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Sleet-less in Seattle: Exploring Atmospheric Measurement Through Analysis of Western Washington Cold Air Outbreaks

Abstract

Measurement of atmospheric quantities is difficult. Instruments must be well-calibrated, well-placed, and well-monitored to provide reliable observations over any given period. Here we have designed an experiment where 5 Davis Vantage Pro II weather stations were deployed around Seattle, WA, and recorded observations over a period of 6 weeks during the winter of 2022. Observations were statistically compared against a reference standard located at the University of Washington. To demonstrate the usefulness of such measurements, a cold air event induced by a regional phenomenon, Fraser River Valley flow, is discussed and time-series measurements from the Davis weather stations are shown to capture data from the event. Overall we find that measurement of temperature ($0.914 < r < 0.989$) and pressure ($0.997 < r < 1.000$) are well correlated amongst stations while measurements of wind speed ($0.361 < r < 0.880$), wind direction ($-0.348 < r < 0.683$), and precipitation ($0.076 < r < 0.703$) are much more variable.

Introduction

Atmospheric measurements are critical to many important aspects of our daily lives. Without accurate and meaningful measurements, our ability to understand the current state of the atmosphere is limited to qualitative observations that are of little use to weather prediction and tasks such as air quality monitoring. But measurement of meteorological data is a complicated process. Factors such as what quantities to measure, where to measure them from, and how reliable are such measurements must all be considered.

Quantities of interest to atmospheric scientists often include air temperature, air pressure, wind speed, wind direction, and precipitation.[1] With knowledge of these quantities and their change over time, one can understand the local thermodynamic state of the atmosphere and how local conditions might develop. On larger scales, measurements of such variables on the ground and at different levels of the atmosphere may be used to initialize weather models that can predict the state of the atmosphere at a future time.

Siting of meteorological instruments is of major importance. In particular, ground-based instruments are susceptible to ground heat and moisture fluxes, blocking of winds, and coverage by vegetation. Almost no location is perfect, and so in any situation, there is a tradeoff between getting the best data and realistically being able to collect the data. The reliability of measurements is greatly impacted by siting. Non-representative measurements may negatively impact the applications of collected data. Furthermore, the reliability of instruments themselves by means of calibration and relative uncertainty must be considered in the collection and analysis of observations.

To better understand the application of such measurements, we choose to analyze a recent cold air event that occurred near Seattle, WA, on 21 Feb. 2022 – 23 Feb. 2022. The event consisted of artic airflow through the Fraser River Valley that dramatically cooled the western Washington lowlands that promoted two separate snowfall events in a region where snowfall is notoriously difficult to forecast.[2]

The Fraser River Valley flow is a regional phenomenon characterized by arctic air trapped East of the Cascade Mountains in British Columbia being funneled through the Fraser River Valley due to a strong surface pressure gradient that induces fast Northeasterly flow (Figure 1). Weather data from Bellingham, WA, which is located at the outflow region of the Fraser River Valley, is useful for identifying when such flow is occurring. Because the cold, dry arctic air is not lifted over the mountains, it enters Western Washington at very low temperatures and such a flow is often a key ingredient for receiving lowland snow.[2]

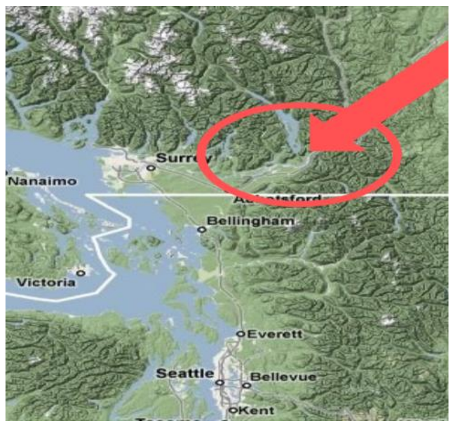

Figure 1) Illustration of Fraser River Valley flow.

In this paper, we discuss and compare the observations made by 5 locally placed weather stations and the University of Washington Atmospheric Science Departments' (UWATG) own roof-based weather station. Statistical analyses are conducted to compare station data against each other and to demonstrate the nuances of meteorological observation. We also seek to quantify the atmospheric state present during the recent cold air event and see how well the stations were able to observe changes during this period.

Methods

For this project, data were collected from 5 Davis Vantage Pro II weather stations. Additionally, data was retrieved from the UWATG rooftop weather station to serve as a reference standard to compare data against. Station 1 was located at 47.67N, 122.31W at an elevation of 60 meters above sea level and in a small yard surrounded by tall homes. Station 2 was located at 47.7N, 122.3W on the roof of an urban house. Station 3 was located at 47.68N, 122.33W in a small fenced-in yard near many plants and a fence. Stations 4 and 5 were located 10 feet apart on the roof of UWATG at an elevation of 61 meters above sea level.

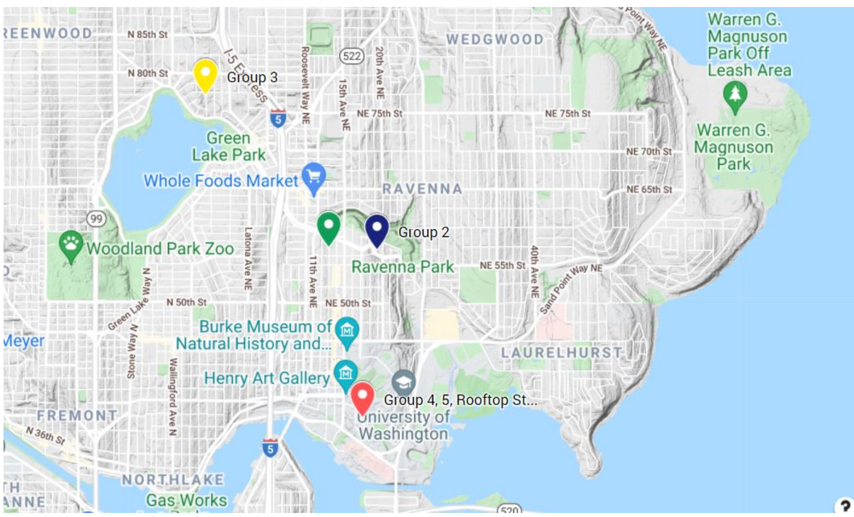

Figure 2) Map of weather station locations.

Temperature, rainfall, pressure, wind speed, and wind direction data were collected over a period of six weeks from 12 January 2022 to 23 February 2022. Various issues were encountered that limit the usability of data early in the observation period. Station 4 had an elevation error that led to excessively high pressure measurements. Various stations were unable to record data during the early period leading to a lack of measurements across stations. Station 3 and Station 5 both experienced intermittent data collection errors that led to periods of missing data in late January. Ultimately, all data prior to 01 February 2022 was omitted from the analysis due to many sources of incomplete and unreliable data. The observation period used in this paper is from 01 February 2022 to 23 February 2022, a period where all 6 stations had consistent data logging with correctable errors.

The Davis weather stations record wind directions in cardinal directions (North, North-Northeast, Northeast, etc.). To make meaningful comparisons, the wind directions were converted to degrees from North (0-359 degrees) in even intervals.

All analysis was completed using the Python programming language. Pearson correlation coefficients (Equation 1) were computed and used to produce correlation matrices (Tables 1-5). Additionally, Ordinary Least Squares (OLS) regression (Equation 2) was performed to compute gain bias, offset bias, and their associated errors (Tables 6-25).

$$r = \frac{\sum(x-\overline{x})(y-\overline{y})}{\sqrt{\sum(x-\overline{x})^2\sum(y-\overline{y})^2}}$$

$$\hat{\beta}_0 = \bar{y} - \hat{\beta}_1\bar{x};$$

$$\hat{\beta}_1 = \frac{\sum_{i=1}^{n}(x_i-\bar{x})(y_i-\bar{y})}{\sum_{i=1}^{n}(x_i-\bar{x})^2},$$

Equation 1) Pearson Correlation Coefficient

Equation 2) OLS Regression

Analysis of the cold air event focused primarily on time-series analysis of temperature and pressure. The goal of this was to see how well the Davis and UWATG stations recorded the event. Furthermore, wind and temperature data for Bellingham, WA made available from Time and Date are explored to correlate the change in Seattle weather conditions to this Fraser River Valley flow that occurs to the North.[5]

Results and Discussion

Correlation tables for temperature, pressure, wind speed, wind direction, and rain are presented in Tables 1-5, respectively. We observe from Table 1 that temperatures are well correlated across all stations ($0.914 < r < 0.989$). Groups 1 ($r = 0.918$) and 3 ($r = 0.914$) have the lowest correlation to the UWATG station. This is possibly because stations 1 and 3 are located in grassy areas more subject to ground effects. Table 2 indicates that pressures are very well correlated ($0.997 < r < 1.000$).

Wind speed correlations are shown in Table 3. We observe a large range of correlations ($0.361 < r < 0.880$). This may be in part due to the large spatial variability in winds near the ground and due to siting issues, recalling that stations 1 and 3 are located within a few feet of tall obstacles in an urban environment. Of particular interest is that Station 4 has stronger correlation ($r = 0.880$) with UWATG than station 5 ($r = 0.361$). This is possibly because Station 5 had intermittent data logging errors that are not readily detectable during analysis.

Wind directions (Table 4) ($-0.348 < r < 0.683$) are not meaningfully comparable given the limited range of measurements of the Davis instrument, spatial variability, siting issues, and data logging errors. A particular issue with the Davis wind vane is that it must be sighted with the vane facing magnetic North and this introduces another possible siting error. Precipitation (Table 5) ($0.076 < r < 0.703$) is also difficult to compare given the high spatial variability and siting errors. Of particular note are the Station 4 ($r = 0.507$) and Station 5 ($r = 0.076$) observations against UWATG. Given that these stations are all sited next to each other on a tall rooftop, we speculate that the variability may come from calibration, data logging, or measurement unit errors.

Tables for gain bias and error, and offset bias and error are presented in Tables 6-25. Of particular interest are the pressure gain bias and offset bias. All stations have gain biases near unity (0.988-1.007) indicating that all stations detect the same changes in pressure nearly perfectly, with respect to each other. Many stations had significant pressure offset biases (-6.632hPa – 12.536 hPa). This is possibly due to the elevation parameter on the Davis Vantage Pro II console since the console records pressure and may be at a different elevation than the station. Furthermore, accurately determining the elevation where the pressure is recorded may be challenging given the available tools to do so.

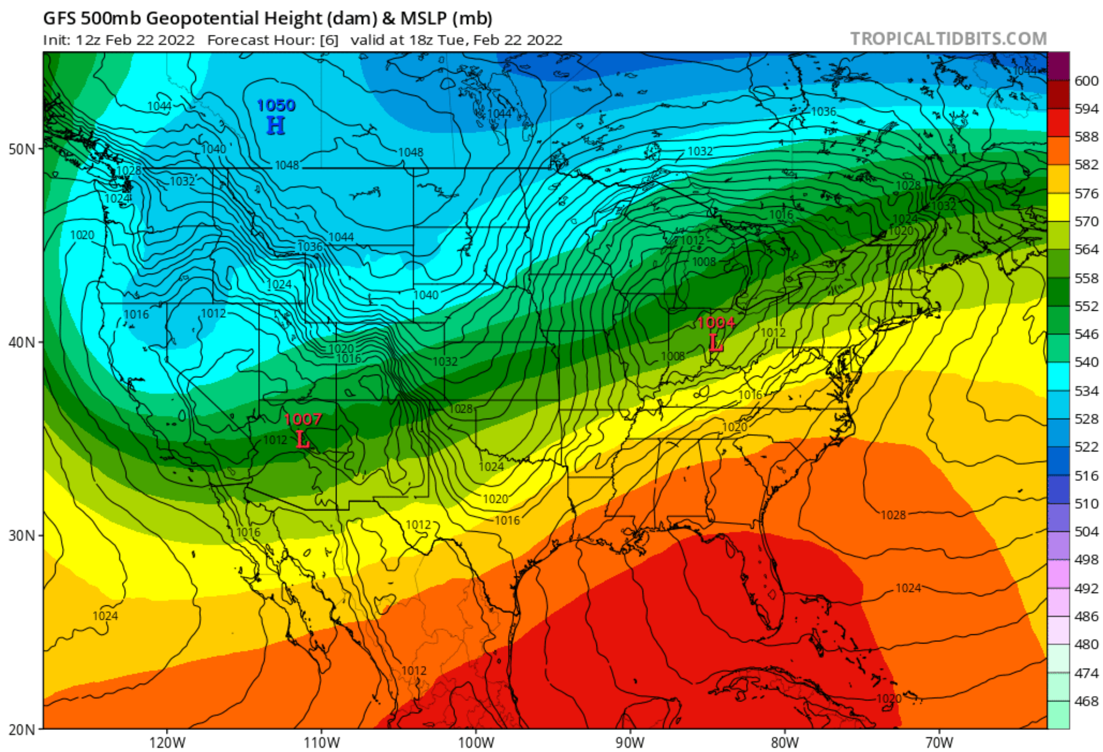

Figure 3) Forecasted 500 hPa heights and MSLP (hPa) for 22 Feb 2022.[3]

The 500 hPa height field and MSLP, shown in Figure 3, give a good synoptic overview of the region during the cold air event. We observe that a persistent trough coupled with a strong surface pressure gradient that induces low-level Northeasterly winds were present over Northwest Washington. This upper air setup is conducive to both precipitation and lower temperatures across Western Washington. Furthermore, the strong surface pressure gradient is the signature setup for Fraser River Valley cold airflow to occur.[2]

To see how well the stations observed the cold air event, time-series of temperature and pressure are shown in Figures 4 and 5. We see a clear drop in pressure that persists, associated with the upper-level trough, and dropping temperatures that follow. Snow was observed around the local area on the evening of 21 Feb. In the early morning of 23 Feb, a daily record low temperature of -5 Celsius was recorded at SeaTac Airport.[4] We observe that all stations approached this temperature and that Station 1 dropped below.

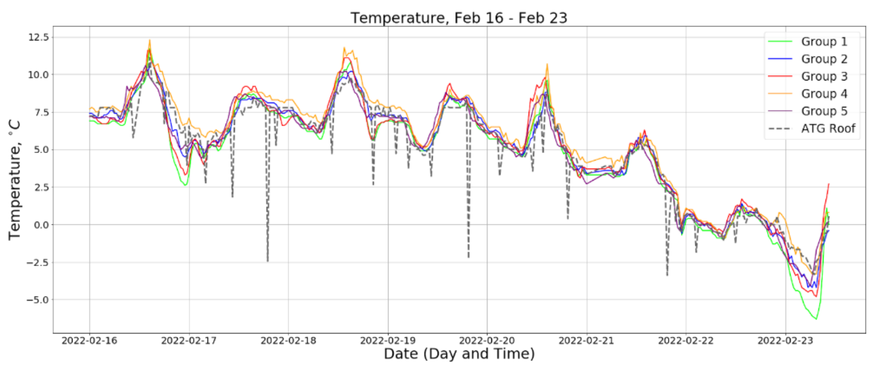

Figure 4) Temperature Time Series 16 Feb 22 – 23 Feb 22

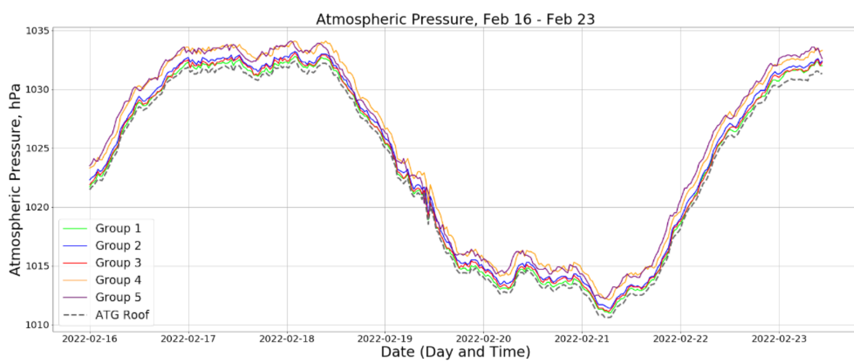

Figure 5) Pressure time series 16 Feb 22 – 23 Feb 22

The city of Bellingham, WA, experienced Northeasterly surface winds exceeding 11 m/s (Figure 6).[5] We also observe dropping temperatures associated with such winds. The time-series data augmented with the Bellingham weather data show that Fraser River Valley cold airflow can contribute to low temperatures across all the Western Washington lowlands. This enhancement to low temperatures is an important mechanism for receiving snow in the lowlands where the temperature is moderated by the Puget Sound and Lake Washington.

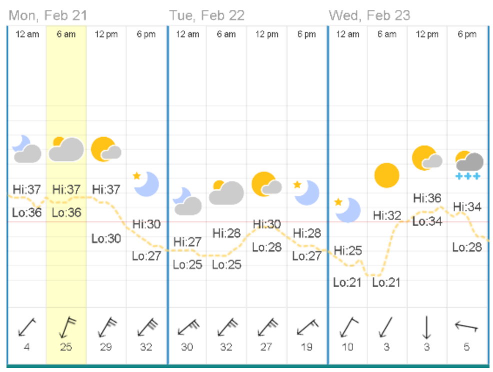

Figure 6) Bellingham, WA weather 21 Feb 22 – 23 Feb 23. Temperature (Degrees F), Wind Speed (mph).

Conclusions

Through this analysis, we have seen firsthand the challenges of atmospheric measurement. We saw that some quantities, such as pressure ($0.997 < r < 1.000$) and temperature ($0.914 < r < 0.989$), vary less across a local area and with a reasonably calibrated instrument can provide reliable information. We also saw that other quantities like wind speed ($0.361 < r < 0.880$), wind direction ($-0.348 < r < 0.683$), and precipitation ($0.076 < r < 0.703$) are much more variable and subject to siting errors. Siting of instrumentation is critical to making reliable wind and precipitation measurements. Sources of error such as obstructions, setup errors, and nearby vegetation can lead to measurements being non-representative.

Through a recent weather analysis, we examined how the Fraser River Valley flow can drastically reduce temperatures within just one day in Western Washington and how it is often a key ingredient in receiving low-level snow in the region, which was observed once during the analysis period and again the day after this period ended, 24 Feb 22. We showed that with reasonably affordable instruments one could observe these features so long as the instruments are sited reasonably.

Table 1) Correlation Table for Temperature (Degrees C)

	Group_1 Temperature	Group_2 Temperature	Group_3 Temperature	Group_4 Temperature	Group_5 Temperature	ATG_Roof Temperature
Group_1 Temperature	1.000000	0.986481	0.988946	0.963844	0.971708	0.917853
Group_2 Temperature	0.986481	1.000000	0.979868	0.986901	0.982356	0.948482
Group_3 Temperature	0.988946	0.979868	1.000000	0.959000	0.978967	0.914432
Group_4 Temperature	0.963844	0.986901	0.959000	1.000000	0.971178	0.957891
Group_5 Temperature	0.971708	0.982356	0.978967	0.971178	1.000000	0.933192
ATG_Roof Temperature	0.917853	0.948482	0.914432	0.957891	0.933192	1.000000

Table 2) Correlation Table for Pressure (hPa)

	Group_1 Pressure	Group_2 Pressure	Group_3 Pressure	Group_4 Pressure	Group_5 Pressure	ATG_Roof Pressure
Group_1 Pressure	1.000000	0.999931	0.999785	0.999568	0.997722	0.999867
Group_2 Pressure	0.999931	1.000000	0.999789	0.999569	0.997751	0.999879
Group_3 Pressure	0.999785	0.999789	1.000000	0.999408	0.997561	0.999788
Group_4 Pressure	0.999568	0.999569	0.999408	1.000000	0.997150	0.999510
Group_5 Pressure	0.997722	0.997751	0.997561	0.997150	1.000000	0.997929
ATG_Roof Pressure	0.999867	0.999879	0.999788	0.999510	0.997929	1.000000

Table 3) Correlation Table for Wind Speed (m/s)

	Group_1 Wind Speed	Group_2 Wind Speed	Group_3 Wind Speed	Group_4 Wind Speed	Group_5 Wind Speed	ATG_Roof Wind Speed
Group_1 Wind Speed	1.000000	0.671625	0.765404	0.601835	0.663800	0.514414
Group_2 Wind Speed	0.671625	1.000000	0.738672	0.698863	0.492459	0.691959
Group_3 Wind Speed	0.765404	0.738672	1.000000	0.619956	0.590907	0.580786
Group_4 Wind Speed	0.601835	0.698863	0.619956	1.000000	0.455163	0.879663
Group_5 Wind Speed	0.663800	0.492459	0.590907	0.455163	1.000000	0.361229
ATG_Roof Wind Speed	0.514414	0.691959	0.580786	0.879663	0.361229	1.000000

Table 4) Correlation Table for Wind Direction (Degrees from North)

	Group_1 Wind Direction	Group_2 Wind Direction	Group_3 Wind Direction	Group_4 Wind Direction	Group_5 Wind Direction	ATG_Roof Wind Direction
Group_1 Wind Direction	1.000000	0.195692	0.369174	0.601679	-0.347609	0.581823
Group_2 Wind Direction	0.195692	1.000000	0.272277	0.093885	-0.113544	0.199801
Group_3 Wind Direction	0.369174	0.272277	1.000000	0.357038	-0.243900	0.401089
Group_4 Wind Direction	0.601679	0.093885	0.357038	1.000000	-0.278827	0.682606
Group_5 Wind Direction	-0.347609	-0.113544	-0.243900	-0.278827	1.000000	-0.329687
ATG_Roof Wind Direction	0.581823	0.199801	0.401089	0.682606	-0.329687	1.000000

Table 5) Correlation Table for Precipitation (mm)

	Group_1 Rain	Group_2 Rain	Group_3 Rain	Group_4 Rain	Group_5 Rain	ATG_Roof Rain
Group_1 Rain	1.000000	0.703221	0.633239	0.446693	0.110900	0.532797
Group_2 Rain	0.703221	1.000000	0.629121	0.601485	0.203324	0.460129
Group_3 Rain	0.633239	0.629121	1.000000	0.477633	0.193065	0.470265
Group_4 Rain	0.446693	0.601485	0.477633	1.000000	0.126071	0.506841
Group_5 Rain	0.110900	0.203324	0.193065	0.126071	1.000000	0.075605
ATG_Roof Rain	0.532797	0.460129	0.470265	0.506841	0.075605	1.000000

Table 6) Temperature Gain Bias (Unitless)

	Group_1 Temperature	Group_2 Temperature	Group_3 Temperature	Group_4 Temperature	Group_5 Temperature	ATG_Roof Temperature
Group_1 Temperature	1.000000	0.925516	0.961500	0.890756	0.877222	0.849470
Group_2 Temperature	1.051462	1.000000	1.015428	0.972143	0.945252	0.935641
Group_3 Temperature	1.017175	0.945553	1.000000	0.911578	0.909002	0.870462
Group_4 Temperature	1.042929	1.001882	1.008890	1.000000	0.948682	0.959266
Group_5 Temperature	1.076370	1.020916	1.054316	0.994208	1.000000	0.956692
ATG_Roof Temperature	0.991740	0.961500	0.960624	0.956517	0.910270	1.000000

Table 7) Temperature Gain Bias Error (Unitless)

	Group_1 Temperature	Group_2 Temperature	Group_3 Temperature	Group_4 Temperature	Group_5 Temperature	ATG_Roof Temperature
Group_1 Temperature	0.000000	0.005512	0.005168	0.008829	0.007644	0.013170
Group_2 Temperature	0.006262	0.000000	0.007417	0.005697	0.006452	0.011205
Group_3 Temperature	0.005468	0.006907	0.000000	0.009658	0.006792	0.013813
Group_4 Temperature	0.010337	0.005872	0.010689	0.000000	0.008348	0.010309
Group_5 Temperature	0.009380	0.006968	0.007877	0.008748	0.000000	0.013209
ATG_Roof Temperature	0.015376	0.011515	0.015244	0.010280	0.012568	0.000000

Table 8) Temperature Offset Bias (Degrees C)

	Group_1 Temperature	Group_2 Temperature	Group_3 Temperature	Group_4 Temperature	Group_5 Temperature	ATG_Roof Temperature
Group_1 Temperature	0.000000	0.867105	0.644070	1.720242	1.071816	1.319903
Group_2 Temperature	-0.760422	0.000000	-0.114118	0.826705	0.265570	0.415747
Group_3 Temperature	-0.531259	0.350318	0.000000	1.213540	0.504473	0.829808
Group_4 Temperature	-1.394029	-0.669972	-0.737486	0.000000	-0.378851	-0.358447
Group_5 Temperature	-0.839366	-0.058406	-0.279574	0.759518	0.000000	0.352190
ATG_Roof Temperature	-0.421341	0.210749	0.195809	0.898463	0.456174	0.000000

Table 9) Temperature Offset Bias Error (Degrees C)

	Group_1 Temperature	Group_2 Temperature	Group_3 Temperature	Group_4 Temperature	Group_5 Temperature	ATG_Roof Temperature
Group_1 Temperature	0.000000	0.036672	0.034386	0.058740	0.050859	0.087623
Group_2 Temperature	0.043389	0.000000	0.051394	0.039476	0.044702	0.077637
Group_3 Temperature	0.038107	0.048139	0.000000	0.067313	0.047335	0.096269
Group_4 Temperature	0.077430	0.043982	0.080066	0.000000	0.062526	0.077219
Group_5 Temperature	0.063876	0.047453	0.053645	0.059574	0.000000	0.089951
ATG_Roof Temperature	0.106535	0.079783	0.105618	0.071224	0.087079	0.000000

Table 10) Pressure Gain Bias (Unitless)

	Group_1 Pressure	Group_2 Pressure	Group_3 Pressure	Group_4 Pressure	Group_5 Pressure	ATG_Roof Pressure
Group_1 Pressure	1.000000	0.998551	1.003961	1.004343	0.993099	0.997388
Group_2 Pressure	1.001313	1.000000	1.005354	1.005732	0.994501	0.998779
Group_3 Pressure	0.995625	0.994255	1.000000	1.000004	0.988808	0.993159
Group_4 Pressure	0.994816	0.993444	0.998812	1.000000	0.987811	0.992291
Group_5 Pressure	1.002367	1.001012	1.006392	1.006578	1.000000	1.000089
ATG_Roof Pressure	1.002353	1.000981	1.006460	1.006780	0.995774	1.000000

Table 11) Pressure Gain Bias Error (Unitless)

	Group_1 Pressure	Group_2 Pressure	Group_3 Pressure	Group_4 Pressure	Group_5 Pressure	ATG_Roof Pressure
Group_1 Pressure	0.000000	0.000353	0.000628	0.000889	0.002023	0.000489
Group_2 Pressure	0.000354	0.000000	0.000622	0.000890	0.002012	0.000467
Group_3 Pressure	0.000623	0.000615	0.000000	0.001037	0.002084	0.000617
Group_4 Pressure	0.000881	0.000879	0.001036	0.000000	0.002251	0.000937
Group_5 Pressure	0.002041	0.002026	0.002121	0.002294	0.000000	0.001942
ATG_Roof Pressure	0.000492	0.000468	0.000625	0.000950	0.001934	0.000000

Table 12) Pressure Offset Bias (hPa)

	Group_1 Pressure	Group_2 Pressure	Group_3 Pressure	Group_4 Pressure	Group_5 Pressure	ATG_Roof Pressure
Group_1 Pressure	0.000000	1.910063	-3.875968	-3.097187	8.319608	2.287049
Group_2 Pressure	-1.771182	0.000000	-5.730106	-4.947858	6.460732	0.437496
Group_3 Pressure	4.301641	6.130387	0.000000	1.166992	12.536447	6.438984
Group_4 Pressure	3.967553	5.800883	0.051161	0.000000	12.403709	6.168878
Group_5 Pressure	-3.665525	-1.850801	-7.612168	-6.631990	0.000000	-1.718208
ATG_Roof Pressure	-2.019935	-0.190059	-6.044151	-5.202226	5.966364	0.000000

Table 13) Pressure Offset Bias Error (hPa)

	Group_1 Pressure	Group_2 Pressure	Group_3 Pressure	Group_4 Pressure	Group_5 Pressure	ATG_Roof Pressure
Group_1 Pressure	0.000000	0.362529	0.645007	0.913319	2.077542	0.502729
Group_2 Pressure	0.363681	0.000000	0.639111	0.914275	2.068046	0.480233
Group_3 Pressure	0.639772	0.631915	0.000000	1.065704	2.141031	0.633639
Group_4 Pressure	0.905857	0.903932	1.065647	0.000000	2.315449	0.963179
Group_5 Pressure	2.099444	2.083227	2.181308	2.359133	0.000000	1.997115
ATG_Roof Pressure	0.505037	0.480909	0.641757	0.975570	1.985353	0.000000

Table 14) Wind Speed Gain Bias (Unitless)

	Group_1 Wind Speed	Group_2 Wind Speed	Group_3 Wind Speed	Group_4 Wind Speed	Group_5 Wind Speed	ATG_Roof Wind Speed
Group_1 Wind Speed	1.000000	2.445960	0.670160	1.818948	0.608889	1.955730
Group_2 Wind Speed	0.184418	1.000000	0.177589	0.579979	0.124036	0.722359
Group_3 Wind Speed	0.874184	3.072464	1.000000	2.140011	0.619061	2.521877
Group_4 Wind Speed	0.199129	0.842117	0.179600	1.000000	0.138142	1.106545
Group_5 Wind Speed	0.723662	1.955202	0.564035	1.499715	1.000000	1.497189
ATG_Roof Wind Speed	0.135306	0.662838	0.133754	0.699300	0.087154	1.000000

Table 15) Wind Speed Gain Bias Error (Unitless)

	Group_1 Wind Speed	Group_2 Wind Speed	Group_3 Wind Speed	Group_4 Wind Speed	Group_5 Wind Speed	ATG_Roof Wind Speed
Group_1 Wind Speed	0.000000	0.081281	0.016974	0.072710	0.020666	0.098211
Group_2 Wind Speed	0.006128	0.000000	0.004882	0.017881	0.006603	0.022703
Group_3 Wind Speed	0.022141	0.084459	0.000000	0.081589	0.025460	0.106481
Group_4 Wind Speed	0.007960	0.025963	0.006847	0.000000	0.008141	0.018022
Group_5 Wind Speed	0.024562	0.104092	0.023197	0.088377	0.000000	0.116424
ATG_Roof Wind Speed	0.006795	0.020832	0.005647	0.011389	0.006777	0.000000

Table 16) Wind Speed Offset Bias (m/s)

	Group_1 Wind Speed	Group_2 Wind Speed	Group_3 Wind Speed	Group_4 Wind Speed	Group_5 Wind Speed	ATG_Roof Wind Speed
Group_1 Wind Speed	0.000000	0.627282	0.062374	0.919336	0.040914	3.325062
Group_2 Wind Speed	-0.023616	0.000000	-0.009479	0.622671	0.014347	2.903616
Group_3 Wind Speed	0.014937	0.500536	0.000000	0.850394	0.034842	3.212322
Group_4 Wind Speed	-0.076094	0.006425	-0.045130	0.000000	-0.026105	2.298213
Group_5 Wind Speed	0.064210	0.757854	0.094096	1.009896	0.000000	3.438925
ATG_Roof Wind Speed	-0.326562	-1.383878	-0.313841	-1.330187	-0.175343	0.000000

Table 17) Wind Speed Offset Bias Error (m/s)

	Group_1 Wind Speed	Group_2 Wind Speed	Group_3 Wind Speed	Group_4 Wind Speed	Group_5 Wind Speed	ATG_Roof Wind Speed
Group_1 Wind Speed	0.000000	0.030191	0.006305	0.027007	0.007676	0.036479
Group_2 Wind Speed	0.009754	0.000000	0.007770	0.028459	0.010510	0.036134
Group_3 Wind Speed	0.007500	0.028610	0.000000	0.027638	0.008624	0.036070
Group_4 Wind Speed	0.012592	0.041071	0.010832	0.000000	0.012878	0.028509
Group_5 Wind Speed	0.008252	0.034972	0.007793	0.029692	0.000000	0.039115
ATG_Roof Wind Speed	0.026256	0.080501	0.021823	0.044011	0.026189	0.000000

Table 18) Wind Direction Gain Bias (Unitless)

	Group_1 Wind Direction	Group_2 Wind Direction	Group_3 Wind Direction	Group_4 Wind Direction	Group_5 Wind Direction	ATG_Roof Wind Direction
Group_1 Wind Direction	1.000000	0.212596	0.392008	0.653253	-0.283204	0.496559
Group_2 Wind Direction	0.180133	1.000000	0.266131	0.093828	-0.085152	0.156964
Group_3 Wind Direction	0.347670	0.278566	1.000000	0.365062	-0.187135	0.322371
Group_4 Wind Direction	0.554177	0.093942	0.349190	1.000000	-0.209231	0.536579
Group_5 Wind Direction	-0.426660	-0.151404	-0.317882	-0.371572	1.000000	-0.345361
ATG_Roof Wind Direction	0.681728	0.254331	0.499028	0.868374	-0.314725	1.000000

Table 19) Wind Direction Gain Bias Error (Unitless)

	Group_1 Wind Direction	Group_2 Wind Direction	Group_3 Wind Direction	Group_4 Wind Direction	Group_5 Wind Direction	ATG_Roof Wind Direction
Group_1 Wind Direction	0.000000	0.049727	0.046062	0.040478	0.035657	0.032399
Group_2 Wind Direction	0.042134	0.000000	0.043899	0.046442	0.034778	0.035929
Group_3 Wind Direction	0.040852	0.045950	0.000000	0.044580	0.034731	0.034366
Group_4 Wind Direction	0.034339	0.046498	0.042641	0.000000	0.033636	0.026813
Group_5 Wind Direction	0.053718	0.061837	0.058997	0.059735	0.000000	0.046161
ATG_Roof Wind Direction	0.044481	0.058217	0.053198	0.043393	0.042066	0.000000

Table 20) Wind Direction Offset Bias Error (Degrees from North)

	Group_1 Wind Direction	Group_2 Wind Direction	Group_3 Wind Direction	Group_4 Wind Direction	Group_5 Wind Direction	ATG_Roof Wind Direction
Group_1 Wind Direction	0.000000	111.090555	118.674752	56.084237	214.997230	89.321955
Group_2 Wind Direction	193.225577	0.000000	163.484335	186.082461	165.676498	174.586868
Group_3 Wind Direction	150.249030	100.957508	0.000000	125.874171	190.676887	133.145403
Group_4 Wind Direction	110.377763	139.353337	135.431629	0.000000	194.243607	91.608833
Group_5 Wind Direction	286.666805	181.273069	253.976609	257.483040	0.000000	251.988088
ATG_Roof Wind Direction	85.775684	107.509537	106.076365	27.755028	214.966371	0.000000

Table 21) Wind Direction Offset Bias (Degrees from North)

	Group_1 Wind Direction	Group_2 Wind Direction	Group_3 Wind Direction	Group_4 Wind Direction	Group_5 Wind Direction	ATG_Roof Wind Direction
Group_1 Wind Direction	0.000000	12.112849	11.220014	9.859750	8.685400	7.891949
Group_2 Wind Direction	8.109039	0.000000	8.448635	8.938047	6.693288	6.914843
Group_3 Wind Direction	9.469972	10.651697	0.000000	10.334033	8.051109	7.966341
Group_4 Wind Direction	7.857541	10.639968	9.757427	0.000000	7.696917	6.135544
Group_5 Wind Direction	9.291334	10.695589	10.204428	10.331998	0.000000	7.984280
ATG_Roof Wind Direction	9.661414	12.644909	11.554735	9.425161	9.137007	0.000000

Table 22) Precipitation Gain Bias (Unitless)

	Group_1 Rain	Group_2 Rain	Group_3 Rain	Group_4 Rain	Group_5 Rain	ATG_Roof Rain
Group_1 Rain	1.000000	0.032238	1.505627	0.404945	0.100536	0.051758
Group_2 Rain	15.339571	1.000000	32.629106	11.894132	4.020645	0.975034
Group_3 Rain	0.266329	0.012130	1.000000	0.182109	0.073611	0.019214
Group_4 Rain	0.492745	0.030417	1.252727	1.000000	0.126071	0.054313
Group_5 Rain	0.122334	0.010282	0.506367	0.126071	1.000000	0.008102
ATG_Roof Rain	5.484571	0.217140	11.509935	4.729770	0.705539	1.000000

Table 23) Precipitation Gain Bias Error (Unitless)

	Group_1 Rain	Group_2 Rain	Group_3 Rain	Group_4 Rain	Group_5 Rain	ATG_Roof Rain
Group_1 Rain	0.000000	0.000982	0.055434	0.024432	0.027140	0.002476
Group_2 Rain	0.467178	0.000000	1.214430	0.475884	0.583243	0.056675
Group_3 Rain	0.009806	0.000452	0.000000	0.010091	0.011269	0.001086
Group_4 Rain	0.029730	0.001217	0.069413	0.000000	0.029883	0.002783
Group_5 Rain	0.033024	0.001491	0.077522	0.029883	0.000000	0.003219
ATG_Roof Rain	0.262413	0.012622	0.650679	0.242328	0.280306	0.000000

Table 24) Precipitation Offset Bias (mm)

	Group_1 Rain	Group_2 Rain	Group_3 Rain	Group_4 Rain	Group_5 Rain	ATG_Roof Rain
Group_1 Rain	0.000000	0.000060	0.009248	0.001897	0.003210	0.000307
Group_2 Rain	0.001262	0.000000	0.009251	0.001278	0.002844	0.000337
Group_3 Rain	0.000120	0.000008	0.000000	0.000777	0.002485	0.000228
Group_4 Rain	0.002517	0.000088	0.011177	0.000000	0.003184	0.000333
Group_5 Rain	0.003867	0.000161	0.013896	0.003184	0.000000	0.000501
ATG_Roof Rain	0.001402	0.000084	0.009632	0.001133	0.003269	0.000000

Table 25) Precipitation Offset Bias Error (mm)

	Group_1 Rain	Group_2 Rain	Group_3 Rain	Group_4 Rain	Group_5 Rain	ATG_Roof Rain
Group_1 Rain	0.000000	0.000039	0.002181	0.000962	0.001068	0.000097
Group_2 Rain	0.000843	0.000000	0.002191	0.000859	0.001052	0.000102
Group_3 Rain	0.000925	0.000043	0.000000	0.000952	0.001063	0.000102
Group_4 Rain	0.001060	0.000043	0.002474	0.000000	0.001065	0.000099
Group_5 Rain	0.001177	0.000053	0.002763	0.001065	0.000000	0.000115
ATG_Roof Rain	0.001007	0.000048	0.002496	0.000930	0.001075	0.000000

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