CLUSTER ANALYSIS RESOLUTION OF DIURNAL CLIMATOLOGICAL WIND PATTERN MODES UTILIZING K-MEANS – A CASE STUDY WITH BOSTON, MA. DATA (LOGAN INTERNATIONAL AIRPORT - 1945-2019)

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1. INTRODUCTION

Climatological wind variability is an important meteorological element to be considered in planning, forecasting, and decision-making activities in which wind conditions are crucial on some level. Wind rose diagrams, for example, can provide insights into the wind character for individual hours of interest by depicting the most favored compass directions and associated speeds. Resultant wind calculations can be valuable in producing distilled single-value statistics derived from many different individual observations, either for an specific hour of interest or a consolidation of differing hours into one.

Also operationally useful but more complicated to produce would be characterizations of a station's most important *contiguous* climatological hour-to-hour wind patterns, encompassing, for example, an entire day, midnight-to-midnight. In the same manner as there are favored individual hourly directions and related speeds, there are undoubtedly preferred, adjacent hour-to-hour *progressions*, or "modes". Such patterns are also likely to exhibit varying seasonal preferences. Resolving' idealized wind patterns of this kind can be accomplished by a clustering analysis, making use of individual hour wind observations' u and v components, and to this end, K-Means Clustering Analysis integrated with a special optimizing add-on capability, the V-Fold Cross-Validation Algorithm, is employed.

Traditional K-Means is a trial-and-error procedure, and the V-Fold Algorithm is an automated, iterative, and enhancing training sample/testing sample procedure that rapidly produces in ascending order, 2 to K cluster sets, the iterations ceasing at some "optimal" number K, depending on a choice of statistical distance metric (Euclidean, Squared Euclidean, etc.), number of folds or training sample subsets, and percent improvements between successive v-fold iterations of individual observations vs. centroid mean statistical distance magnitudes. The software that offers the K-Means/V-Fold capability, however, also gives the option of fixing the number of clusters, all the while retaining the V-fold algorithms' processing speed and efficiency, and its superior means of cluster membership selection through the training sample/testing sample methodology. This product has already been applied with good results on many stations' data in the Southern California area, both for operational and purely informative purposes, including those of several NOAA Buoys, local military bases, NWS Offices, and automatic weather stations. Two-station analyses have been done as well, for Daggett vs. Victorville in the California High Desert, and Pt. Mugu Naval Air Base vs. Laguna Peak tracking facility (a station atop a 1500 foot mountain several miles inland from Pt. Mugu).

In this study, as a further demonstration of the technique, resultant wind cluster modes are resolved for Boston, Massachusetts (Logan International Airport), near the venue of the AMS 2020 Annual Meeting. Logan Airport has a voluminous record of digitized hourly wind observations, dating back to the start of 1945. Presentation of the results, in addition to the hourly mean vector wind depictions, will include bar graph percent frequency comparisons, month-by-month. Also, as a special supplementary analysis, individual midnight-to-midnight cases with the most extreme individual statistical distances from cluster centroid (irrespective of cluster) are identified, presented, and described. The most extreme six (out of nearly 23000 possible) are highlighted.

2. DATA AND PROCEDURES

Period of record for the Logan International station was January 1945-June 2019. The raw hourly data were downloaded, decoded, QC'd, and processed from the Integrated Surface Hourly data base, an online resource accessible from NOAA's National Centers for Environmental Information (NCEI), formerly NCDC. Only those individual days with completely intact hour-to-hour wind observation sets (no missing hours) could be processed, and in case of Logan, some 22560 midnight-to-midnight observations qualified, or 90.2% of possible. The squared-Euclidean distant metric, along with the default 5-percent improvement cutoff threshold were chosen, and through an automatic internal software feature, the 24 pairs of u and v wind observations, by hour, were normalized in advance to reduce them to a common scale.

For a single station midnight-to-midnight analysis; the analysis was thus one in 48-dimensional space (the two-station analysis would be a 96-dimensional application). Each of the resulting individual cluster "clouds" would have midpoints or centroids in 48-D space, made up of mean u and v values for each hour of the day. These would then be recombined, hour-by-hour using the arctangent function, producing 24 sets of hourly mean vector wind statistics; The cluster arrays would be independent self-contained entities, depicting

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idealized *progressions* of mean vector wind character hour-by-hour through the course of a day.

Since the clustering process assigned diurnal wind observations of a very similar character to a given group, the individual-hour mean vector wind direction results in many cases could be interpreted, with only slight loss of generality, as *average wind directions.* Also, the accompanying mean vector wind *speeds*, would be comparable (but slightly less) than their counterpart mean scalar wind speed statistics,

A "one-size-fits-all' approach was taken with the clustering analysis applied to all months' data as a single unit. A validation of this tactic, also based on experience/experimentation, was that the modes' frequencies, per month, in most cases, exhibit monotonically increasing and decreasing magnitudes.

The results, cluster by cluster, are depicted graphically on single-chart layouts, the hourly mean vector wind directions as arrows, proportional in length to their magnitude (the highest magnitude vector is annotated), "constancy" statistics (mean vector wind speed/mean scalar wind speeds*100; a measure of cluster directional homogeneity) as colored circles (ordered from dark blue to dark red), and month-by-month cluster relative frequencies, contained in a vertical bar-chart.

Since mean scalar wind magnitudes are not depicted on the charts, the constancy magnitude shadings can be utilized to estimate them, if desired, from the vector wind magnitude depictions. For example, constancy values that are say, 90 (or higher - a not infrequent result seen in clusters' output), would require a correction factor of 1/.90 or just 1.11 (a mean vector wind speed annotation of 10 knots, for example, would be converted to a mean scalar wind speed of 11.1 knots). In such cases the vector wind info could be effectively interpreted as a combined average wind direction AND scalar speed.

In other less ideal cases (with lower constancies), a results array might portray a diurnal pattern that had inherently lighter and more variable winds (for example, weak diurnal circulation regimes), and/or one with natural diurnal breaks (for example, land-breeze/sea-breeze transitions and vice-versa). The "average wind direction/wind speed" intepretation of the high constancy cases might not be as applicable here, but patterns of this nature, being an integral part of the given station's diurnal climatological "landscape" are, of course, no less important to present and describe.

3. RESULTS

Five clusters or "modes" were generated for Boston, ranging in overall frequency from 29.5 % to 12.5 %. Clear, sometimes pronounced seasonal preferences were indicated from the individual months' percent frequencies, and the frequencies, collectively, exhibited mostly smooth montonic progressions, month to month. The Boston patterns, in rank order of relative importance, are now presented in both graphical and tabular form.

3.1 Boston Mode 1: "Land-Breeze/Sea-Breeze" (29.5% Overall Frequency)

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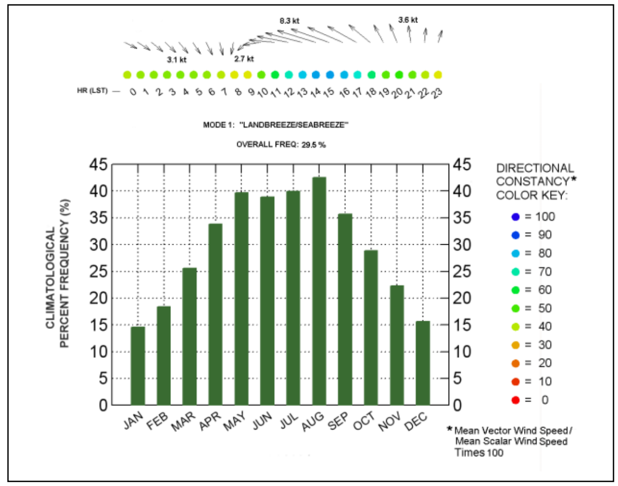

Figure 1: Boston Mode 1 - Graphic Version

MODE 1: "LANDBREEZE/SEABREEZE" OVERALL FREQ: 29.5 %					
HRLST	RDIR	RDIR$	RSPD (kts)	SSPD (kts)	CONSTANCY
0	295.28	WNW	2.99	7.47	39.98
1	301.46	WNW	3.08	7.26	42.42
2	307.40	NW	3.09	7.07	43.66
3	313.37	NW	3.05	6.89	44.31
4	320.34	NW	3.03	6.78	44.61
5	325.82	NW	2.96	6.71	44.07
6	332.51	NNW	2.93	6.80	43.04
7	345.70	NNW	2.79	6.98	40.01
8	10.56	N	2.61	7.21	36.24
9	49.59	NE	2.68	7.48	35.79
10	81.53	E	3.73	7.98	46.72
11	95.21	E	5.25	8.64	60.78
12	101.02	E	6.59	9.23	71.33
13	104.50	ESE	7.67	9.80	78.32
14	107.13	ESE	8.23	10.09	81.58
15	109.40	ESE	8.33	10.12	82.31
16	113.32	ESE	7.84	9.83	79.81
17	119.39	ESE	6.79	9.26	73.32
18	130.10	SE	5.68	8.68	65.43
19	151.07	SSE	4.14	8.69	47.61
20	158.11	SSE	4.12	7.90	52.10
21	171.99	S	3.59	7.67	46.78
22	185.09	S	3.06	7.59	40.33
23	197.85	SSW	2.64	7.57	34.89

Figure 2: Boston Mode 1 - Tabular Version

Figures 1 and 2 show the results for Mode 1, the most frequent of the five overall (29.5% frequency). The resultants' depictions in the top section of Figure 1 describe a light west-northwesterly to north-northwesterly resultant land breeze transitioning to a stronger east to east-southeasterly sea-breeze, at "light" to "gentle" scalar magnitudes (Beaufort scale terminology), as indicated in the "SSP(kts)" column in Figure 2. The annotations to the vectors in the top section of Figure 1 are resultant magnitudes, listed also in the "RSP(kts)" column in Figure 2. Constancy statistics, depicted by a color scheme in Figure 1 and listed in the rightmost column in Figure 2 are at relatively low levels for the land-breeze hours, in the

30's and 40's, (the minimum 35.79 for 0900 LST, interpretable as the most favored transition hour), but during the seabreeze hours reaching 81.58 and 82.31 at 1400 LST and 1500 LST, respectively, corresponding to east-southeasterly resultant flow. From inspection of the bar graph in Figure 1, this is obviously a warm season preferred pattern, driven of course by the longer days and higher insolation received at that time of year. Highest relative frequencies are noted for May thru August, all at 38% or higher, the absolute maximum for August (42.6 %). Minimum relative frequencies are seen for December and January, both about 15 %.

3.2 Boston Mode 2: "SSW'lys to SW'lys Throughout"- (19.8%)

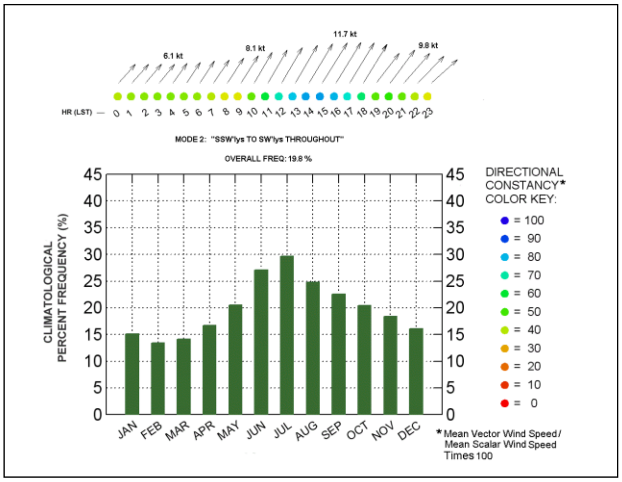

Figure 3: Boston Mode 2 - Graphic Version

MODE 2: "SSW'lys TO SW'lys THROUGHOUT" OVERALL FREQ: 19.8 %					
HRLST	RDIR	RDIR$	RSPD (kts)	SSPD (kts)	CONSTANCY
0	222.50	SW	6.36	8.90	71.46
1	221.87	SW	6.28	8.72	72.05
2	220.44	SW	6.13	8.53	71.87
3	218.97	SW	6.07	8.38	72.46
4	215.90	SW	6.09	8.32	73.14
5	213.85	SW	6.23	8.30	75.02
6	213.04	SSW	6.51	8.50	76.61
7	213.53	SW	6.93	8.91	77.80
8	213.07	SSW	7.48	9.51	78.61
9	212.22	SSW	8.08	10.21	79.14
10	210.23	SSW	8.78	10.93	80.36
11	210.25	SSW	9.54	11.85	80.51
12	209.93	SSW	10.20	12.51	81.50
13	210.80	SSW	10.88	13.10	83.05
14	211.39	SSW	11.33	13.37	84.73
15	211.78	SSW	11.70	13.52	86.56
16	211.87	SSW	11.81	13.38	88.21
17	211.37	SSW	11.62	13.02	89.29
18	211.86	SSW	11.16	12.53	89.04
19	217.57	SW	9.15	11.71	78.17
20	216.32	SW	10.11	11.57	87.42
21	220.68	SW	9.78	11.34	86.25
22	224.82	SW	9.38	11.05	84.83
23	227.98	SW	8.84	10.76	82.18

Figure 4: Boston Mode 2 - Tabular Version

Figures 3 and 4 show the results for Mode 2, ranking second of the five overall (19.8% frequency). The resultants in Figure 3 are southwesterly to south-southwesterly throughout the day at 70's to 80's constancy levels, the maximum 89.29 at 1700 LST (see Figure 4). Mean scalar speeds are all above 13 knots for 1300 LST to 1700 LST, inclusive (see Figure 4), a "moderate" Beaufort scale magnitude. Mode 2 is also a summer-preferred pattern with the maximum relative frequencies noted for June, July, and August (the maximum 29.6% for July). Mimimum frequencies are recorded for February (13.4%) and March (14.1%) Physically, this mode might reflect multiple synoptic situations, such as relatively strong Azores-Bermuda High episodes (more during the warmer months) or pre-frontal influences (more so in the colder ones).

3.3 Boston Mode 3: "NW'lys Throughout Except WNW'ly for 2300 LST"- (19.7%)

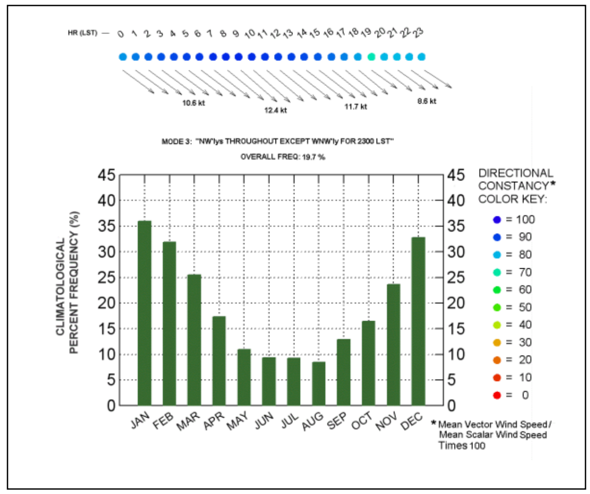

Figure 5: Boston Mode 3 - Graphic Version

MODE 3: NW'lys THROUGHOUT EXCEPT WNW'ly FOR 2300 LST OVERALL FREQ: 19.7 %					
HRLST	RDIR	RDIR$	RSPD (kts)	SSPD (kts)	CONSTANCY
0	306.23	NW	10.07	12.18	82.68
1	306.13	NW	10.31	12.15	84.89
2	306.62	NW	10.53	12.14	86.77
3	306.14	NW	10.59	12.01	88.19
4	306.17	NW	10.76	12.07	89.17
5	306.46	NW	10.89	12.10	90.02
6	306.75	NW	11.10	12.24	90.74
7	307.76	NW	11.54	12.59	91.66
8	309.34	NW	12.05	13.10	91.96
9	311.06	NW	12.39	13.47	91.99
10	311.39	NW	12.46	13.56	91.88
11	310.27	NW	12.32	13.50	91.27
12	308.89	NW	12.18	13.46	90.46
13	307.95	NW	12.16	13.50	90.06
14	307.63	NW	11.89	13.35	89.01
15	307.74	NW	11.66	13.30	87.71
16	308.41	NW	11.18	12.97	86.14
17	309.10	NW	10.48	12.46	84.14
18	309.46	NW	9.72	11.92	81.50
19	305.57	NW	7.94	11.16	71.18
20	307.26	NW	8.82	11.14	79.13
21	305.67	NW	8.63	10.93	78.95
22	304.34	NW	8.58	10.80	79.43
23	302.86	WNW	8.41	10.61	79.20

Figure 6: Boston Mode 3 - Tabular Version

Figures 5 and 6 show the results for Mode 3, ranking third most important of the five, with an overall 19.7% frequency. The resultants in Figure 5, with one exception, are northwesterly in orientation, with most constancies above 85, the highest 91.99 for 0900 LST.

With the exception of the evening hours (1800 LST or later), the associated mean scalar speeds are 12 knots or greater, the maximum, 13.56 knots at 1000 LST (see Figure 6). This obviously depicts an idealized post-frontal pattern, and from the Figure 5 bar chart, the individual month-to-month percent frequencies show a striking monotonic progression, from an absolute maximum in January (36.0%), to the absolute minimum for August (8.4%), back to a secondary maximum for December (32.8%).

3.4 Boston Mode 4: "WSW'lys to WNW'lys Progression"- (18.4%)

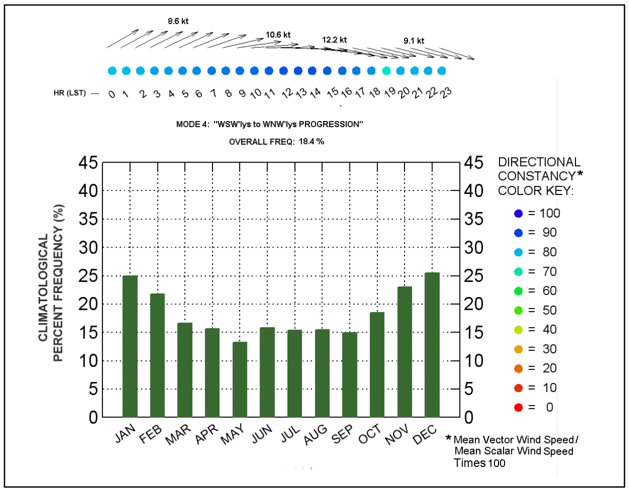

Figure 7: Boston Mode 4 - Graphic Version

MODE 4: "WSW'lys to WNW'lys PROGRESSION" PERCENT FREQ: 18.4 %					
HRLST	RDIR	RDIR$	RSPD (kts)	SSPD (kts)	CONSTANCY
0	240.19	WSW	8.64	11.02	78.37
1	241.70	WSW	8.63	10.91	79.09
2	242.28	WSW	8.60	10.74	80.06
3	243.27	WSW	8.58	10.61	80.87
4	244.38	WSW	8.70	10.65	81.70
5	245.74	WSW	8.81	10.63	82.83
6	247.50	WSW	9.07	10.87	83.41
7	251.22	WSW	9.49	11.23	84.53
8	256.86	WSW	9.98	11.74	85.01
9	261.83	W	10.55	12.35	85.46
10	265.52	W	11.07	12.84	86.20
11	268.56	W	11.55	13.28	87.01
12	271.00	W	11.96	13.63	87.80
13	272.80	W	12.31	13.93	88.32
14	275.77	W	12.38	14.05	88.15
15	278.56	W	12.16	13.90	87.43
16	281.14	W	11.73	13.59	86.25
17	282.44	WNW	10.98	12.97	84.65
18	282.99	WNW	10.15	12.32	82.39
19	283.44	WNW	8.35	11.47	72.79
20	283.74	WNW	9.27	11.56	80.19
21	284.56	WNW	9.05	11.33	79.90
22	286.18	WNW	8.97	11.19	80.16
23	287.58	WNW	8.67	10.92	79.40

Figure 8: Boston Mode 4 - Tabular Version

Figures 7 and 8 show the results for Mode 4, fourth most important of the five (overall incidence: 18.4 %). The resultants' vectors in Figure 7 portray the approach and passage of a cold front, the directions shifting clockwise during the day from west-southwesterly to westerly, and then to west-northwesterly. Constancy figures are mostly in the 80's, the maximum values aligned with the eight-hour contiguous segment with westerly resultants (0900 LST to 1600 LST, inclusive). Mean scalar speeds reach as high as 14.05 knots at 1400 LST. This, like Mode 3, is also a winter preferred pattern, but the contrast in relative frequencies with the other seasons is not as pronounced. Maximum relative frequencies are for January (25.5 %) and December (24.9 %), the least for May (13.3 %).

3.5 Boston Mode 5: "Mostly NE'lys except for NNE'lys >2000 LST" – (12.5%)

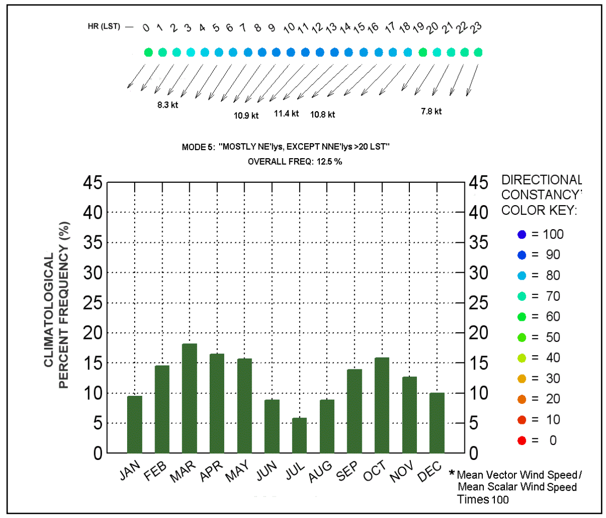

Figure 9: Boston Mode 5- Graphic Version

MODE 5: :MOSTLY NE'lys EXCEPT NNE'lys FOR 2100-2300 LST PERCENT FREQ: 12.5 %					
HRLST	RDIR	RDIR$	RSPD (kts)	SSPD (kts)	CONSTANCY
0	37.81	NE	6.63	10.19	65.06
1	36.19	NE	7.24	10.43	69.44
2	35.10	NE	7.76	10.70	72.51
3	35.38	NE	8.32	11.02	75.51
4	35.20	NE	8.79	11.31	77.73
5	34.41	NE	9.05	11.50	78.72
6	34.86	NE	9.45	11.81	80.02
7	35.52	NE	9.98	12.24	81.55
8	37.17	NE	10.48	12.64	82.86
9	39.82	NE	10.90	13.05	83.52
10	41.89	NE	11.19	13.36	83.72
11	44.71	NE	11.41	13.57	84.10
12	46.51	NE	11.36	13.60	83.53
13	47.54	NE	11.39	13.58	83.88
14	48.55	NE	11.14	13.45	82.78
15	48.41	NE	10.75	13.12	81.95
16	47.88	NE	10.31	12.71	81.11
17	45.46	NE	9.78	12.19	80.23
18	42.36	NE	9.14	11.61	78.66
19	36.64	NE	7.21	11.07	65.11
20	34.08	NE	8.15	11.11	73.38
21	29.31	NNE	7.82	10.99	71.18
22	24.83	NNE	7.50	10.84	69.14
23	20.62	NNE	7.40	10.85	68.20

Figure 10: Boston Mode 5 – Tabular Version

Lastly, Figures 9 and 10 show the results for Mode 5 (overall relative frequency: 12.5 %). The mean vectors in Figure 9 portray the Nor'easter wind regime, with northeasterly orientations present for the first 20 hours, and north-northeasterlies for the closing three (see Figure 10). In contrast with the other four modes, Mode 5's is bi-modal as to seasonal preferences (see Figure 9), favoring Spring (March, April, and May) and Fall (September, October, and November). Maximum incidence is for March (18.1 %), April (16.4 %), and October (15.8 %), the minimum (5.8 %), for July. Mean scalar wind speeds for the pattern are at 13 knots or greater for the contiguous hours 0900 LST thru 1500 LST, the maximum figure, 13.6 knots, noted for 1200 LST (see Figure 10). Constancy figures are mostly in the 70's and 80's, with a maximum (84.1) seen for 1100 LST.

3.6 Identication of Boston Most Extreme Individual Diurnal Wind Patterns Utilizing Ranked Statistical Distances from Centroids

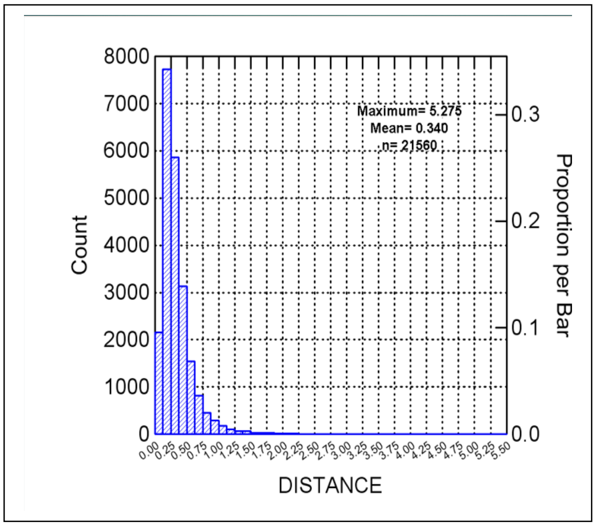

Figure 11: Histogram of Boston Individual Cases' Distances from Respective Cluster Centroids

An interesting spinoff of a cluster analysis of this kind is that one can get an indication of the most extreme individual diurnal patterns that have occurred over the history of the available station history through the ranking of statistical distances from cluster centroids,

As previously described, some 21560 Boston observations were completely intact on a midnight-to-midnight individual hourly basis for the 1945-2019 history. All deviated to some extent from their respective idealized 48-D cluster centroids, and their departures, or "distances" in 48-D space were quantified. Combining the distances, irrespective of mode, into a single data set and then ranking the statistics in order of lowest to highest, one could identify the most extreme of the extremes. The rationale of combining the distances from different clusters to arrive at overall most anomalous observations, is that a given daily observational series of normalized u's and v's whose statistical distance was the maximum observed for a particular cluster, would certainly be more "distant" from centroids of the other clusters of which it was not a member.

Figure 11 is a histogram of the Boston observations' distances. Mean overall statistic was 0.340, but the largest figure (5.275) was more than fifteen times greater. Thus, as an exercise to throw light on the most extreme Boston events, information (including the actual hourly scalar wind speeds and directions) of the six most "anomalous" cases is collected in Figure 12 below. The maximum 5.275 distance (far right column) was associated with the strong easterlies and east-south-easterlies that accompanied the "Great Appalacian Storm of 1950", occurring on 25 November of that year. All the other five cases had at least some north-easterlies, east-north-easterlies, or easterlies, to go with a subset of cases that also experienced clockwise turnings during the day into the southerly or westerly quadrants.

The five other extreme cases for Boston in descending rank order from #2 to #6, are the "Strong Nor'easter of 29 November 1945" (distance:4.406), the "Powerful Nor'easter of 4 March 1971" (distance: 4.283), the "Early November Storm of 7 November 1953" (distance: 3.933), "Hurricane Carol Passage of 31 August 1954" (distance: 3.603), and the "New England Ice Storm of 9 January 1956" (distance: 3.412).

SIX MOST EXTREME BOSTON HOURLY MIDNIGHT-TO-MIDNIGHT WIND PROGRESSIONS AS RANKED BY GREATEST STATISTICAL DISTANCES FROM RESPECTIVE CLUSTER CENTROIDS

DISTANCE	3.412		3.603		3.933		4.283		4.406		5.275	
CLUSTER#	5		2		5		2		5		5	
EVENT	" NEW ENGLAND ICE STORM"		HURRICANE CAROL		"EARLY NOVEMBER STORM OF 1953"		"POWERFUL NOR'EASTER"		STRONG NOR'EASTER		"GREAT APPALACHIAN STORM OF 1950"	
DATE	9-Jan-56		31-Aug-54		7-Nov-53		4-Mar-71		29-Nov-45		25-Nov-50	
LST	WDIR	WSPDKT	WDIR	WSPDKT	WDIR	WSPDKT	WDIR	WSPDKT	WDIR	WSPDKT	WDIR	WSPDKT
0	ENE	28	ENE	10	ENE	36	ENE	23	ENE	35	ESE	29
1	ENE	30	ENE	16	NE	46	ENE	24	ENE	39	ESE	27
2	ENE	32	ENE	13	NE	40	ENE	26	ENE	37	E	31
3	ENE	31	ENE	14	NE	48	ENE	25	ENE	49	E	33
4	NE	31	NE	15	NE	47	ENE	27	ENE	37	E	35
5	NE	31	NE	22	NE	47	ENE	28	ENE	49	E	39
6	NE	35	ENE	19	NE	43	ENE	33	ENE	43	E	36
7	NE	34	ENE	25	ENE	43	ENE	30	ENE	52	E	37
8	NE	35	ENE	33	ENE	42	NE	25	ENE	48	E	35
9	NE	34	ENE	36	ENE	42	NE	20	ENE	50	E	31
10	NE	33	E	61	ENE	33	ESE	6	ENE	45	E	32
11	NE	35	SE	75	E	26	S	40	NE	45	E	34
12	NE	44	SSE	49	E	28	S	36	NE	43	E	38
13	NE	40	SSW	45	SE	10	S	38	ENE	42	E	36
14	NE	34	SSW	43	SW	10	WSW	35	NE	36	E	34
15	NE	39	SSW	32	SW	13	W	33	NE	35	E	35
16	NE	39	SW	23	SSW	12	WSW	33	NE	35	E	39
17	NE	33	SW	30	SSW	10	WSW	35	NE	23	E	40
18	NE	41	SW	17	SSW	10	W	38	NNE	24	E	37
19	NE	35	SSW	19	SSW	10	W	37	NE	30	E	48
20	ENE	31	SW	16	SSW	13	W	33	NE	33	E	40
21	NE	31	SW	17	SW	10	W	33	NE	35	ESE	49
22	NE	29	SW	19	SW	9	W	33	NE	31	ESE	43
23	NE	31	SW	15	SW	7	WSW	35	NE	31	ESE	47

Figure 12*:* Six Most Extreme Boston Hourly Wind Progressions as Ranked by Distances from Cluster Centroids

4. REFERENCES

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