Solar and Climate Effects Explain the Wide Variation in Legionellosis Incidence Rates in the United States

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ABSTRACT Legionellosis, an infection caused by the environmental bacteria *Legionella* spp., has become a significant public health problem in the United States in recent years; however, among the states, the incidence rates vary widely without a clear explanation. This study examined environmental effects on the 2014-to-2016 average annual legionellosis incidence rates in the U.S. states through correlative analyses with long-term precipitation, temperature, solar UV radiation, and sunshine hours. The continental states west of $\sim 95^{\circ}\text{W}$ showed low incidence rates of 0.51 to 1.20 cases per 100,000 population, which corresponded to low precipitation, below 750 mm annually. For the eastern states, where precipitation was higher, solar effects were prominent and mixed, leading to wide incidence variation. Robust regressions suggested a dividing line at 40°N : north of this line, rising temperature, mainly from solar heat, raised legionellosis incidence to a peak of 4.25/100,000 in Ohio; south of the line, intensifying sunlight in terms of high UV indices and long sunshine hours prevailed to limit incidence gradually to 0.99/100,000 in Louisiana. On or near the 40°N line were 15 eastern states that had leading legionellosis incidence rates of $>2.0/100,000$. These states all showed modest environmental parameters. In contrast, the frigid climate in Alaska and the strong year-round solar UV in Hawaii explained the lowest U.S. incidences, 0.14/100,000 and 0.47/100,000, respectively, in these states. The findings of solar and climate effects explain the wide variation of legionellosis incidence rates in the United States and may offer insights into the potential exposure to and prevention of infection.

IMPORTANCE Legionellosis, caused by the environmental bacteria *Legionella* spp., has become a significant public health problem in the United States in recent years, with $\sim 6,000$ cases annually. The present study showed, through a series of correlative analyses with long-term precipitation, temperature, solar UV radiation, and sunshine hours, that these environmental conditions strongly influence the legionellosis incidence rates across the United States in mixed and dynamic fashions. The incidence rates varied remarkably by region, with the highest in Ohio and New York and the lowest in Alaska. A precipitation threshold above 750 mm was required for elevated legionellosis activity. Regression models and dividing lines between regions were established to show the promotive effect of temperature, as well as the inhibitive effects of solar UV and sunshine hours. These findings explain the wide variation of legionellosis incidence rates in the United States. They may also offer insights into potential exposure to and prevention of infection.

KEYWORDS legionellosis, ultraviolet, solar radiation, temperature, precipitation, seasonality of disease

Legionellosis, caused by the environmental bacteria *Legionella pneumophila* and other *Legionella* spp., includes Legionnaires' disease, Pontiac fever, and rare extrapulmonary disease (1, 2). Infections may occur sporadically or in outbreaks following inhalation of bacteria-bearing aerosols or dust (3–5). Since its recognition after a large

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FIG 1 Map of the United States with 2014-to-2016 averaged annual legionellosis incidence (drawn using <https://mapchart.net/usa.html>). Annotated are the 40°N line, the ~95°W line, and the Great Lakes, Mississippi River, and Ohio River.

outbreak in 1976 (3), legionellosis has become a significant public health problem in the United States, particularly in recent years, with more than 6,000 cases annually or ~1.80 cases per 100,000 population, a 5-fold increase from 2000 (6). Among the states, the rates varied widely without clear explanation or in-depth analysis.

As freshwater and soil organisms (2), *Legionella* spp. require adequate temperature and water for survival and proliferation and are thus affected by the season and weather. The effects of river systems, temperature, and rainfall on the occurrence of legionellosis have been noted, using local or state level data over time (7–9). A recent study assessed the weather-dependent risk for legionellosis among hospitalized patients with pneumonia in 26 U.S. states and found increased risk during the warm and humid summer in the mid-Atlantic states but decreased risk in the dry southwestern states (10). Our previous and ongoing studies on legionellosis in a cancer population noted seasonal fluctuations in incidence (11), also hinting at environmental influence, in addition to host vulnerabilities.

In this study, we systematically examined the legionellosis incidence rates in the United States with regard to environmental conditions in an attempt to uncover the reasons behind the wide incidence variation among the states. In addition to precipitation and temperature, effects of solar UV radiation and sunshine hours, rarely studied before, were also explored. These parameters were correlated with incidence rates using linear regression to assess their qualitative and quantitative effects.

RESULTS

The average annual incidence rates during 2014 to 2016 by U.S. state were first assessed (Fig. 1). The rates averaged 1.80/100,000 in the United States and varied remarkably by region.

High incidence rates were concentrated in the Great Lakes region. Ohio and New York led the United States with 4.25/100,000 and 3.79/100,000, respectively, and Michigan was the fifth highest with 2.60/100,000. The three states have annual precipitation levels of 833 to 1,062 mm and low annual sunshine at 2,245 to 2,392 h. These states, along with lakeside Minnesota and Wisconsin, all have cold winters, mild to

FIG 2 Correlation of legionellosis incidence with temperature in the northern United States: 5 Great Lakes area states (gray), 6 New England states (orange), and 10 northwestern states (blue).

warm summers, and low annual mean solar UV indices of 2.5 to 3.05. As shown in Fig. 2 (gray circles) and Table 1, the annual mean temperatures for these states, from 5.1 to 10.4°C, correlated linearly with the legionellosis incidence rates ($R^2 = 0.9897$; $P = 4.48E-4$), suggesting a strong solar warming effect. A weak inverse correlation with sunshine hours was also noted, but it was diminished by the temperature effect in multiple regressions (Table 2). Upstate New York, bordering the lakes, had an incidence of 3.91/100,000, above that of the Atlantic-side New York City (3.64/100,000, or 3.10/100,000 if the cases of the 2015 Bronx outbreak due to cooling towers are excluded) (12). Therefore, the high legionellosis rates in Ohio, New York, and Michigan were inferably related to the Great Lakes.

TABLE 1 Correlation of legionellosis incidence with temperature in the northern United States

State	Incidence (no. of cases/100,000)	Annual mean temp (°C)	Annual mean UV index	Annual precipitation (mm)	Annual sunshine h
Great Lakes area					
Minnesota	1.37	5.1	2.50	693	2,711
Wisconsin	1.89	6.2	2.68	829	2,468
Michigan	2.60	6.9	2.70	833	2,392
New York	3.79	9.4	2.87	1,062	2,306
Ohio	4.25	10.4	3.05	993	2,245
New England					
Maine	1.28	5.0	2.31	1,072	2,513
Vermont	1.86	6.1	2.51	1,085	2,407
New Hampshire	1.80	6.6	2.61	1,103	2,519
Massachusetts	2.19	8.8	2.97	1,211	2,572
Connecticut	1.81	9.4	3.02	1,279	2,602
Rhode Island	2.71	10.1	3.03	1,218	2,606
Northwest					
Alaska	0.14	−3.0	0.57	572	2,061
North Dakota	0.62	4.7	2.48	452	2,738
Wyoming	0.51	5.6	3.91	328	3,073
Montana	0.71	5.9	2.84	390	2,698
Idaho	0.81	6.9	3.34	481	2,993
South Dakota	1.13	7.3	3.07	511	2,947
Iowa	1.09	8.8	3.20	864	2,691
Washington	0.83	9.1	2.51	976	2,170
Oregon	0.96	9.1	3.30	695	2,341
Nebraska	1.02	9.3	3.75	599	2,762

TABLE 2 Significant regressions between legionellosis incidence rates and environmental parameters for the Great Lakes area and New England states^a

Region/parameter	Coefficient	P value	Interpretation/note ^b
Great Lakes area (<i>n</i> = 5)			
Sunshine h	−0.0063	0.024	Weakly inhibitive?
Intercept	17.95	0.015	
<i>R</i> ² value	0.8567	0.024	Weak
Temp (°C)	0.4941	0.030	Promotive
Sunshine h	−0.0007	0.57	Loss of significance
Intercept	0.7785	0.83	Not statistically significant
Adjusted <i>R</i> ² value	0.9832	0.0084	Modest
New England (<i>n</i> = 6)			
Temp (°C)	0.5331	0.0021	Promotive
Precipitation (mm)	−0.0088	0.0063	Inhibitive
Intercept	8.042	0.0054	
Adjusted <i>R</i> ² value	0.9644	0.0029	Modest
Both regions (<i>n</i> = 11)			
Temp (°C)	0.7587	0.0013	Strongly promotive
Precipitation (mm)	−0.0024	0.0011	Inhibitive
Sunshine h	−0.0024	0.0030	Inhibitive
UV index	−2.6794	0.027	Inhibitive
Intercept	12.46	1.4E−04	
Adjusted <i>R</i> ² value	0.9708	2.13E−05	Robust

^aIncidence equation, $12.46 + 0.7587 \times T - 0.0024 \times P - 0.0024 \times S - 2.6794 \times U$, where *T* is temperature, *P* is precipitation, *S* is sunshine hours, and *U* is UV index.

^bWeak means the *P* value is <0.05 but >0.01; robust means *P* value is E−5 and *R*² is >0.9; modest is between weak and robust.

Seasonally, most cases in Ohio and upstate New York occurred in June to November following warm weather from May to September (see Fig. S1 and S2 in the supplemental material). These cases comprised 75% and 69% of the 494 and 439 annual cases in these states, respectively. In addition, the falling solar UV indices of 4 to 0.6 from September to November also coincided with the sustained infections in October and November, hinting at a permissive role of low UV. This result led to regression analyses of the monthly data (see Table S2 in the supplemental material), which showed a strong temperature effect, as well as an inhibitive effect of UV radiation that peaked in the summer (indices of 6 to 5.6).

The New England states were led by Rhode Island, which had an incidence of 2.71/100,000, the fourth highest in the United States (Fig. 2, orange circles, and Table 1). From Maine to Rhode Island, the incidence also rose with temperature, but at a slow pace with variations (*R*² = 0.6614; *P* = 0.049). A multiple regression analysis further revealed a negative effect of precipitation to account for the variation, as well as to improve regression (adjusted *R*² = 0.9644; *P* = 0.0029) (Table 2). The temperature effect was also noted to be stronger, an increase in the coefficient from 0.19 to 0.5331, similar to the coefficient of 0.5479 for the lake area states. This congruence, together with the similar gradients of temperature and UV index for both regions, led to the merging of data for combined analysis of the 11 states (Table 2). The result showed, in robust multiple regressions (adjusted *R*² = 0.9708; *P* = 2.13E−5), not only the anticipated promotive effect of temperature, but also inhibitive effects of precipitation, sunshine hours, and UV radiation. The finding of inhibitive solar effects of sunshine hours and UV radiation, while surprising, is supported by early experimental studies showing that both sunlight and UV radiation kill *L. pneumophila* (13, 14). With this model, the prediction matched the incidence well, by an average variance of 4.4% (Table 3).

Therefore, more precipitation and sunshine in the coastal New England states, particularly Massachusetts, Connecticut, and Rhode Island, with temperatures and UV indices similar to those of neighboring upstate New York, were the likely sources of variation and lower overall incidence rates (Fig. 2 and Table 1). Conversely, the low

TABLE 3 Variances of actual and predicted legionellosis incidence rates in the 11 Great Lakes area and New England states^a

State	Actual rate (no. of cases/100,000)	Prediction from Table 2 equation		
		Predict-1	Variance-1	V-1 %
Connecticut	1.81	2.0677	0.2576	14.23
Maine	1.28	1.3519	0.0730	5.71
Wisconsin	1.89	1.9684	0.0740	3.90
Ohio	4.25	4.2956	0.0448	1.05
Vermont	1.86	1.8733	0.0097	0.52
Michigan	2.60	2.6106	0.0105	0.40
Rhode Island	2.71	2.6911	−0.0228	−0.84
Minnesota	1.37	1.3399	−0.0264	−1.93
New York	3.79	3.7082	−0.0822	−2.17
New Hampshire	1.80	1.6657	−0.1380	−7.65
Massachusetts	2.19	1.9640	−0.2289	−10.44
Mean				4.44

^aVariance = predicted rate − actual rate; percent variance = (variance/actual rate) × 100. The mean was calculated upon conversion of negative percent variance to absolute.

sunshine hours in Ohio and New York, the third and fourth lowest in the United States, following Alaska and Washington (Fig. 2 and Table 1), permitted and contributed to the high incidences in these states.

The 20 states and District of Columbia, located south of the 11 states discussed above were led by Pennsylvania, which had the third-highest incidence in the United States (2.80/100,000) (Fig. 3 and Table 4). Hawaii was also included in this group, in view of its similar warm and wet climate. These states all have abundant precipitation and sunshine, 927 to 1,528 mm (median, 1,178 mm) and 2,408 to 3,036 h (median, 2,639 h), respectively. From north to south, as the temperatures and UV indices rose, the incidence rates declined gradually, suggesting an inversion, which accorded again with the germicidal effect of UV in the sunlight spectrum. As plotted in Fig. 3 and shown in Table 4, the inverse regression with the UV index was robust in view of the vast area of the region. Similarly, the sunshine hours also showed an inverse correlation with incidence rates, verified by multiple regressions (Table 5). Precipitation was also noted to be a weak negative factor. However, multiple regressions with temperature were hindered by multicollinearity.

Florida showed a higher-than-predicted incidence of 1.50/100,000 (Fig. 3 and Table 4). This was related to its peninsular climate, where the warm winter (nadir, 15.7°C) and modest UV indices of 2.5 to 5.7 from October to March led to more infections in December to May (44% of the annual 305 cases) than for other states in these months (see Fig. S3 in the supplemental material). Strong sunlight, with UV indices of 6.5 to a peak of 8.1, and longer sunshine hours from April to September limited legionellosis from June to November (56%). A multiple regression analysis of the seasonal data also showed these counteractive effects (see Table S2). In contrast, Hawaii has a tropical climate without winter, i.e., similar temperature, rainfall, and strong sunlight all year (a UV index of 6.1, the highest in the United States) (Fig. 3 and Table 4), which explained its second-lowest U.S. legionellosis incidence (0.47/100,000).

Together, in the 33 eastern states analyzed above, a wide range of legionellosis incidence rates reflected the net outcome of strong mixed solar effects. Robust regressions (Fig. 2 and 3 and Tables 1, 2, 4, and 5) pointed to a dividing line at a latitude of 40°N that passes through Columbus, OH, and Philadelphia, PA. North of this line, rising temperature, mainly from solar heat, was dominant in raising legionellosis incidence to a peak of 4.25/100,000 in Ohio; south of this line, intensifying sunlight in terms of high UV radiation and long sunshine hours prevailed to limit incidence gradually to 0.99/100,000 in Louisiana. On or near the 40°N line were 15 states that had leading incidence rates in the United States, above 2.0/100,000 (Fig. 1). These states together had an incidence of 2.81/100,000, with 3,270 cases, or 56.4% of all the cases in the United States. The states all had moderate climates with narrow ranges of

FIG 3 Inverse correlation of legionellosis incidence with solar UV index in 22 eastern U.S. states and the District of Columbia.

temperature (6.9 to 14.2°C), UV indices (2.7 to 4.15), precipitation (833 to 1,376 mm), and sunshine duration (2,245 to 2,626 h).

For all 33 eastern states, the merged data overcame multicollinearity and the polar dominant effectors across the 40°N line to allow multiple regressions that were unified in showing the promotive effect of temperature, as well as the inhibitive effects of sunshine hours, UV, and precipitation (Table 6). In support of the analytic validity, the incidence rates and environmental parameters were found to follow a normal distribution (data not shown). This model carried a predictive variance of 14.5% on average (see Table S3 in the supplemental material).

The potential effects of major rivers on the legionellosis activity were also examined. Near the 40°N line, the Ohio River flows to the west to exert its influence. At its origin at the confluence with the Allegheny and Monongahela Rivers, Pittsburgh (40.4°N, 80.0°W) has a high legionellosis rate, up to 7.05/100,000 in 1993 (15). The city has 2,021 h of sunshine annually, among the least in the United States. The river forms part

TABLE 4 Inverse correlation of legionellosis incidence with solar UV index in the eastern United States

State/district	Incidence (no. of cases/100,000)	Annual mean temp (°C)	Annual mean UV index	Annual precipitation (mm)	Annual sunshine h
Pennsylvania	2.80	9.3	3.06	1,089	2,408
Delaware	2.47	12.9	3.45	1,160	2,527
Maryland	2.44	12.3	3.49	1,131	2,582
Indiana	2.41	10.9	3.37	1,060	2,476
Illinois	2.29	11.0	3.50	996	2,544
New Jersey	2.28	11.5	3.13	1,196	2,517
Missouri	2.26	12.5	3.89	1,071	2,626
Kentucky	2.14	13.1	3.87	1,242	2,514
Tennessee	2.05	14.2	4.15	1,376	2,510
West Virginia	2.04	11.0	3.53	1,147	2,550
North Carolina	1.98	15.0	4.13	1,279	2,651
District of Columbia	1.88	13.2	3.68	1,035	2,528
Virginia	1.64	12.8	3.88	1,125	2,760
Arkansas	1.38	15.8	4.49	1,284	2,771
Alabama	1.27	17.1	4.84	1,480	2,666
Oklahoma	1.23	15.3	4.62	927	2,938
Mississippi	1.15	17.4	4.89	1,499	2,720
South Carolina	1.13	16.9	4.50	1,264	2,826
Georgia	1.08	17.5	4.77	1,287	2,868
Louisiana	0.99	19.1	5.19	1,528	2,714
Hawaii	0.47	21.1	6.10	1,026	3,036
Florida	1.50	21.5	5.72	1,385	2,927

TABLE 5 Significant regressions between legionellosis incidence rates and environmental parameters for 22 eastern U.S. states and District of Columbia

Regression/parameter	Coefficient	P value	Interpretation or note ^a
Simple linear (<i>n</i> = 22)			
UV index	−0.6652	2.32E−08	Inhibitive ^c
Intercept	4.556	6.46E−12	
<i>R</i> ² value	0.7970	2.32E−08	Robust
Sunshine h	−0.0031	1.76E−07	Inhibitive
Intercept	10.02	8.32E−09	
<i>R</i> ² value	0.7520	1.76E−07	Modest
Multiple linear ^b (<i>n</i> = 22)			
UV index	−0.4203	0.0059	Strongly inhibitive
Sunshine h	−0.0014	0.049	Inhibitive
Intercept	7.19	2.06E−05	
Adjusted <i>R</i> ² value	0.8180	3.61E−08	Robust
UV index	−0.6766	1.87E−07	Strongly inhibitive
Precipitation (mm)	0.0001	0.76	Loss of significance
Intercept	4.45	1.54E−08	
Adjusted <i>R</i> ² value	0.7767	2.52E−07	Modest
Sunshine h	−0.003	4.67E−08	Inhibitive
Precipitation (mm)	−0.001	0.011	Likely inhibitive
Intercept	10.94	7.5E−10	
Adjusted <i>R</i> ² value	0.8068	6.38E−08	Robust

^aRobust means *P* is equal to E−8 and *R*² is at or near 0.80.

^bRegressions with temperature, as well as involving three parameters, were hindered by multicollinearity in this data set.

^cFrom Fig. 3 and Table 4.

of the eastern and southern borders of Ohio, which, along with Lake Erie, likely contributed to the peak incidence in Ohio. Further west, the Mississippi River (~90°W) had less influence on the 10 states it borders; the highest incidence was 2.29/100,000 in Illinois, due to its origin in cold northern Minnesota with its entire course of flow under stronger sunlight.

The western United States was also analyzed from north to south, divided at or near the 40°N line. With Alaska included, the northern 10 states had temperatures of −3 to 9.3°C, UV indices of 0.57 to 3.91, precipitation of 328 to 976 mm (median, 541 mm), and 2,061 to 3,073 h of sunshine (median, 2,718 h) (Fig. 2, blue circles, and Table 1). These states all had low legionellosis incidence rates, from 0.14/100,000 in Alaska—the lowest in the United States—to 1.13/100,000 in South Dakota, which also correlated with temperature (*R*² = 0.7964; *P* = 5.1E−04). Hence, the frigid climate in Alaska was responsible for the lowest incidence. Similarly, the cold, dry, and sunny climate in Wyoming and North Dakota explained the third- and fourth-lowest incidences in these states (Fig. 2 and Table 1). Washington, in spite of the annual 976 mm of precipitation, had a seasonal drought from June to September (118 mm) to deter legionellosis in the summer. As rainfall increased in October (88 mm) and the temperature remained warm

TABLE 6 Multiple regression analysis between the legionellosis incidence rates and environmental parameters for 33 eastern U.S. states and District of Columbia^a

Parameter	Coefficient	P value	Interpretation/note ^b
Temp (°C)	0.3341	5.38E−04	Promotive
Precipitation (mm)	−0.0016	0.0031	Inhibitive
Sunshine h	−0.0036	4.14E−06	Inhibitive
UV index	−1.2522	0.0049	Inhibitive
Intercept	13.76	2.1E−10	
Adjusted <i>R</i> ² value	0.7713	2.02E−09	Robust

^aIncidence equation, $13.76 + 0.3341 \times T - 0.0016 \times P - 0.0036 \times S - 1.2522 \times U$, where *T* is temperature, *P* is precipitation, *S* is sunshine hours, and *U* is UV index.

^bRobust means the *P* value is equal to E−09.

TABLE 7 Legionellosis incidences and environmental parameters in 8 southwestern U.S. states

State	Incidence (no. of cases/100,000)	Annual mean temp (°C)	Annual mean UV index	Annual precipitation (mm)	Annual sunshine h
Nevada	0.88	9.9	4.50	241	3,646
Utah	0.99	9.2	4.62	310	3,029
Arizona	1.11	15.7	5.72	345	3,806
New Mexico	0.75	11.9	5.72	370	3,415
Colorado	1.20	7.3	4.98	405	3,204
California	1.18	15.2	4.85	563	3,055
Kansas	0.94	12.4	4.25	733	2,922
Texas	0.99	18.2	5.36	734	2,850

(11.6°C), the number of cases rose to a small annual peak in November (20%; 11 of 54 cases). The low incidence in Iowa was unexplained, given that the state's environmental parameters would predict an elevated rate.

The 8 states in the southwest all had low legionellosis incidence rates (0.75 to 1.20 per 100,000), low precipitation (241 to 734 mm), strong UV (indices of 4.50 to 5.72), intense sunshine (2,850 to 3,806 h), and mostly high temperatures (7.3 to 18.2°C) (Table 7). There were no correlations between environmental conditions and incidence. This result, in concert with the findings in other regions, suggests that annual precipitation above 750 mm is a prerequisite for elevated legionellosis activity. Together, the 18 western states, ~95°W and beyond, had an overall incidence rate of 1.04/100,000, below the U.S. average of 1.80/100,000, or 2.21/100,000 in the eastern states. Low soil moisture limits indwelling bacteria.

DISCUSSION

The above analyses show that environmental conditions strongly influence, in mixed and dynamic fashions, the incidence of legionellosis across the United States. In the western states, low precipitation (below a threshold of 750 mm) corresponds to low incidence. In the eastern states, with more precipitation, solar effects are prominent. While the sun warms the cold north to raise the incidence, strong UV radiation and long sunshine hours in the south limit the incidence. The 40°N line separates the dominant solar effects. Additional effects inferably come from water bodies. The peak incidence in Ohio, well above those of nearby states, can be explained by the promotive warm spring and summer (up to 24°C) and adequate precipitation (993 mm), the permissive low solar UV index (3.05) and low sunshine hours, and the likely contributions from Lake Erie and the Ohio River. Away from the continental United States, the lowest incidence rates, in Alaska and Hawaii, are explained by the coldest climate and the strongest UV radiation, respectively.

The revelation of inhibitive solar effects from UV radiation and sunshine hours lends insights into exposure to and prevention of infection, and sporadic cases in particular. Solar UV radiation, being superficial, may inhibit bacteria on the surface of soil and within a depth of water that depends on solar strength and water clarity. Most vulnerable are bacteria on paved road surfaces, deposited incidentally by rainfall, soil/water work, or other means. However, bacteria may survive at night or under weak or attenuated sunlight, such as in the northern United States, on wet roads, or in puddles due to rainy/cloudy days, fog, high humidity, etc.

The isolation of viable *Legionella* spp. on road surfaces implies that bacteria-bearing aerosols or dust can be stirred up by motor vehicle traffic to become a source of exposure to drivers and passengers (16, 17). In the south, intense sunlight abates this risk, particularly in the spring and summer, with long days, high temperatures, and UV indices of 7 to 10, sufficient to sterilize road surfaces and to inhibit soil and water bacteria. In the north, however, road exposure may be significant for several reasons. First, daily driving is a way of life for most Americans. Second, professional drivers have been shown to be at elevated risk of legionellosis (18–20). Third, exposure to *Legionella* spp. is relatively common, according to serologic studies showing that 20 to 30% of

residents in Ohio and Michigan carry antibodies to the bacteria (21–23). Finally, sporadic or community-acquired legionellosis cases make up ~80% of all cases in the United States and Europe without clear sources of exposure (6, 24, 25), hinting at the likelihood of a common hidden source.

In New York City, noted legionellosis risks include working in transportation, repair, protective services, cleaning, and construction (18), suggesting exposure during driving, outdoor/street duties, or soil/water work. Located at 40.7°N, the city has weak solar radiation, favoring the proliferation of bacteria in nature and their survival on roads. Skyscrapers may boost bacterial density in the spring and summer by providing shade. It is possible that some sporadic legionellosis cases can be attributed to inhaling aerosols or dust brought by busy traffic and/or wind.

The Netherlands and United Kingdom also have weak sunlight, as well as mild summers, and professional drivers incur a higher risk of legionellosis (19, 20). The Netherlands, where *Legionella* spp. have been isolated on roads in May and August (13.8 to 17.2°C) (17), had an incidence of 2.39/100,000 in 2015, well above the European average of 1.30/100,000 (24). In addition to driving, bicycling is common in the country and could be a source of road exposure. Elsewhere, automobile parts, such as the windshield water tank, cabin air filter, and air-conditioning system, have also been found to carry the bacteria (19, 26, 27).

Future studies can be designed to assess the risk of road exposure by inquiring about the driving or transportation history of patients with sporadic legionellosis and by monitoring *Legionella* spp. on the roads in the states with the highest incidences: Ohio and New York. Further, personal preventive measures may be needed for individuals with risk factors, e.g., those with underlying illnesses, such as diabetes or lung disease, or with weakened immunity; older individuals; smokers; professional drivers; soil/water workers; and travelers. Measures may include wearing a mask, driving with vehicle windows closed, and performing routine vehicle maintenance to clean or change the parts that harbor bacteria.

As part of North America, Canada has a cold climate and thus a low incidence of legionellosis. However, in view of the lake effect noted above and two reports related to Lakes Erie and Ontario (28, 29), the Niagara region of Ontario may be an exception. Additional research is needed to substantiate or define the lake effect and potential risk of exposure to *Legionella* spp. in the mist from waterfalls. Likewise, the effects of major rivers require further elucidation beyond presumed effects on local climate and as a reservoir of the bacteria.

The inhibitive solar effects may also play a role in limiting aerosol-related outbreaks. Strong sunlight in the southern states should quickly sterilize or dry aerosols that are emitted from cooling towers to prevent or reduce their reaching vulnerable hosts. A dry atmosphere (low humidity), such as in the west, further enhances this effect, whereas night, rain, and shade negate it. It is also likely that the densities of *Legionella* bacteria in the soil and bodies of water in the south and west are lower than those in the north and east, implying less opportunity for the bacteria to contaminate cooling towers and water systems and facilities.

The lack of solar control makes indoor aerosols, such as those generated inadvertently from whirlpool spas and decorative fountains if contaminated with *Legionella* spp., more effective in spreading these aerobic bacteria due to their presence in the air, while a high bacterial load is amplified by high temperature in the case of a heated spa or room and by aeration through the whirling or flow of water. For instance, in the largest known whirlpool spa-related outbreak, which sickened 188 individuals in the Netherlands (30), all of these elements were operative.

Much progress has been made in the control of legionellosis outbreaks that are related to the water supply, cooling towers, and hospital settings. In addition to the current measures, future efforts can be considered in the design and placement of cooling towers, such as incorporating germicidal UV lamps immediately before emission of aerosols and placing them at a minimal height above the ground to limit the exposure of pedestrians. These approaches may be beneficial in New York City, where

the densities of cooling towers and population are the highest (12). The design of indoor spas should aim to reduce aeration and thus the generation of aerosols.

Humidity has been found to aid the occurrence of legionellosis in studies that analyzed focused geographic areas over time (8, 31). It is plausible that high humidity retains *Legionella*-bearing aerosols generated by road traffic or from water sources longer in the air to increase human exposure. Instead of humidity, the present study examined precipitation and geographical location, the main determinants of humidity. While the low precipitation, and thus low humidity, in the west agreed well with low incidence rates, the warm, wet southeastern states also exhibited low incidences, disproving its effect. Rather, the amplitude of precipitation in the southeast and the New England region was found to be weakly inhibitive (Tables 2 and 6). The biological basis for this inhibition across a wide landscape remains to be elucidated. More precipitation, which has been shown to antedate a rise in legionellosis cases by days to weeks (8, 9, 31), also means less sunlight to curb the bacteria, leading to more and immediate host exposure.

The present study represents a cross-sectional analysis of the average legionellosis incidence from 2014 to 2016. Future research may consider longitudinal studies to assess and control the rising trend of the infection in the United States. Accordingly, the correlative parameters should come from corresponding years instead of the 30-year norms used in this study. The large area with diverse solar and climate patterns across the United States may also require separate consideration of each region or state. Priority in research into and control of the infection should be given to the 15 states with the leading incidence rates, Ohio and New York in particular.

In summary, across the United States, the levels of precipitation, temperature, solar UV radiation, and sunshine hours affect the occurrence of legionellosis in mixed and dynamic fashions. The finding of inhibitive solar effects of UV radiation and sunshine hours may inform exposure to and prevention of infection and warrants further investigation.

MATERIALS AND METHODS

The legionellosis case data were from the *Morbidity and Mortality Weekly Report* of the Centers for Disease Control and Prevention (<https://www.cdc.gov>). To reduce yearly fluctuation, means of the 2014 to 2016 cases were used to calculate incidence rates in states as denominated by the 2015 populations (<https://factfinder.census.gov>). Crude rates were used due to the lack of ideal age-adjusted rates. Based on the National Notifiable Diseases Surveillance System (NNDSS) data, seasonal cases were examined for Ohio, upstate New York (without data on New York City), Florida, and Washington. For these four states, the unrefined NNDSS data had completenesses of 97%, 87%, 100%, and 90%, respectively.

Climate data were from the National Weather Service (<https://www.weather.gov>); for ready access, a source with compiled data (Current Results) was used upon verification of accuracy. Norms used 30-year averages, as published in the sources: 1971 to 2000 for temperatures, 1981 to 2010 for precipitation, and 1961 to 1990 for sunshine hours. Seasonal climate data for the analyses of four states used Columbus for Ohio, the average of Buffalo and Albany for upstate New York, Orlando for Florida, and Seattle for Washington. The annual mean temperature for New York was adjusted from 7.4°C, listed in the source, to 9.4°C in view of the location of New York City in the southeastern tip (12.7°C), which contained 45% of the population and 41% of the cases in the state (6). The precipitation in Hawaii was adjusted by using the average of Honolulu (434 mm) and the state average (1,618 mm) to reduce the influence of heavy rainfall on the mountains of the islands (<http://rainfall.geography.hawaii.edu>).

Statewide average data were available for temperature and precipitation, but not for sunshine hours, because few weather stations in each state measure sunshine. Therefore, in order to be representative, sunshine hours used a centrally located city in each state or averaged data from two to four sites in a number of states, with consideration of data availability, location, and population (see Table S1 in the supplemental material). The sunshine hours in West Virginia were estimated from the available annual numbers and percentages of sunny days in Beckley and Charleston. Data on cities, lakes, and rivers were from Wikipedia and the Encyclopaedia Britannica, based on searches.

Solar UV indices were calculated from the monthly sun safety map generated by the Environmental Protection Agency (<https://www.epa.gov/sunsafety/sun-safety-monthly-average-uv-index>). The indices range from 0 to 11, with 0 to 2.9 being weak, 3 to 5.9 moderate, 6 to 7.9 high, 8 to 10.9 very high, and ≥ 11 extreme. They are based on daily UV energy irradiance at solar noon at a latitude, with consideration of global ozone amounts.

Data analyses included assessment of distribution and correlative plots and linear regression analyses between incidence rates (dependent variables) and environmental parameters (independent variables) using Excel version 2013 (32). The plots identified the U.S. regions that showed a trend, gradient, geographic feature, etc., on a certain variable(s) for further in-depth regression analysis. Simple linear

regressions were applied to each of the environmental parameters first, followed by multiple linear regressions with two to all parameters to assess the contributive and/or inhibitive role of each parameter. Caution was taken during multiple regressions to recognize and avoid spurious results due to the inherent relatedness of solar parameters (temperature, UV, and sunshine hours), known as multicollinearity (33). When compatible, data sets from different regions were merged for analysis to improve statistical efficiency and/or to overcome multicollinearity. Only statistically significant results are presented.

SUPPLEMENTAL MATERIAL

Supplemental material for this article may be found at <https://doi.org/10.1128/AEM.01776-19>.

SUPPLEMENTAL FILE 1, PDF file, 0.4 MB.

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