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Response of phytoplankton and enhanced biogeochemical activity to an episodic typhoon event in the coastal waters of Japan

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ABSTRACT

Daily field surveys were conducted at a coastal-shelf station in Sagami Bay, Japan after the passage of typhoon *Malou* in 2010 to evaluate the after-effect of a typhoon passage on the physical-chemical environment, phytoplankton bloom formation and microbial processes within and below the euphotic layer. The passage of *Malou* induced an abrupt decrease in salinity and increased loading of nutrients to the euphotic layer. Dinoflagellates dominated the phytoplankton community at the surface, whereas diatoms dominated below the surface just after the passage of *Malou*. Four days later, the dominant dinoflagellate taxa at the surface changed from *Protoperidinium* spp. to *Prorocentrum* spp. and *Ceratium* spp., indicating a dinoflagellate community succession from heterotrophic to autotrophic functional groups. Five days after passage, the dominant phytoplankton taxa shifted from dinoflagellates to diatom groups of *Chaetoceros* spp. and *Cerataulina* spp. throughout the water column. Below the euphotic layer, there were increases in diatom frustules, mainly composed of *Chaetoceros* spp. and *Cerataulina* spp., bacterial abundance and NH_4^+ concentrations. Diatom carbon biomass contributed to approximately half of particulate organic carbon (POC) below the euphotic layer, suggesting a significant contribution of diatoms to POC sinking flux after the passage of a typhoon. Bacterial abundance was positively correlated to both phaeopigment concentrations ($p < 0.01$) and NH_4^+ concentrations ($p < 0.01$), suggesting bacterial growth was associated with zooplankton grazing and remineralization of NH_4^+. The results suggest that the passage of a typhoon could significantly affect biogeochemical activities within and below the euphotic layer in temperate coastal waters.

1. Introduction

As indications of climate change and global warming become more apparent, the intensity and magnitude of typhoons, tropical cyclones, and hurricanes has increased (Emanuel, 2005; Webster et al., 2005; Elsner et al., 2008; Yamada et al., 2010; Kunkel et al., 2013; Tu and Chou, 2013; Tsuboki et al., 2014). The intensification of typhoons may significantly influence biogeochemical cycles and ecosystem dynamics at various spatial and temporal scales (Hoegh-Guldberg and Bruno, 2010).

Typhoons, including hurricanes and tropical cyclones, supply large amount of nutrients to euphotic layers through physical disturbances (Hung et al., 2013), which enhances primary production (reviewed in Tsuchiya et al., 2013). Generally, diatom blooms contribute to the increase in primary production (Chen et al., 2009), whereas dinoflagellate blooms were observed in coastal areas just after the passage of typhoons (Tsuchiya et al., 2014). It has been

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hypothesized that dinoflagellates utilize a "swim" strategy, whereas diatoms use a "sink" strategy (Smayda, 1997), implying that their ecological functions are distinct. Diatoms can contribute well to particulate organic carbon (POC) sinking flux (Rynearson et al., 2013), whereas dinoflagellates often stay in the surface layer due to their swimming ability, and can contribute to a link between bacteria and some metazoan predators which are unable to ingest bacteria directly (Jeong et al., 2010).

Opportunities of *in situ* sampling before and after the passage of a typhoon are limited because of their dangerousness and difficulty to predict the typhoon track (Chung et al., 2012). Thus, observations using a remote sensing platform exhibiting a typhoon-influence on chlorophyll *a* variability have increased (Huang et al., 2016). However, remote sensing of chlorophyll generally captures near-surface pigments up to one optical depth (the reciprocal of the attenuation coefficient; K_d, m^{-1}; Kasai et al., 1998). In temperate coastal waters, the mean attenuation coefficient K_d (PAR) in summer is 0.105 ~ 0.109 m^{-1} (July ~ September; Kuwahara et al., 2015), and the one optical depths are 9.2 ~ 9.5 m. Phytoplankton blooms after the passage of a typhoon do not occur only within the one optical depth layer but also have possibly their peak below the one optical depth, and the remote sensing observation cannot capture the latter case. The vertical distribution and bloom formation process of diatoms and dinoflagellates after the passage of a typhoon are still relatively unknown (Chung et al., 2012). It enables us to integrate the vertical information obtained by *in situ* sampling to high resolution data obtained by the remote sensing that relationships among one optical depths, water mass structures and phytoplankton vertical distributions are clarified.

Fates of increased phytoplankton biomass after the passage of typhoons have received increasing attention in recent years (Hung et al., 2010; Chung et al., 2012). Previous studies suggest increases in zooplankton grazing, biomass and subsequent fecal pellets due to high resource availability derived from phytoplankton blooms after storm runoff (Hoover et al., 2006) and after the passage of typhoons (Chung et al., 2012). Moreover, a significant correlation between phytoplankton growth rate and microzooplankton grazing rate was observed through dilution experiments after the passage of a typhoon (Zhou et al., 2011). Increases in fecal pellets, in particular, can accelerate sinking of phytoplankton from the euphotic layer to deeper waters (Turner, 2002). In the southern East China Sea, typhoon events induced phytoplankton blooms and enhanced a POC flux up to 1.7-fold higher than that of the same season when no typhoons occurred (Hung et al., 2010). In coastal regions, river runoff from increased rainfall transports large amount of terrigenous organic matter. We hypothesize that phenomena such as grazing activity, and sinking of phytoplankton, biogenic carbon and detrital POC will significantly influence biogeochemical processes below the euphotic layer. In addition, rapid nutrient remineralization caused by grazing activity and/or microbial decomposition of organic matter should occur below the euphotic layer. There have been few studies concerning short-term environmental variations below the euphotic layer just after the passage of typhoon.

In the present study, we conducted *in situ* daily observations of physical-chemical factors and biological response at a coastal-shelf station in Sagami Bay after the passage of typhoon *Malou* in 2010 to understand the alterations of ecosystem functioning induced by typhoon passage. The aims of the present study were to elucidate: (1) phytoplankton bloom forming process in the euphotic layer, and (2) microbial process below the euphotic layer after the passage of a typhoon.

2. Materials and methods

2.1. Typhoon Malou

Malou developed 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 the Sea of Japan, and then made landfall from the Sea of Japan Sea on 8 September 2010. After *Malou* made landfall from the Sea of Japan, 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 survey station. Wind speed and wind direction are mean values per hour. Precipitation was calculated as daily integrated values.

2.3. Sampling

The present study was conducted in Sagami Bay, located in the central part of Japan (Fig. 1a and b), opening towards the Pacific Ocean to the south. This bay is considered one of the key representative bays for temperate areas and well suited for quantification of typhoon impacts on coastal ecosystems because background environmental conditions have been well documented (Tsuchiya et al., 2013, 2014; Kuwahara et al., 2015). 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). In summer, the water column is highly stratified and relatively nutrient depleted, which results in the dominance of dinoflagellates such as *Ceratium* spp. (Satoh et al., 2000; Baek et al., 2008; Ara et al., 2011).

Daily sampling was carried out after the passage of typhoon *Malou* in 2010 at the coastal-shelf station (Station M, ~120 m depth, 35° 09.0′ N, 139° 10.5' E) around noon from 9 to 13 Sep in 2010 (Fig. 1c). The sampling was conducted aboard the R.V. "*Tachibana*" of the Manazuru Marine Center for Environmental Research and Education (MMCER), Yokohama National University. Sea surface water (0 m) was collected by means of a bucket and from 10, 20, 30, 40, 60 and 100 m depths by 5 L Niskin bottles. Collected water samples were pre-screened through 180 μm nylon mesh to remove large zooplankton and debris, and were immediately (~1 h) 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 at the survey station in Sagami Bay.

Solar irradiance profiles (at 0.5 m per second) were conducted using the PUV-500 submersible radiometer (Biospherical Instruments, Inc.) to determine the attenuation of photosynthetically available radiance (PAR) at Sta. M. The diffuse attenuation coefficient for downwelling irradiance of PAR (K_d) was determined from the slope of the linear regression of natural logarithm of down welling irradiance against depth assuming that solar irradiance reduces exponentially,

$$E_d(z) = E_d(-0)\, e^{-Kd\, z} \quad (1)$$

where $E_d(z)$ is the downwelling irradiance at depth z, and $E_d(-0)$ is