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Opinion

Do airborne microbes matter for atmospheric chemistry and cloud formation?

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Summary

The role of airborne microbial cells in the chemistry of the atmosphere and cloud formation remains essentially speculative. Recent studies have indicated that microbes might be more important than previously anticipated for atmospheric processes. However, more work and direct communication between microbiologists and atmospheric scientists and modellers are necessary to better understand and model bioaerosol–cloud–precipitation–climate interactions.

Micro-organisms control the biogeochemical cycles that sustain life on every habitat on Earth. It is reasonable to expect that they also have significant contributions to the chemistry of the atmosphere, cloud formation and the hydrological cycle. Besides, several studies have shown that the number of airborne microbial cells is frequently high enough to be potentially important (e.g. Harrison *et al.*, 2005; Bowers *et al.*, 2011). Although most of these studies were conducted on Earth surface (e.g. peaks of mountains) and hence the influence of the terrestrial environment on the derived results cannot be easily assessed, our recent study revealed that high bacterial cell numbers can be found at high altitudes above the oceans (8–10 km), at least in air masses associated with tropical hurricanes (DeLeon-Rodriguez *et al.*, 2013a). However, except for these diversity surveys and a few experimental studies that assessed microbial activity under controlled laboratory conditions that aimed to simulate the *in-situ* conditions in the troposphere (e.g. Vaitilingom *et al.*, 2013), we know very little about the dynamics of microbial cells in the troposphere and their activities. The recent technological advancements in genomic and atmospheric sciences provide the opportunity to rigorously address these issues and provide a more complete picture of the role of micro-organisms in the troposphere and climate.

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Micro-organisms could potentially have a significant role in atmospheric chemistry by actively metabolizing the organic compounds present in the air and/or affect cloud formation and the hydrologic cycle by serving as nuclei for the formation of water droplets or ice crystals. With respect to the former, there are several small molecular weight organic compounds such as carboxylic acids and dimethylsulfone that are ubiquitous in the troposphere and show high enough concentrations, especially within the aqueous phase of clouds, to support microbial activity. Experiments in the laboratory with organisms isolated from cloud water have shown that these organic compounds can sustain life when provided at concentrations similar to those found in clouds, leading to the hypothesis that clouds represent 'atmospheric oases' of microbial activity (Vaitilingom *et al.*, 2013). However, the relevance of these findings for processes occurring *in-situ* remains to be tested. Such tests could be performed on board specialized aircrafts that can sample clouds, or with state-of-the-art atmospheric chamber facilities that can simulate well the conditions in the troposphere and the cloud environment. With respect to cloud formation, nucleating particles are necessary to cause condensation of the water vapours, wherever the latter are abundant in the atmosphere, and form liquid water (cloud condensation nuclei or CCN; typically when ambient temperature is above or right below freezing point) or ice (ice nuclei or IN; when ambient temperature is lower). It can be hypothesized that a hydrophilic cell wall makes for a good CCN; in contrast, IN efficiency depends more on tertiary structure (to match that of ice crystals). Certain bacterial species are the most efficient ice nucleators known, through the action of a specialized protein they produce (*inaZ*), while other species as well as fungal species can act as CCN. For instance, plant pathogens of the *Gammaproteobacteria* class employ *inaZ* to promote ice formation and hence physically damage the leave surface, which facilitates invasion, and *inaZ*-encoding pseudomonas can nucleate ice at temperatures higher than any other abiotic IN, i.e. –2 to –5°C (Vali *et al.*, 1976). Beyond this, however, very little quantitative understanding exists on the CCN/IN efficiency of different microbial species, their distribution in the troposphere, and more importantly, which cell properties – other than the excretion of *inaZ* protein – control the observed CCN/IN activity and the effect of ambient environmental conditions on the activity. Advancing these issues and obtaining a more complete picture of microbial cell abundances and dynamics in different parts of the globe will be essential to better appreciate the importance of airborne microbes for the atmosphere and incorporate bioaerosols into climate models.

Our recent work (DeLeon-Rodriguez *et al.*, 2013a) has indicated that the role of atmospheric microbes in atmospheric chemistry and cloud formation could be significant. More specifically, we observed that airborne microbial cells are in the same order of magnitude as abiotic particles at high altitudes in air masses associated with tropical hurricanes. This is perhaps not surprising because hurricanes can aerosolize a large number of particles, including cells (millions-to-billions of cells are present in one litre of seawater or gram of soil), and many of the cells – especially bacterial – are of the right size to reach high altitudes, remain aloft for several days or weeks, and serve as CCN/IN. What is, however, interesting is that although distinct microbial communities were associated with different hurricanes, as expected for these immense weather systems that perturb the troposphere, there were a few 'core' species that were viable (based on live/dead microscopy staining) and present in all hurricane and also in no-hurricane associated background air samples. We also confirmed that these results do not represent sampling artefacts or contamination (DeLeon-Rodriguez *et al.*, 2013b). These findings indicate that the latter species might have developed mechanisms to survive in the atmosphere and be metabolically active, consistent with previous laboratory studies (Vaitilingom *et al.*, 2013). Further, even if these cells are not efficient IN or metabolically active, they could 'passively' contribute to cloud formation based on their size (0.1–1 μm), (high) relative *in-situ* abundance and the prevailing conditions at high altitudes, which are highly conducive for the formation of ice crystals. Notably, the core species did not include the highly efficient ice-nucleating pseudomonas species, which, in contrast, are usually more abundant at low altitudes and rain water collected in vegetated areas (reviewed in Christner, 2012). The latter findings indicate that cells that are efficient CCN/IN may contribute to cloud formation and are precipitation scavenged at lower altitudes during updraft, while cells that are less efficient CCN/IN can reach higher altitudes. These findings also imply that the life cycle of bioaerosols may differ from that of abiotic particles, which may be important for modelling. Finally, our results have implications for microbial biogeography because they indicate that different species may show varied degrees of dispersion through the atmosphere. The more hydrophobic cells and spores are expected to be more abundant at high altitudes and hence transported over longer distances due to Earth's jet stream, because they are unlikely to serve as CCN and thus be removed from the troposphere through precipitation. On the other hand, cells that are efficient CCN/IN may be efficiently transported via the air over relatively shorter distances.

There are several ecological factors that could select for varied CCN/IN efficiencies of different bacterial species and hence account for the diversity patterns observed in the troposphere. For instance, bacterial species may show different abundances in the atmosphere because of their cell properties, e.g. degree of hydrophobicity of the cell wall or production of *inaZ*, and these properties may be directly selected for efficient transportation through the air or for other unrelated ecological factors, e.g. planktonic versus attached/biofilm lifestyle, and plant invasion.

Finally, it should be mentioned that a few studies have not found significant numbers of microbial cells in ice crystals collected at high altitudes based on single-particle laser mass spectrometry, suggesting that airborne cells are not important at these altitudes and cirrus cloud formation (e.g. Cziczo *et al.*, 2013). These findings contrast with those of our study (DeLeon-Rodriguez *et al.*, 2013a) as well as a recent mass spectrometry-based study of high altitude air masses in Pacific Northwest USA (Creamean *et al.*, 2013). Thus, it appears as if airborne cells might be associated with certain air masses and not others, e.g. those affected by Sahara dust (relatively low in viable cells but probably high in spores) versus strong storms (high in viable cells). In any case, the low abundance of cells in ice crystals at high altitudes is consistent with the precipitation-scavenging hypothesis outlined earlier (i.e. efficient CCN/IN cells do not reach high altitudes) and implies that airborne cells may be more important at lower altitudes or specific air masses at high altitudes.

Clearly, more samples representing different parts of the globe and ecosystems and quantitative data are still necessary to corroborate these early findings and rigorously test the abovementioned hypotheses. It is also possible that microbial cells encode several additional proteins or cell wall components that promote CCN/IN – similar to *inaZ* – and these represent hypothetical or poorly characterized genes in the current functional databases. It will be important to obtain a more complete understanding of what cell properties and proteins constitute an efficient CCN/IN. More importantly, this research field requires the close interactions between atmospheric scientists, modellers and microbiologists and the historic lack of such interactions accounts, at least in part, for our limited understanding of atmospheric bioaerosols. At Georgia Tech, we have built such an interdisciplinary team and a state-of-the-art atmospheric chamber facility to attempt to close these gaps in knowledge and determine whether the activities and abundances of airborne cells are important for atmospheric chemistry, cloud formation and modelling. My gut feeling is that they are important and therefore require more attention.

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