Chlorophyll variations over coastal area of China due to typhoon *Rananim*

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Typhoon winds cause a disturbance over sea surface water in the right side of typhoon where divergence occurred, which leads to upwelling and chlorophyll maximum found after typhoon landfall. Ekman transport at the surface was computed during the typhoon period. Upwelling can be observed through lower SST and Ekman transport at the surface over the coast, and chlorophyll maximum found after typhoon landfall. This study also compared MODIS and SeaWiFS satellite data and also the chlorophyll maximum area. The chlorophyll area decreased 3% and 5.9% while typhoon passing and after landfall area increased 13% and 76% in SeaWiFS and MODIS data respectively.

**Key words:** chlorophyll, SST, upwelling, Ekman transport, MODIS, SeaWiFS

**Introduction**

Due to its unique and complex geographical environment, China becomes a country which has a high frequency of natural disasters and severe influence over coastal area. Since typhoon causes severe damage, meteorologists and oceanographers have studied on the cause and influence of typhoon for a long time. Typhoon will cause strong air-sea interaction\(^1\),\(^2\)&\(^3\), which has an obvious influence on cooling of sea surface temperature (SST). SST cooling can be highly related to the ocean’s surface condition\(^4\),\(^5\),\(^6\),\(^7\),\(^8\),\(^9\),\(^10\)&\(^11\). Previous studies indicated that, intensity of typhoon is very sensitive to the level of SST\(^12\),\(^13\)&\(^14\). Warm waters are the energy source of typhoon and prevailing strong wind can cause a disturbance on surface water resulting in driving surface water apart, creating zones of upwelling.

Upwelling events have been largely studied along eastern boundary coastal systems all over the world. Coastal upwelling is a result of horizontal divergence near the sea surface and manifests itself by the presence at surface of relatively cold water. When the process occurs over a continental shelf, it can have both economic and climatological effects\(^15\). Upwelling brings subsurface cold nutrient-rich water to the surface layer is one of the reason for lower SST and the passage of typhoon can also results in chlorophyll enhancement\(^9\),\(^16\),\(^17\),\(^18\),\(^19\),\(^20\),\(^21\),\(^22\),\(^23\)&\(^24\). Particulate organic carbon flux in subsurface waters, suspended matter concentration, re-suspension and terrestrial runoff, entrainment of riverine-mixing, Integrated Primary Production are also affected by typhoons when passing and landfall\(^25\),\(^26\),\(^27\),\(^28\)&\(^29\). It is well known that, ocean phytoplankton production (primary production) plays a considerable role in the ecosystem. Primary production can be indexed by chlorophyll concentration. The spatial and temporal variation patterns of Chlorophyll were quite diverse; however detailed information on Chlorophyll variations in the subsurface was lacking\(^25\). Typhoon can impact the ocean surface leading to improve the productivity of a certain area of the sea. Typhoon *Rananim*, which recorded as the strongest typhoon that landed Zhejiang since 1997\(^30\), was chosen as a case study to identify typhoon induced SST and chlorophyll changes over coastal region. Present article consist typhoon relation to SST cooling and chlorophyll concentration. The dynamical processes happening over the coastal area by calculating Ekman transport and compared with the higher Chlorophyll area. We also compared the chlorophyll concentration between two satellites data (MODIS and SeaWiFS) and the escalation of maximum Chlorophyll area over the coastal region after typhoon passage.

**Materials and Methods**

To understand the effect of typhoon *Rananim* on ocean surface, the study area is delimited to 10-35°N; 110-140°E and the study period is set between 5\(^{th}\) and 13\(^{th}\) August, 2004. The following data
is used for analysis: Oceanographic research need more accurate SST provides great advances. Recently Satellite microwave radiometers are capable of retrieving SST accurately\textsuperscript{31}. Daily SST data used for this study has been acquired from Advanced Microwave Scanning Radiometer-Earth Observing System (AMSR-E) sensor on NASA’s Aqua satellite. Data corresponding to one pass present numerous shadow areas, therefore, to increase the coverage, composites of both pass are considered, however there are still missing values in every image. QuikSCAT winds have been reported to identify tropical depressions prior to their detection by other observations\textsuperscript{32,33}. Wind component (u and v) data include both on ascending and descending passes has been obtained from QuickSCAT. The composite of both passes data has been extrapolated to one degree for better visualisation and to ensure the variations during typhoon. The most typical optical sensors used in the SeaWiFS sensor and Moderate Resolution Imaging Spectroradiometer (MODIS) sensor are used for Chlorophyll survey with Global Algorithms\textsuperscript{34,35,36}. The Weekly chlorophyll concentration data has been obtained from MODIS Aqua and SeaWiFS used for this analysis and also compare the chlorophyll data especially after the typhoon landfall. TRMM/TMI rainfall data used to confirm the water discharge from the river stream to coastal waters which can relate to the chlorophyll boom.

Typhoon \textit{Rananim} began with a tropical disturbance on northwest Pacific on 5th August 2004. It turned to a tropical low pressure in the morning of 8th August (decrease in pressure to 990 mb and wind speed of 45 knots). Under the influence of southwest wind flow, it moved to northeast and enhanced by the rather good condition of the atmosphere environment. Finally, the tropical cyclone formed on the evening as what we called \textit{Rananim}. On the next day, \textit{Rananim} turned to north direction and enhanced to be a strong tropical cyclone. On 9th August, \textit{Rananim} turned to northwest direction and came near Taiwan (pressure decreased to 980 mb and wind speed increased to 55 knots). \textit{Rananim} became strong enough to be a typhoon. On 10th August, the pressure decreased to 965 mb and wind speed increased to 70 knots. On 11th August, pressure decreased to 950 mb with 80 knots winds speed and the strength of typhoon \textit{Rananim} reached a peak. On the evening of 12th August, with the peak intensity, \textit{Rananim} landed at Zhejiang province with heavy rainfall and strong winds. After landing Zhejiang, \textit{Rananim} lowed rapidly and turned to northeast.

**Results**

Figure 1, depicts the variation of SST (contours) from AMSR-E SST and wind (vectors) from QuikScat during the typhoon \textit{Rananim} period (5-13 August, 2004). Over the study area there are gaps in data due to the satellite passes. Over the Northwest Pacific, SST is indicating warmer leading to the formations of low pressure on 6th August, then intensified on 8th August with decrease in pressure of 10 mb when compared with the previous day and the wind speed increased to 45 knots. On 9th August, low pressure system became typhoon (10 mb decrease in pressure and 10 knots increase in wind speed). Typhoon following warm temperature, however after typhoon passing temperature decreased of 1°C and cooler temperatures persisting. On 10th August \textit{Rananim} intensified (15 mb decrease in pressure with 15 knots increase in wind speed when compared with the previous day) and moving towards China coast. Along the typhoon track, there are obvious low temperatures found from 10th August. Typhoon is moving over warmer surfaces with higher intensity of winds, upwelling is happening which is leading to cold wake and lower SST patches can be observed after typhoon passes. Low temperature area (of 28.9°C) formed immediately when typhoon passed. Moreover, the temperature remains low for a couple of days. On 11th August peak intensity (950 mb pressure with 80 knots wind speed) of the typhoon is observed and cool wake (decrease in temperature of 1.15°C) observed after passing. Peak intensity persisted on 12th August with 3°C cool wake is visible. \textit{Rananim} landfall on 12th August with strong winds, however cooler waters persisted on 13th August after landfall also. The areas are obtaining lower temperature waters due to entrainment or upwelling. It takes few days for the temperature to recover to normal SST.

SeaWiFS and MODIS Aqua-Weekly Ocean Colour data of Chlorophyll concentration has chosen for the study area and study period of 4th to 20th August 2004. Weekly chlorophyll figures depict before typhoon, during typhoon and after typhoon landfall are in the figure 3. From the three weekly figures it is clearly observe that chlorophyll concentrations are higher along the shore except during the typhoon for both. Figure 3a and d reveals the chlorophyll concentration...
before typhoon, indicating higher concentration is resulted from the previous typhoon. When typhoon landed on 12th August 2004 over Zhejiang province figures 3b and e, chlorophyll concentration decreased significantly. However, figures 3c and f reveals the chlorophyll boom after typhoon landfall. From the figures, the detailed process ensues for chlorophyll concentration will enhanced after the passage of typhoon. Factors influencing chlorophyll enhancement is given in further sections. Typhoon Rananim landed in Zhejiang province on the night of 12th August, however a low chlorophyll concentration is obvious during the typhoon due to strong winds entrain the sub-surface water. Chlorophyll concentration enriched after typhoon passed, which can be observed in the figure 3 c and f.

The temporal and spatial resolutions of SeaWiFS, and MODIS are very different. The temporal and spatial resolution of space borne sensors degrades further passing from raw to processed imagery. In this study, weekly data were used both for SeaWiFS and MODIS, compared chlorophyll and ensures the best
accuracy. The finer temporal resolution of SeaWIFS and MODIS are readily comparable however one SeaWIFS pixel contains exactly four MODIS pixels. From the Table 1, the area of chlorophyll maximum area is indicating higher from the SeaWIFS data than MODIS. The area covering over the coastal region is indicating differently. However the spatial extent increased in both after typhoon landfall. SeaWIFS data reveals Chlorophyll concentration decreased by 3% during the typhoon passing when compared with the before typhoon passing. However, there is an increment in area after passing is about 13%. MODIS data indicating that chlorophyll concentration was decreased (6%) during the typhoon compared with before typhoon passing. An obvious increase in chlorophyll concentration of 76% found after typhoon landfall, which is higher than SeaWIFS. The difference in both MODIS and SeaWIFS may be due the algorithms the sensors used are different. The temporal resolution not sufficient to observe the growth of chlorophyll; however SeaWIFS and MODIS data give a clear picture of chlorophyll concentration growth in spatial extent, which is sufficient input for the fishery industry. Daily data will ensure the variations of chlorophyll spatial and temporal growth for research purpose as well as for identifying the fish colonies.

To find out process for chlorophyll boom, we checked the surface water transport due to typhoon. The Ekman transport at surface can be calculated in terms of the wind speed components at surface, the sea water density et al as the following equations using QuickScat wind data:

\[ Q_x = \frac{\tau_y}{\rho f} \]

\[ Q_y = \frac{\tau_x}{\rho f} \]

\( \rho \) is the sea water density which equals to 1025 kg/m³, \( \tau_x \) and \( \tau_y \) are zonal and meridional components of wind stress (calculated from QuickScat winds). \( f \) is the Coriolis parameter.

Using both the equations given above, surface water transport has been calculated and plotted in figure 4 during the Ranim’s peak intensity days. From the figures it is clearly understand that advection of surface water is away from the typhoon centre. While typhoon is moving to coastal area, wind speed will increase tremendously leading to advection and surface water move away from the center of the typhoon (i.e. Upwelling). Surface water transport calculated for the period of typhoon by taken different locations along the typhoon track and presented the variations in the figure 5. We have chosen 7 random locations along the typhoon track are as follows: L1: 15.4°N, 134.6°E; L2 - 16.1°N, 130.4°E; L3 - 19.1°N, 130.6°E; L4 - 20.4°N, 129.1°E; L5 - 22.1°N, 128.1°E; L6 - 23.6°N, 126.1°E; L7 - 25.4°N, 124.4°E (L indicates the Location). Figure 5 depicts the total water transport (shading) and horizontal moment (vector) over typhoon Ranim period and different locations. The areas of surface divergence (convergence) indicates upwelling (downwelling) along the typhoon track can be observed. Along the track water is transported away from the typhoon track. However when the intensity increased water transport is higher. When Ranim near to coastal area, divergence will be higher (red colour area) and the vectors also indicating waters are moving away from the typhoon center, which reveals the upwelling over that area. In the area of divergence sub-surface higher nutrient waters come to surface and that water move away from the center. After typhoon landfall, chlorophyll boom can be observed over higher nutrient area. However need few days to identify the booms.

**Discussion**

Typhoons persuade to move towards the regions of warmer SST as the SST gradient is at right angles to the easterly current. Ranim typhoon is westward moving along warm temperatures over Northwest Pacific and landfall at Zhejiang, China. Cold wake can be observed along and usually to the right side of typhoon track through a combination of upwelling, and mixing of the upper ocean.
The lifetime of the cold wakes, as measured by SST, varies from a few days to a few weeks.\textsuperscript{5,9,39,40} Figure 1 is depicting the cold wake along and right side of the track and is persisting for 2 days. Higher SST cooling of around $3^\circ$C on 12\textsuperscript{th} August, due to higher intensity (wind speed of 30 m/s) of the typhoon combined with heavy rainfall (123.7 mm). As high wind speed prevails, upwelling happens which is clearly observed in the figures 4 and 5.

During typhoon, nutrients concentration will increase, due to high precipitation the terrestrial flux significantly increased especially in estuarine and coastal water. The terrestrial flux brought abundant nutrients material as non-point pollution source. Chlorophyll boom can be observed after the typhoon landfall. While typhoon was moving heavy cyclonic wind prevail due to that upwelling happens near the coast, which divulges in the figure 4. Slowest translation speeds of the typhoon produce strong upwelling increased chlorophyll during its strongest intensities.\textsuperscript{9,41} While typhoon moving the most immediate effect is decrease chlorophyll concentration, due to strong wind shear is known to be damage Phytoplankton cells\textsuperscript{42} and most material contents decreased gradually in contrast to the days of typhoon landfall\textsuperscript{43}. Figure 5 is revealing the same, L6 position which is near to the coast and due to heavy cyclonic winds, divergence of surface waters happens and due to advection leading to cooling of SST. Due to divergence of surface waters indicating there is a strong upwelling, which brings the sub-surface waters to surface and chlorophyll boom can be seen after few days (figure 3c and f, after typhoon landfall). After passing position L6 typhoon intensity decreased and land fall over Zhejiang province. Before typhoon is going to landfall, typhoon induced heavy rainfall over the sea as well as in the land (figure 6). Figure 6 clearly indicating after typhoon landfall, rainfall over
the coastal region decreased obviously. However the rainfall over the land increased and persisted for few more days brings cumulative rainfall of 155.2 cm. Due to heavy rainfall over the land rain water is drained to river leading to higher river discharge. River discharge brings lot of sediment to sea, which moved from river to the sea. Sediment can be a source of nutrients (silicon, another nutrient element) supply and would transport during typhoon time, when the near-shore sediment disturbed and nutrients released from it\textsuperscript{44}. When there was typhoon, the chlorophyll concentration in the coastal waters would increase, but usually there would be a lag about 3-6 days\textsuperscript{45}. During typhoon time, upwelling will happen due to stronger cyclonic winds at the coastal waters, nutrients in the subsurface waters will be transported to surface, cooling in SST, heavy rainfall, and increase in the runoff from terrestrial will be the input to coastal waters. As a result, nutrients increase leading to increase in the chlorophyll concentration.

**Conclusions**

Typhoon *Rananim* brought a heavy surface water transport due to its strong wind occurred on 11\textsuperscript{th} August leading to strong upwelling, which is one day before landfall. Due to strong upwelling and rainfall there is 3°C decrease in SST on 12\textsuperscript{th} August, when comparing with 10\textsuperscript{th} August. The ocean process of upwelling brought the nutrient water to the surface layers and terrestrial runoff also brought nutrients due to heavy rainfall over the land, enhancing the chlorophyll concentration over coastal waters. SeaWiFS is displaying higher area of chlorophyll than MODIS. After landfall 76% increase of chlorophyll area observed from MODIS data.
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References