Biological response to typhoon in northern South China Sea: A case study of “Koppu”

Huaxue Liu\textsuperscript{a,b}, Zifeng Hu\textsuperscript{a}, Liangmin Huang\textsuperscript{a}, Honghui Huang\textsuperscript{b}, Zuozhi Chen\textsuperscript{b}, Xingyu Song\textsuperscript{a,c,*}, Zhixin Ke\textsuperscript{a}, Linbin Zhou\textsuperscript{a}

\textsuperscript{a} Laboratory of Marine Bio-resource Sustainable Utilization, South China Sea Institute of Oceanology, Chinese Academy of Sciences, Guangzhou 510301, China
\textsuperscript{b} South China Sea Fisheries Research Institute, Chinese Academy of Fisheries Sciences, Guangzhou 510300, China
\textsuperscript{c} Marine Biology Research Station at Daya Bay, Chinese Academy of Science, Shenzhen 518121, China

Abstract

Obviously increased phytoplankton biomass and primary production was observed via both in situ investigation and remote sensing analysis in the northern South China Sea during typhoon “Koppu”’s intrusion in September 2009. Sea surface temperature declined in both coastal and offshore area when Koppu arrived. In the offshore waters, stratification was weakened due to vertical mixing and sea surface temperature distribution pattern changed after the Koppu’s arrival. The \textit{in situ} data showed that extreme high primary production (PP) value (35 mgC m\textsuperscript{-2} h\textsuperscript{-1}) appeared near the Dan’gan Island indicating a potential algal bloom around the southern coastal waters of Hong Kong. Obviously increased nutrient loadings were also observed in the near-shore surface waters shortly after the typhoon’s arrival. According to both \textit{in situ} observation and remote sensing results, it is suggested that PP in the offshore water was stimulated by extra vertical nutrient transport induced by Koppu; while the enhanced phytoplankton biomass and potential bloom along the coastal was mostly contributed by the increased Pearl River discharge after rainfall, which was also regulated by the typhoon event.

1. Introduction

Tropical storms, also known as typhoons, hurricanes or cyclones, are among the most extreme weather events affecting marine and coastal areas in the tropical ocean (Price, 1981). In addition to the SST cooling, hurricane-induced vertical mixing can also bring up the nutrient-rich water to the upper euphotic zone and thus stimulate biological production. The processes of entrainment and upwelling bring up nutrients such as nitrate and phosphate from deeper layer to the upper euphotic zone and can stimulate phytoplankton blooms (Wu et al., 2007). Many studies have been carried out on biological effect induced by typhoons, such as those in the East China Sea (Son et al., 2006; Chang et al., 2008), in the South China Sea (Lin et al., 2003; Zhao et al., 2008) and in the Northwest Atlantic (Babin et al., 2004; Davis and Yan, 2004; Platt et al., 2005). Typhoons or tropical cyclones occurs frequently in the South China Sea (SCS), bringing sea surface cooling and phytoplankton blooms near their paths in the SCS, through strong vertical mixing (Chang et al., 1996; Zheng and Tang, 2007; Zhao et al., 2009). Previous studies were mostly focused on the biological effects of typhoons on phytoplankton biomass in the offshore waters basically using ocean-color satellite data, while \textit{in situ} studies, especially the possible responses of \textit{in situ} primary production (PP) and related vertical biological profiles to typhoons in an aquatic ecosystem have seldom been reported (Fogel et al., 1999).

Koppu was a category 1 typhoon that passed over the northern SCS during September 11–15, 2009. Around this typhoon period, an \textit{in situ} investigation was conducted in the near-shore waters of the northern SCS. In addition, remote sensing data is also available at that time, which provides us an opportunity to study the typhoon impact on PP in the SCS with the coupled data. In present study, we aimed to find out how the typhoon “Koppu” affected the aquatic environment and further exerted influence on phytoplankton primary production based on both remote sensing and \textit{in situ} observation in the northern SCS.

2. Material and methods

Koppu was a category 1 typhoon (Saffir-Simpson hurricane scale), originated from the tropical depression in the Northwest Pacific (13.9\textdegree N, 129.6\textdegree E) at 0600 UTC on September 11, 2009, strengthened to be a typhoon at 1200 UTC on September 14 with...
the strongest wind speed near continental shelf of the northern SCS (Fig. 1). It has a relatively slow moving speed of 19.3 mph from 0000 UTC on September 11 to 0000 UTC on September 13, and a relatively fast moving speed of 70 mph from 1200 to 1800 UTC on September 14 near the Pearl River Estuary (PRE). Koppu reached its peak intensity with estimated maximum wind speed of 140 mph near its center on 15 September. It landed at Taishan in the western Guangdong Province in the morning and then weakened into a severe tropical storm.

2.1. Satellite data

To better understand the impact of typhoon, satellite observations were separated into three periods in 2009: before the typhoon’s arrival (September 4–10), under Koppu’s impact (September 14–20) and after the typhoon (October 1–7). Satellite data during the same periods in 2008 were also analyzed for comparison. Satellite sea surface temperature (SST) and chlorophyll a (Chl a) data were acquired from the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard Aqua via NASA’s Ocean Color Working Group (http://oceancolor.gsfc.nasa.gov/). Daily MODIS standard Level 3 SST (4 × 4 km; nighttime) and chlorophyll (4 × 4 km) data were processed, and the composite images were based on the daily averages within different periods.

Chl a data derived from ocean-color images were used to calculate the primary production with the VGPM algorithm (Behrenfeld and Falkowski, 1997). The VGPM algorithm for estimation of the depth-integrated primary production (IPP) is expressed below:

$$IPP_{eu} = 0.66125P_{opt}^{pb}(E_0/(E_0 + 4.1))C_{sat}Z_{eu}D_{irr}$$

where $$IPP_{eu}$$ is the daily euphotic zone-IPP (mgC m⁻² d⁻¹), $$C_{sat}$$ the surface chlorophyll concentration (mgChl m⁻³), $$P_{opt}^{pb}$$ is the optimal specific primary productivity, $$D_{irr}$$ the daily photoperiod (h), $$E_0$$ the sea surface daily photosynthetically active radiation (PAR) (mol quanta m⁻² d⁻¹), $$Z_{eu}$$ is physical depth (m) of the euphoric zone calculated from the satellite surface Chl a concentration (Cao and Yang, 2002). Compared with other algorithms for retrieval of euphotic depth based on the satellite surface Chl a concentration, this has higher precision (Tang et al., 2007). The vertically integrated Chl a stock in the euphotic zone was derived from the SeaWiFS surface Chl a concentration following the algorithm of Behrenfeld and Falkowski (1997). $$P_{opt}^{pb}$$ was calculated from the empirical equation provided by Behrenfeld and Falkowski (1997). Aside from surface Chl a concentration, the major input data for the VGPM include sea surface daily PAR, SST, and length of solar radiation (Wang et al., 2008). The composites of PAR derived from SeaWiFS are taken from the web site (http://seadas.gsfc.nasa.gov). The lengths of solar radiation are taken from the data bank of IMCS Ocean Primary Productivity Team (http://marine.rutgers.edu/opp/).

2.2. Typhoon track data

The typhoon track data used in this study were available from the Unisys Weather Web site, which is based on the hurricane track data issued from the Joint Typhoon Warning Center (Shang et al., 2008). The data include the maximum sustained surface wind speed and the location of the hurricane center every 6 h.

2.3. In situ data

Locations of sampling sites were shown in Fig. 2. Station C1–C5 was investigated by the “Shiyian3” RV in August 16–17, 2008 and
September 19, 2009 respectively, initiated by the South China Sea Institute of Oceanology, CAS. Station D near the Dan gan Island was also investigated during the 2009 cruise.

Discrete samples were collected at various depths using a Rosette sampler at four sites in 2008 (prior to the typhoon event) and six sites in 2009 (influenced by the typhoon event). Seawater salinity and temperature were determined by CTD (Seabird, USA). Seawater samples for Chl a analysis were immediately filtered through GF/F filters, and stored at −20 °C. Chl a concentration was measured with a fluorometer (Turner-I0-AU) according to Parsons et al. (1984). PP incubation experiments were carried out in 2008 (C3) and 2009 (C3 and D). PP was measured by the 14C assimilation method according to Knap et al. (1996) and Liu et al. (2011). The incorporated radiocarbon was detected using a Beckman L6500 liquid scintillation counter.

The water quality data of station E1 and E2 were obtained from the Hong Kong Environmental Protection Department (http://epic.epd.gov.hk/ca/uid/marinehistorical). These two sites were close to each other; in addition, based on correlation analysis results between them on salinity (E2 = 0.9864 × E1, r = 0.796, n = 108, P < 0.001), temperature (E2 = 1.0213 × E1, r = 0.940, n = 108, P < 0.001) and nitrate concentration (E2 = 0.9766 × E1, r = 0.806, n = 103, P < 0.001), they had very similar environmental distributions during the year of 2007–2009. During the monthly investigations on September, 2009, E1 was sampled on September 7 before the Koppu’s arrival; while E2 was sampled on September 18 after the typhoon event. Therefore, in this study, we compare the differences between these two sites to indicate the typhoon impacts on environmental distributions.

Data from the Hong Kong observatory (about 20 km away from station D) were also used (http://www.hko.gov.hk/informtc/tcMain_u.n_uc.htm) for further analysis.

3. Results

3.1. Satellite observations

SST generally decreased from near-shore to offshore waters in the northern SCS. When the Koppu affected the northern SCS in 2009, SST decreased around the typhoon-affected area in contrast with that before Koppu’s arrival, despite the mean SST within the whole northern SCS appeared to be similar (Fig. 3a and b).

In 2008, the mean SST within the study area was 28.97 °C during September 3–9 (Fig. 3d), since typhoon T. Nuri influenced SST during that period (Zhao et al., 2009); then it increased to 30.01 °C during September 14–20 (Fig. 3e).

During September 14–20, the mean SST in 2009 was about 0.6 °C lower than that in the same period in 2008. During October 1–7, northeast monsoon prevailed in the SCS, and the mean SST decreased obviously in both the year of 2008 (26.95 °C, Fig. 3f) and 2009 (27.90 °C, Fig. 3e).

Chl a always showed higher concentrations in the near-shore regions than offshore regions in the northern SCS. In 2008, the mean Chl a concentration was 2.72 mg m−3 (Fig. 4d) during September 3–9 when typhoon T. Nuri influenced the northern SCS. It decreased to 0.81 mg m−3 during September 14–20 (Fig. 4e). In 2009, the mean Chl a concentration was 0.85 mg m−3 (Fig. 4a) before Koppu’s arrival, and increased to 2.01 mg m−3 when the typhoon passed through the northern SCS (Fig. 4a and b). During October 1–7, Mean Chl a concentration was 0.65 mg m−3 (Fig. 4f) in 2008 and 1.0 mg m−3 in 2009, respectively (Fig. 4c).

The temporal variation of IPP showed similar distribution pattern with that of Chl a in 2008 and 2009. IPP averaged 1030 mgC m−2 d−1 (Fig. 5d) during September 3–9, 2008, and then decreased rapidly to 562 mgC m−2 d−1 during September 14–20 (Fig. 5b). Conversely, in 2009, the mean IPP was 517 mgC m−2 d−1 before Koppu’s arrival while it increased to 652 mgC m−2 d−1 when the typhoon passed through the study area, and then decreased (Fig. 5a–c).

3.2. Field observations

In Hong Kong, the wind was moderate and blew easterly on the night of September 13. The wind direction changed to be northeast on the morning of September 14. As Koppu continued to move closer to Hong Kong, the northeast wind became stronger in the afternoon. Thereafter, the wind direction gradually changed to be southeast in the small hours of September 15 (Fig. 6). Free air temperature decreased obviously during the passage of Koppu (Fig. 6). It was sunny in Hong Kong on September 13 but squally thunderstorms affected Hong Kong in the evening. It was cloudy with squally showers on September 14. Heavy squally showers affected Hong Kong on September 15 and more than 100 mm of rainfall were recorded in many meteorological stations of Hong Kong. Table 1 shows the main environmental characters in station E1 and E2 in September, 2009. These 2 stations showed very similar environmental distribution patterns according to the historical observation data (http://epic.epd.gov.hk/ca/uid/marinehistorical, as suggested in section 1.3). Station E2 was investigated shortly after the Koppu’s arrival (September 18), and showed 0.3–0.5 °C lower on temperature than station E1, which was investigated before the Koppu’s arrival (September 7). Obviously higher nitrate concentration in the upper water layer was also observed in E2 in contrast with E1. Salinity and turbidity were similar between the two sites in the upper layer, but were obviously higher in the bottom water of E2 than that of E1. The surface Chl a of station E2 was nearly equal to Station D, and appeared to be much higher than that of E1. The difference on Chl a was little in the middle and bottom water layers between E1 and E2.

The vertical distribution of seawater temperature, salinity and Chl a concentration along stations C1–C4 were shown in Fig. 7. At station C1, low salinity water dominated the upper water layer in both years, with both SSS values lower than 32. At C2, SSS was lower than 32 in 2008 but higher than 32 in 2009. At C3 and C4, salinity in water column was higher than 33. In 2009, the thermocline intensity in the investigated offshore area was weaker than that in 2008, and the vertical stratification was less obvious than in 2008. In 2008, surface Chl a concentration decreased seaward from the coastal waters, and the maximum record appeared at C1.
Subsurface Chl a maximum (SCM) were found at 10 m depth at station C2, 50 m depth at station C3 and C4, respectively. In 2009, a near-surface phytoplankton bloom occurred at 10 m depth of C1, with a maximum Chl a concentration of 3.11 mg m\(^{-3}\). Chl a concentration at station C3 and C4 in 2009 was also obviously higher than in 2008.

The distribution of PP and IPP were shown in Table 2. The surface PP at C3 was close to C5. An extreme high surface PP record (35.00 mgC m\(^{-3}\) h\(^{-1}\)) was found at the adjacent waters of Dan’gan Island (Station D). If the column-integrated primary production in the whole euphotic layer is concerned, IPP at station C5 reached 1053 mgC m\(^{-2}\) d\(^{-1}\), which was more than twice of the value at C3.
4. Discussion

4.1. Impact of SST cooling and vertical mixing on PP

The SST cooling depends on many factors, such as the mixed layer depth, the thermocline depth and the air-sea heat fluxes (Emanuel, 1999; Lee and Niller, 2003). Koppu decreased SST and weakened stratification in the northern SCS in 2009. Remote sensing result suggested that SST variation was influenced by typhoon and monsoon transition in 2008 (T. Nuri) and 2009 (Koppu). In situ data also showed obviously different distribution patterns on SST in the year of 2008 and 2009. SST increased from

Fig. 4. Comparison on composed satellite image of Chl a concentration between 2009 and 2008. (A) Chl a in September 3–9, 2009 (before Koppu’s arrival); (B) Chl a in September 14–20, 2009 (during Koppu’s arrival); (C) Chl a in October 1–7, 2009 (after Koppu’s arrival); (D) Chl a in September 3–9, 2008; (E) Chl a in September 14–20, 2008; (F) Chl a in October 1–7, 2008.

near-shore to offshore in 2007 (Liu et al., 2011), which was similar to that in 2008; in contrast, the spatial variation of SST in 2009 confirmed that Koppu decreased SST in the northern SCS.

Nutrients are often deficient in the upper layer of SCS and limits phytoplankton growth (Chen and Chen, 2006). In this study, both in situ and remote sensing results suggested that the variation of SST during the typhoon event did not have a direct relationship with PP or phytoplankton biomass; therefore, the accompanying variation of nutrient supply was probably the key via which coupled the physical and biological processes, and those physical processes which brought more nutrients to the euphotic layer were important driving factors that could stimulate primary production in this sea area.

According to the vertical profile of environmental factors when Koppu passed through, stratification in the upper layer along the relatively offshore waters (C1–C5) was weakened during the

Fig. 5. Comparison on composed satellite image of IPP between 2009 and 2008. (A) IPP in September 3–9, 2009 (before Koppu’s arrival); (B) IPP in September 14–20, 2009 (during Koppu’s arrival); (C) IPP in October 1–7, 2009 (after Koppu’s arrival); (D) IPP in September 3–9, 2008; (E) IPP September 14–20, 2008; (F) IPP in October 1–7, 2008.
typhoon event, especially at C2 and C3, which was caused by vertical mixing induced by Koppu. The distinctly increased phytoplankton biomass and IPP based on in situ and remote sensing data also suggested the contribution of nutrient supplement via vertical mixing during the typhoon event.

The ecological process in coastal waters may also be affected by meteorological forcing such as storms and hurricanes via vertical mixing. For example, hurricane Gordon resulted in significant change in primary production in the Atlantic coastal and Gulf Stream waters (Fogel et al., 1999). Similarly, phytoplankton bloom occurred in Gulf of Mexico after the passage of the hurricane Katrina, and the mean Chl a concentration increased about 42%, which was attributed to enhanced nutrient supply brought up by the wind-driven upwelling and vertical mixing (Shi and Wang, 2007; Liu et al., 2009). However, in this study, nutrient supply in the coastal waters was not contributed mainly by the vertical transport, since the bottom water had much lower nutrient concentration than the upper layer during the typhoon event (Table 1).

**Fig. 6.** Temporal change of wind speed (m/s), precipitation (mm) and temperature of Hong Kong (near the Dangan Island) from September 3 to October 7, 2009.

**Table 1**
Comparison on environmental characters between E1 and E2.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Surface water</th>
<th>Middle water</th>
<th>Bottom water</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>E1</td>
<td>E2</td>
<td>E1</td>
</tr>
<tr>
<td>Salinity (PSU)</td>
<td>31.5</td>
<td>31.4</td>
<td>31.6</td>
</tr>
<tr>
<td>Temperature (°C)</td>
<td>29.7</td>
<td>29.4</td>
<td>29.5</td>
</tr>
<tr>
<td>Turbidity (NTU)</td>
<td>1.6</td>
<td>2.7</td>
<td>1.7</td>
</tr>
<tr>
<td>Nitrate nitrogen (mg dm⁻³)</td>
<td>&lt;0.002</td>
<td>0.023</td>
<td>0.004</td>
</tr>
<tr>
<td>Chlorophyll a (mg m⁻³)</td>
<td>1.2</td>
<td>2.2</td>
<td>0.9</td>
</tr>
</tbody>
</table>
Fig. 7. Vertical distributions of temperature, salinity and chlorophyll a concentration in August 2008 and September 2009.
increased rapidly with obviously high primary production around both two physical processes. As a result, phytoplankton biomass salinity did not vary very much, which indicate a mixed impact by coastal and estuarine area (Song et al., 2011). The vertical pro the algal growth in the offshore waters compared with that in the and diffusion by the oceanic water, and had much less impact on still limited within the near-shore waters of our study area. Song medium-nutrient-level bottom water. This result agrees with the during the typhoon period, which could not be supported by the river discharge induced by typhoon event was the main contributor to the high phytoplankton biomass and potential algal bloom in the near-shore waters.

4.2. Impact of river discharge on primary production during the typhoon event

Typhoon-associated precipitation often increased river runoff, resulted in an export of dissolved and particulate matter to coastal waters after the typhoon, and stimulated phytoplankton growth (Herbeck et al., 2011). In this study, typhoon Koppu passed through the Pearl River estuary, where the second largest river in China releases its discharge. The Pearl River discharge has been proved to have great impacts on phytoplankton distribution around the estuary and its adjacent waters (e.g. Yin et al., 2004; Song et al., 2011).

High PP near the Dangan Island (35 mgC m$^{-3}$ h$^{-1}$) indicated a potential algae bloom in the western PRE mouth, which was in accordance with the satellite data results. The low salinity there suggested that it was probably due to the increased discharge from the Pearl River discharge after rainfall and favorable current. The vertical distribution of environmental parameters suggested that the near-shore waters was affected by the offshore water’s intrusion during the typhoon event, since salinity and turbidity showed great increase at the bottom layer; however, the surface water was mainly affected by increased river discharge rather than the vertical transportation, since the nutrient level was very high during the typhoon period, which could not be supported by the medium-nutrient-level bottom water. This result agrees with the findings near the Dan’gan Island. On the other hand, the surface salinity did not vary very much, which indicate a mixed impact by both two physical processes. As a result, phytoplankton biomass increased rapidly with obviously high primary production around the southern near-shore waters of Hong Kong, suggesting a potential bloom there (Tables 1 and 2).

Although typhoon events could increase the river discharge and extend the river plume to a wider range, the impact of river discharge on phytoplankton growth via nutrient transport may be still limited within the near-shore waters of our study area. Song et al. (2011) demonstrated that the Pearl River plume had a widest range during summer; however, it is limited within the southern offshore waters of the estuary and the adjacent near-shore waters around Hong Kong. The nutrient loadings along the seaward river discharge decreased rapidly due to both phytoplankton uptake and diffusion by the oceanic water, and had much less impact on the algal growth in the offshore waters compared with that in the coastal and estuarine area (Song et al., 2011). The vertical profiles of salinity and temperature along C1 to C4 proved that they were rather affected by the vertical mixing than the river discharge.

5. Conclusion

Both satellite and in situ data indicated that the typhoon Koppu brought decreased SST and enhanced PP around its affecting area in the northern South China Sea. In the offshore waters, the thermocline was weakened and PP was potentially stimulated by vertical mixing and increased nutrient supply; however, enlarged river discharge induced by typhoon event was the main contributor to the high phytoplankton biomass and potential algal bloom in the near-shore waters.

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