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Typhoon-induced response of phytoplankton and bacteria in temperate coastal waters

Kenji Tsuchiya [a, *], Victor S. Kuwahara [a], Koji Hamasaki [b], Yuya Tada [b, c], Tadafumi Ichikawa [d], Tomoko Yoshiki [e], Ryota Nakajima [f], Akio Imai [g], Shinji Shimode [h], Tatsuki Toda [a]

[a] Faculty of Science and Engineering, Soka University, 1-236 Tangi-cho, Hachioji, Tokyo 192-8577, Japan
[b] Atmosphere and Ocean Research Institute, The University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa, Chiba 277-8564, Japan
[c] Graduate School of Environmental Science, Hokkaido University, N10W5 Sapporo, Hokkaido 060-0810, Japan
[d] National Research Institute of Fisheries Science, Fisheries Research Agency, 2-12-4 Fukuura, Kanazawa, Yokohama, Kanagawa 236-8648, Japan
[e] Research and Development Center for Global Change, Japan Agency for Marine-Earth Science and Technology (JAMSTEC), 3173-25, Showa-machi, Kanazawa, Yokohama, Kanagawa 236-0001, Japan
[f] Department of Marine Biodiversity Research, Japan Agency for Marine-Earth Science and Technology (JAMSTEC), 2-15 Natsushima-cho, Yokosuka, Kanagawa 237-0061, Japan
[g] National Institute for Environmental Studies, 16-2 Onogawa, Tsukuba, Ibaraki 305-8506, Japan
[h] Graduate School of Environment and Information Science, Yokohama National University, 79-7, Tokiwadai, Hodogaya-ku, Yokohama, Kanagawa 240-8501, Japan

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ABSTRACT

After the passage of typhoon *Malou* in 2010, daily field samplings were conducted at both inshore (Sta. A) and offshore (Sta. M) stations in Sagami Bay, Japan, to evaluate responses of bacteria and phytoplankton to variations of physical-chemical environments induced by typhoon passage. *Malou* passage caused an abrupt decline of salinity and a large increase in the amount of nutrients at both stations. The relationships between salinity and nutrient concentrations suggested that major nutrient sources were terrestrial runoff at Sta. M and sediment resuspension in addition to terrestrial runoff at Sta. A. Bacterial production (BP) at Sta. A showed 114 ± 21 mg C m^{-3} d^{-1} one day after *Malou* passage, while primary production (PP) was 76 ± 8 mg C m^{-3} d^{-1}, suggesting the dominance of BP (BP/PP ratio = 1.5). PP exceeded BP two days after *Malou* passage, and then reached a maximum of 554 ± 32 mg C m^{-3} d^{-1} five days later (BP/PP ratio = 0.10). PP was always dominant at Sta. M throughout the study period (BP/PP ratio = 0.13 ± 0.05). The ratio of BP to bacterial abundance (BP/BA ratio) at Sta. M showed a positive correlation with PP, suggesting that bacterial productivity depended on autochthonous substrates derived from phytoplankton. The BP/BA ratio at Sta. A showed no relationship with PP, suggesting that bacterial productivity was enhanced not only by PP, but also loading of allochthonous substrates. BP/BA ratios at both stations increased exponentially with the increase of PO_4 and NH_4 concentrations; these concentrations are likely coming from sediment pore waters. The results suggest that sediment resuspension induced by typhoon passage enhanced bacterial productivity abruptly just after the passage at an inshore station. The bacterial response could be regulated by difference in relative contribution of nutrient sources after the passage of typhoon.

1. Introduction

Typhoons, including hurricanes and tropical cyclones, are the most extreme episodic weather events affecting coastal and adjacent marine waters in low and mid latitudes. Typhoon-induced perturbations can enhance primary and bacterial production; Primary production was enhanced up to 19-fold, and bacterial production was enhanced up to 6.4-fold compared to those of non-typhoon periods, or before typhoon passage in coastal waters (e.g. Shiah et al., 2000). In recent years the destructiveness of

* Corresponding author.
E-mail address: ktsuchiya@soka.gr.jp (K. Tsuchiya).

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typhoons has increased with the advent of the effects of climate change and global warming (Emanuel, 2005; Webster et al., 2005; Elsner et al., 2008; Yamada et al., 2010). It is credible that intensification of typhoons will cause stronger perturbations in aquatic ecosystems, and typhoon impacts on oceanic biogeochemistry will also be magnified (Hoegh-Guldberg and Bruno, 2010).

The passage of typhoons causes physical disturbances such as upwelling and vertical mixing (Price, 1981; Lin et al., 2003; Zheng and Tang, 2007), terrestrial runoff (Zheng and Tang, 2007; Chen et al., 2009) and sediment resuspension (Fogel et al., 1999), which supply nutrients to the euphotic zone (Chang et al., 1996; Chen et al., 2009; Chung et al., 2012). Relative importance of nutrient sources could be different between areas whose depths and distance from coast are different. In offshore waters where depths are >50 m depth, upwelling, vertical mixing and terrestrial runoff can be possible nutrient sources. On the other hand, storm-associated winds also have the potential of completely mixing shallow coastal waters (<50 m) down to the sediment surface (Ridderinkhof, 1992), which suggests that sediment resuspension could be one of the major nutrient sources besides terrestrial runoff and upwelling in shallow inshore waters. These nutrient sources have their own quantifiable nutrient stoichiometry (e.g. Howarth, 1988, Jordan et al., 2008). For example, terrestrial waters supply a large amount of nitrate and silicate to coastal regions (Fujiki et al., 2004), and sedimentary pore water has high concentration of ammonium and phosphate concentrations, and low concentrations of nitrate + nitrite (Jordan et al., 2008). Thus relative contribution of nutrient sources can lead to difference in biological responses.

Fogel et al. (1999) reported that bacterial production was enhanced by sediment resuspension that accompanied a hurricane in North Carolina. Sediment resuspension caused by simulated storms in a mesocosm experiment led to a dramatic short-term (a day) increase in bacterial production in coastal waters (Chróst and Riemann, 1994). Although bacterial production and abundance might exhibit a short-term variation before and after the passage of typhoons, little is known about the short-term evolution of bacterial production and abundance during the passage of typhoon. Since phytoplankton blooms have been known to occur 3–6 days after the passage of typhoons (reviewed in Tsuchiya et al., 2014), bacterial production may be rapidly enhanced by such nutrient loadings and became dominant before phytoplankton bloom occurs at inshore waters. Microbial food webs can be the main route of carbon flow to higher trophic levels rather than grazing food chain (e.g. Ara and Hiromi, 2009), and bacteria can play a key role to drive the microbial food web. It is important to clarify short-term variations of primary and bacterial production after the passage of typhoons in order to estimate the effect of typhoons on carbon cycling in ocean ecosystems. Therefore, in the present study, we conducted *in situ* daily observations of physical-chemical environments and responses of bacteria and phytoplankton at both inshore and offshore stations in Sagami Bay after the passage of typhoon *Malou* in 2010. The aim of the present study was to elucidate couplings between nutrients and primary and bacterial production just after the perturbation of the passage of a typhoon.

2. Materials and methods

2.1. Typhoon Malou

Malou occurred in the East of the Philippine Sea as a tropical depression on 1 September 2010, and then was upgraded from tropical depression to a typhoon on 4 September (Japan Meteorological Agency, 2012, Fig. 1a). The lowest sea-level pressure of *Malou* was 992 hPa and the maximum wind speed was approximately 25 m s^{-1}. *Malou* passed over the East China Sea, Tsushima Straits and Japan Sea, and then it made landfall from Japan Sea on 8 September 2010. After *Malou* made landfall from the Japan Sea, it was downgraded to a tropical depression at 12:00 on 8 September 2010.

2.2. Meteorological data

Wind speed and wind direction were obtained from the Japan Meteorological Agency (2011) at the Ajiro Office (35°02.7′ N, 139°05.5′ E), and precipitation data were obtained at the Odawara Office (35°16.6′ N, 139°09.3′ E). Both are located less than 15 km away from our sampling site. Wind speed and wind direction are mean values per hour. Precipitation is shown as daily integrated values.

2.3. Sampling

The present study was conducted in Sagami Bay, located in the central part of Japan (Fig. 1), opening towards the Pacific Ocean to the south. Twenty rivers including 2 large rivers (Sakawa River and Sagami River) flow into the bay, which leads to the formation of a low salinity water mass in nearshore areas (Hirano, 1969, Fig. 1b). Although the water column is highly stratified and relatively nutrient depleted in summer (Satoh et al., 2000; Baek et al., 2008), once the typhoon passes the bay, large phytoplankton blooms have been shown to occur (Tsuchiya et al., 2013, 2014).

Daily samplings were carried out after the passage of typhoon *Malou* in 2010, at Manazuru Port, inshore station (Sta. A; 5 m depth; 35° 08.9′ N, 139° 09.1′ E) from 8–16 Sep in 2010, the offshore-shelf station (Sta. M; 120 m depth; 35° 09.0′ N, 139° 10.5′ E) from 9–13 Sep in 2010, and the mouth of Sakawa River (Sta. S; 1 m depth; 35° 15.4′ N, 139° 11.3′ E) on 8 Sep in 2010 (Fig. 1b, c). The sampling at Sta. M was conducted aboard the R.V. of the Manazuru Marine Center for Environmental Research and Education (MMCER), Yokohama National University. Surface water was collected by means of a bucket at Sta. A, Sta. M and Sta. S. Collected water samples were pre-screened through a 180 μm nylon mesh to remove large zooplankton and debris, and were immediately (within an hour) brought back to the field laboratory (MMCER). In the present study, we define 8 Sep in 2010 as Day 0 or the day typhoon *Malou* reached maximum effect in Sagami Bay.

2.4. Sample analysis

Water temperature, salinity, nutrients {NO_2, NO_3, PO_4, $Si(OH)_4$ and NH_4}, particulate organic carbon (POC), chlorophyll *a* (chl *a*) concentration, primary production, bacterial abundance and bacterial production were investigated for seawater samples. For river water, water temperature, nutrients and POC were measured.

Salinity was obtained using an inductive salinometer (Inductively coupled salinometer model 601 Mk1V, Watanabe Keiki MFG. Co., Ltd.). Triplicate subsamples for inorganic macronutrient analyses were filtered through a 0.45 μm pore size (Millex SLHA, Millipore) membrane filter, placed into 10 mL plastic tubes, and stored at −20 °C until analysis. The concentrations of NO_2, NO_3, NH_4, PO_4 and $Si(OH)_4$ were measured as described by Parsons et al. (1984) and Hansen and Koroleff (1999) using a nutrient auto-analyzer (SWAAT, BL TEC). Duplicate subsamples of 300–500 mL for POC measurement were filtered onto pre-combusted (450 °C, 4 h) glass fiber filters (GF/F, Whatman). The filters were treated with HCl fumes for 2 h to remove inorganic carbon, dried at 60 °C for 12 h in a dry oven, and stored in a desiccator until analysis. POC concentration was determined using an elemental analyzer (Flash EA-1112, Thermo Finningan). For chl *a* measurement, the seawater subsamples of >100 mL were filtered onto GF/F filters (Whatman) and