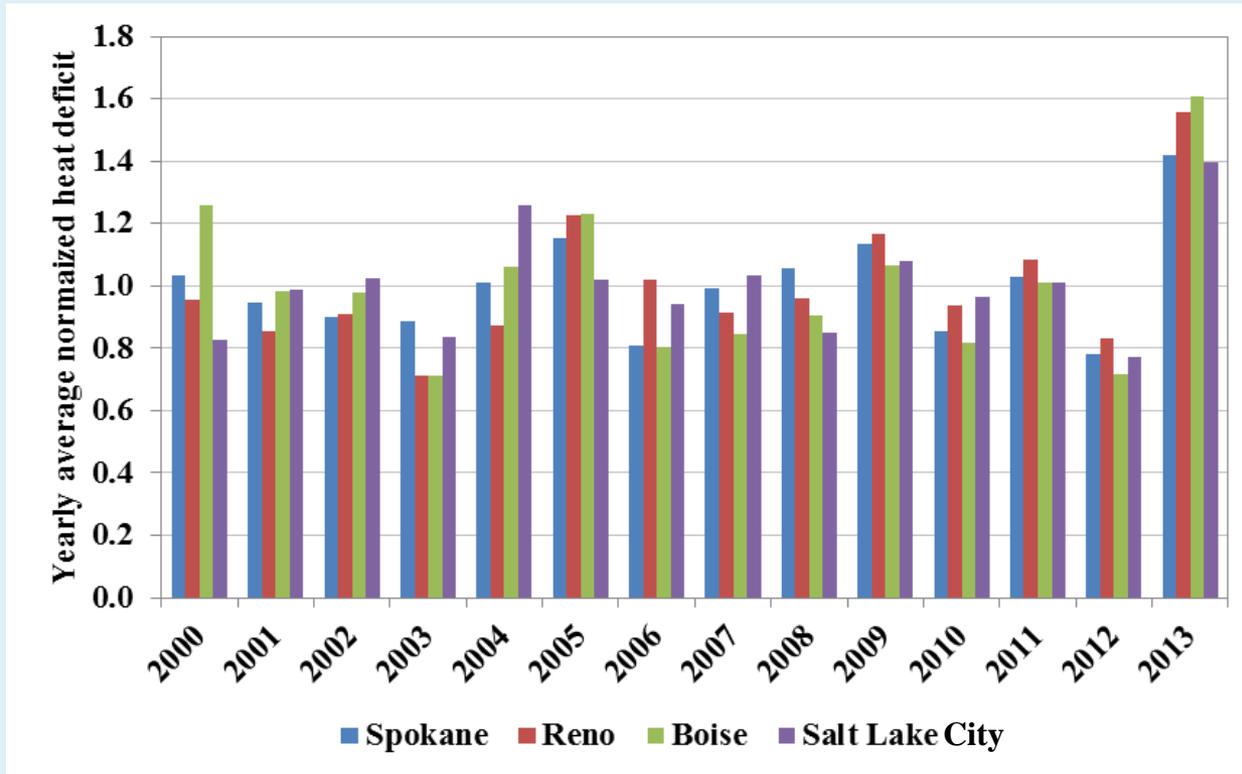


Decreased NH₄NO₃ in Salt Lake City and Boise



Downward trend is largest for OM.

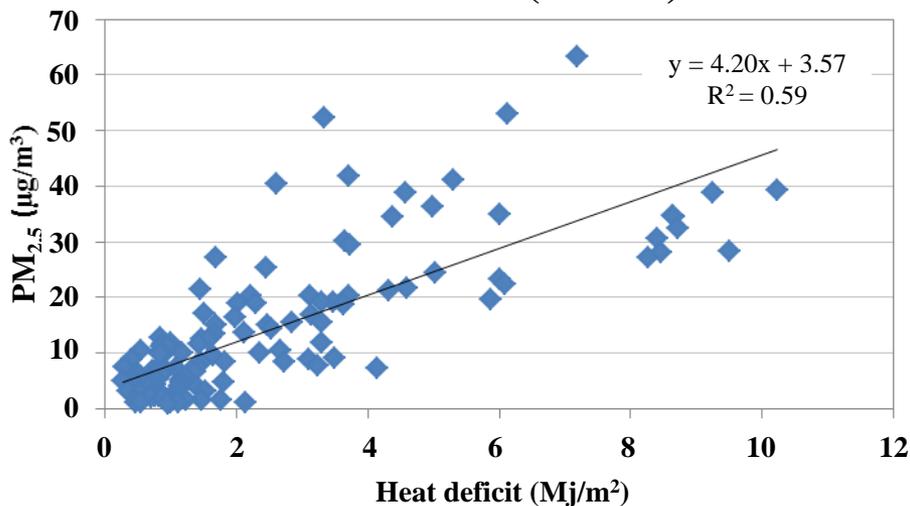
Winter average heat deficit correlated well among the cities



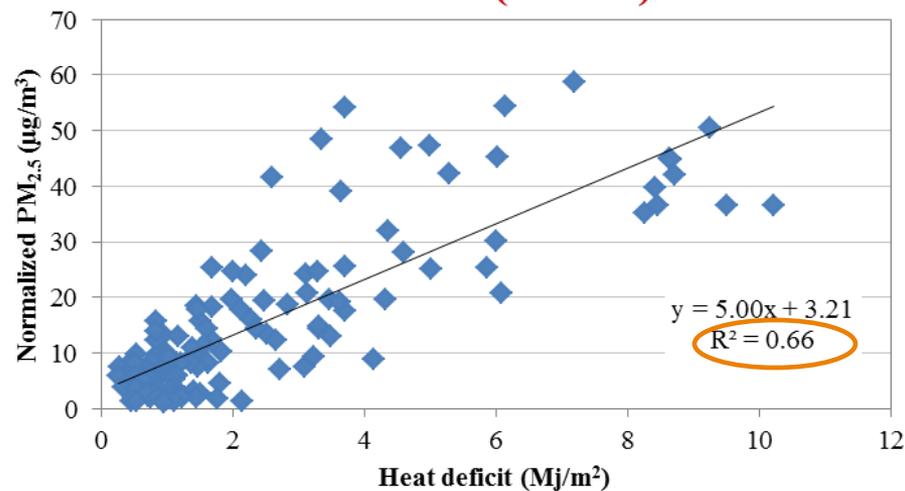
Correlations for annual heat deficit			
	Reno	Boise	Salt Lake City
Spokane	0.85	0.90	0.78
Reno		0.82	0.75
Boise			0.78

Accounting for trend (yearly variations) somewhat improves PM_{2.5}-heat deficit relationship

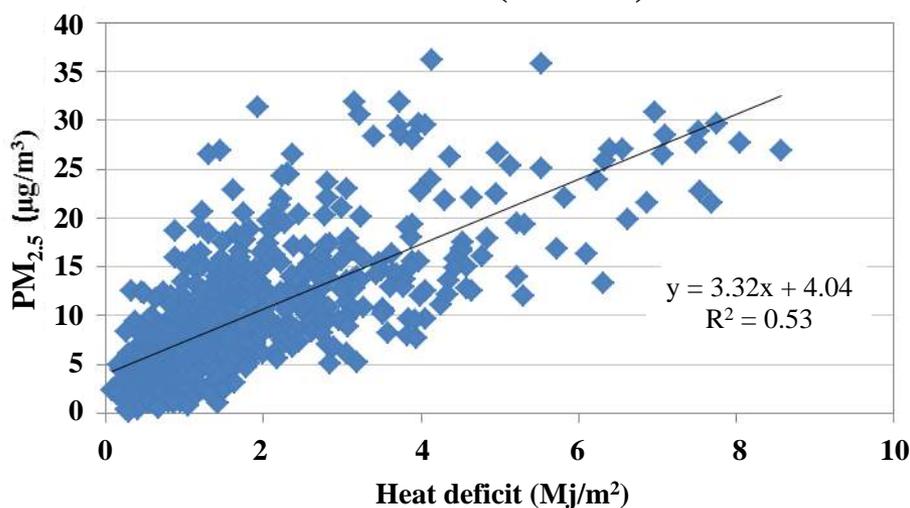
Reno SD>0 (n=128)



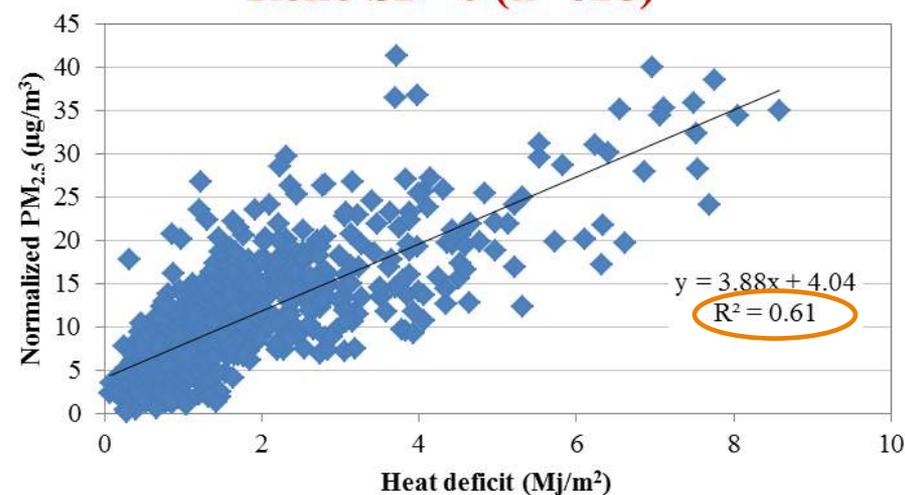
Reno SD>0 (n=128)



Reno SD=0 (n=628)



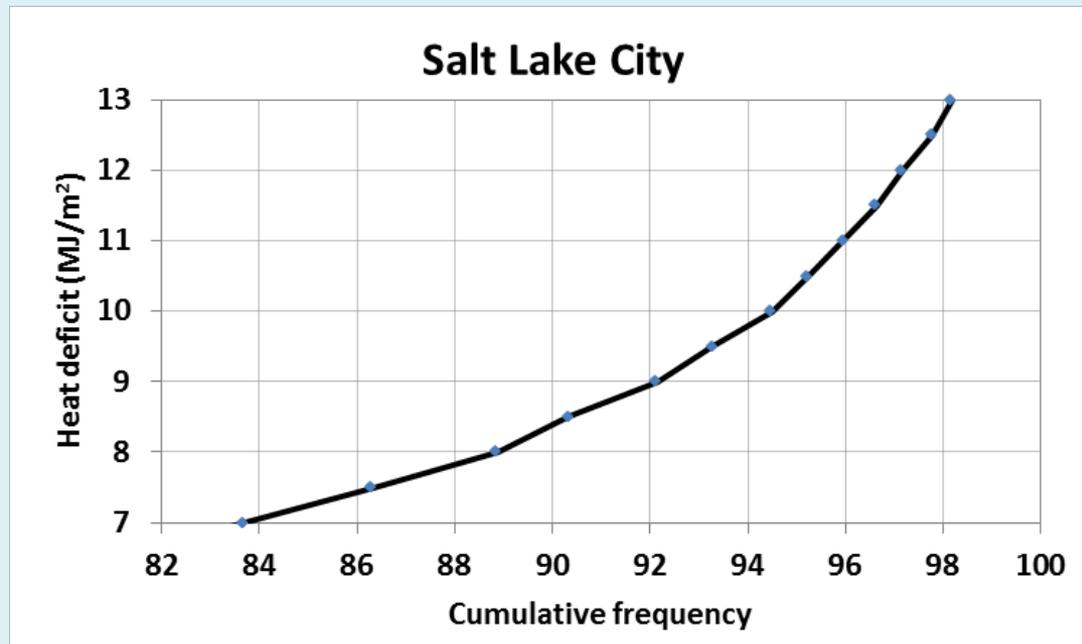
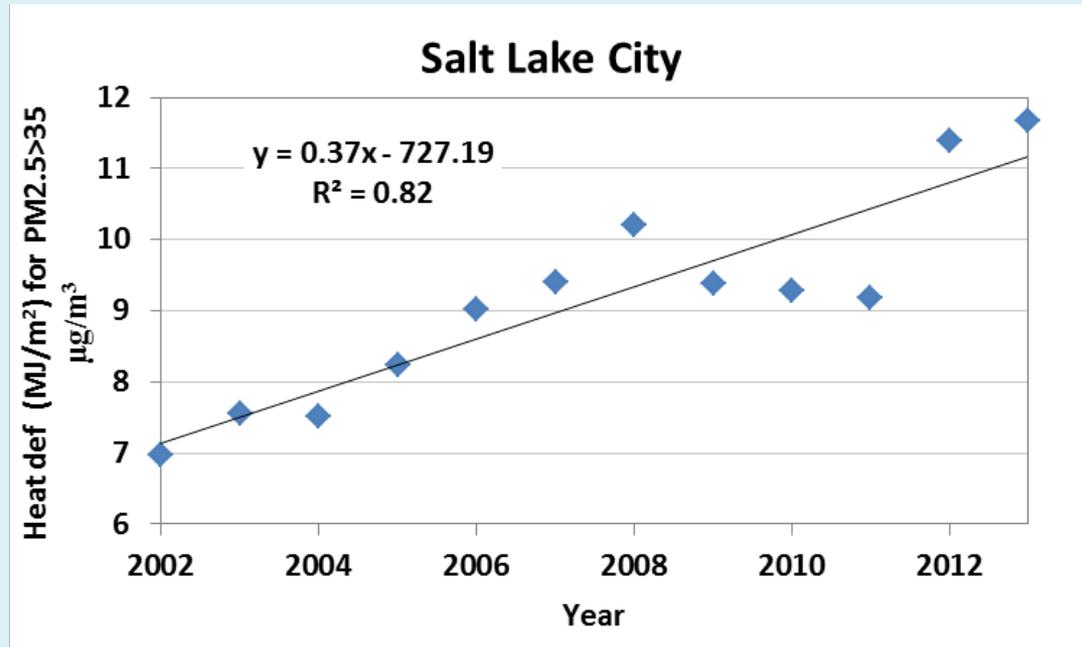
Reno SD=0 (n=628)



Heat deficit needed to get PM2.5 > NAAQS increases with year

In 2000-2002 about 15% of days for a typical winter had sufficient heat deficit to cause exceedances, by 2011-2013 only about 3.5% of days did

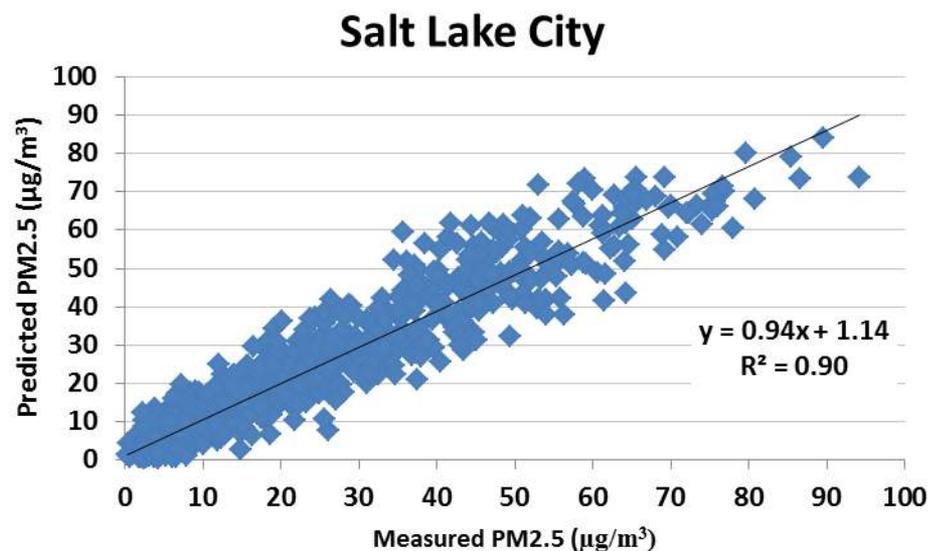
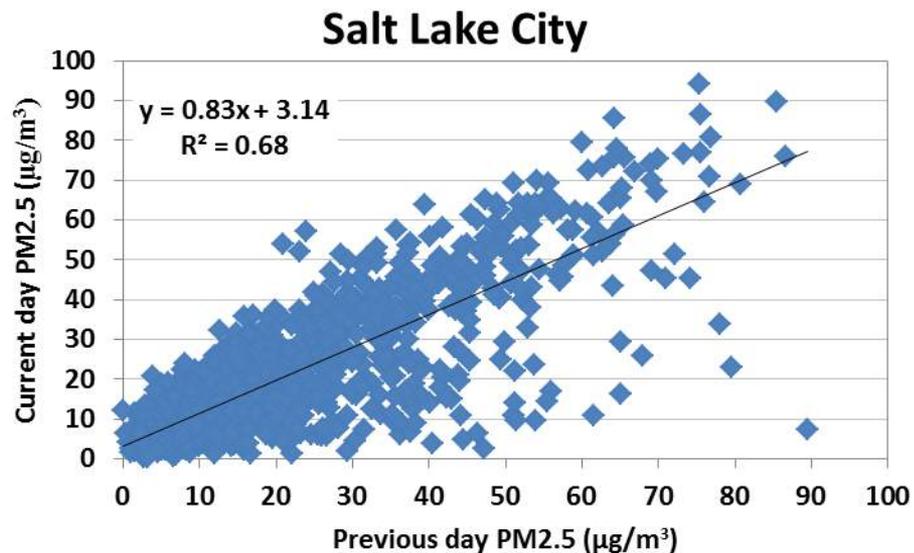
Note that the results are for a typical winter heat deficit distribution



Daily PM2.5 correlated with previous day PM2.5

Heat deficit and previous day PM2.5 reasonable predictor of daily PM2.5.

Can heat deficit be well predicted by models to allow for a forecast?



SD>0, 132 days PM2.5>35, 126 pred, 6 missed, 11 falsely predicted>35
SD=0, 82 days PM2.5>35, 51 pred, 31 missed, 14 falsely predicted >35

Summary/Conclusions

- Cold-air pools affect western U.S. valley cities
- Increased $PM_{2.5}$ is associated with increased heat deficit (or Delta T) on snow cover days
- Most exceedances of 24-hour $PM_{2.5}$ NAAQS are on snow cover days with increasing ammonium nitrate (and associated liquid water)
- Reduction in ammonia (NH_3) and nitrogen oxides (NO_x) on statically stable days with snow cover would reduce NAAQS exceedances
- Downward $PM_{2.5}$ trends are discernable when controlling for variations in heat deficit – emissions controls working
- Heat deficit may be useful parameter to aid air quality forecasting

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