A Novel Meteorological Method to Classify Wintertime Cold-Air Pool Events

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SUPPLEMENTAL INFORMATION

S.1 VHD example when including data from station on valley floor

One winter of twice-daily VHD in Reno is shown in Figure S1, showing the diurnal variability when the KRNO data is considered in the analysis. The difference in stability when considering the valley meteorology is evident during a CAP episode in mid-January 2005. In Reno, the radiosonde is released 174-meters above the valley floor and does not accurately capture every temperature inversion that occurs. Pierce et al., (2019) approached the missing data in Reno a similar way, appending local meteorology data on the valley floor to the radiosonde data. When the data from KRNO is appended to the corresponding radiosonde, a more representative VHD (and stability) can be calculated. Table 2 shows the comparison of the radiosonde data and the appended data, highlighting major differences in overall stability for all winter months from 2002-2018. Typically, the appended VHD is greater in the 12Z observations than the radiosonde VHD because of the increased cooling seen at KRNO compared with REV. The opposite can be seen for the some 00Z observations when the valley VHD is lower, likely because of the urban environment increasing the sensible heat flux near the surface, producing a super-adiabatic lapse rate in the lowest layer (during a non-CAP episode). The VHD is more representative when the valley meteorology is appended and is ~1-2 MJ m^{-2} greater during this specific event for Reno. This can also be interpreted to potentially represent underestimated VHD values in other locations without ASOS data.

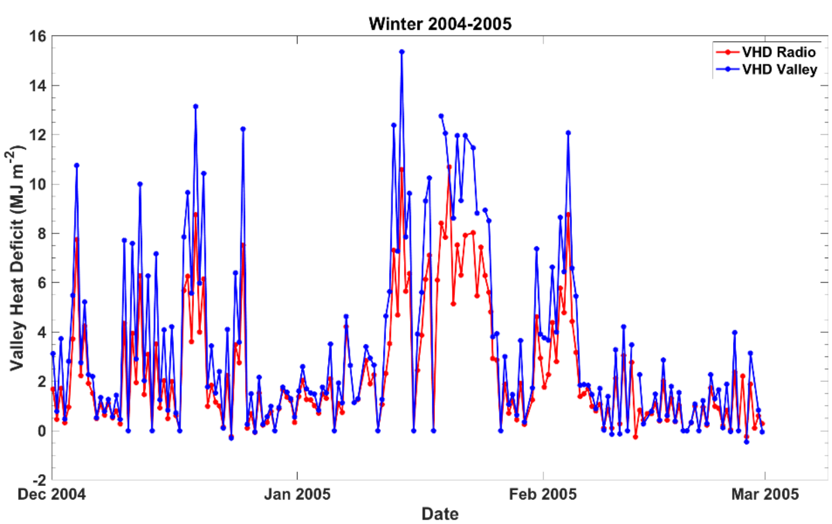


Figure S1. Comparison of VHD calculated using only radiosonde data (red line) and the station appended data (blue line) for Reno, NV in Winter 2004-2005.

To visualize the comparison of radiosonde only vertical profiles and the appended vertical profiles using the data from the valley floor a regression plot was used (Figure S2). In Spokane, the correlation coefficient is 0.994 with a slope of 1.237. In Elko, the correlation coefficient is 0.997 with a slope of 1.199. In Reno, the correlation coefficient is 0.968 with a slope of 1.691. All slopes were found using a y-intercept of zero.

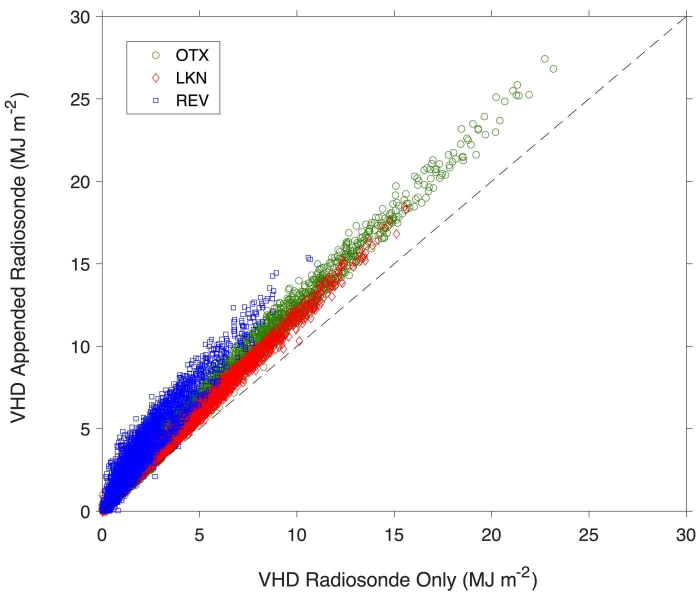


Figure S2. Spokane [OTX], Elko [LKN], and Reno [REV] comparison of VHD from radiosonde only and radiosonde appended data.

S.2 Monthly valley heat deficit

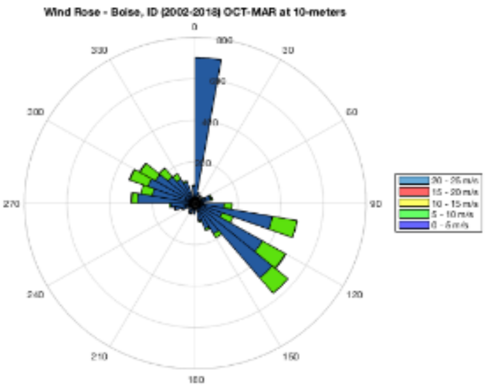
CAP events vary during the times of the year, typically with the greatest frequency during winter months (December to February). This study includes CAP events from October to March, with Table S1 showing the variability in mean, median, and standard deviation of VHD stratified by month. For several locations (Salem [SLE], Medford [MFR], Boise [BOI], Salt Lake City [SLC], and Denver [DNR]) October median VHD is slightly greater, or near, that of February, which could indicate local topography influencing CAP formation, duration, and breakup during transitional synoptic patterns in the Fall. Ridges in the western U.S. can last into fall before being broken down by incoming troughs when the seasonal jet stream placement dips farther south.

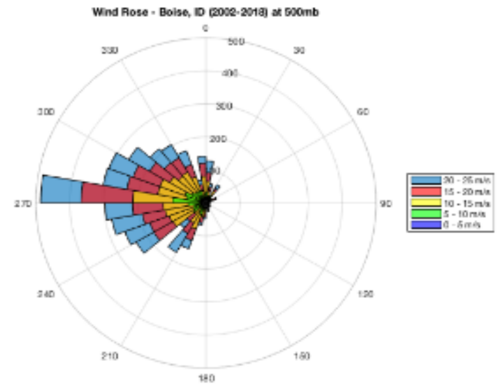
Reno [REV] and Quillayute [QUI] experience the greatest variability in VHD from October-March. The distribution of VHD is similar in Elko [LKN], with less variability in VHD during the winter months. During the winter months in Elko, troughs are more frequent due to it being farther east (i.e., troughs that come down from Canada are less frequent for western Nevada) which spill cold air into the lower levels of valley in Elko. Also, of note, the months with the greatest VHD (December-February for all locations) have values that are close to the 75th percentile of the overall VHD.

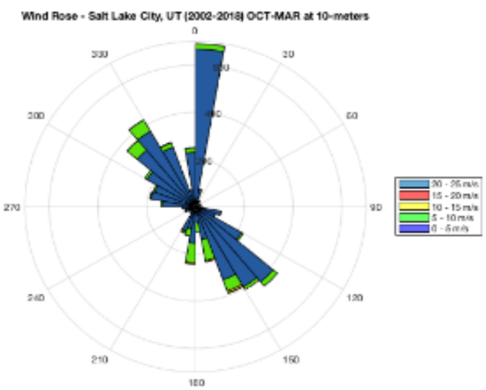
Table S1. Monthly VHD values (MJ m^{-2}) for 2002-2018 in 12 cities across the western U.S.

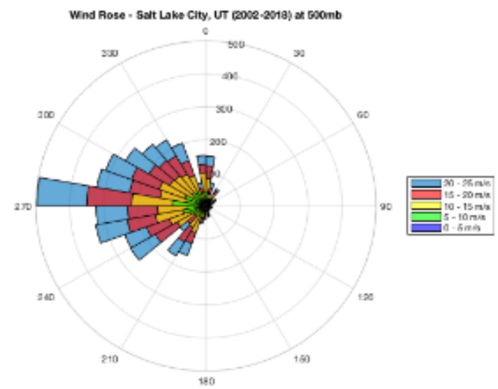
	Oct	Nov	Dec	Jan	Feb	Mar
			BOI			
Mean	2.37	3.13	3.94	4.91	2.54	1.61
Median	2.02	2.54	3.22	3.75	2.07	1.46
St. Dev	1.99	2.64	3.04	3.83	2.30	1.57
			SLC			
Mean	2.84	3.86	4.97	6.01	3.26	2.17
Median	2.62	3.30	4.06	4.86	2.81	1.91
St. Dev	2.06	2.67	3.38	4.31	2.62	1.91
			REV			
Mean	1.55	2.00	2.74	3.05	1.52	0.97
Median	0.68	1.02	1.58	2.15	0.89	0.48
St. Dev	2.18	2.40	2.97	3.04	2.07	1.70
			MFR			
Mean	2.81	3.71	4.00	4.45	2.72	1.99
Median	2.11	2.99	3.20	3.82	2.18	1.48
St. Dev	2.56	2.90	3.16	3.33	2.36	1.97
			SLE			
Mean	3.00	3.66	4.23	4.91	3.08	2.08
Median	2.41	2.56	2.99	3.38	2.28	1.74
St. Dev	2.50	3.07	3.41	3.98	2.59	1.82
			DNR			
Mean	2.96	3.58	4.13	3.84	3.46	2.50
Median	2.64	2.98	3.51	3.27	2.79	2.03
St. Dev	2.86	3.02	3.13	3.12	3.42	2.80
			OTX			
Mean	4.21	5.95	7.26	8.25	5.25	3.32
Median	4.15	5.24	6.53	7.45	4.96	3.43
St. Dev	3.36	4.02	4.30	4.77	3.50	2.75
			GJT			
Mean	3.04	4.33	5.91	6.46	3.69	2.22
Median	2.71	4.00	5.51	5.93	3.61	1.89
St. Dev	2.30	2.85	3.62	3.76	2.62	2.17
			LKN			
Mean	2.38	3.00	3.78	4.74	2.86	1.77
Median	1.42	2.22	2.79	3.59	2.16	1.15
St. Dev	2.67	2.78	3.22	3.93	2.86	2.17
			TFX			
Mean	2.37	3.00	3.91	4.24	3.34	2.52
Median	2.07	2.30	3.03	3.21	2.45	1.88
St. Dev	1.91	2.62	3.21	3.87	3.32	3.06
			RIW			
Mean	2.71	3.58	4.72	5.07	3.64	2.13
Median	2.51	3.07	3.98	4.41	2.96	1.85
St. Dev	2.09	2.63	3.16	3.28	2.87	2.08
			QUI			
Mean	1.86	1.75	1.71	1.88	1.49	1.25
Median	1.37	1.42	1.28	1.36	0.91	0.71
St. Dev	2.17	1.96	1.97	2.13	1.82	1.52

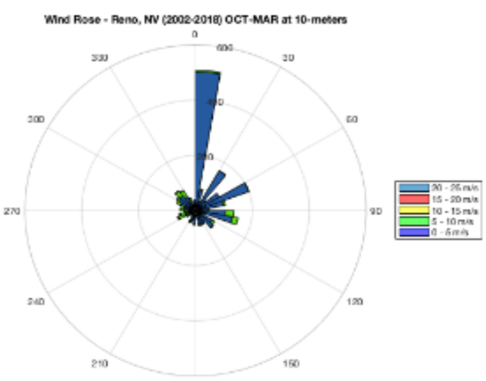
S.3 Surface and Upper Level Winds

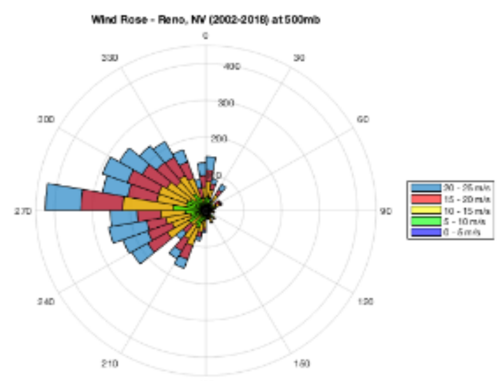


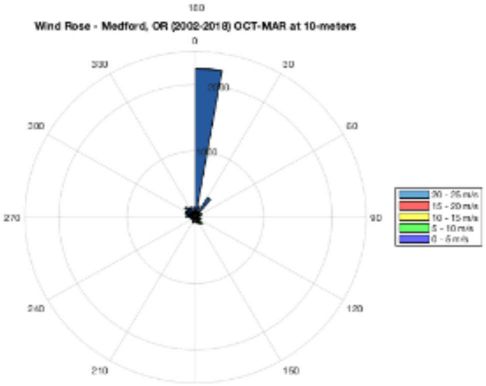


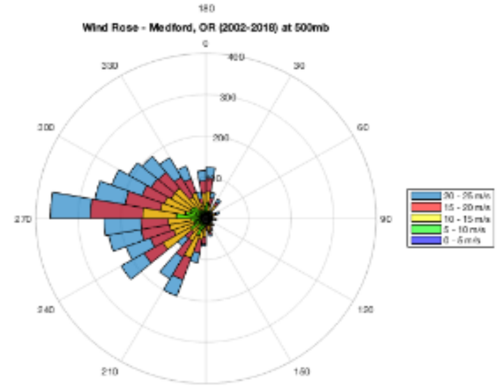




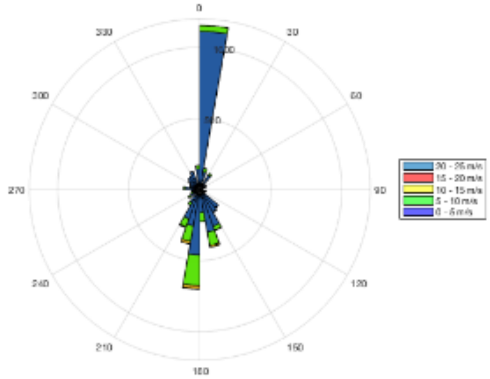




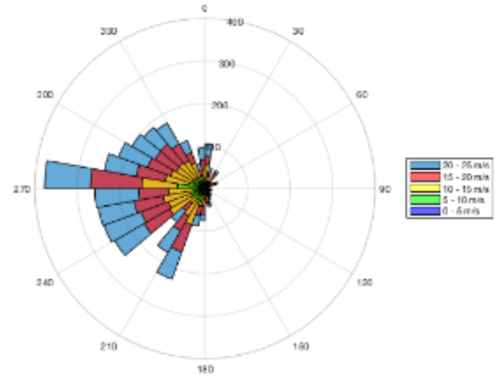




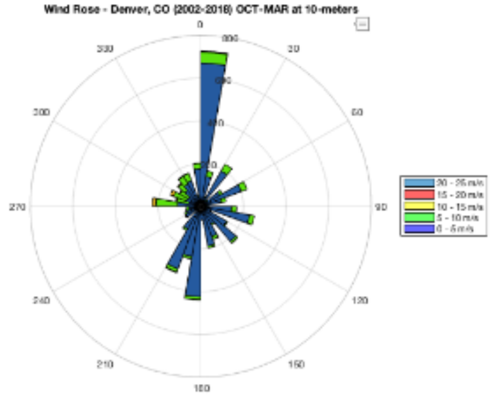
Wind Rose - Salem, OR (2002-2018) OCT-MAR at 10-meters



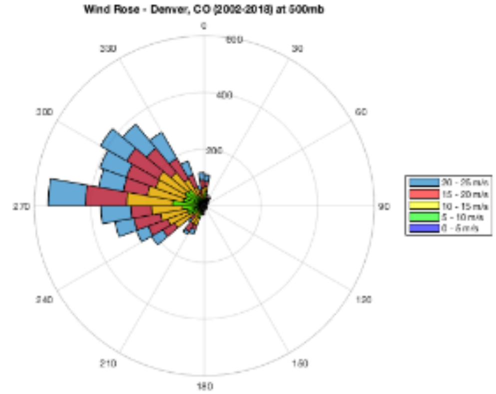
Wind Rose - Salem, OR (2002-2018) at 500mb



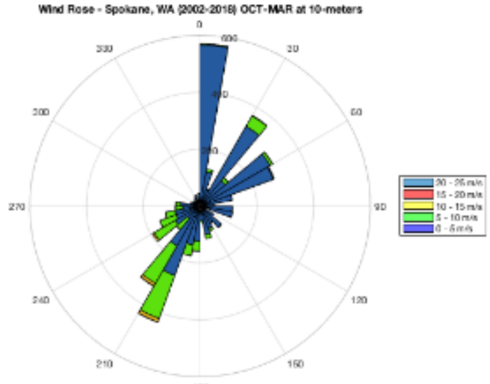
Wind Rose - Denver, CO (2002-2018) OCT-MAR at 10-meters



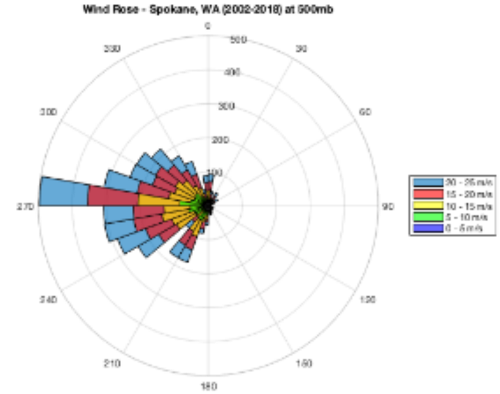
Wind Rose - Denver, CO (2002-2018) at 500mb



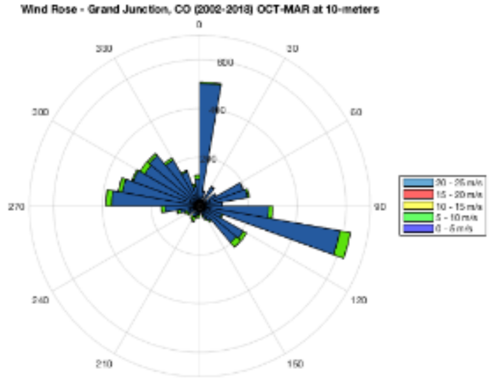
Wind Rose - Spokane, WA (2002-2018) OCT-MAR at 10-meters



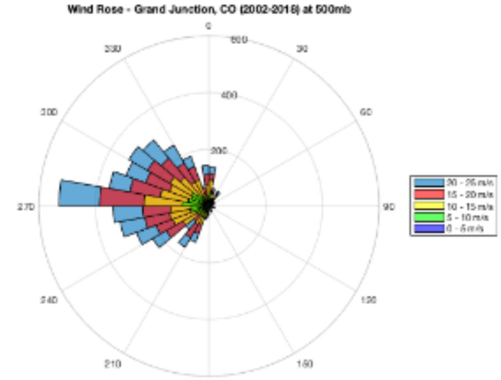
Wind Rose - Spokane, WA (2002-2018) at 500mb



Wind Rose - Grand Junction, CO (2002-2018) OCT-MAR at 10-meters



Wind Rose - Grand Junction, CO (2002-2018) at 500mb



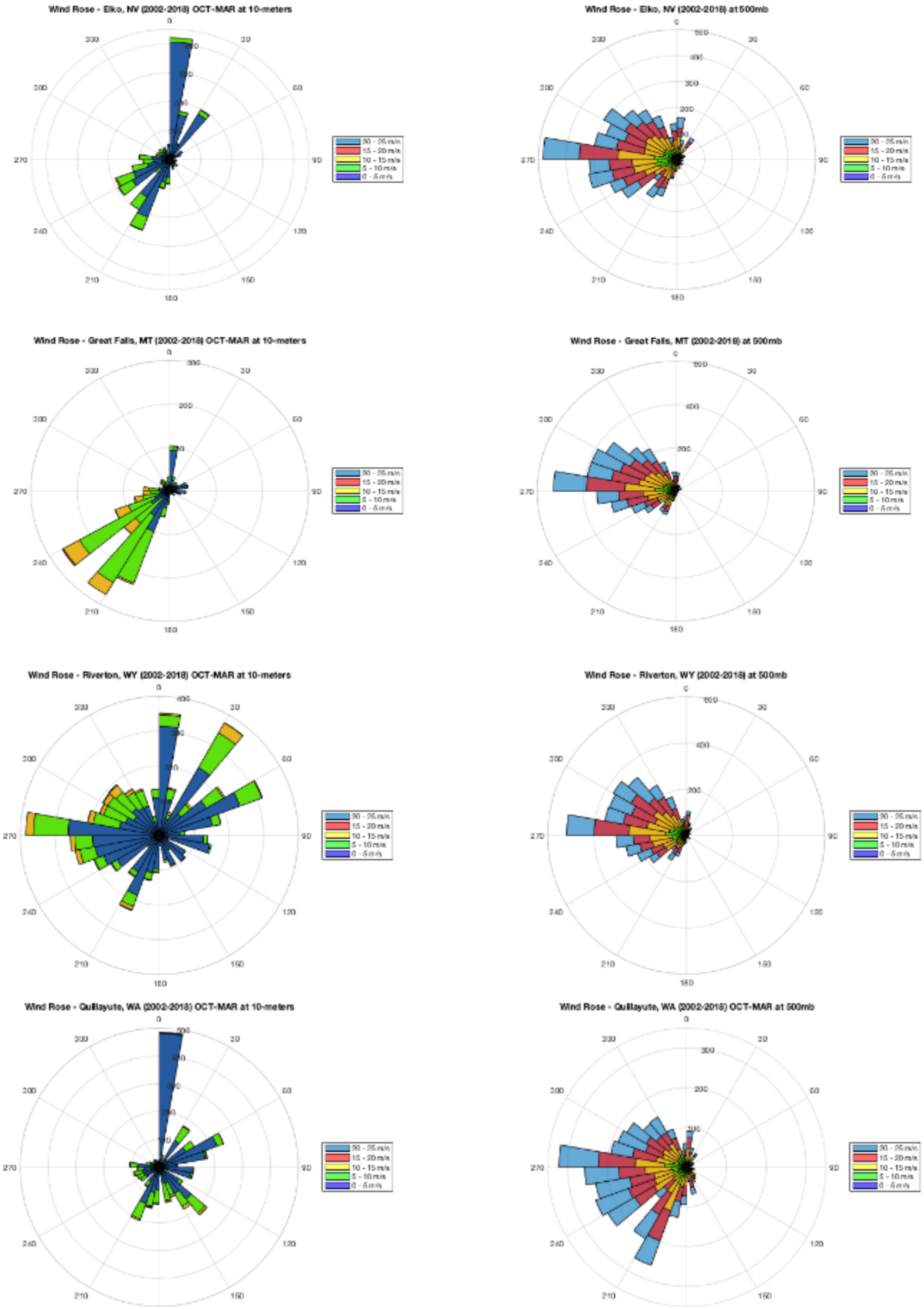


Figure S3. Wind roses for 12 cities for surface winds (10-m, *left*) and upper level winds (500-mb, *right*). All wind roses use surface and radiosonde data from Oct-Mar for 2002-2018.

Wind roses for all locations at 10-meters and 500-mb (well above the CAP and mean ridge height) are shown in Figure S3. The 500-mb winds represents synoptic motions in the atmosphere and can be used to determine large-scale patterns (i.e., troughs and ridges). For all locations at 500-mb, the dominant wind direction is from the west during Oct-Mar with very few winds from the east, suggesting similar synoptic features across the western U.S. during the winter months. The differences lie in the 10-m wind roses, implying that unique topography impacts wind speed and direction near the surface and a decoupling from the middle troposphere. The Riverton [RIW] NWS sits 194 m AGL above the city of Riverton and lies on a mesa, prone to non-specific wind directions and increased wind speeds. On the contrary, the 10-m wind rose at Medford [MFR] shows exceptionally low wind speeds and a dominant northerly wind. It is important to note that when the wind speed is zero, the wind direction is recorded as zero also, creating a false narrative in the wind rose and should be taken into account when analyzing wind roses during CAP events. For example, Medford has 1,924 soundings and Great Falls has 171 soundings with wind speed and wind direction recorded as 0, over the same time period from 2002-2018.

S.4 CAP Classification Test Case

Figure S4 shows the spatial distribution of VHD across the 12 locations for the same 4 days as the spatial plots of normalized VHD shown in Figure 5. During this time period the western U.S. was under a persistent high-pressure ridge leading to CAP formation in many locations. Comparing the VHD values in Figure S4 with the VHD threshold values for CAP classification in Table 3 (VHD_17.5, VHD_75, VHD_met) the CAPs can be classified using the other methods evaluated in the paper. When comparing these CAP classifications to the ones in Figure 5 using the Normalized VHD_met method major differences in the classifications can be found. Here we focus on investigating the differences between the two CAP classifications that use VHD thresholds based on air quality measurements (VHD_17.5 and VHD_75) and our new method (Normalized VHD_met). The first difference is that in three locations (Riverton [RIW], Elko [LKN], and Quillayute [QUI]) the CAPs cannot be classified using VHD_17.5/VHD_75 because there are no $PM_{2.5}$ monitors.

The next major difference is the spatial pattern of the CAP classification, where Normalized VHD_met classifies CAPs with a more consistent spatial pattern (i.e., more clustered CAP locations) while the CAP locations for VHD_17.5/VHD_75 are not clustered geographically. This can be seen in the first spatial plot (28 Jan 2017 00Z) where Normalized VHD_met classifies CAPs in seven locations (Spokane [OTX], Medford [MFR], Salem [SLE], Boise [BOI], Elko [LKN], Salt Lake City [SLC], Riverton [RIW]), VHD 17.5 has only one CAP (BOI), and VHD_75 has 2 CAPs (Great Falls [TFX], BOI). Interestingly, TFX does not meet the CAP criteria for Normalized VHD_met but does for the VHD_75 method on this day. While the other Normalized VHD_met CAP locations, with the exception of Boise, do not meet the air quality VHD thresholds for CAPs. Only four locations have the same CAP classification for all three methods; CAP: BOI and non-CAP: REV, GJT, and DNR.

To investigate the differences in more detail vertical temperature profiles are required (Figure S5 for the same day, 28 Jan 2017 00Z). Three of the locations (Spokane [OTX], Medford [MFR], Salt Lake City [SLC]) illustrate improvements in the Normalized VHD_met method compared to the other methods in classifying a CAP. For all three of these locations the VHD_17.5/VHD_75 classified the soundings as non-CAPs while Normalized VHD_met classified them as CAPs. Based on the vertical temperature profiles in these three locations it is evident that a CAP is present, where both the stability and meteorological criteria for CAPs were met. In MFR and SLC, the $PM_{2.5}$ concentrations are also above the 75^{th} percentile (Table 3) indicative of poor air quality. Great Falls [TFX] provides an example of the Normalized VHD_met not classifying a CAP when VHD_75 does. From the sounding, it is clear that a slightly stable layer exists, however, the meteorological criteria are not met for this sounding. Additionally, the $PM_{2.5}$ concentration in TFX is below the 75^{th} percentile.

During the peak of the high-pressure event there are also differences in the CAP classifications. Where in the morning (29 Jan 2017 12Z) and afternoon (30 Jan 2017 00Z) there are 10 CAPs and 9 CAPs, respectively based on Normalized VHD_met. However, based on the VHD threshold using air pollution concentrations the number of CAPs decreases to 7 and 5 for the morning and afternoon. Because this region is under a persistent high-pressure ridge there are PCAPs in many of these locations (as indicated by Figure 5) that are not classified as CAPs using the VHD air quality thresholds (Figure S4).

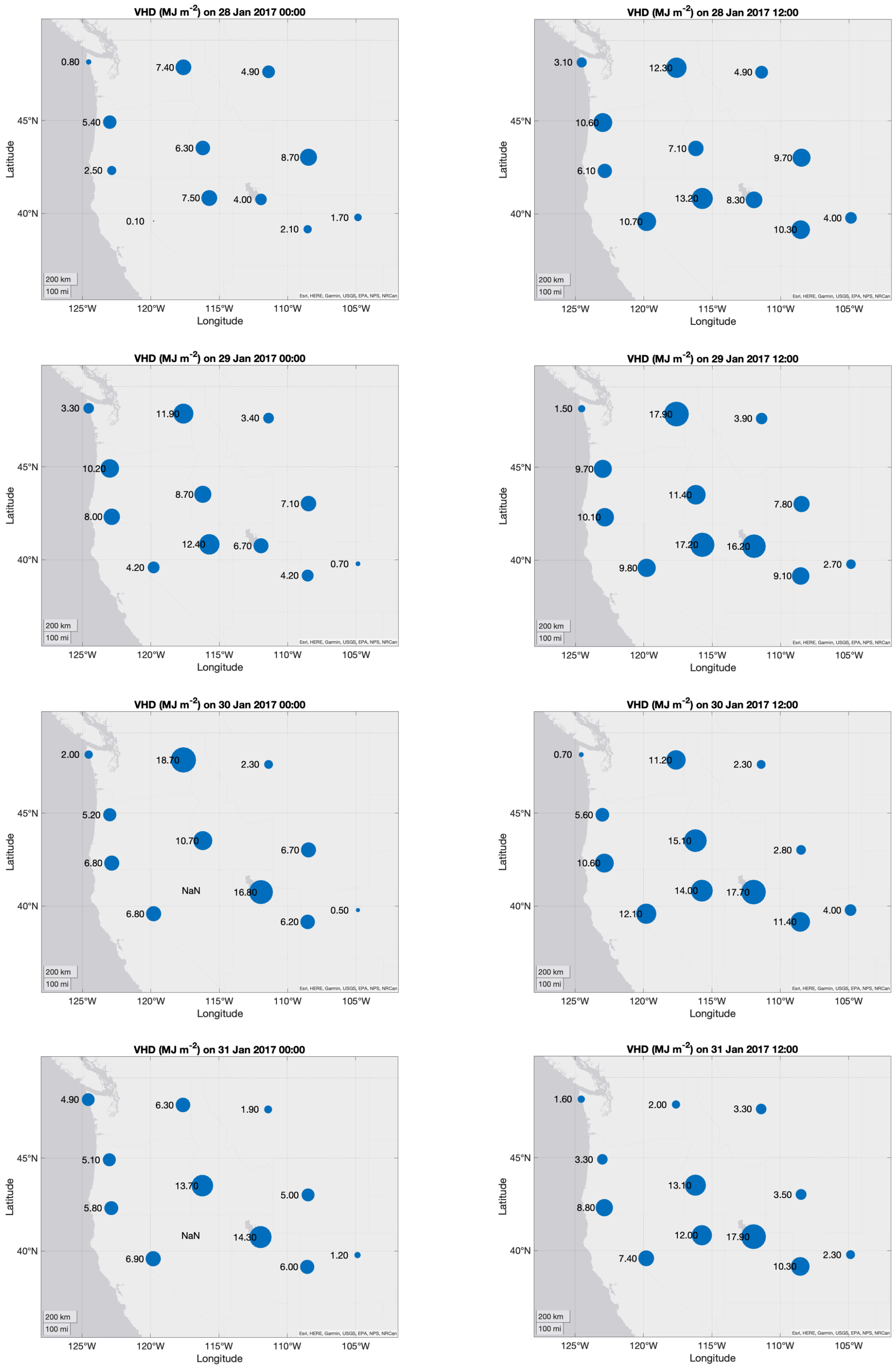
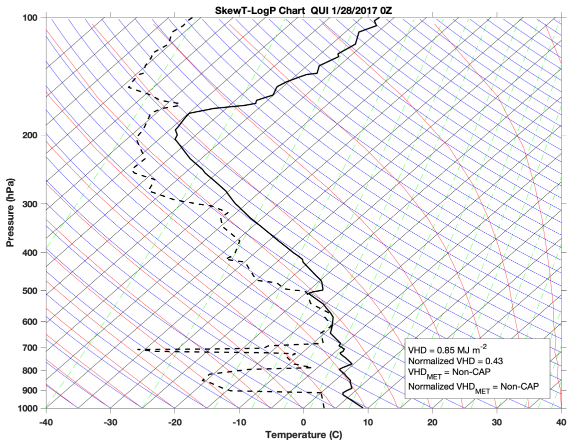
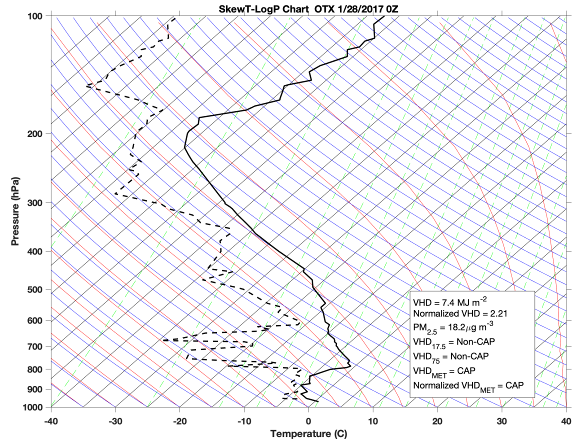
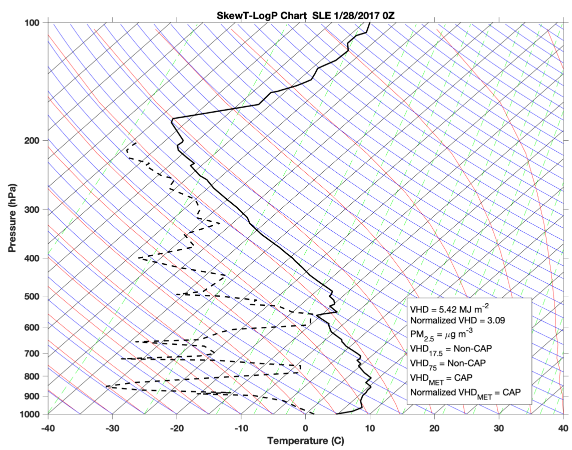
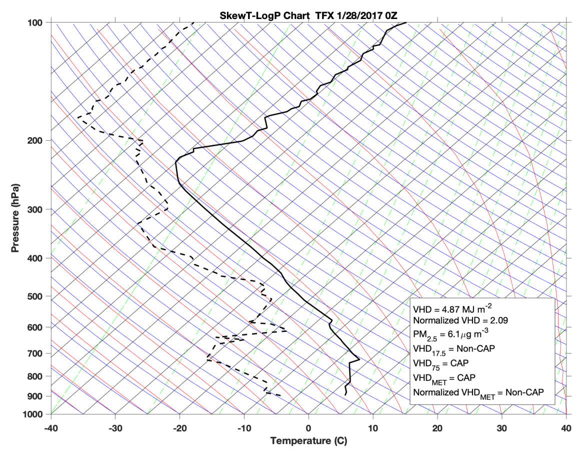


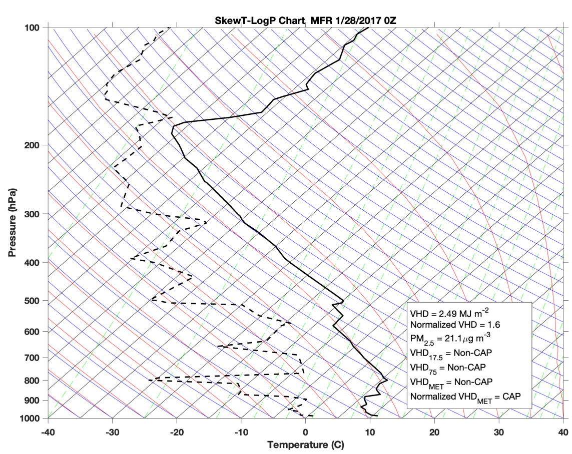
Figure S4. VHD (MJ m^{-2}) for 28-31 January 2017 UTC. (Left) Afternoon soundings, 00Z. (Right) Morning soundings, 12Z.

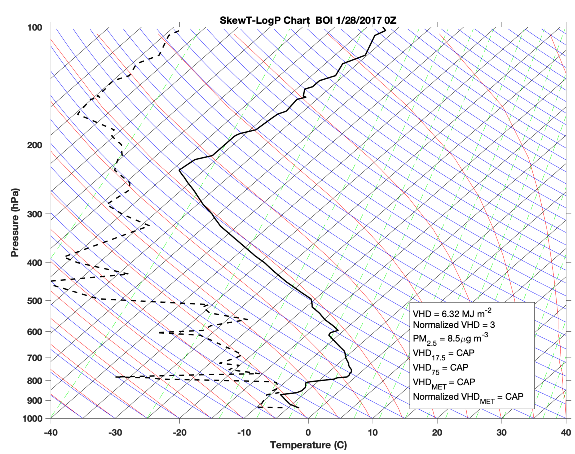

SkewT-LogP Chart QUI 1/28/2017 0Z
VHD = 0.85 MJ m^-2
Normalized VHD = 0.43
VHD_MET = Non-CAP
Normalized VHD_MET = Non-CAP
Pressure (hPa)
Temperature (C)


SkewT-LogP Chart OTX 1/28/2017 0Z
VHD = 7.4 MJ m^-2
Normalized VHD = 2.21
PM2.5 = 18.2μg m^-3
VHD17.5 = Non-CAP
VHD75 = Non-CAP
VHD_MET = CAP
Normalized VHD_MET = CAP
Pressure (hPa)
Temperature (C)


SkewT-LogP Chart SLE 1/28/2017 0Z
VHD = 5.42 MJ m^-2
Normalized VHD = 3.09
PM2.5 = μg m^-3
VHD17.5 = Non-CAP
VHD75 = Non-CAP
VHD_MET = CAP
Normalized VHD_MET = CAP
Pressure (hPa)
Temperature (C)


SkewT-LogP Chart TFX 1/28/2017 0Z
VHD = 4.87 MJ m^-2
Normalized VHD = 2.09
PM2.5 = 6.1μg m^-3
VHD17.5 = Non-CAP
VHD75 = CAP
VHD_MET = CAP
Normalized VHD_MET = Non-CAP
Pressure (hPa)
Temperature (C)


SkewT-LogP Chart MFR 1/28/2017 0Z
VHD = 2.49 MJ m^-2
Normalized VHD = 1.6
PM2.5 = 21.1μg m^-3
VHD17.5 = Non-CAP
VHD75 = Non-CAP
VHD_MET = Non-CAP
Normalized VHD_MET = CAP
Pressure (hPa)
Temperature (C)


SkewT-LogP Chart BOI 1/28/2017 0Z
VHD = 6.32 MJ m^-2
Normalized VHD = 3
PM2.5 = 8.5μg m^-3
VHD17.5 = CAP
VHD75 = CAP
VHD_MET = CAP
Normalized VHD_MET = CAP
Pressure (hPa)
Temperature (C)

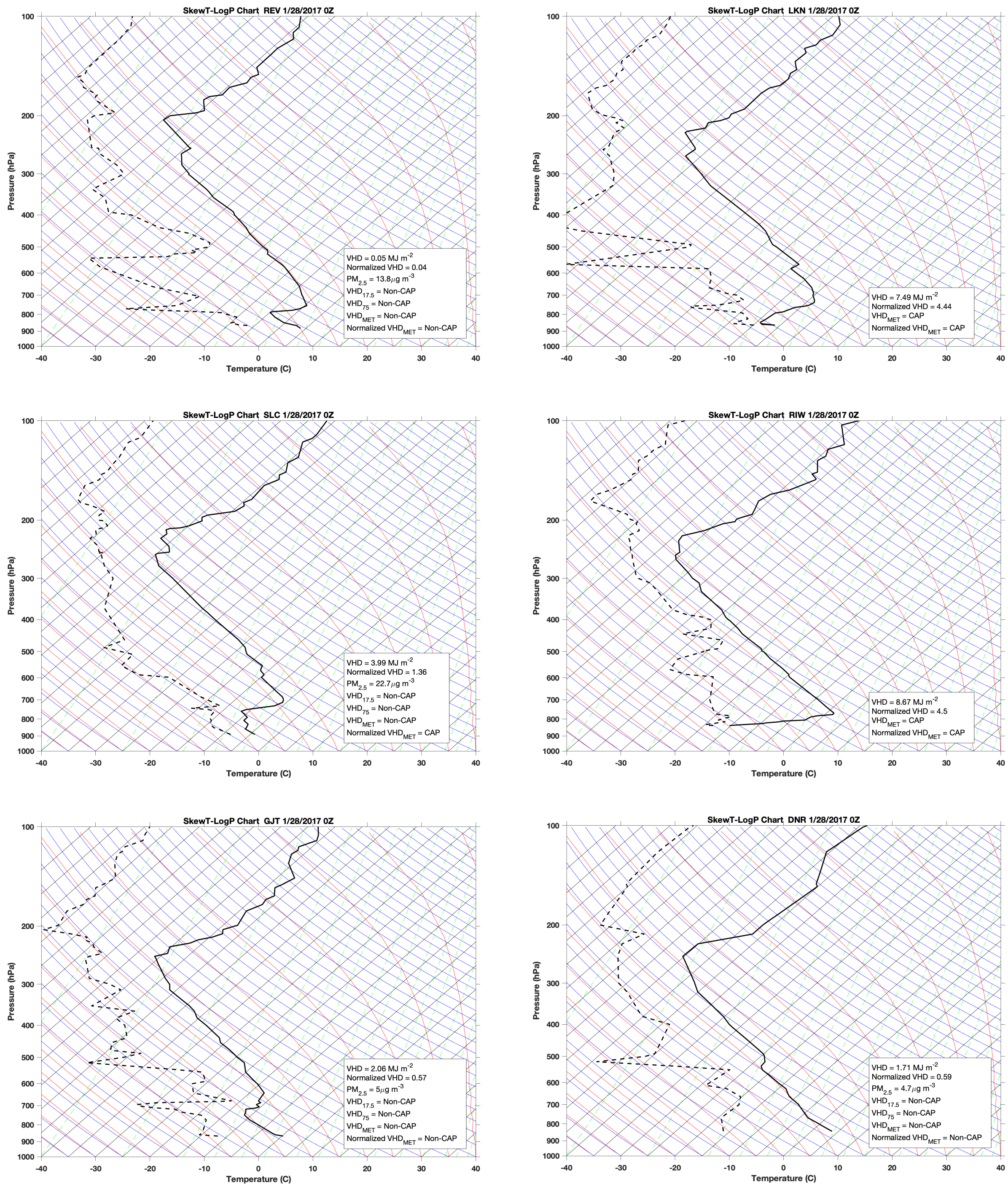


Figure S5. Skew-T Log-P plots for 28 January 2017 00Z UTC (afternoon sounding).

S.5 Local meteorology influences on CAP events

S5.1 Spokane CAP Events (OTX)

Whiteman et al., (2001) found that PCAPs in the Columbia Basin often have a layer of enhanced stability at their top and the surrounding high plateaus have continuous snow cover that limits the surface from emitting longwave radiation, generating a flow of cold air into the basin causing frequent inversions. Spokane lies on the northeast section of the Columbia Basin and is near mountains with continuous snow cover throughout winter. For soundings that met the new Normalized VHD_met threshold, the predominant wind direction was from the northeast with wind speeds less than 3 m s^{-1}. During December and January, most days had a northeast prevailing wind direction, which explains the high VHD, especially when in conjunction with an enhanced stable layer at the CAP top. Whiteman et al., (2001) indicated that about 11.6 PCAPs occurred each year from 1989-1999 based on the temperature difference between two meteorological sites. This study indicates that there are 11.75 PCAPs per year from 2002-2018 using the new method also based on meteorology (VHD_met) and 14.8 PCAPs per year using the Normalized VHD_met method. The number of PCAPs based on meteorology is consistent with past findings but using air quality to classify the PCAPs resulted in less events per year, an average of 6.1 and 8.4 PCAPs per year using VHD_17.5 and VHD_75, respectively.

S5.2 Great Falls CAP Events (TFX)

Great Falls, MT experienced the most PCAPs in this study from 2002-2018, with approximately 15.5 PCAPs occurring each year. One explanation for this, despite a lack of substantial downwind mountains, could be the continuous snow cover and intrusion of a polar continental airmass from Canada. All other locations, except Denver, are generally protected by the Rocky Mountains with respect to the polar continental airmass. The intrusion of polar continental airmasses could also explain the higher wind speed observed in Great Falls. Great Falls has the least number of soundings with a 10-m wind speed of 0 m s^{-1} and the greatest number of soundings with a 10-m wind speed over 3 m s^{-1}, 171 and 4,511 soundings, respectively.

S5.3 Salt Lake City CAP Events (SLC)

Whiteman et al., (2014) calculated a VHD threshold of 4.04 MJ m^{-2} from radiosondes during the time period of 1979-2010 using a $PM_{2.5}$ concentration of 17.5 µg m^{-3}. However, the overall $PM_{2.5}$ concentrations continue to change over time, with $PM_{2.5}$ concentrations in 2018 about 10% higher than in 2016 in the western U.S. (Clay and Muller 2019). Using the winter data from 2002-2018, a mean VHD for SLV based on a $PM_{2.5}$ concentration of 17.5 µg m^{-3}, was 7.49 MJ m^{-2}, much larger than the value from Whiteman et al., (2014). However, the new VHD_met threshold yields a value of 4.40 MJ m^{-2}, similar to Whiteman et al., (2014) threshold of 4.04 MJ m^{-2}. If air pollution concentrations decrease over time, the VHD threshold for each location would increase if the value is based on $PM_{2.5}$ concentrations, as discussed in Green et al., (2015).

S5.4 Medford CAP Events (MFR)

The Rogue Valley is confined between the Cascade Range to the east and the Oregon Coast Range to the west, creating a region effective for stagnation within the valley. Medford sounding data indicates that only 876 soundings have a 10-m wind speed of greater than 3 m s^{-1} over the entire period, out of a possible 5,800 soundings over the October to March 2002-2018 timeframe. Medford has the greatest number of deep stable layers when compared to other locations in this study. Synoptic patterns are predominantly similar for all locations, but topography varies from valley to valley. It appears that topography around Medford is favorable for deep stagnation near the surface and ridges, indicative by the number of DSLs.

S5.5 Salem CAP Events (SLE)

Salem is similar to the Rogue Valley with the Cascades to the east and Coast Range to the west, blocking most polar airmasses from reaching the valley. Salem is located in a favorable synoptic pattern for prolonged wet periods (farther north than Medford and upwind mountains are lower in elevation) during the winter months. As evidence, fewer soundings recorded calm winds, 825 soundings, an indicator of PCAPs. Average surface relative humidity is 80.3% throughout the study period and 994 soundings with a surface RH greater than 95%. The high relative humidity may be attributed to frequency of Pacific storms and PCAP frequency. There may be scenarios in Salem of which a PCAP develops after a prolonged period of precipitation.

S5.6 Quillayute CAP Events (QUI)

Quillayute has the lowest VHD threshold in our study and this is to be expected given the proximity to the Pacific Coast. However, an average of 9.7 PCAPs per year occur during the timeframe of the study, albeit less stability is required to reach such event than other locations. The number of PCAPs is consistent with other locations in this study. The Olympic Mountains are downwind which could be aid in CAP development during surface high pressure days. As expected, Quillayute experiences the highest relative humidity over the study period with an average RH of 85.6%. During PCAP events, the predominant wind direction is from the northeast, where the Olympic Mountains are located. Additionally, this drainage flow is common in mountainous valleys during PCAPs (Grand Junction for example), despite the vast synoptic differences Quillayute experiences.

S5.7 Boise CAP Events (BOI)

Boise, located in the Snake River Basin, is prone to CAP events because of the proximity to polar airmass intrusions and high elevation downwind mountains that promote stagnation. Boise often gets intrusions of marine airmasses due to the topography to the west, which may explain the average RH of 64.6%, despite being inland and away from the coast. PCAPs are also accompanied by higher RH values, possibly contributing to the RH. A dry polar airmass occurred 19.7% of the time from 1989-2004 in south-central Idaho, around Boise, the most prominent wintertime synoptic pattern for diurnal CAPs and PCAP events (Blandford et al., 2008). Boise experiences about 9.4 PCAP events per year with 75th percentile wintertime $PM_{2.5}$ concentrations of 12.2 μg m^{-3}.

S5.8 Reno CAP Events (REV)

Reno is in a small valley, within the Great Basin, that lies between the Sierra Nevada Mountains to the west and desert mountains to the east, a scenario favorable for downslope winds to form during landfalling coastal storms in the winter months. The low VHD values in Reno can be attributed to the land surface type, where Reno is an urban environment and a steppe climate. For example, locations in the southwestern U.S. have median PBL depths around 1200 m due to orographic influence, prevailing aridity and dryland ecosystems (Pal et al., 2016). Snow cover in the valley typically melts within days and even hours, where snow enhances CAP formation. The average RH during the study timeframe was 53.4%, the lowest among all locations, another possible indication of fewer PCAPs. For example, during PCAPs, the lower atmosphere tends to be more saturated due to cooler temperatures with higher wintertime RH in the lower valley indicative of a CAP event. The number of soundings with a 10-m wind speed with calm winds from the NWS in Reno (1,516 m MSL) are 571 compared to the ASOS station on the valley floor (1,342 m MSL) at 2,025 occurrences. It is important to note that the instruments are different at the two locations, but spatially are not so distant (i.e., less than 7 km apart).

S5.9 Elko CAP Events (LKN)

Elko is also located in the Great Basin and lies between two small mountain ranges that are parallel to each other with a SW-NE orientation. Elko experiences about 13.1 PCAPs per winter, higher than Reno, and has a lower occurrence of calm winds at 10 m, only 1262. Elko has a 10-m wind direction that is predominantly from the northeast during CAP events with the average RH of 75.5% during CAP events and an average surface temperature of -4.8°C, possibly indicating polar airmass intrusions and moist CAP events. Since Elko sits in NE Nevada, the influence of continental polar airmasses are more likely in Elko than Reno. This contributes to colder conditions during the wintertime at/near the surface and when combined with synoptic scale ridges, produces more PCAPs.

S5.10 Denver CAP Events (DNR)

Denver is located on the lee side of the Rocky Mountains with no downwind mountain range to promote frequent blocking. However, with polar cold fronts moving south out of Canada and pooling against the Rockies, blocking becomes favorable. The dominant wind direction during CAP events is from the south with an average RH of 71.1% and surface temperature of -1.96°C. Denver experiences 12.3 PCAPs on average per winter, despite the unfavorable PCAP topography (i.e., no downwind mountains). Continuous snow cover and polar airmass intrusions likely assist with CAP formation in Denver during the winter months.

S5.11 Riverton CAP Events (RIW)

Riverton is in Central Wyoming downwind of a high elevation mountain range and lacks substantial downwind mountains that could promote blocking. Riverton radiosondes are released above the river valley that Riverton lies in, by about 200 m. It is likely that Riverton itself experiences more CAP events, cooler temperatures, and slightly greater $PM_{2.5}$ concentrations than found in our study. For example, the vertical profile analysis done at Medford suggests that the VHD in Riverton is underestimated by as much as 2 MJ m^{-2}. Riverton is located well inland and to the east, experiencing polar airmasses which promote CAP events. Polar cold air near the surface combined with an incoming ridge, promotes strong temperature inversions, likely well below the radiosonde launch elevation. The 10-m wind speed at the Riverton NWS had calm winds for only 177 soundings, likely underestimating the true calm wind occurrences when compared to locations where radiosondes are released on the valley floor.

S5.12 Grand Junction CAP Events (GJT)

Grand Junction is in a small valley on the western side of Colorado and is characterized by large downwind mountains and typically has continuous snow cover surrounding the valley during winter months. During CAP events, 12Z soundings had an easterly dominant flow while

00Z soundings had a westerly dominant flow. In the early morning hours, drainage flow from the Rocky Mountains, an easterly wind, could be causing a flow reversal where the afternoon has a westerly predominant flow when weak thermals begin to develop with daytime heating.

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