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Responses of phytoplankton and heterotrophs in open oceans to nutrient supply

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Many elements are required for the photosynthesis and growth of phytoplankton. However, Liebig's law of the minimum states only one element limits the growth of organisms at any given time. Here we briefly introduce the behavior of limited nutrients for phytoplankton in the sea, and the responses of not only phytoplankton, but also heterotrophs in open waters, especially the western North Pacific, to nutrient additions. In the subarctic western North Pacific, ample amount of nutrients are supplied from deeper layers to the surface through winter mixing. From spring to summer, phytoplankton growth is stimulated by increases in solar radiation and stratification of the water column. However, levels of chlorophyll (Chl) *a*, an indicator of phytoplankton biomass, in this region during summer are lower than expected from surface nitrate concentrations. Hence, the subarctic western North Pacific has recently been recognized as one of the HNLC (high nitrate, low Chl) regions, where iron (Fe) availability in seawater is often very low, because of low Fe solubility in seawater and low Fe supplies from land. To verify Fe deficiency in phytoplankton assemblages in this region, two in situ Fe fertilization experiments, SEEDS and SEEDS-II, were carried out in summers of 2001 and 2004, respectively. The large chain-forming centric diatom *Chaetoceros debilis* dramatically bloomed after Fe enrichment during SEEDS, while small phytoflagellates such as green algae and cryptophytes flourished with a small magnitude during SEEDS-II. The causes of the different responses of phytoplankton between the two experiments could be due to: 1) high grazing pressure of mesozooplankton during SEEDS-II, and 2) a dilution of bioavailable Fe by deeper mixed layer in SEEDS-II, resulting in continued Fe deficiency in large diatoms. Increases in bacterial productivity were also observed even in SEEDS-II, although apparent dissolved organic carbon concentrations little changed. From the results of the two in situ Fe enrichment experiments, it has become evident that Fe availability controls the ecosystems and biogeochemical processes in the subarctic western North Pacific. On the other hand, in the tropical and subtropical western North Pacific, permanent pycnocline has well developed throughout the year, resulting in the depletion of surface nitrate. In such conditions, pico-sized autotrophic cells, which have advantage in nutrient uptake because of their high surface area to volume ratios, become dominant in the phytoplankton assemblages. Recently, it has been pointed out that intensity of tropical cyclones including typhoon may have increased. During 1997-2007, total number of typhoon was 170, and 63% out of them induced substantial increases in Chl *a* level as estimated from satellite remote sensing. As a typical example, in fall 2003, Chl *a* concentrations increased by ca. 7 times after the passage of Typhoon *Ketsana*, which probably caused a strong upwelling in the sea. Relatively high concentrations of the Chl *a* continued for approximately 1 month. However, it is still unclear which phytoplankton species became dominant after typhoon passage. Effects of the phytoplankton assemblages increased by typhoon on the ecosystems and biogeochemical processes are also uncertain. Therefore, we conducted on-deck incubation experiments using the mixture of surface and subsurface waters in the areas on September 2007 and 2008. As common results of the experiments, levels of specific chemotaxonomic carotenoids probably derived from diatoms and chrysophytes increased after incubation. Our microscope observations also revealed that micro-sized diatoms such as *Pseudo-nitzchia seriata* complex increased. These results suggest that the enhancement of typhoon intensity may increase number of the blooms mainly consisted of diatoms in the tropical and subtropical North Pacific.

Keywords: limited nutrients, in situ iron fertilization experiments, typhoon disturbance