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Evaluating the Impact of Land Cover and Topography on Meteorological Parameters' Relations and Similarities in the Alberta Oil Sands Region

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Abstract: Herein, the focus was on the identification of similarities in the weather parameters collected within 19 stations, consisting of 3 weather networks located in the Lower Athabasca River Basin operated under the Oil Sands Monitoring program. These stations were then categorised into seven distinct groups based on comparable topography and land cover. With regard to weather parameters, these were air temperature (AT), precipitation (PR), relative humidity (RH), solar radiation (SR), atmospheric/barometric pressure (BP), snowfall depth (SD), and wind speed/direction (WSD). For all seven groups, relational analysis was conducted for every station pair using Pearson's coefficient (r) and average absolute error (AAE), except for wind direction and wind speed. Similarity analysis was also performed for each station pair across all seven groups using percentage of similarity (PS) measures. Our similarity analysis revealed that there were no similarities (i.e., PS value < 75%) for: (i) SR, PR, and WSD for all groups; (ii) AT for all groups except group G3; (iii) RH for group G7; and (iv) BP for group G1. This study could potentially be decisive in optimizing or rationalising existing weather networks. Furthermore, it could be constructive in the development of meteorological prediction models for any place and that requires input from surrounding stations.

Keywords: Athabasca River Basin; network optimization; redundancy analysis; weather parameters

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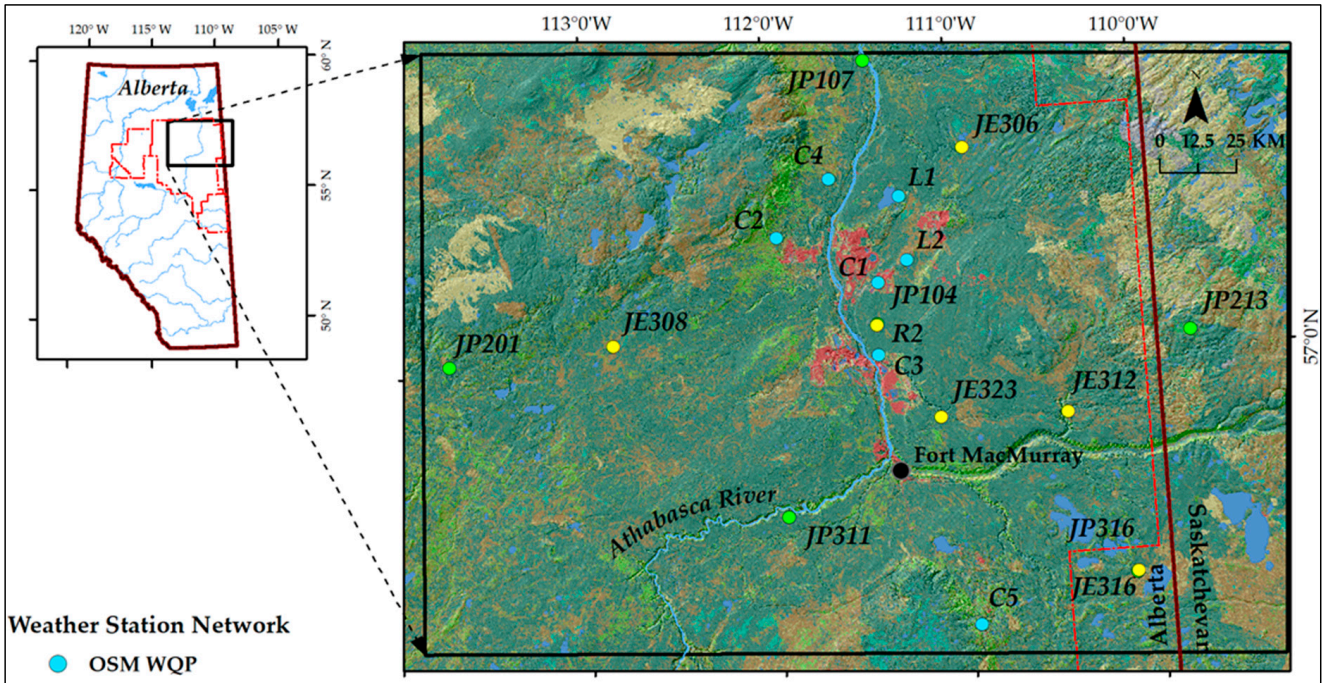
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1. Introduction

Meteorology/weather refers to the comprehension of the atmospheric state/condition at a finer temporal scale. Such conditions can be defined as a function of several meteorological parameters comprising air temperature (AT), precipitation (PR), relative humidity (RH), solar radiation (SR), atmospheric/barometric pressure (BP), snowfall/snow depth (SD), and wind speed and direction(WSD) [1]. In fact, these parameters regulate and affect the functioning of human activities on a daily basis, including work performance, and social and mental behaviors [2]. In general, weather parameters vary at various short temporal scales, i.e., minute, hour, and day, and at seasonal scales. Their measurements are needed for planning and maintaining human activities and the functioning of the ecosystem. For instance, minute-to-minute measurements are needed for scheduling and maintaining aviation operations [1] and broadcasting weather related warnings, e.g., snowstorms, hurricanes, and cyclones that could cause loss of life and the destruction of properties and infrastructures [3,4]. Hourly, daily and seasonal records of weather parameters are also needed for understanding agricultural activities [5,6]; public and environmental services [7–9]; hydrological and water resources analysis [10]; atmospheric circulation [11]; mass and energy balances [12]; and renewable energy potentials [12,13], etc. On the other hand, long-term records of weather (more than 30 years) are required for the comprehension of climate change, trend analysis, and the prediction of extreme weather events, etc.

Consequently, it is critical to have a properly designed meteorological station network in an area of interest because it may be useful in detecting variation in weather conditions and uncertainty in measurements. Additionally, it ensures adequate representation of the landscape dynamics, and helps to avoid redundancy in observation.

In the design of a weather station network in a region, the World Meteorological Organization (WMO) suggested several rules. For instance, two stations should be placed within 250 and 300 km horizontally in inhabited and uninhabited zones, respectively [14]. The frequency of recording parameters depends on the application, such as minute-to-minute for air navigation, and hour-to-hour for agricultural crops, etc. [15]. As for the density of stations for predicting weather, a minimum of one station is needed over an area of 100, 2500, and 10,000 km^2 for regional, global, and numerical weather prediction models, respectively [16]. In Canada, an oil sands enriched reserve known as the Alberta Oil Sands Area (which possesses the fourth largest oil reserve at global level [17]) comprises about 140,000 km^2 area [18,19], and accounts for 79 meteorological stations operated by various agencies. Among them, 19 stations were operational under the Oil Sands Monitoring (OSM) program in the scope of 3 networks. Specifically, (i) OSM Water Quantity Program (WQP) that contains seven stations known as C1, C2, C3, C4, C5, L1 and L2; (ii) Wood Buffalo Environmental Association (WBEA) Edge Sites (ES) which contains six stations known as JE323, JE316, JE312, JE308, JE306, and R2; and (iii) WBEA Meteorological Towers (MT) which contains six stations known as JP316, JP311, JP213, JP201, JP107, and JP104 [20,21] (see Figure 1). From the distribution of the three networks, it seems apparent that they had overlapped with each other and close spaced, for example JP316 and JE316. In fact, in the scope of our recent articles [22,23], we evaluated the weather parameter-specific similarities/redundancies within each individual network of OSM WQP, WBEA ES, and WBEA MT. We observed some level of similarity in the case of each parameter except for combined WSD. However, these studies did not evaluate the parameter-specific similarities among the networks, which might be important due to several reasons. Firstly, some stations were placed close to each other. Secondly, they might measure the parameters by considering similar landscape characteristics in terms of topography, land cover, and river valley conditions (i.e., within the valley or outside of a valley). In fact, literature showed that the characteristics of the surroundings of the weather stations and their recorded weather parameters were interlinked and pose significant influence [24–26]. For example, topography and valley conditions around the weather station often influence AT and PR [24–26], and wind parameters [27,28]. The land cover types have influences on incident solar radiation, sensible heat flux, and surface/soil moisture, which further affect the overall regional climatic conditions [24,29–33]. In addition, the accurate and finer input of types of land use and the varying topography is demonstrably necessary in weather prediction models for the accurate prediction of meteorological parameters [34]. Moreover, the optimum design of weather networks is often required accurate representation of types of land use and varying topography (elevation zones and terrain slopes) in order to provide adequate observations for the accurate analysis of results [35–38]. Additionally, the presence of a lake around a weather station has an impact on its surrounding conditions that affects weather parameters such as AT, RH, and wind, in comparison to stations away from the lake and located in the same region [39]. Thus, categorizing these 19 stations based on topography and land cover is expectedly important, as is the analysis of the similarities/redundancies for each of the weather parameters within the groups.



Categorization of the weather station based on land cover and topography

Group	Station	Distance from Landcover		River Valley
		Forest	Waterbody	
G1	C1, C4, and JE323	Coniferous (< 500 m away)	≥10 km	Athabasca Valley
G2	JP316 and JE316	Coniferous (< 500 m away)	≤10 km	No Valley
G3	C3, JP104, JP107, JP311, and JE306	Coniferous (< 500 m away)	≤10 km	Athabasca Valley
G4	C5, JP201, and JP213	Coniferous (> 500 m away)	≥10 km	No Valley
G5	L1, L2, R2, and JE306	Shrubland (< 500 m away)	≤10 km	Athabasca Valley
G6	C2, C4, and JE323	Broadleaf (< 500 m away)	≥10 km	Athabasca Valley
G7	JE308* and JE312**	Station without any similarities in land cover and valley		

* For JE308: Shrubland (< 500 m away), water body (≥ 10 km), and no valley.

** For JE312: Coniferous (< 500 m away), water body (≥ 10 km), and clearwater valley.

Figure 1. Location of stations belonging to different groups based on topographical features and networks that are being considered for analysis.

Here, our overall aim was to evaluate the similarities/redundancies in the weather parameters among the three weather networks operating under the OSM program based on land cover and topography. To achieve this, we identified two specific objectives. Firstly, we attempted to find relationships using Pearson's coefficient (r) and average absolute error (AAE) for all the weather parameters except WD and WS. In addition, r-values and AAE were estimated for each of the station pairs within seven individual groups. These groups were defined as a function of land cover and topography (see Figure 1). Notably, the measures r and AAE were found to be the best representative index in determining the relations between the parameters of interest in our earlier studies mentioned above [22,23]. Note that, it is documented that 'r' is a widely used statistical measure quantifying strength and

direction between two variables [40,41]. Furthermore, AAE is a natural simplistic measure to calculate the error between two datasets compared to the highly used root mean squared error (RMSE) [10,42]. Secondly, we applied the percentage of similarity (PS) to evaluate the likeliness between the station pairs for each of the parameters within the individual groups, where the same index was also implemented in our earlier studies [22,23]. This analysis led us to determine the required stations within each individual group.

2. Study Area and Data Availability

Our study area is in Northern Alberta, Canada, i.e., between longitude 109° W and 114° W, and latitude 56° N and 58° N (see Figure 1). It is known as the lower Athabasca River Basin (ARB), which holds a significant portion of the Athabasca oil sands area. Here, the 19 weather stations, operational under OSM WQP, WBEA ES, and WBEA MT, were further categorized into 7 groups (G1 to G7) considering their likenesses in topographical features, i.e., land use, distance from the waterbody, and river valley (see Figure 1). In the case of elevation of these groups, they are variable in the range of the mean sea level (i) 295 to 443 m for G1, (ii) 487–489 m msl for G2, (iii) 299 to 462 m for G3, (iv) 557–626 m for G4, (v) 294–335 m for G5, (vi) 295–443 m for G6, and (viii) 486–520 m for G7.

Through the study area, the Athabasca River flows from the mountain floodplain and meets the Clearwater River at Fort MacMurray, and travels in the northern direction. The study area exhibits dominantly boreal forests and poorly-drained wetlands [43]. In the case of climate, it experiences subarctic climate [44], i.e., short and wet summer, long and cold winter, and short fall and spring seasons. For the region, the average annual AT varies in the range of 0.7 to 1 °C and the annual total PR is in the range of 376 to 456 mm, where July is the wettest month and the driest months extend between November and April [43]. In addition, the study area experiences an annual average wind speed of 9.6 km/h, whereas the lowest and highest magnitudes of 8.8 km/h were observed in winter and 10.7 km/h were recorded in spring, respectively [45].

Table 1 describes the details of the data availability for analysis. The measurement units for the parameters were °C for AT, % for RH, W/m^2 for SR, kPa for BP, mm for PR, cm for SD, and km/h and ° for combined WSD. Notably, the OSM WQP stations (C1 to C5, L1 to L2) measure all the parameters at 2 m height on a daily scale with an exception for WSD at 10 m height. In the case of WBEA MT stations (i.e., JPs), they measure parameters at 2, 16, 21, and 29 m height on an hourly scale. Whereas WBEA ES stations (i.e., JEs and R2) measure at 2 m height on an hourly scale. For comparison between an OSM WQP station and a WBEA one, all the measurements were converted into a daily scale, while in all other cases both the time scale and height were considered at the same level.

Table 1. A brief description of the available data records for each of the seven groups (as illustrated in Figure 1) used in this study.

Group	Station Pair	Comparison		Common Meteorological Parameter	Common Data Period	
		Height (m)	Scale		From	To
G1	C1 vs. C4	2 and 10 *	daily	AT, RH, SR, PR SD, and WSD	25-July-2011	31-March-2017
	C1 vs. JE323	2	daily	AT, RH, and SR	15-March-2014	31-March-2017
	C4 vs. JE323			AT, RH, SR, and BP	15-March-2014	31-March-2017
G2	JP316 vs. JE316	2	hourly	AT, RH, SR, and WSD	11-April-2014	01-April-2018
G3	C3 vs. JE306	2	daily	AT, RH, SR, and BP	25-March-2014	31-March-2017
	C3 vs. JP104			AT, RH, and SR	30-May-2014	31-March-2017
	C3 vs. JP107			AT, RH, SR, and PR	29-August-2012	31-March-2017
	C3 vs. JP311			AT, RH, SR, and PR	30-May-2014	31-March-2017
	JP 104 vs. JE306		hourly	AT, RH, and SR WD	30-May-2014 03-September-2014	31-January-2019 31-January-2019
	JP 107 vs. JE306			AT, RH, and SR WSD	01-May-2014 03-September-2014	01-April-2018 01-April-2018
	JP 311 vs. JE306			AT, RH, and SR WSD	25-March-2014 03-September-2014	01-April-2018 01-April-2018
	JP 104 vs. JP107	2, 16, 21, and 29	hourly	AT, RH, SR, and WSD	30-May-2014	01-April-2018
	JP 104 vs. JP311			AT, RH, SR, and WSD	30-May-2014	01-April-2018
	JP 107 vs. JP311			AT, RH, SR, and WSD	30-July-2013	01-April-2018
G4	C5 vs. JP201	2	daily	AT, RH, and SR	27-May-2014	31-March-2017
	C5 vs. JP213			AT, RH, SR, and PR	18-July-2012	31-March-2017
	JP201 vs. JP213	2, 16, 21, and 29	hourly	AT, RH, SR, and WSD	03-September-2014 27-May-2014	01-April-2018 01-April-2018
G5	L1 vs. L2	2	daily	AT and RH PR	25-September-2007 01-August-2008	31-March-2017 31-March-2017
	L1 vs. R2			AT and RH	24-January-2011	02-January-2016
	L2 vs. R2					
	L1 vs. JE306	2	daily	AT and RH	25-March-2014	31-March-2017
	L2 vs. JE306					
	R2 vs. JE306	2	hourly	AT, RH, SR, and BP WSD	25-March-2014 01-January-2015	01-April-2019 01-April-2019
G6	C2 vs. C4	2 and 10 *	daily	AT, RH, SR, BP, PR SD, and WSD	25-July-2011	31-March-2017
	C2 vs. JE323	2	daily	AT, RH, SR, and BP	15-March-2014	31-March-2017
	C4 vs. JE323					
G7	JE308 vs. JE312	2	hourly	AT, RH, SR, and BP WSD	25-March-2014 03-September-2014	01-April-2019 31-March-2019

Note: * Only parameters of WSD measured at 10 m height.

3. Methods

3.1. Establishing Relationships for AT, RH, SR, BP, PR, and SD

Here, we used r and AAE for quantifying the meteorological parameter-specific association and coincidence between a pair of meteorological stations [22], as indicated as follows.

$$r = \left[\frac{\sum_{i=1}^{n} (D1_i - \overline{D1})(D2_i - \overline{D2})}{\sqrt{\sum_{i=1}^{n} (D1_i - \overline{D1})^2} \sqrt{\sum_{i=1}^{n} (D2_i - \overline{D2})^2}} \right] \quad (1)$$

$$AAE = \frac{1}{n} \sum_{i=1}^{n} |(D1_i - D2_i)| \quad (2)$$

where D1 and D2 indicate station-specific measurements at the sites of A and B, respectively. The total number of measurements is denoted by n.

3.2. Measures for WSD and WD

We found that expressing wind using speed and direction together was most appropriate for the similarity analysis [23]. In addition, we also noticed that the similarity approach is the most convincing approach in finding similarity between two wind datasets of weather stations. Therefore, we applied a similarity approach to the combined term of WSD to quantify the similarity between the wind data of two weather stations from each group.

3.3. Similarity Analysis of Meteororlogical Parameters

For similarity analysis, we compared the meteorological parameters for every station pair of each group against the acceptable instrumental error ranges that were found in the standard operating procedure (SOP; [46–49]) using the following expression:

$$PS = \frac{N2}{N1} \times 100 \quad (3)$$

where N1 and N2 are the total and final data counts, respectively. Notably, N2 requires to meet the following criteria:

- If D1-D2 is ± 0.5 °C for AT, ± 2.5 cm for SD, and $\pm 5\%$ for RH as per SOP's recommendation.
- If the percentage deviation for D1 and D2 is $\leq 20\%$ for hourly SR, 10% for daily SR, 1% for BP, and 2% for PR as per SOP's recommendation. Here, we used the larger one between D1 and D2 in calculating the deviation. Notably, the larger one between D1 and D2 is used to compute the percentage deviation, and
- If D1-D2 is ± 0.5 m/s (i.e., 1.8 km/h) for wind speed and $\pm 5^{\circ}$ for wind direction as per SOP's recommendation.

Upon determining the similarities, we summarized them to identify the required stations in the scope of each individual group. An example of computing PS is shown in Figure 2.

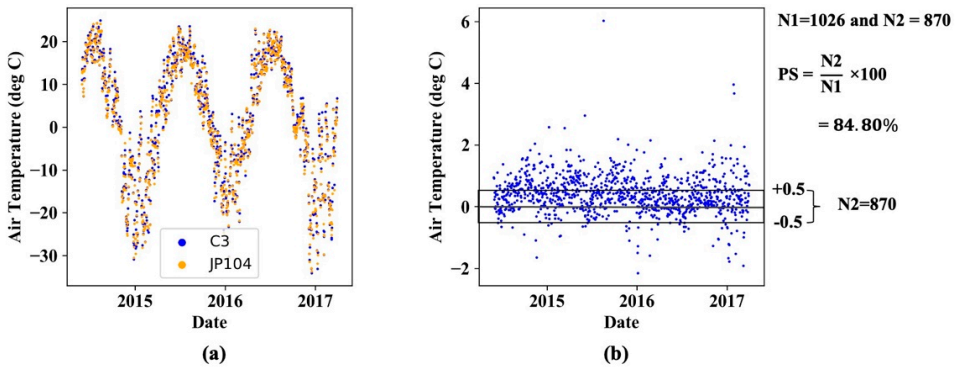


Figure 2. Example calculation of percentage of similarity (PS) for the parameter of air temperature (AT) for station-pair C3 vs. JP104 in Group 3 along with their time-series (**a**), and differences (**b**).

4. Results

4.1. Relations and Similarity Analysis for AT, RH, SR, BP, PR, and SD

We computed relations (r and AAE) and similarity (PS) measure for seven groups of stations for the parameters, such as AT, RH, SR, BP, PR, and SD. In this analysis, values of r from 0 to 0.3, 0.3 to 0.7, 0.7 to 1.0 indicate weak, moderate, and strong linear relationships, respectively [40]. In addition, the values of AAE close to zero are considered as no error between two datasets [10]. For similarity, we assumed the value of PS with a minimum of 75% in determining the acceptable likeliness between station-pairs [22,23]. The computed values of r, AAE, and PS for each station-pair for the seven groups (G1-G7) are shown in Tables 2–4. The results of relations and similarity analysis for determining the minimum number of required station/s in each group for a given meteorological parameter are presented in the following sub-sections.

Table 2. Analysis of similarity and relations among the meteorological parameters for G1, G2, and G4 groups. The sign '-' means the measurements were unavailable for comparison, and highlighted bold values mean strong PS with ≥75%.

Met. Parameter	Measure	Group									
		G1			G2		G4				
		* C1 vs. C4	* C1 vs. JE323	* C4 vs. JE323	* JP316 vs. JE316	* C5 vs. JP201	* C5 vs. JP213	* JP201 vs. JP213	** JP201 vs. JP213	^ JP201 vs. JP213	^^ JP201 vs. JP213
AT	n	2076	1112	1112	32,736	1035	1607	30,758	33,282	29,601	32,783
	AAE (°C)	1.16	2.49	1.82	1.31	1.82	3.92	4.27	2.65	2.44	2.36
	r	1.00	0.99	0.99	0.99	0.99	0.68	0.72	0.97	0.97	0.98
	PS (%)	53.76	22.75	32.55	55.97	29.08	28.44	24.18	26.47	28.35	29.47
RH	n	2076	1112	1112	32,737	1035	1711	33,064	33,284	29,601	32,327
	AAE (%)	5.76	5.04	5.08	4.81	8.16	6.66	9.68	9.57	9.39	9.47
	r	0.88	0.93	0.88	0.93	0.69	0.81	0.74	0.77	0.78	0.78
	PS (%)	**83.00**	**87.68**	**87.32**	**86.87**	73.33	**79.02**	68.34	66.36	67.1	66.71
SR	n	2076	1112	1112	21,511	1035	1710	25,402	-	-	-
	AAE (W/m^2)	16.41	29.74	37.18	59.77	24.69	22.71	63.39	-	-	-
	r	0.97	0.88	0.85	0.92	0.93	0.93	0.85	-	-	-
	PS (%)	32.38	24.85	21.12	30.81	26.98	32.12	27.30	-	-	-
BP	n	-	-	1112	-	-	-	-	-	-	-
	AAE (kPa)	-	-	1.82	-	-	-	-	-	-	-
	r	-	-	0.98	-	-	-	-	-	-	-
	PS (%)	-	-	0.00	-	-	-	-	-	-	-
PR	n	2002	-	-	-	-	1710	-	-	-	-
	AAE (mm)	0.92	-	-	-	-	22.71	-	-	-	-
	r	0.69	-	-	-	-	0.93	-	-	-	-
	PS (%)	8.85	-	-	-	-	32.12	-	-	-	-
SD	n	2076	-	-	-	-	-	-	-	-	-
	AAE (cm)	2.83	-	-	-	-	-	-	-	-	-
	r	0.95	-	-	-	-	-	-	-	-	-
	PS (%)	**76.40**	-	-	-	-	-	-	-	-	-

The measurement heights of the meteorological parameters are denoted by *, **, ^, and ^^ which correspond to 2, 16, 21, and 29 m, respectively.

Table 3. The analysis of similarity and relations among the meteorological parameters for the G3 group, measured at 2 m height. The sign '-'means the measurements were unavailable for comparison and highlighted bold values mean strong PS with ≥75%.

Met. Parameters	Measures	G3																		
		* C3 vs. JE306	* C3 vs. JP104	* C3 vs. JP107	* C3 vs. JP311	* JP104 vs. JE306	* JP107 vs. JE306	* JP311 vs. JE306	* JP104 vs. JP107	* JP104 vs. JP311	* JP107 vs. JP311	** JP104 vs. JP107	** JP104 vs. JP311	** JP107 vs. JP311	^ JP104 vs. JP107	^ JP104 vs. JP311	^ JP107 vs. JP311	^^ JP104 vs. JP107	^^ JP104 vs. JP311	^^ JP107 vs. JP311
AT	n	1054	1026	1581	1307	38,408	31,635	33,116	32,402	32,675	37,515	32,110	32,701	36,898	32,217	32,198	37,476	32,456	31,637	35,534
	AAE (°C)	1.5	0.56	1.61	1.35	1.81	1.62	2.51	2.05	1.89	2.72	1.77	1.64	2.32	1.69	1.56	2.24	1.62	1.53	2.21
	r	1	1	0.99	0.99	0.99	0.99	0.97	0.98	0.98	0.97	0.99	0.99	0.98	0.99	0.99	0.98	0.99	0.99	0.98
	PS (%)	41.46	**84.80**	42.69	44.61	39.31	44.82	30.40	34.48	36.11	26.75	37.66	40.52	29.35	39.79	41.90	30.70	41.52	42.81	30.89
RH	n	1054	1026	1581	1307	38,405	31,643	32,503	32,413	32,031	36,882	32,109	32,701	36,893	30,123	31,468	34,632	32,454	31,536	35,431
	AAE (%)	5.58	3.21	5.40	4.73	6.62	5.57	9.14	7.09	6.61	8.60	7.05	6.27	8.79	6.70	6.36	8.74	7.41	6.75	8.84
	r	0.92	0.97	0.86	0.91	0.89	0.92	0.80	0.87	0.89	0.81	0.88	0.90	0.81	0.88	0.90	0.81	0.84	0.86	0.80
	PS (%)	**89.28**	**98.64**	**88.05**	**89.82**	**79.47**	**84.54**	66.80	**76.77**	**78.75**	69.63	**76.36**	**79.96**	68.31	**78.33**	**80.06**	69.34	**76.19**	**79.30**	68.44
SR	n	1054	1026	1573	1307	23,977	21,031	21,672	28,677	27,329	34,763	-	-	-	-	-	-	-	-	-
	AAE (W/m^2)	19.66	8.87	16.96	18.93	59.22	51.75	70.79	50.39	53.02	39.13	-	-	-	-	-	-	-	-	-
	r	0.93	0.99	0.96	0.95	0.89	0.90	0.85	0.90	0.90	0.90	-	-	-	-	-	-	-	-	-
	PS (%)	38.61	64.79	39.25	34.69	38.82	44.14	33.31	26.67	27.53	40.72	-	-	-	-	-	-	-	-	-
BP	n	1055	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	AAE (kPa)	5.97	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	r	0.66	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	PS (%)	**82.27**	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
PR	n	-	-	1606	1308	-	-	-	-	-	38,185	-	-	-	-	-	-	-	-	-
	AAE (mm)	-	-	1.20	1.06	-	-	-	-	-	0.56	-	-	-	-	-	-	-	-	-
	r	-	-	0.55	0.57	-	-	-	-	-	0.31	-	-	-	-	-	-	-	-	-
	PS (%)	-	-	1.17	0.87	-	-	-	-	-	2.73	-	-	-	-	-	-	-	-	-

The measurement heights of the meteorological parameters are denoted by *, **, ^, and ^^ which correspond to 2, 16, 21, and 29 m, respectively.

G1, G2, and G4 Groups: The outcomes of relation and similarity analysis are presented in Table 2 for G1 (i.e., C1, C4, and JE323), G2 (i.e., JP316 and JE316), and G4 (i.e., C5, JP201, and JP213) for the relevant weather parameters, such as AT, PR, RH, SR, BP, and SD. In the case of AT, strong relations, such as r-values (≥0.97) and AAE (in the range 1.16 and 2.65 °C), and unacceptable similarities, such as PS value (≤55.97%), were observed for 8 out of 10 station pairs across all the groups. Regarding RH, strong relations, such as r-values (≥0.74) and AAE (≤9.68%), were found for all the station pairs. At the same time, the acceptable PS values (>75%) were revealed in all the station pairs of G1 and G2, and one pair (i.e., C5 vs. JP213) of G4 groups. Regarding SR, strong relations, such as r-values (≥0.85) and AAE (in the range 16.41 and 63.39 W/m^2), and unacceptable similarities, such as PS value (≤32.38%) were observed. Regarding BP, data for only one station pair (i.e., C4 vs. JE323 in group G1) was available; where strong relations, such as r-value (=0.98) and AAE (=1.82 kPa), and unacceptable similarities, such as PS value (=0%) were revealed. Regarding PR, there were two station-pairs (i.e., C1 vs. C4 in group G1, and C5 vs. JP213 in G4); where moderate-to-strong relations, such as *r-values* (≥0.69) and AAE (≤22.71 mm), and unacceptable similarities, such as PS value (≤32.12%) were observed. Regarding SD, data for only one station-pair (i.e., C1 vs. C4 in group G1) was available; where strong relations, such as r-value (=0.95) and AAE (=2.83 cm), and acceptable similarities, such as PS value (=76.40%) were found.

G3 Group: Among all seven groups, G3 was the largest one comprising 19 station pairs where the weather parameters of AT, PR, RH, BP, SR, and SD were measured. The station pair-wise relations and similarity measures are given in Table 3. In the case of AT, strong relations, such as r-values (≥0.97) and AAE (in the range 0.56 and 2.72 °C) for all the station pairs, and unacceptable similarities, such as PS value (≤44.82%) for all the stations except the C3 vs. JP104 pair (with having an acceptable similarity with a magnitude of 84.80%), were found. Regarding RH, strong relations, such as r-values (≥0.80) and AAE (≤9.14%), were observed for all the station pairs. At the same time, the acceptable PS values (≥75%) were witnessed for 14 out of 19 station pairs. Regarding SR, strong relations, such as r-values (≥0.85) and AAE values (≤70.79 W/m^2), and unacceptable similarities, such as PS values including ≤64.79% were seen. Regarding BP, data for only one station pair (i.e., C3 vs. JE306) was available. Both moderate relations, such as r-value (=0.66) and AAE (=5.97 kPa), and acceptable similarities, such as PS value (=82.27%) were found. Regarding PR, there were three station pairs (i.e., C3 vs. JP107, C3 vs. JP311, and JP107 vs.

JP 311) available. Moderate relations, such as r-values (between 0.31 and 0.57) and AAE (≤1.20 mm), and unacceptable similarities, such as PS value (≤2.73%) were seen.

Table 4. The analysis of similarity and relations among the meteorological parameters for G5 and G6 groups, measured at 2 m height. The sign '-' meant the measurements were unavailable for comparison, and highlighted bold values meant strong PS with ≥75%.

Met. Parameters	Measure	G5						G6			G7
		L1 vs. JE306	**L1 vs. L2**	**L1 vs. R2**	**L2 vs. JE306**	**L2 vs. R2**	**R2 vs. JE306**	**C2 vs. C4**	**C2 vs. JE323**	**C4 vs. JE323**	**JE308 vs. JE312**
AT	n	1039	3227	1726	1055	1726	23,847	2060	1112	1112	40,860
	AAE (°C)	1.07	0.88	1.24	1.17	0.98	1.81	0.98	2.20	1.82	2.04
	r	1.00	1.00	1.00	1.00	1.00	0.99	1.00	0.99	0.99	0.98
	PS (%)	53.90	68.79	50.75	53.55	57.13	40.50	67.28	30.13	32.55	35.68
RH	n	1039	3116	1244	1055	1243	22,499	2060	1112	1112	28,762
	AAE (%)	5.4	4.23	4.99	5.62	3.79	6.49	4.55	4.97	5.08	7.53
	r	0.91	0.92	0.88	0.95	0.92	0.89	0.92	0.90	0.88	0.86
	PS (%)	**84.22**	**92.49**	**90.51**	**90.90**	**96.62**	**80.60**	**91.41**	**88.58**	**87.32**	74.61
SR	n	-	-	-	-	-	19,333	2060	1112	1112	24,680
	AAE (W/m^2)	-	-	-	-	-	73.52	23.10	43.27	37.18	69.65
	r	-	-	-	-	-	0.86	0.96	0.84	0.85	0.87
	PS (%)	-	-	-	-	-	31.57	29.84	17.72	21.12	36.93
BP	n	-	-	-	-	-	23,860	2060	1112	1112	25,053
	AAE (kPa)	-	-	-	-	-	7.86	1.57	0.45	1.82	5.28
	r	-	-	-	-	-	0.14	0.82	0.77	0.98	0.37
	PS (%)	-	-	-	-	-	**92.85**	0.44	**96.67**	0.00	**99.94**
PR	n	-	3083	-	-	-	-	2002	-	-	-
	AAE (mm)	-	0.68	-	-	-	-	0.92	-	-	-
	r	-	0.77	-	-	-	-	0.69	-	-	-
	PS (%)	-	9.25	-	-	-	-	8.85	-	-	-
SD	n	-	-	-	-	-	-	1786	-	-	-
	AAE (cm)	-	-	-	-	-	-	2.16	-	-	-
	r	-	-	-	-	-	-	0.97	-	-	-
	PS (%)	-	-	-	-	-	-	**85.95**	-	-	-

G5, G6, and G7 Groups: The outcomes of relation and similarity analysis are presented in Table 4 for G5 (i.e., L1, L2, R2, and JE306), G6 (i.e., C2, C4 and JE323), and G7 (i.e., JE308 and JE312) for the relevant weather parameters, such as AT, PR, RH, SR, BP, and SD. In the case of AT, strong relations, such as r-values (≥0.98) and AAE (in the range 0.88 and 2.20 °C), and unacceptable similarities (≤68.79%), were observed for all station pairs. Regarding RH, strong relations, such as r-values (≥0.86) and AAE (≤7.53%), and acceptable similarities, such as PS values (~75%) were found for all the station pairs. Regarding SR, strong relations, such as r-values (≥0.84) and AAE (in the range 23.10 and 73.52 W/m^2), and unacceptable similarities, such as PS value (≤36.93%) were observed. Regarding BP, weak-to-moderate-strong relations, such as r-values (=0.14, 0.37, and ≥ 0.77) and AAE (≥7.86 kPa), and acceptable similarities, such as PS value (≥92.85%) were witnessed for three station pairs. For example, R2 vs. JE306 in G5, C2 vs. JE323 in G6, and JE308 vs. JE312 in G7.

However, two station pairs of G6 (i.e., C2 vs. C4 and C4 vs. JE323) showed very weak similarity (≤0.44%). Regarding PR, there were two station pairs (i.e., L1 vs. L2 in group G5, and C2 vs. C4 in G6) available; where moderate-to-strong relations, such as r-values (≥0.69) and AAE (≤0.92 mm), and unacceptable similarities, such as PS value (≤9.25%) were observed. Regarding SD, data for only one station pair (i.e., C2 vs. C4 in group G6)

was available; where strong relations, such as r-value (=0.97) and AAE (=2.16 cm), and acceptable similarities, such as PS value (=85.95%) were seen.

4.2. Similarity Analysis for WSD

Table 5 shows the similarity analysis for all seven groups. In these groups, the station pairs measured the WSD at the height of: (i) 10 m in G1 and G6 groups; (ii) 2 m in G2, G5, and G7; and (iii) 2, 16, 21, 29 m in G3 and G4. It revealed that unacceptable similarities with PS values ($\leq$19.16%) were observed across all the groups.

Table 5. Analysis of similarity for available data of wind speed and direction for all seven groups. Here, '-' indicates that measurements were not available (or comparable) for the pair.

Group	Station Pair	Measurement at Different Wind Measurement Heights									
		2 m		10 m		16 m		21 m		29 m	
		n	PS (%)	n	PS (%)	n	PS (%)	n	PS (%)	n	PS (%)
G1	C1 vs. C4	-	-	2076	11.46	-	-	-	-	-	-
G2	JP316 vs. JE316	28,699	4.09	-	-	-	-	-	-	-	-
G3	JP 104 vs. JE306	36,112	3.73	-	-	-	-	-	-	-	-
	JP 107 vs. JE306	27,888	5.47	-	-	-	-	-	-	-	-
	JP 311 vs. JE306	26,850	2.75	-	-	-	-	-	-	-	-
	JP 104 vs. JP107	31,121	10.22	-	-	32,835	15.13	32,842	19.16	32,834	14.51
	JP 104 vs. JP311	29,855	6.94	-	-	32,394	9.00	32,402	12.35	32,540	8.03
	JP 107 vs. JP311	33,622	10.60	-	-	37,775	11.00	37,851	10.96	37,983	10.91
G4	JP201 vs. JP213	30,376	10.69	-	-	31,758	13.36	33,156	13.55	32,910	12.89
G5	R2 vs. JE306	16,846	4.93			-	-	-	-	-	-
G6	C2 vs. C4	-	-	2060	13.64	-	-	-	-	-	-
G7	JE308 vs. JE312	20,576	10.72	-	-	-	-	-	-	-	-

4.3. Determining the Required Stations within Each Individual Group

Table 6 shows the weather stations needed for measuring every individual parameter in each group upon summarizing the similarity analysis described in the previous two sub-sections. It revealed that every weather station would be essential for the following parameters of interest, i.e., (i) AT for all groups except G3; (ii) SR, PR, and WSD for all groups; (iii) RH for G7; and (iv) BP for G1. Furthermore, we found that three parameters, namely RH, BP, and SD showed some degree of redundancy. Despite this, we would recommend not to get rid of them as they might be essential in the event of malfunctioning of a same parameter-specific instrument from another station.

Table 6. Group-specific required stations for each of the meteorological parameters.

Group	Station ID	Network	Meteorological Parameter						
			AT	RH	SR	BP	PR	SD	WSD
G1	C1	OSM WQP		JE323					
	C4			JE323				C1	
	JE323	WBEA ES							
G2	JP316	WBEA MT							
	JE316	WBEA ES		JP316					
G3	C3	OSM WQP	JP104						
	JP104	WBEA MT							
	JP107			JP104					
	JP311			JP104					
	JE306	WBEA ES		JP104		C3			
G4	C5	OSM WQP		JP213					
	JP201	WBEA MT							
	JP213								
G5	L1	OSM WQP		L2					
	L2								
	R2	WBEA ES		L2		JE306			
	JE306			L2					
G6	C2	OSM WQP							
	C4			C2				C2	
	JE323	WBEA ES		C2		C2			
G7	JE308	WBEA ES				JE312			
	JE312								

Color Legend: Station is required to capture spatial variability in meteorological parameter; AAA: Meteorological parameter shows at 70% similarity with station 'AAA'; There is no sensor for recording the meteorological parameter of interest

5. Discussion

Upon synthesizing all the seven groups for all parameters except WSD, we found a maximum of 39 station pairs of data could be available for analysis for a weather parameter of interest. Specifically, the maximum number of pairs (i.e., 39) was seen for both AT and RH, 22 for SR (as these measurements were available at 2 m height only), 7 for both BP and PR, and 2 for SD. In the case of WSD, we observed that there were 12 station pairs for comparison, while the stations L1 and L2 did not have any measurements. Thus, it is imperative to establish protocols to measure the parameters of BP, PR, SR, and WSD at the missing stations to facilitate better comparisons and understanding across the landscape.

Regarding AT and SR, our results indicated that strong relations (including r-values ≥ 0.72 for at least 97% of the station pairs) and very limited acceptable similarities (with PS value $\geq 75\%$ for one station pair) (see Tables 2–4) were witnessed. In fact, SR mainly varies as a function of latitude, such as exhibiting gradual declination towards the higher latitudes, which also cause lower AT in the similar fashion [50,51]. Additionally, the SR regimes also vary with the atmospheric state like clear sky, partially cloud, overcast conditions, etc. [52]. On the contrary, AT regimes also depend on the land cover type as it determines the amount of absorption/reflection of the incident sunlight (SR), a key component defining the eventual temperature at a given location [53]. Thus, it might be possible to observe strong relations for AT and SR at two different latitudes for the same parameter; however, similarities might not exist. This implies that both AT and SR from a nearby station could be used to predict/model other stations' regimes; however, these must be thoroughly evaluated prior to implementation, which was beyond the scope of this study.

Regarding RH, it is interesting to mention that both strong relations (i.e., r-values ≥ 0.74 for about 97% of the station pairs) and acceptable similarities (i.e., PS values $\geq 75\%$ for about

74% of the station pairs) were observed. These findings refer to the fact that RH would be similar over a small area like this study [22,54]. In addition, regarding BP, about 57% of the station pairs showed strong relations (i.e., r-values $\geq$ 0.77) and acceptable similarities (i.e., PS values $\geq$ 75%). In at least two cases, we found weak-to-moderate relations (i.e., r-values < 0.70), yet with acceptable similarities. This can be attributed to the presence of outliers in these datasets. Moreover, acceptable similarities were likely also due to their comparable altitude [22]. Regarding PR, about 28% of the station pairs showed strong relations (i.e., r-values $\geq$ 0.77), while there were no acceptable similarities across all the station pairs. In fact, these unacceptable similarities were probably because of the PR's dynamic behaviour within a relatively small region of interest [10]. Regarding SD, among the two available station pairs, we observed that both had strong relations (i.e., r-values $\geq$ 0.95) and acceptable similarities (i.e., PS values $\geq$ 75%). These higher degrees of relations and similarities might be because of similar altitudes between the station pairs, while the snow accumulation might depend on timing, latitude, wind, and vegetation [22,54]. Regarding WSD, there were no acceptable similarities among the 12 station pairs (see Table 5). In fact, the wind fields would be highly variable across the landscape as the factors such as topography, land cover, surface roughness, and uneven heating of the earth surface would influence them to a great extent [23,55,56].

6. Conclusions

In this study, we evaluated relations and similarities for a set of meteorological parameters among seven groups of meteorological stations that were clustered based on land use and topography. This study complements our earlier work that evaluated relations and similarity for the meteorological parameters within each of the weather networks in the area: WQP, WBEA MT, and WBEA ES. Our analysis revealed that there were strong relations in 97% of the station pairs among some of the parameters such as AT and SR, but with limited acceptable similarity in all the pairs except one. Only the RH parameter exhibited both strong relations and high similarity in more than 97% and 74% of the pairs, respectively. It was also found that there was no redundancy in the existing weather stations in most parameters except RH, BP, and SD. This redundancy did not justify the elimination of any of the existing stations and indicate future research to develop models predicting the meteorological parameters at certain locations based on surrounding stations. However, these models will require robust calibration and verification. Future work also includes the evaluation of the similarity and relations of all 19 stations in the region.

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