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Transport of bacterial cells toward the Pacific in Northern Hemisphere westerly winds

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HIGHLIGHTS

- Airborne bacteria were investigated on southwestern Japan coast.
- Bacterial concentration was in the order of 10^5 cells m^{-3} or more.
- Postfrontal air conveyed bacteria efficiently from the Asian continent.
- Bacteria in postfrontal air correlated with aerosol particles larger than 1 μm.
- Bacterial viability in postfrontal air was low.

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ABSTRACT

Viable and non-viable bacteria in the air were investigated on the southwestern Japan coast to outline the manner by which bacteria were transported and to quantify the bacterial abundance and viability in the Northern Hemisphere westerly winds. The observations were conducted when the weather was governed by cyclones or anticyclones associated with Asian continent outflow between 12 October 2011 and 7 April 2013. Bacterial concentration in thermodynamically different air parcels was in the same order but different ranges: 4.5×10^5–1.3×10^6 cells m^{-3} in postfrontal air, 2.4×10^5–1.4×10^6 cells m^{-3} in prefrontal air, 5.4×10^5–9.9×10^5 cells m^{-3} in the air between cyclones and anticyclones and 2.9×10^5–4.1×10^5 cells m^{-3} in anticyclone air. In postfrontal air, the concentration correlated closely with coarse aerosol particles (diameter > 1.0 μm). In contrast, bacteria did not show a correlation with coarse particles in prefrontal air and anticyclone air. Bacterial viability was approximately 70% on average of all samples. However, the viability in postfrontal air was smaller than 60% if cases of stationary fronts with stagnant air were excluded. These results indicate that air parcels following fast-moving cold fronts in the westerly wind flow constantly and efficiently conveyed airborne bacteria from the Asian continent toward northwestern Pacific and the bacteria were characterized by coarse particle-correlated high abundance and low viability. The bacteria in slowly moving anticyclone and prefrontal air, characterized by low abundance and high viability, were more likely a mixture of long-range transported ones and regionally or locally originated ones.

1. Introduction

Airborne bacteria constitute a major component of atmospheric biological particles (Morris et al., 2011). They have a relatively long atmospheric residence time because of their small size, approximately 1 μm or smaller, and can be transported long distances in the atmosphere (Kellogg and Griffin, 2006; Smith et al., 2012). The widespread dispersal of viable bacteria in the air and their settlement to the surface function as links of bacterial communities between geographically isolated regions such as islands or pelagic zones and, consequently, contribute to the development and succession of the microbial communities (Hervàs et al., 2009; Maki et al., 2011; Womack et al., 2010). Another important fact is that bacteria including viable and non-viable ones and even cell fragments in elevated air can affect cloud development and influence hydrological cycles by enhancing ice nucleation (Christner et al., 2008; Möhler et al., 2008; Sun and Ariya, 2006). In order to assess these roles and functions, the dispersion of bacteria via wind flow and their biological activity need to be quantitatively evaluated.

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In two earlier review papers, Kellogg and Griffin (2006) and Griffin (2007) demonstrated the global transport of bacteria with atmospheric dust. Recent studies showed the remarkable increase of airborne microorganisms caused by atmospheric dust at the downstream areas of the Asian continent (Hara and Zhang, 2012; Jeon et al., 2011; Wu et al., 2004; Yamaguchi et al., 2012; Yeo and Kim, 2002). Creamean et al. (2013) found the contribution of bacteria and dust particles from Asia to the nucleation of ice clouds over North America. Although it has been gradually recognized that bacteria are widely transported in air parcels such as dust plumes, spatial-temporal variability of bacterial cell concentration and viability in the air under different weather conditions has not been carefully addressed.

Bacteria are constantly released into the air from surfaces such as vegetation, soil and water (Burrows et al., 2009). The abundance of airborne bacteria is closely dependent on the history of air parcels (e.g. the origin of air parcels and/or where they have passed) and bacterial multiplication in the air (Fulton and Mitchell, 1966; Jones and Harrison, 2004; Shaffer and Lighthart, 1997). It is usually considered that bacteria in the air hardly multiply because air is a severe environment for bacteria, compared to water and soil except in some specific cases such as cloud droplets or ice crystals (Sattler et al., 2001; Womack et al., 2010). Without scavenging via precipitation and droplet or ice nucleation, dry deposition will be the only efficient removal process for airborne bacteria. On a certain scale of time or space, the variation or movement of an air parcel can be regarded as an adiabatic process, for which there is rare mass or heat exchange between the parcel and the ambient air except work. The consequences of such atmospheric phenomena are, for example, the frontogenesis and cloud formation in cyclones. Therefore, the abundance and viability of bacteria may be very different in thermodynamically and historically different air parcels.

In the Northern Hemisphere middle latitude regions, westerly wind flows blow airborne particulate matter from the Asian continent to downstream areas, sometimes to North America and even globally (IGAC, 2006; Uno et al., 2009). The wind flows advect cyclones and anticyclones eastward, the result of which is the alternative passage of counterclockwise and clockwise vortexes. Such synoptic air movement dominates the weather in East Asia and governs the export manner of the particulate matter from East Asia for long-range transport (Jacob et al., 2003). Air within the territory of anticyclone is stagnant, which easily results in the accumulation of air pollutants. In contrast, the passage of cyclones causes rapid alternation of air parcels from warm and humid prefrontal air to cold and dry postfrontal air, accompanied with rapid weather changes. Prefrontal air and postfrontal air within a cyclone arriving at southwestern Japan usually have passed different areas and approach from different directions before arrival. Consequently, airborne particles are expected to be completely different before and after the arrival of a cold front even if they are within the same territory of a cyclone. Airborne particles including bacteria therefore need to be identified separately according to the thermodynamic and historical properties of the air parcels in which they are loaded.

In this study, abundance and viability of airborne bacteria and their evolution associated with cyclones and anticyclones were investigated using a fluorescent staining, LIVE/DEAD BacLight Bacterial Viability Kit, and microscopic enumeration at Kumamoto in southwestern Japan. Kumamoto is located in the coastal area of Kyushu with the East China Sea to its west. Westerly wind flows sweep continentally-originated particulate matter to this area with less influence of local emissions in the Kyushu area except that from ocean areas, which allows the area to be suitable for investigation of particulate matter from the Asian continent. Here we report the bacterial abundance and viability according to different synoptic weather conditions and outline how and how many bacteria were transported in the westerly wind flow from the East Asia toward northwestern Pacific.

2. Material and methods

2.1. Observation site and period

Samples were collected during the passage of five cyclones and nine anticyclones on the balcony (32.806°N, 130.766°E; approximately 20 m above the ground) of a building at Prefectural University of Kumamoto between 12 October 2011 and 7 April 2013 (Fig. 1). Details of sample collection time and the weather conditions are illustrated in Supplementary Table A.1. The surrounding areas of the site are residences. Emissions of local particulate matter that might severely influence the site were not expected.

Samples associated with anticyclones were collected when the weather was governed by anticyclones or was in the transition stage from cyclones to anticyclones (the approaching of anticyclones after the passage of cyclones). We defined these two conditions as (a) anticyclone and (b) approaching anticyclone (surface chart examples in Fig. 1a and b). Under such weather conditions, the weather was fine and wind was weak. There was no short-term rapid variation in the air. These samples enabled us to acquire the information on bacterial accumulation in the air. In total, ten samples were obtained, five of which were anticyclone samples and five were approaching anticyclone samples.

Samples during cyclone passage were obtained during five periods: 15–16 October 2011 (front-case 1), 6–7 November 2011 (front-case 2), 22–24 November 2011 (front-case 3), 9–10 March 2013 (front-case 4) and 5–7 March 2013 (front-case 5) when Northern Hemisphere middle latitude cyclones passed the observation site. We defined prefrontal and postfrontal conditions as (c) prefrontal: cyclones were approaching or arrived at the site with their cold fronts to the west of the site, and (d) postfrontal: from the cold front passage to the end of the cyclone coverage (weather chart examples in Fig. 1c and d). In order to get the variation of bacterial cell concentration and viability during the passage of cold fronts, multiple samples were collected with the time interval of three hours or larger. We did not collect samples when it was raining because of the lack of knowledge on wet removal of bacterial cells. For this reason, no samples in the prefrontal air of front-cases 1 and 2 were available. Samples in both prefrontal and postfrontal air were obtained in front-cases 3, 4 and 5. In addition, weak Asian dust occurred in the postfrontal air of front-case 4 according to the weather report of Japan Meteorological Agency.

In addition to the sample collection, size-segregated number concentration of aerosol particles was measured with an optical particle counter (MetOne HHPC-6, Hach Co., the U.S.). The counter measured the concentration in six size ranges of 0.3–0.5, 0.5–0.7, 0.7–1.0, 1.0–2.0, 2.0–5.0 and >5.0 μm with the time interval of 10 min. Weather conditions were monitored with an automatic weather observation system that was set up on the roof of a building next to the observation site. The system recorded temperature, relative humidity, pressure, wind speed, wind direction and global solar radiation every minute, and in this study we used 10-min averages to document the weather evolution. Due to instrument troubles, data from 10:00 JST (Japan Standard Time) to 19:00 JST on 22 November in front-case 3 and pressure in front-case 4 were not available. Meteorological records by the Kumamoto Meteorological Observatory (approximately 8 km from the observation site) were used to compensate the data loss.