YALE
PEABODY
MUSEUM

P.O. BOX 208118 | NEW HAVEN CT 06520-8118 USA | PEABODY.YALE. EDU

Journal of Marine Research

The *Journal of Marine Research,* one of the oldest journals in American marine science, published important peer-reviewed original research on a broad array of topics in physical, biological, and chemical oceanography vital to the academic oceanographic community in the long and rich tradition of the Sears Foundation for Marine Research at Yale University.

An archive of all issues from 1937 to 2021 (Volume 1–79) are available through EliScholar, a digital platform for scholarly publishing provided by Yale University Library at https://elischolar.library.yale.edu/.

Requests for permission to clear rights for use of this content should be directed to the authors, their estates, or other representatives. The *Journal of Marine Research* has no contact information beyond the affiliations listed in the published articles. We ask that you provide attribution to the *Journal of Marine Research*.

Yale University provides access to these materials for educational and research purposes only. Copyright or other proprietary rights to content contained in this document may be held by individuals or entities other than, or in addition to, Yale University. You are solely responsible for determining the ownership of the copyright, and for obtaining permission for your intended use. Yale University makes no warranty that your distribution, reproduction, or other use of these materials will not infringe the rights of third parties.

This work is licensed under a Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International License.
https://creativecommons.org/licenses/by-nc-sa/4.0/

A DISCUSSION OF PHYSICAL FACTORS GOVERNING THE DISTRIBUTION OF MICROORGANISMS IN THE ATMOSPHERE

By

WOODROW C. JACOBS

*Scripps Institution of Oceanography,**
University of California
La Jolla, California

The preceding paper by Rittenberg, together with the number of articles on the same subject which have appeared recently, indicate an ever increasing interest on the part of biologists in the atmosphere as a medium for the dispersal of bacteria, molds, spores and pollens. Meteorologists, on the other hand, are interested in the results of such biological investigation to the extent that they show certain mixing processes within the atmosphere and the movements of air masses. In view of the large quantity of data which has already been accumulated by the biologists, it becomes of considerable interest to consider some of the results from the standpoint of fluid mechanics.

All investigations point to the fact that the atmosphere contains viable organisms at all times, even at free air elevations of eighteen to twenty thousand feet (Proctor 1934, 1935) indicating that large numbers of organisms are able to withstand the adverse gaseous environment for considerable periods. The natural questions that now arise are:

(1) How are the microorganisms introduced into the air?
(2) What is the nature of the mixing processes that govern or limit the vertical and horizontal transport of the organisms?
(3) How long can the organisms survive free air conditions?

THE MECHANICS OF EXCHANGE OF MICROORGANISMS BETWEEN EARTH AND ATMOSPHERE

It is assumed that nearly all surfaces, whatever their nature or composition, will contribute to the bacterial population of the atmosphere but that some surfaces, because of greater populations of microorganisms, greater mobility of surface materials or more intense atmospheric turbulence, will contribute far more than others. It is a statistically remote possibility that any single organism in the soil will be lifted by itself into the air; in all

---

* Contribution from the Scripps Institution of Oceanography, New Series No. 76.

probability they are most frequently associated with debris of some kind such as bits of organic matter, dust motes or, in the case of marine forms, with salt particles or droplets of concentrated sea water. Thus, with the exceptions of spores and pollen, the organisms in the air must frequently exist as colonies rather than single individuals. The laboratory method of plating and counting the bacteria and molds permits of no distinction between individuals and groups.

In light of such reasoning it can safely be assumed that the processes governing the exchange of soil bacteria between earth and atmosphere are the same as for the exchange of other terrigenous materials. The quantity of material exchanged will be greatest in those areas where: (1) ample supplies of loose particles exist on the surface, (2) surface winds are strong enough to stir up these materials and (3) steep lapse rates exist in the air to favor the vertical transport of the particles. Without the third factor very little surface material will be transported over significant distances although there may be local transport over short distances within the surface layers of air. The supply of microorganisms should be greatest where the surface is dry due to deficient rainfall, where there is an abundance of organic matter in the soil, where intensive cultivation is practiced and in and near wooded areas. The data given by Proctor (loc. cit.) and others appear to bear out these conclusions. A spring maximum of dust in the atmosphere is noted in the solar-radiation measurements in the United States (Wexler, 1936) which is to be expected since the soil is dryest at this season, cultivation is most extensive, surface winds are strongest and the vertical temperature lapse rates are steepest. It can be assumed that the population of microorganisms in the atmosphere would also be greatest during this season for the same reasons.

The processes governing the exchange of bacteria between sea and atmosphere are not wholly analagous to those governing the exchange between soil and air. In the latter case much of the kinetic energy of the air at the surface goes to produce turbulence and is thus available for lifting and transporting the loose surface particles; in the first case most of the energy exchanged through surface friction goes toward producing waves on the sea surface or in initiating and maintaining the flow of surface waters. Except for evaporation, there is no exchange of water between sea and air in such processes. It is only when the waves become unstable or break and spray is formed that any significant exchange takes place and thus it is to be expected that the tidal zone along open coastlines will constitute a primary source of marine bacteria. The spray droplets will, of course, include any bacteria present in the water and upon evaporation may leave the organism associated with a salt particle or droplet of concentrated sea water. Since such hygroscopic particles are extremely effective nuclei for the condensation of water vapor in the atmosphere, they are more readily removed than are the non-hygroscopic dust particles. In a recent study, Jacobs (1937) determined the amounts of sea salt in the air upon a number of occasions. The collections were made only 200 feet from the ocean high-tide mark and approximately 100 feet above sea level thus they represent the extreme conditions within the tidal zone. The series of 23 analyses gave an average salt content (magnesium chloride and sodium chloride) of 0.38 mg. per cubic meter of air which is equivalent to approximately 0.01 gms. of sea water. Since the number of bacteria in sea water is usually less than 500 per cc. (ZoBell and Feltham, 1934; Benecke, 1933), it can be computed, on the basis of the above salt values, that the number of marine bacteria per cubic meter of sea air will usually be less than 5. The results obtained by ZoBell and Mathews (1936) indicate that this number is too small, however.

On the other hand, the bacteria in a cubic centimeter of soil may be numbered in the millions or hundreds of millions. Proctor (1934), during his determinations of the number of bacteria at high levels, also collected and counted the number of dust particles at the same time. Although he makes no volumetric calculations, rough computations by the writer indicate that he collected approximately 510 visible and collectable dust particles per cubic meter of air averaged for all levels. Above 9000 feet there were approximately 25% fewer particles than the general average. He found the ratio of microorganisms (bacteria and molds) to dust particles to be 1 to 107.95 for all levels and 1 to 117.93 above 9000 feet. The first figure would give 4.7 collectable bacteria per cubic meter of air. Considering the great number of bacteria that must exist in the lowest layers of air, these results show that either a very small percentage of the organisms survive or that the original number is dispersed throughout large volumes of air. By the same reasoning, however, the possibility of encountering even one marine bacterium at these high elevations during a normal collection appears remote.

VERTICAL AND HORIZONTAL TRANSPORT OF MICROORGANISMS

The tendency of turbulence in the atmosphere is to create a uniform distribution of properties throughout the air mass. This action, however, is of far greater magnitude than the mere diffusion of properties between layers; apparently the mixing takes place through motions of eddies or masses which are pushed from their original surroundings at irregular intervals. As stated by Byers (1937, p. 238):

> "The significance of these traveling eddies lies in the fact that they carry the properties of their 'mother layer' into the new environment."

Thus it would be expected that microorganisms in the atmosphere, whose source is at the surface of the earth, would be distributed throughout the atmosphere but that the density would decrease the greater the distance from the source. The biological work to date shows this to be true. For example, Proctor (loc. cit.) notes a general decrease in both dust particles and bacteria with elevation and an increase in the bacterial count in the vicinity of wooded areas, while Rittenberg has just presented data which show a general decrease in the bacteria count the greater the distance from shore. On first analysis, it might be assumed that the number of marine bacteria should increase from the shore seaward but it still remains to be considered that the primary source of marine bacteria is the tidal zone with its foam and breaking waves. The high bacterial counts obtained by ZoBell and Mathews (1936) within the tidal zone are probably much too large for the open ocean.

While the tendency is to create uniformity of properties throughout the air mass, at any given instant this air mass must contain variously large and small masses (eddies) with somewhat different properties than the surrounding air. This reasoning no doubt accounts for at least part of the extreme variability in bacteria counts within small areas, or over short intervals of time, which has been noted by various investigators of the problem and mentioned by Rittenberg. The more intense or prolonged the turbulent action, however, the more nearly will uniformity of properties be approached, although at the same time there must be a general decrease in density of the property relative to the total air mass the greater the distance of the observation from the source area.

If this "uniformity of properties" were actually *attained* in a given region (which would be the case were the process one of pure diffusion), the frequency distribution of mold or bacteria counts per hour would be approximately of the Poisson type, and the ratio of the variance (i. e. mean squared deviation) to the mean of the counts made in the region, should approximatly equal 1.00. A higher ratio indicates the presence of eddy masses which still retain the properties derived from their sources. However, the longer the time elapsed since such an eddy mass left its source, the more completely will its properties become equalized with those of its surroundings on account of diffusion and small scale turbulence, hence the above ratio should diminish for any property with distance from its source.

The region off the coast of California presents unusually stable conditions throughout practically all months, therefore it is not expected that the mixing processes will be as effective here as in many other areas. Nevertheless, the data accumulated by Rittenberg show the above reasoning to be valid. The data in his Table II show that the average mold count[1] per

---

[1] Rittenberg assumes that all the molds are of land origin regardless of whether they develop on sea water media or tap water media.

hour for the region from 0–100 miles off the coast is 155.6 molds while it is 29.0 molds in the region from 100–400 miles off the coast. Taking the mean of the differences in count between individual stations as a measure of the variability, a value of 250.1 molds per hour is found for the coastal region and 30.8 molds for the region beyond the 100-mile zone. These figures are interesting in that they give ratios between the mean differences in count and mean counts of 1.61 for the first region and 1.06 for the second. However, the actual mixing processes are probably best represented if the ratio of the variance (mean squared deviation) to the mean of the counts is taken. In this case, the ratio is 402.0 in the first region and 32.7 in the second. As suggested, if the mixing were accomplished solely by pure diffusion, the ratios would approach 1.00 in both areas. Approximately the same number of counts were obtained in each of the areas under consideration.

One may speculate as to the origin of these molds. The prevailing winds in the Southern California area are from the sea and thus the air masses usually present over the coastal region are essentially marine in character and may have passed over several thousand miles of sea surface since contact with any land mass. Since the mold collections were made by Rittenberg at intervals of varying length and on several cruises, it may safely be assumed that a large number of the counts were made within true marine air masses. If the molds are primarily of land origin they must have originated either over the continental land masses to the east or over the far removed land areas bordering the North Pacific Ocean on the west or north. It is possible that these microorganisms could have originated in Alaska or Asia but the fact that Rittenberg notes a decrease in the mold counts from shore seaward might indicate that these organisms actually originated from the land surfaces of the United States but were transported westward across the prevailing wind stream through lateral mixing.

Such considerations as those just presented suggest the use of bacterial counts in the identification of air masses. According to ZoBell (1939), it is possible to differentiate between bacteria of marine origin and bacteria of land origin in at least 90% of the cases. If this is true, a determination of the ratio between the two types of bacteria present in the air should indicate whether the air mass is of marine or continental origin and, perhaps, the recency of contact with sea surface. The further identification of particular species of microorganisms, particularly spores and pollens, would permit additional conclusions to be drawn concerning the local movements of small air masses.

The data so far presented indicate the importance of the horizontal and vertical mixing processes in distributing microorganisms throughout the atmosphere. The height to which the microorganisms may be transported will depend largely upon the degree of stability and the height of the turbulent or convective layer of air. Since the height of the layer of turbulent influence varies as the surface wind speed, roughness of surface and latitude, it would be expected that the vertical transport of organisms will also be governed by these factors. The presence of a discontinuity surface in the upper air will limit vertical transport in either direction resulting in concentrations of foreign particles in the air both above and below the surface. Biologists should look for evidences of similar biologic stratification.

In general, the horizontal transport will be determined by the general stream flow in the atmosphere but lateral mixing along isentropic surfaces will transport the organisms laterally away from the trajectories indicated in the general wind observations. Thus, in these latitudes, the greater transport will be from west to east and, considering the greater carrying power of polar air masses,—from north to south. The horizontal distance over which the individual organism may be transported is almost limitless and is largely determined by its ability to survive the atmospheric environment.

THE ATMOSPHERE AS AN ENVIRONMENT FOR MICROORGANISMS

This question is largely a problem for the biologist but there remain several meteorological factors to be considered. The organisms must first be able to withstand great extremes in temperature, pressure and humidity if they are to survive transport over great distances. It has been argued that solid particles (thus all microorganisms) in the air will radiate and absorb radiation very nearly as a black body and, as a result, they must undergo extreme temperature changes which are not represented by temperature changes within the air mass. However, the heat capacity of the organism, or the particle with which it is associated, must be very small, thus it can be assumed that the temperature of the organism at any instant must be very nearly the temperature of the surrounding air.

Bacteriologists have shown that exposure to ultra violet radiations for short periods is lethal to most bacteria. However, the solid particles to which they are attached may afford some protection against this type of radiation. Nevertheless, the bacteria counts should show a diurnal variation due to this cause.

It has previously been pointed out that Proctor obtained a ratio between bacteria and dust particles of 1 to 107.95 for all levels and one of 1 to 117.93 above 9000 feet. This would show about 8% fewer bacteria per particle for the higher levels which might indicate that this proportion was killed since the physical factors governing their removal from the air would be the same as for the dust particles. He does not give average values for the layer below 9000 feet, therefore it can be assumed that the proportion that did not survive was somewhat greater than 8%.

CONCLUDING REMARKS

No attempt has been made in these pages to cover the list of possibilities for research in this field; either from the standpoint of the biologist or the meteorologist. The writer merely hopes that the discussion will serve as an added stimulus toward future investigation of the problem by both groups and that it will, in some measure, give guidance to the biologist. It will be the problem of the meteorologist to apply the results of the biological investigations to the atmosphere; it is the problem of the biologist to develop certain and rapid methods for identifying the organisms with respect to type and place of origin.

REFERENCES

BENECKE, W.
1933. Bakteriologie des Meeres. Abderhalden's Handb. der biol. Arbeitsmethoden. 404: 717–854.

BYERS, H. R.
1937. Synoptic and Aeronautical Meteorology. McGraw-Hill, New York, 1937.

JACOBS, W. C.
1937. Preliminary Report on a Study of Atmospheric Chlorides. Mo. Wea. Rev. 65: 147–151.

PROCTOR, B. E.
1934. The Microbiology of the Upper Air I. Proc. Amer. Acad. Arts and Sci. 69: 315–340.
1935. The Microbiology of the Upper Air II. Jour. Bact. 30: 363–375.

WEXLER, H.
1936. A Note on Dust in the Atmosphere. Bull. Amer. Meteorol. Soc. 17: 303–305.

ZOBELL, C. E. and FELTHAM, C. B.
1934. Preliminary Studies on the Distribution and Characteristics of Marine Bacteria. Scripps Inst. Oceanog. Bull. Tech. Ser. 3: 279–295.

ZOBELL, C. E. and MATHEWS, H. M.
1936. A Qualitative Study of the Bacterial Flora of Sea and Land Breezes. Nat. Acad. Sci. Proceed. 22: 567–572.

ZOBELL, C. E.
1939. Personal communication from bacteriologist at the Scripps Institution of Oceanography.