

Atmospheric culturable bacteria associated with meteorological conditions at a summer-time site in the mid-Willamette Valley, Oregon

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Abstract A set of simultaneously collected quantitative measurements of 12 meteorological and 6 culturable atmospheric bacterial (CAB) variables was made over a grass seed field during several early, mid, and late summer days. The observation site was located between the Cascade and Coastal Mountain Ranges near Corvallis in the Willamette Valley, Oregon. Principal component analysis identified those meteorological variables that had the highest loadings in six eigenvectors that account for 95.9% of variation in the data factors, i.e., temperature @ 6.3 m above

ground level (AGL), wind velocity @ 10.0 m AGL, wind velocity difference @ 1.7–10.0 m, barometric pressure, wind direction standard deviation, and wind direction. When these variables were used in a cluster analysis, they formed three statistically distinct meteorological variable clusters with means at ca. “midnight”, ca. “midday”, and ca. “evening.” The highest mean density of CAB (i.e., 153.4 ± 162.5 CFU/m³) was associated with the “midday” meteorological Cluster-1 that had warm, dry “gentle breezes” from the southeast, in the relatively bacteria loaded Willamette Valley air. The lowest mean density of CAB (i.e., 35.5 ± 24.1 CFU/m³) was associated with meteorological Cluster-3 in the late afternoon and “evening” occurring during the hottest and driest part of the day with “fresh breezes” coming from the north northwest in air off the Pacific Ocean. Finally, the last cluster, Cluster-2 occurred about midnight and had an intermediate density of CAB (74.2 ± 76.2 CFU/m³) in “light air” coming from the northwest, perhaps off the Pacific Ocean. The CAB associated with each of the three meteorological clusters was only partially statistically distinct. Partially because the CAB in both the Pacific Ocean derived air masses of the “evening” Cluster-3 and “midnight” Cluster-2 were not statically separable, though both were statistically separable from the midday, Willamette Valley derived Cluster-1. Further indicating their common source, both Pacific Ocean derived air masses had very similar percentages of pigmented bacteria, which were dissimilar to the pigmented bacterial population

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density in the Willamette Valley air masses. In short, it is speculated that “midnight” atmosphere may simply contain the settling concentrated residual bacterial particles in the abated fresh Pacific Ocean breezes after sundown. It is clearly shown that with the methods employed, it is possible to associate the uniqueness of the quantity, and to a lesser extent the quality, of the CAB population with the atmospheric conditions reported herein. From this project comes speculation that the strategies relating the quasi-conservative bacterial populations associated with distinct but nonconservative air mass properties can help to better understand more of the bacterial dynamics found in such situations. And to a further extent, molecular biological methods could be applied to identify bacterial taxa in specific air masses.

Keywords Airborne · Bacteria · Atmospheric · Concentration · Principal component analysis · Cluster analysis

1 Introduction

It is important to understand the population dynamics of bacteria dispersed by the atmosphere because of their contributions to various ecosystem circumstances. Specifically, with regard to the dynamics of the culturable atmospheric bacteria [CAB = culturable (unpigmented + pigmented) bacteria] in the atmospheric surface layer, we have begun to understand the quantitative standing stock, and from the dynamics of a few locations, in the overlying atmosphere (e.g., Miquel 1883; Miquel and Bnoist 1890; Kelly and Pady 1954; Vladavets and Mats 1958; Bovallius et al. 1978; Shaffer and Lighthart 1997). From these reports, annual cycles of bacteria were shown to be maximal in the summer and minimal in the winter. On a larger scale, from aircraft measurements, Fulton and Mitchell (1965) observed CAB varied with air mass, altitude (Fulton 1965a), and Earth’s meteorological characteristics (Fulton 1965b). More recently, it has been shown that quantities of CAB can vary considerably between environments, e.g., between four relatively closely located environments in or near the Willamette Valley, Oregon. The greatest numbers were observed at an urban site [609 CFU (i.e., Colony Forming Units)/m³] followed

by forest (522 CFU/m³), then a rural site (242 CFU/m³), and least at the Pacific Ocean shore (103 CFU/m³) (Shaffer and Lighthart 1997). Further, within an environment we have learned that there can be great variation in the CAB densities, e.g., as much as 1,400% change in concentration in a 2 min time span has been observed (Lighthart and Shaffer 1995; Lighthart 2000) and that the total atmospheric bacterial quantity might be at least 100 times that of the CAB in Willamette Valley, Oregon (Tong and Lighthart 1999, 2000). This relationship was also shown using molecular methods (Brodie et al. 2007; Beardsley 2006, and Rinsoz et al. 2008). Rinsoz et al. (2008) found 270–290-fold greater airborne bacterial load in poultry houses and sewage treatment plants using real-time quantitative PCR and epifluorescence methods compared to cultural methods, while Brodie et al. (2007) were able to identify approximately 1,800 bacterial types in urban aerosols using DNA microarrays. However, these molecular-based methods did not take local meteorological conditions into consideration. The relationship of the CAB to ambient meteorological conditions was a subject for speculation in Lighthart and Shaffer (1995) and is the subject of this communication based on the following logic.

As has been found in Pacific Coast ventilation studies (Neff and King 1987; Olson and Tuft 1970), cool mountain air flows down-slope during the night, while morning solar heating results in the formation of warm thermal updrafts. In the Cascade Mountains, large volumes of air are thus transported vertically as solar heating proceeds causing upward thermal transport of air with resultant need for replacement air being drawn, in this case, into and through the Willamette Valley through gaps in the Coast Range mountains in onshore breezes from the Pacific Ocean (Fig. 1). These winds then dissipate to light breezes at night. Finally, the cool, heavy air flowing down the mountain into the valley between the two mountain ranges at night fills the valley through the gaps in the mountains.

It now seems reasonable to expect that whether an understanding of the local micrometeorological processes is known, as indicated above, and whether measurements of the local ambient meteorological conditions and their contained atmospheric bacteria were measured, it would perhaps allow a better understanding and prediction, crude though it might be, of the quantity (and quality) of the atmospheric

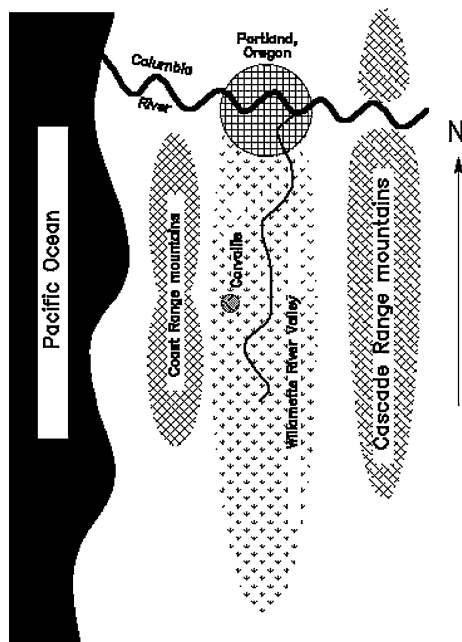


Fig. 1 Diagrammatic map of observation site (N 44° 31.958' W123°17.570) near Corvallis in the Willamette Valley, Oregon

bacteria. This is particularly true with recent advances in meteorological forecasting, modeling, and satellite-derived information (Andersen et al. 2009; Mandrioli and Ariatti 2001).

1.1 Purpose

The purpose of this study is to describe an experiment that expands upon our 1993 observations (Lighthart and Shaffer 1995) and confirms the speculations concerning the bacterial dynamics in the 1993 experiment. Specifically, we want to know whether the quantity of the bacteria associated with identifiable air masses passing an observation station is statistically unique.

The strategy is to determine whether the CAB associated with a set of meteorological conditions at an observation site is relatively simple. First, a set of varied meteorological and bacteriological parameters coincidentally observed in a time sequence must be measured. Secondly, determine which meteorological parameters are the overall major variance definers in the meteorological data, e.g., using principal component analysis (PCA) would be suitable. Third, using PCA-defined meteorological parameters and grouping the PCA meteorological data with similar overall properties into unique clusters, e.g., using cluster analysis. Finally,

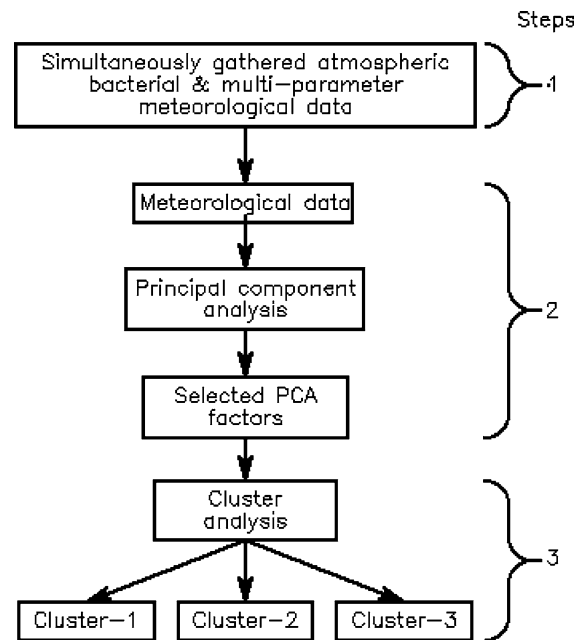


Fig. 2 Bacteriological and meteorological data analysis scheme

determine whether the quantity and in some way the quality of the atmospheric bacteria measured concurrently with the meteorologically defined clusters are relatively unique in a particular cluster, e.g., evaluate CAB means associated with clusters by Tukey–Kramer HSD (T–K) comparisons (Fig. 2).

2 Methods

Culturable atmospheric bacteria were collected with instruments located on a 10 m meteorological tower located at a site in the middle of a 400 ha grass seed growing field, located approximately 5 km southwest of the city of Corvallis in the mid-Willamette River Valley, Oregon (N 44° 31.958' W123°17.570; Fig. 1). A house was located approximately 30 m to the north northwest; otherwise, there were no other wind impedances for at least 500 m around the tower observation site. The tower held meteorological instruments and two platforms to support bacteriological samplers above ground level (AGL) (see Lighthart and Shaffer (1994) for the tower's detailed description). Collections were made during each of the following periods: the early (22–25 July), mid (6–9 and 19–22 August), and late (2–5 September) summer of 1996. In

each of the periods, samples were collected continuously during three 10 h segments: 10:00–20:00, 18:00–04:00, and 02:00–12:00, except on the last day (5 Sept) when samples were collected continuously from 05:00 to 22:00. Only those days in each period that were completely clear were used in the analysis.

2.1 Bacteriological

Two pairs of slit-impact bacteriological samplers (Model STA; New Brunswick Scientific Co., Inc., Edison, NJ) were placed on each platform. They were located at 0.3 and 6.3 m AGL and were suspended at their four corners by stainless steel cables from the top of the meteorological tower. Each slit-impact sampler was calibrated to run at an inflow rate of 28.3 l/min.

All bacterial samples collected were impacted onto 150 mm diameter Luria Bertani (Difco Laboratories, Detroit, MI) agar loaded plates and then incubated in the dark for 7 days at 25°C. Colony outgrowth was counted and recorded in each of the 2 min collection interval sections appearing on the agar surface i.e., 30°, 18°, and 12° sections for the 20, 40, or 50 min collection times, respectively, depending on the expected bacterial load with a 10 min off-period to allow the samplers to be removed, reloaded, and returned to the tower. Ten-second “control” samples were taken before and after each sample day to evaluate the potential for contamination of the sterile agar impaction plate during its placement in the sampler and sampler startup procedures. Pigmented CAB and unpigmented CAB are defined as colored and noncolored or white, respectively, while the sum of both together is termed simply total CAB.

2.2 Meteorological

The 10 m meteorological tower (Campbell Scientific, Inc., Logan, Utah) used in the investigation is shown as Fig. 1 in Lighthart and Shaffer (1994). Meteorological instruments placed on the tower consisted of temperature sensors located on the tower at 0.3 m AGL [all tower heights include displacement distance + aerodynamic roughness length (Stull 1988)], 2.3 m AGL, and 6.3 m AGL levels. In addition, there was a hygrometer at the 2.3 m AGL level, a pyranometer approximately 1.8 m AGL, and a cup anemometer at 1.7 and 10 m AGL, and wind direction vane at 10 m AGL. A sonic anemometer was located

at 3.5 m AGL to measure vertical air velocity (Campbell Scientific, Co., Logan, UT). All sensors were located so they had at least a 120° upwind acceptance angle to the prevailing wind. Meteorological data were sampled once every 5 s (except for the sonic anemometer that was collected at a frequency of 10 samples every second). All data were then averaged for every 10 min throughout the entire experiment.

2.3 Analytical

The analysis consisted of a 3-step procedure to find the relationship between 12 atmospheric meteorological factors (Table 1) and their associated pigmented and unpigmented bacteria, or both (termed CAB) in the measurements (Tables 3, 4). The first step was data preparation that consisted of outlier removal of CAB counts identified as beyond the Jackknife threshold. The next step was to select those meteorological factors that account for $\geq 90\%$ of the variance in the data using PCA (Table 1). The eigenvectors generated by the PCA were rotated using the Varimax procedure. Those factor variables with the highest loadings of the initial eigenvectors, which accounted for ca. 95.9% of the variance in the data, were used in the cluster analysis. The Ward-clustering algorithm was used in the cluster analysis. The number of clusters to be generated was contingent upon the fewest number of clusters that would have the greatest number of statistically significant differences between each of the environmental factors in the clusters (i.e., Tukey–Kramer (HSD) test at $P \leq 0.05$). Finally, the CAB population densities associated with the environmental measurements contributing to each cluster were calculated, and their between clusters Tukey–Kramer (T–K) comparisons were also calculated (Table 3).

Numerical analyses were performed using SAS Institute Inc. Cary, NC, JMP Version v7.0.1 and Wolfram Research, Inc., Champaign, IL, Mathematica v5.1 softwares with guidance from the book Applied Multivariate Data Analysis by Everitt and Dunn (2001).

3 Results

Initially, of the 4,181 environmental observations, 188 surpassed the Jackknife outlier test for acceptance and were removed (i.e., 4.5%) from further consideration

Table 1 Tabulation of variables used in principal component analysis, their measurement units, and Varimax rotated eigenvectors with initial 6 highest loaded factors, i.e., see delimited by italics

	Units	Eigen vectors											
		1	2	3	4	5	6	7	8	9	10	11	12
Eigenvalue		6.15	1.91	1.40	0.93	0.71	0.41	0.28	0.15	0.06	0.00	0.00	0.00
Percent		51.2	15.9	11.7	7.7	6.0	3.4	2.3	1.3	0.5	0.0	0.0	0.0
Cum percent		51.2	67.1	78.8	86.5	92.5	95.9	98.2	99.5	100.0	100.0	100.0	100.0
Solar radiation	kW/m ²	0.50	0.13	0.28	0.16	0.24	-0.30	-0.26	0.65	-0.01	0.00	0.00	0.00
Temperature @ 6.3 m	°C	0.97	0.19	0.01	-0.10	0.04	-0.11	0.01	0.06	0.04	0.01	0.00	0.00
Temperature @ 2.3 m	°C	0.96	0.20	0.03	-0.07	0.06	-0.14	-0.07	0.08	0.04	-0.02	0.00	0.00
Temperature @ 0.3 m	°C	0.92	0.24	0.08	-0.02	0.10	-0.17	-0.18	0.13	0.03	0.01	0.00	0.00
Temperature difference @ 0.3–6.3 m	°C	0.45	0.30	0.23	0.19	0.23	-0.28	-0.65	0.26	-0.02	0.00	0.00	0.00
Relative humidity	%	-0.82	-0.33	-0.11	-0.02	-0.16	0.19	0.23	-0.13	0.27	0.00	0.00	0.00
Wind velocity @ 10.0 m	m/s	0.31	0.94	0.07	-0.04	-0.08	0.06	-0.07	0.04	-0.01	0.00	0.00	0.00
Wind velocity @ 1.7 m	m/s	0.30	0.90	0.28	-0.04	-0.06	0.03	-0.09	0.05	-0.01	0.00	0.00	0.00
Wind velocity difference @ 1.7–10.0 m	m/s	0.05	0.24	0.95	-0.02	0.06	-0.12	-0.08	0.09	-0.01	0.00	0.00	0.00
Wind direction	°	-0.29	0.09	-0.13	-0.02	-0.11	0.93	0.10	-0.11	0.01	0.00	0.00	0.00
Wind direction, standard deviation	°	0.14	-0.11	0.06	0.07	0.97	-0.10	-0.08	0.08	-0.01	0.00	0.00	0.00
Barometric pressure	mmHg	-0.10	-0.05	-0.01	0.99	0.07	-0.02	-0.06	0.05	0.00	0.00	0.00	0.00

in the PCA. Next the PCA was performed with 12 meteorological parameters resulting in the first 6 Varimax rotated eigenvectors, accounting for 95.9% of the variance in the data (Table 1). This indicated that the highest loaded variables [i.e., air temperature at 6.3 m AGL, wind velocity at 10.0 m AGL, wind velocity difference @ 1.7–10.0 m, barometric pressure, wind direction standard deviation, and wind direction (Table 1)] in these eigenvectors would have the best chance of forming statistically unique clusters. Cluster analysis did form three statistically distinct clusters with the foregoing six variables (Figs. 3, 4). Except for relative humidity and wind velocity difference, the 12 variables in all 3 clusters were statistically significantly different ($P \leq 0.05$) as indicated by the T–K (HDS) test (Table 2).

In synopsis, 6 out of 12 meteorological variables were identified that formed 3 statistically unique sets of meteorological variables in a cluster analysis. Except for 2 variables, each of the 12 variables in each of the 3 clusters was statistically different.

With respect to the CAB populations associated with the three meteorological clusters, CAB in the 6.3 and 0.3 m tower elevations were statistically associated (i.e., T–K HSD) with either two of the meteorological clusters Clusters-1 (Midday) or Cluster-3 (Evening) and Cluster-2 (Midnight) (Table 3).

See the following for more descriptions of each of the 3 clusters:

Cluster-1 (Red) Cluster-1 is termed the “Midday” cluster because the meteorological conditions that delineated it occur about midday, with a mean time of 11.92 h (PST)¹ and in the range of ca. 08.00 h–ca. 16.00 h (PST). Characteristically, the cluster contained the maximum solar radiation values, and intermediate temperatures and relative humidity. The wind velocity of “gentle breezes” (Petterssen 1969) came from the southeast out of the Willamette Valley (Table 2), and maximum but equal, upward, and downward mean vertical wind velocities resulting in a maximum net air flux (Table 4).

In terms of the CAB, Cluster-1 was characterized by containing the maximum CAB concentration of the 3 clusters with a mean density of 153.4 ± 162.3 CFU/m³ (at 6.3 m AGL, Table 3). This density is approximately 2 times that of the Cluster-2 (“Midnight”

cluster) mean and approximately 4 times that of the Cluster-3 (“Evening” cluster) mean. Cluster-1 also had the highest percentage of pigmented bacteria at 54.8% of the CAB (at 0.3 m AGL, Table 3).

Finally, this cluster had the maximum mean upward flux of CAB into the atmosphere at 154.7 CFU/m²/s (at 0.3 m AGL, Table 4). It is presumed that natural plant, agricultural operations and human activity that generated CAB-associated particulate matter probably were the source of the particles appearing in the upwind fetch in the Willamette Valley.

Cluster-2 (Green) The environmental conditions that delineate Cluster-2 occurred at night (consequently termed the “Midnight” cluster) taking place around midnight to the early morning hours with a mean time of 01.62 h and range from 22.06 to 5.20 h (PDT). One would expect the nighttime conditions of this cluster to have the minimum solar radiation, air temperatures, and maximum relative humidity, which it does. Further, the mean wind velocity was at “slight breezes” out of the northwest (Table 3). And finally, the vertical wind velocity had almost twice the downward velocity as the upward velocity (Table 4).

The mean CAB density of Cluster-2 was approximately half that of the Cluster-1 and twice that of the Cluster-3 (at 6.3 & 0.3 m AGL, Table 3). The pigmented fraction was ca. 37% of the CAB (at 6.3 m AGL, Table 3), which is similar to the content of Cluster-3.

Cluster-3 (Blue) the environmental observation made for this cluster occurred in the late afternoon and “evening” period with a mean time of 17.60 h (PDT) that ranged from ca. 15.80 to 19.40 h. During these observations, environmental conditions were the warmest, the driest and, most characteristically, the windiest with “fresh breezes” out of the north northwest (Table 2).

The CAB in this cluster had the least mean concentration of any cluster at 35.5 CFU/m³ (at 6.3 m AGL, Table 3) with the pigmented proportion almost the same as was observed in Cluster-2. Finally, the downward net CAB flux was the greatest of any of the 3 clusters at -33.9 CFU/m²/s (at 0.3 m AGL, Table 4).

4 Conclusions

It is apparent that the CAB on clear summer days in the Willamette Valley can be associated with the

¹ 24 h clock with hh.hh format.

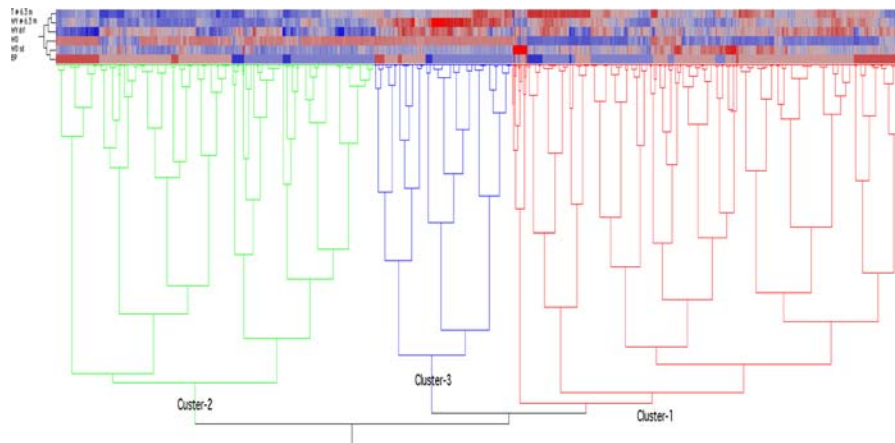


Fig. 3 Dendrogram of the clusters formed showing a color map (top 6 rows) of the 6 variables (i.e., temperature at 6.3 m AGL, wind velocity at 10.0 m AGL, wind velocity difference,

barometric pressure, wind direction, and wind direction standard difference) identified by the principal component analysis accounting for 95.9% of the variation in the data

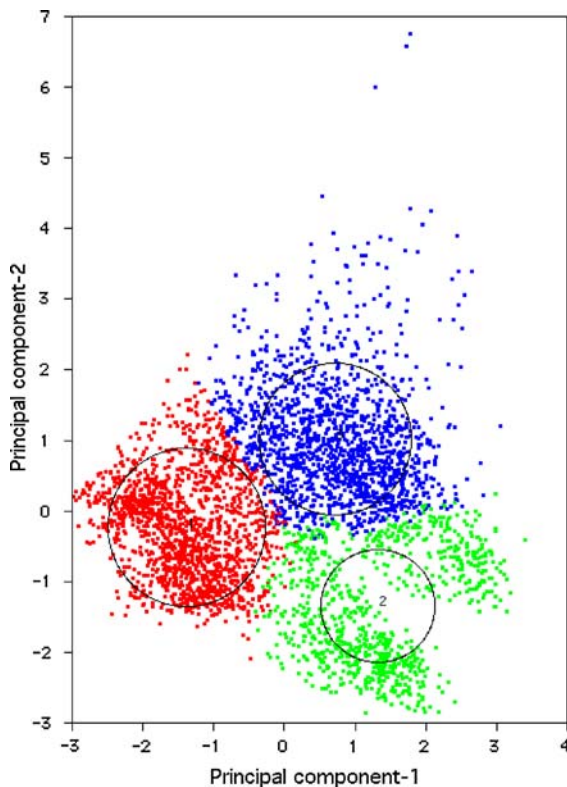


Fig. 4 Biplot showing the 3 meteorological colored data clusters formed using the variables identified by the principal component analysis. These 6 parameters accounted for 95.9% of the variation in the data

meteorological conditions prevailing at the time of their collection.

To begin the understanding of the CAB association with the meteorology in the Willamette Valley, Oregon, the following reasoning is given. As sun rises, solar heating of the soil in the Cascade Range causes the overlying air to warm and rise, resulting in the formation of large updrafts of warm light air and turbulent “light breezes”. As a consequence, soil and vegetation surface CAB are dislodged to rise in updrafts into the atmosphere as indicated by their maximum population in the “midday” Cluster-1. By late afternoon and evening, replacement air with its relatively sparse load of CAB populations in the Pacific Ocean air is drawn into the Willamette Valley through gaps in the Coast Range mountains as occurs in the “evening” Cluster-3. The onshore breezes abate during the night leaving residual ocean air with intermediate CAB population densities to settle out in the cool heavy night air covering the Valley floor as in the “midnight” Cluster-2. Further, the residual bacterial populations in the “midnight” atmosphere have the same proportion of pigmented bacteria as in the Pacific Ocean air (“evening”) and not the Willamette Valley air (“midday”).

It is clear as shown by the uniqueness of the quantity and, to a lesser extent, the quality of the CAB populations that the methods to associate these populations with particular atmospheric conditions suggested herein are promising. It is now speculated that the forgoing analysis methods can be incorporated with information generated by satellite images of ground truth data to evaluate bacteria releasing

Table 2 Chronological tabulation of the indicated meteorological measurement statistics including the Tukey–Kramer HSD, for each of the 3 meteorological clusters

Cluster number (Color) “Name”	Statistic	Time of day (PDT) (24.00 h clock)	Solar radiation (kW/ m2)	Air temperature				Relative humidity (%)	Wind			Direction		Barometric pressure (mmHg)
				6.3 m AGL (°C)	2.3 m AGL (°C)	0.3 m AGL (°C)	0.3 m–6.3 m (°C)		Velocity					
				10.0 m AGL (m/s)	1.7 m AGL (m/s)	1.7 m–10.0 m (m/s)								
2 (Green) “Midnight”	Mean	1.62	0.029	13.7	13.8	12.9	12.9	85	2.2	1.6	1.6	279	7.0	924.669
	SD	3.56	0.079	4.2	4.3	4.5	4.5	12	1.3	1.2	1.2	70	4.4	0.823
	N	1,421	1,421	1,421	1,421	1,421	1,421	1,421	1,421	1,421	1,421	1,421	1,421	1,421
	T–K (HSD) ^a	C ^a	C	C	C	C	C	A	C	C	B	B	A	B
1 (Red) “Midday”	Mean	11.92	0.506	22.0	23.6	25.1	3.1	48	4.0	4.1	0.1	122	15.8	924.818
	SD	4.01	0.284	6.0	6.3	6.7	1.5	17	2.0	2.2	0.5	100	8.8	0.726
	N	2,124	2,124	2,124	2,124	2,124	2,124	2,124	2,124	2,124	2,124	2,124	2,124	2,124
	T–K (HSD)	B	A	B	B	B	A	B	B	B	A	C	C	A
3 (Blue) “Evening”	Mean	17.60	0.271	24.3	25.5	26.6	2.4	47	8.4	8.5	−0.1 ^a	307	9.1	923.962
	SD	1.81	0.225	5.5	5.6	5.4	1.3	10	2.4	2.9	0.7	14	3.3	0.315
	N	448	448	448	448	448	448	448	448	448	448	448	448	448
	T–K (HSD)	A	B	A	A	A	B	B	A	A	A	A	A	B
Composite	Mean	10.38	0.310	19.3	20.3	20.9	1.6	61	3.9	3.7	−0.1	199	11.9	924.669
	SD	6.75	0.316	6.8	7.4	8.4	2.4	23	2.6	2.8	0.6	118	8.1	0.775
	N	3,993	3,993	3,993	3,993	3,993	3,993	3,993	3,993	3,993	3,993	3,993	3,993	3,993

^a Honestly significant difference

Table 3 Tabulation of the airborne pigmented and unpigmented mean bacterial concentrations (CFU/m³) at 0.3 and 6.3 m AGL for each of the 3 PCA identified meteorological clusters

Cluster number (Color) "Name"	Statistics	Time of day (PDT) (24 h clock)	Unpigmented bacteria		Pigmented bacteria		Sum of pigmented + unpigmented (or total) bacteria	
			6.3 m AGL	0.3 m AGL	6.3 m AGL	0.3 m AGL	6.3 m AGL	0.3 m AGL
2	Mean	1.62	47.1	50.0	27.1	26.8	74.2	76.8
(Green)	SD	3.56	45.2	38.8	40.0	37.9	76.2	73.5
"Midnight"	<i>N</i>	1,421	162	162	162	162	162	162
	Tukey–Kramer (HSD)	<i>C^a</i>	AB	A	B	B	B	B
	% Pigmented	NA	NA	NA	NA	NA	36.6	34.9
1	Mean	11.92	74.4	68.1	79.1	82.6	153.4	150.7
(Red)	SD	4.01	102.4	62.8	83.6	93.1	162.3	149.7
"Midday"	<i>N</i>	2,124	227	227	227	227	227	227
	Tukey–Kramer (HSD)	B	A	A	A	A	A	A
	% Pigmented	NA	NA	NA	NA	NA	51.5	62.2
3	Mean	7.60	22.9	25.7	12.6	17.5	35.5	43.2
(Blue)	SD	1.81	17.9	17.7	11.1	10.8	24.1	23.4
"Evening"	<i>N</i>	448	78	78	78	78	78	78
	Tukey–Kramer (HSD)	A	B	B	B	B	B	B
	% Pigmented	NA	NA	NA	NA	NA	46.2	46.1
Composite	Mean	10.38	56.3	54.7	50.0	52.4	106.2	107.1
	SD	6.75	78.9	52.2	69.2	74.8	131.0	121.5
	<i>N</i>	993	467	467	467	467	467	467

^a Honestly significant difference

Table 4 Tabulation of cluster chronology of the mean vertical wind velocity of the unpigmented and pigmented airborne bacteria at 0.3 and 6.3 m AGL

Cluster number (Color) "Name"	Statistic	Time of day (PST) (24 h clock)	Vertical wind velocity		Bacteria					
			Upward $w > 0$ (m/s)	Downward $w < 0$ (m/s)	Unpigmented @ 0.3 m AGL		Pigmented @ 0.3 m AGL		Unpigmented @ 6.3 m AGL	
					Updraft (CFU m ⁻² s ⁻¹)	Downdraft (CFU m ⁻² s ⁻¹)	Updraft (CFU m ⁻² s ⁻¹)	Downdraft (CFU m ⁻² s ⁻¹)	Updraft (CFU m ⁻² s ⁻¹)	Downdraft (CFU m ⁻² s ⁻¹)
2 (Green) "Midnight"	Mean	1.62	0.018	-0.032	73.5	39.5	48.4	19.0	69.0	39.2
	SD	3.56	0.012	0.021	53.0	25.2	58.4	21.6	69.7	29.3
	<i>N</i>	1,421	53	132	31	87	31	87	31	85
	Tukey–Kramer (HSD)	C ^a	B	A	A	A	A	B	A	AB
1 (Red) "Mid day"	Mean	11.92	0.036	-0.036	69.3	49.4	85.4	53.9	87.3	52.2
	SD	4.01	0.025	0.027	66.9	47.4	93.1	72.3	127.3	64.8
	<i>N</i>	2,124	186	167	113	110	113	110	108	107
	Tukey–Kramer (HSD)	A	A	A	A	A	A	A	A	A
3 (Blue) "Evening"	Mean	17.60	0.020	-0.076	24.7	35.4	5.3	28.5	35.3	27.5
	SD	1.81	0	0.037	NA	26.5	NA	30.5	NA	29.4
	<i>N</i>	448	3	84	1	44	1	47	1	46
	Tukey–Kramer (HSD)	B	AB	B	A	A	A	B	A	B
Composite	Mean	10.38	0.032	-0.043	69.9	43.3	77.0	36.5	82.8	42.8
	SD	6.75	0.024	0.033	63.9	37.5	87.9	54.3	116.6	49.4
	<i>N</i>	3,993	242	383	145	241	145	244	140	238

The Tukey–Kramer honestly significant differences (HSD) are also shown for each column variable

^a Honestly significant difference

sources such as vegetation surfaces with known phenologies (e.g., molecular biological identification) or soil surfaces of known characteristics, and meteorological models consisting of wind velocities, directions, gustiness, and durations. It is thought that this will allow a reasonable ability to predict the natural bacterial population concentration (and perhaps the quality) in the Earth's atmospheric surface layer.

Finally, it is clear that given a sufficient set of meteorological parameters and bacterial survival kinetics, an understanding of the dynamics of the local natural viable (and nonviable) bacterial populations in the Earth's al fresco atmospheric surface layer can be much better understood.

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References

- Andersen, G. L., Frisch, A. S., Kellogg, C. A., Levetin, E., Lighthart, B., & Paterno, D. (2009). Aeromicrobiology/air quality. In *Encyclopedia of microbiology* (3rd ed., pp. 11–26).
- Beardsley, T. M. (2006). Metagenomics reveals microbial diversity. *BioScience*, 56(3), 192–196.
- Bovallius, A., Bkkucht, B., Roffey, R., & Anas, P. (1978). Three-year investigation of the natural airborne bacterial flora at four localities in Sweden. *Applied and Environmental Microbiology*, 35(4), 847–852.
- Brodie, E. L., DeSantis, T. Z., Moberg Parker, J. P., Zubieta, I. X., Piceno, Y. M., & Andersen, G. L. (2007). Urban aerosols harbor diverse and dynamic bacterial populations. *PNAS*, 104(1), 299–304.
- Everitt, B. S., & Dunn, G. (2001). *Applied multivariate data analysis*. London, UK: Hodder Headline Group. p. 342.
- Fulton, J. D. (1965a). Microorganisms in the upper atmosphere. III. Relationship between altitude and micropopulation. *Applied Microbiology*, 14, 237–240.
- Fulton, J. D. (1965b). Microorganisms in the upper atmosphere. IV. Microorganisms of a land air mass as it traverses an ocean. *Applied Microbiology*, 14, 241–244.
- Fulton, J. D., & Mitchell, R. B. (1965). Microorganisms in the upper atmosphere. II. Microorganisms in two types of air masses at 690 meters over a city. *Applied Microbiology*, 14, 232–236.
- Kelly, C. D., & Pady, S. M. (1954). Microbiological studies of air masses over Montreal during 1950–1951. *Canadian Journal of Botany*, 32, 591–600.
- Lighthart, B. (2000). Mini-review of the concentration variations found in the al fresco atmospheric bacterial populations. *Aerobiologia*, 16, 7–16.
- Lighthart, B., & Shaffer, B. T. (1994). Bacterial flux from chaparral into the atmosphere in mid-summer at a high desert location. *Atmospheric Environment*, 28(7), 1267–1274.
- Lighthart, B., & Shaffer, B. T. (1995). Airborne bacteria in the atmospheric surface layer: Temporal distribution above a grass seed field. *Applied and Environmental Microbiology*, 61(4), 1492–1496.
- Mandrioli, P., & Ariatti, A. (2001). Aerobiology: Future course of action. *Aerobiologia*, 17, 1–10.
- Miquel, P. (1883). *Les organismes vivantes de n. Annu. Obs. Montisouris* (p. 310). Paris: Bauthier-Villars.
- Miquel, P., & Benoist, L. (1890). De l'enregistrement des poussières atmosphériques brutes et organisées. *Annals Micrographie*, 1, 572–579.
- Neff, W. D., & King, C. W. (1987). Observations of complex-terrain flows using acoustic sounders: Experiments, topography, and winds. *Boundary-Layer Meteorology*, 40, 363–392.
- Olson, L. E., & Tuft, W. L. (1970). *A study of the natural ventilation of the Columbia-Willamette Valley*. Tech. Rpt. NO. 70–6. Corvallis: Oregon State University.
- Pettertsen, S. (1969). *Introduction to meteorology* (3rd ed., pp. 333). New York: McGraw-Hill Book Co.
- Rinsoz, T., Duquenne, P., Greff-Mirguet, G., & Oppliger, A. (2008). Application of real-time PCR for total airborne bacterial assessment: Comparison with epifluorescence microscopy and culture-dependent methods. *Atmospheric Environment*, 42(28), 6767–6774.
- Shaffer, B. T., & Lighthart, B. (1997). Survey of culturable airborne bacteria at four diverse locations in Oregon: Urban, rural forest, and coastal. *Microbial Ecology*, 34, 167–177.
- Stull, R. B. (1988). *An introduction to boundary layer meteorology* (pp. 670). Boston: Kluwer Academic Publishers.
- Tong, Y., & Lighthart, B. (1999). Diurnal distribution of total and culturable atmospheric bacteria at a rural site. *Aerosol Science and Technology*, 30, 246–254.
- Tong, Y., & Lighthart, B. (2000). The annual bacterial particle concentration and size distribution in the ambient atmosphere in a rural area of the Willamette Valley, Oregon. *Aerosol Science and Technology*, 32, 393–403.
- Vladavets, V. V., & Mats, L. I. (1958). The influence of meteorological factors on the microflora. *Microbiologia (English translation)*, 59, 539–544.