Chapter 13. Satellite Observations of Episodic Atmospheric Forcing on the Biogeochemistry of South China Sea: Review and Outlook

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Abstract: Episodic atmospheric forcing on the biogeochemistry and carbon cycle of South China Sea is an important issue which is little-studied. These episodic atmospheric processes include typhoon and aerosol input. With the advancement in satellite remote sensing, it is now possible to have a glimpse of these highly dynamic processes. This chapter provides a review of some existing works and discuss possible outlook.

1. Introduction

Upper-ocean dynamics and biogeochemistry are highly correlated and driven by atmospheric processes. Among different temporal and spatial scale atmospheric processes, the ocean biogeochemical responses to drastic atmospheric episodes like typhoons and dust storms are of high importance but little studied. Progress in studying these processes has been hindered by the lack of observations because a suite of frequent, systematic, synoptic co-incident / co-located ocean and atmospheric physical, chemical, and biological parameters are required to study these highly dynamic systems. Clearly, ship-borne observation is far from sufficient to meet this need. With the advancement in space-borne remote sensing, such observation is becoming more feasible. This study reports the use of a comprehensive set of advanced remote sensing data in synergy to investigate these transient processes. Remote sensing data sets include cloud-penetrating microwave sea surface temperature data (SST) from the Tropical Rainfall Measurement Mission (TRMM, Wentz et al., 2000), Chlorophyll-a concentration (Chl-a) data from the NASA MODIS (MODerate Resolution Imaging Spectro-radiometer; Kaufman et al., 2002) and SeaWiFS (Sea-viewing Wide Field-of-view Scanner, O' Reilly et al., 1998) sensors, atmospheric aerosol optical thickness and fine mode fraction data from the NASA MODIS (Kaufman et al., 2002), and ocean surface wind vectors from the NASA QuikSCAT scatterometer (Liu et al., 1998).

2. The Forcing of Typhoon

Traditionally accepted mechanisms of nutrient supply to the upper ocean are insufficient for supporting the new production in the oligotrophic ocean estimated from geochemical tracers (Schulenberger and Reid, 1981; Jenkins and Goldman, 1985; McGillicuddy and Robinson, 1997). This paradox, whose resolution is critical for a full understanding of the global carbon cycle, has generated an intensive search for sources of allochthonous nutrients to the upper ocean (McGillicuddy and Robinson, 1997; McGillicuddy et al., 1998; Oschlies and Garcon, 1998; Williams and Follows, 1998; Villareal et al., 1999; Uz et al., 2001; Zehr et al., 2001). Episodic injections of nutrients as a result of enhanced vertical mixing and upwelling across the nutricline pumped by tropical cyclones, is a possibility that has been much speculated yet largely undocumented by direct observations (Klein and Coste, 1984; Eppley and Renger, 1988; Marra et al., 1990; Dickey et al., 1998). Using a combination of remote sensors, Lin et al. (2003) provide an observational example of such a process. It is shown that the impact of a moderate cyclone can be far reaching.

The notion that the strong wind associated with typhoons causes entrainment and upwelling in the ocean whereby cold, nutrient-rich water below the mixed layer is brought to the light-replete surface layer to fuel photosynthetic activities and causes a phytoplankton bloom is not new (Klein and Coste, 1984; Eppley and Renger, 1988; Marra et al., 1990; Dickey et al., 1998). However, documenting this biogeochemical response of the ocean to a passing typhoon is a difficult task. Typhoons are transient, drastic atmospheric processes with large variation in trajectory. Thus, their effects on the ocean are not readily amendable to direct observations by using surface ships on prescribed schedules and cruise tracks, or mooring arrays at predetermined locations. Remote sensing allows the effects to be monitored as a surface expression of the ocean. However, whether a passing typhoon may leave a surface imprint is not assured as factors such as the wind speed, the duration that the typhoon stays in one particular location and the depth of the nutricline at that location can all play critical roles in the eventual outcome. Furthermore, the cloud cover that inevitably associates with the typhoons limits the usefulness of any sensor using infrared and visible frequencies. The chances of observing the effects of a typhoon as a surface expression in the ocean are maximized when a slow moving typhoon with a high wind speed passes over an oligotrophic area of the ocean with a shallow nutricline. The South China Sea (SCS) is an area of the world ocean where these conditions are more likely to be met. It is oligotrophic and the top of its nutricline starts at about 50 m or less in the summer (Chen et al., 2001; Liu et al., 2002). Based on Lin et al. (2003), the bloom event induced by typhoon Kai-Tak (2000) is reviewed as follows.

Kai-Tak was a moderate category 2 typhoon in the Saffir-Simpson hurricane scale. It lingered at a near stationary slow speed (0-1.4 ms^{-1}) on the northern SCS from 5 to 8 July 2000 before it proceeded speedily (~6.1 ms^{-1}) northwards thereafter (Figure 1b). Before Kai-Tak's arrival, the SCS is characterised by warm SST predominantly above 30°C (Figure 1a). During 5-8 July, Kai-Tak's strong wind (20-40 ms^{-1}) dominated the wind field. Immediately after Kai-Tak's departure on 9 July, a cold SST (21.5-24°C) pool (118-120°E, 19-20.5°N) of a size of around 150 km co-located with the typhoon's track was observed (Figure 1b). The minimum SST of 21.5°C was found at the centre (118.9°E, 19.9°N) of the cold pool. In comparison with the pre-typhoon condition (30.7°C), the SST dropped as much as 9°C. Using QuikSCAT wind vectors as an input to a ocean mixed layer model (Price, 1981; Price et al., 1986), one finds that the entrainment-induced mixed layer deepening can be as deep as 90m. Also, strong upwelling characterised by high pumping velocity (Pond and Pickard, 1983) of above 20×10^{-4} ms^{-1} (i.e., 100 m vertical displacement over half of the inertial period) at the cold pool location was found. The distributions of SST along a transect, tr1 (location depicted in Figures 1a-1c), crossing over the cold pool before and after the passing of the typhoon together with the 3-year (1998, 1999, and 2001) climatological mean for July are shown in Figure 1f.

The biological response of the SCS to the passing of Kai-Tak was depicted by changes in the surface distribution of Chl-a. The pre-typhoon condition was illustrated in the SeaWiFS composite from 27 June - 4 July 2000 (Figure 1d) which showed the typical summer condition of surface Chl-a concentrations predominantly ≤0.1 mgm^{-3}. After Kai-Tak's passage (5-8 July), the first available cloud free SeaWiFS image composite (12-15 July) illustrated an astonishing enhancement of biological activity (Figure 1e). The bloom patch (117.5-120°E, 19.3-20.7°N), predominantly of Chl-a concentrations around 10 mgm^{-3}, coincided with Kai-Tak's trajectory and its RMW, and the cold pool revealed by TMI (Figure 1c). At certain locations (e.g. 118.4°E, 20°N), the Chl-a concentrations reached as high as 30 mgm^{-3}, 300 fold of the pre-typhoon condition as depicted in the Chl-a distribution (in log scale) along tr1 (Figure 1g). The pre-typhoon (from Figure 1d) and the climatological (July monthly average for the years 1998, 1999, and 2001) Chl-a concentrations along tr1 are also depicted for comparison.

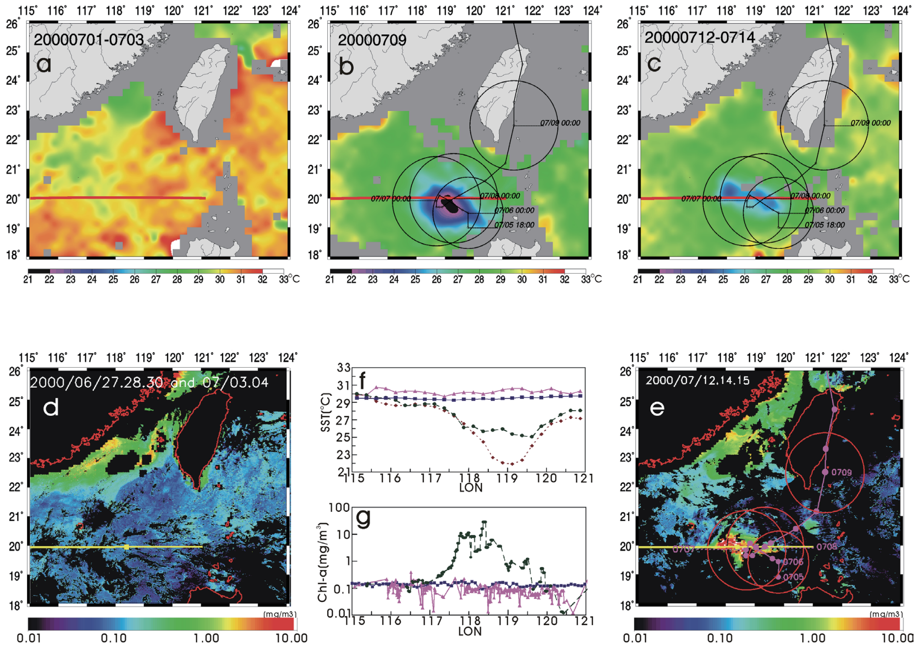

Figure 1. TRMM TMI/SST image on (a) 1-3 July 2000, before the arrival of typhoon Kai-Tak; (b) 9 July 2000, after typhoon Kai-Tak; (c) 12-14 July 2000, illustrating the match between cold SST pool (Fig.1c) and the bloom patch (Fig. 1e). SeaWiFS image composite on (d) 27 June-4 July 2000, before Kai-Tak; and (e) 12, 14, 15 July 2000, after Kai-Tak. The circle denotes Kai-Tak's RMW (Radius of Maximum Wind). The location of the transect tr1 is depicted as the red/yellow line crossing the longitude. (f) Comparison of the SST distribution along tr1. Pink: before, (from Fig. 1a). Brown: after, (from Fig. 1b). Green: after, (from Fig. 1c). Blue: The 3-year (1998, 1999, 2001) climatological average of SST for July. (g) Comparison of the Chl-a distribution along tr1. Pink: before (from Fig. 1d). Green: after, (from Fig. 1e). Blue: The 3-year (1998, 1999, 2001) climatological average of Chl-a for July. (After Lin et al., 2003)

In Lin et al. (2003), it is found that this event alone can contribute to 2-4% of the annual new production of SCS. As illustrated in Figure 2, each year there are on average about 14 typhoons passing over SCS. Among these storms, 35% are tropical storms and depressions (blue tracks), 30% are category-1 and 2 typhoons (green tracks) while another 35% are intense category-3 and 4 typhoons (red tracks). Given Kai-Tak was a category-2 typhoon and yet induced drastic biogeochemical impact. The importance of typhoon to the SCS carbon cycle and new production can be very significant and awaiting further systematic and quantitative investigations.

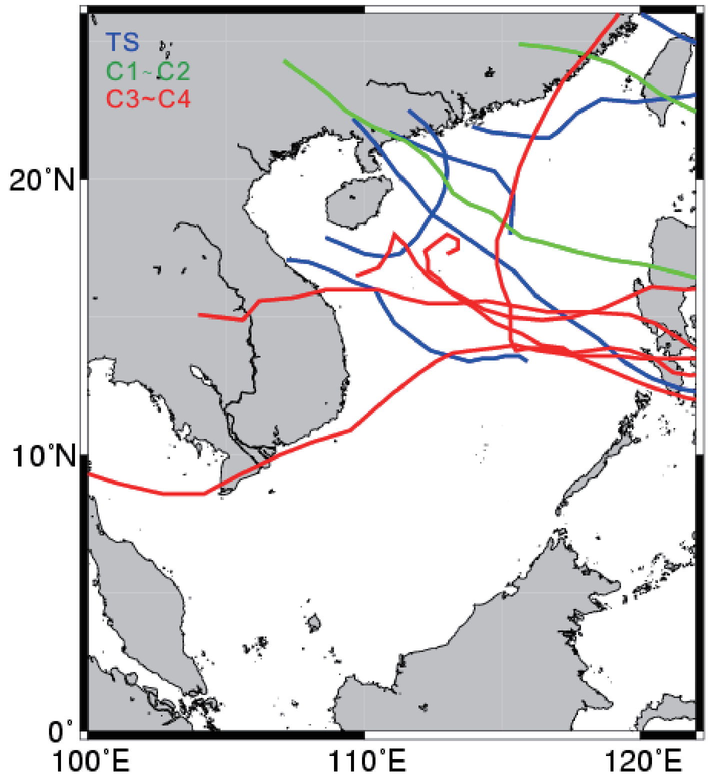

Figure 2. The tracks of typhoons passing over SCS in 2006. (Track source: Unisys Weather)

3. The Forcing of Atmospheric Aerosol

Another atmospheric process which is little studied is the biogeochemical forcing from the atmospheric aerosols. In Lin et al. (2007), MODIS aerosol optical thickness (AOT) and fine mode fraction data together with QuikSCAT wind vectors are used to systematically investigate the aerosol loading situation in the South China Sea. It is found that there are multiple terrestrial aerosol sources to the SCS. These sources includes anthropogenic aerosol from fossil fuel burning in the eastern China, wind-blown dust from the Asian deserts and biomass burning in Indo China (e.g., Sumatra and Borneo). It is found that the aerosol loading in the SCS has large spatial and temporal variability, depending on the source strength and prevailing wind directions.

As depicted in Figure 3, in January and February, anthropogenic aerosols (with major cities of high AOT loadings of 0.5 and above, as depicted in stars in Figure 3) from eastern China were transported by the prevailing northeast monsoon to the SCS. As in Figure 3, higher AOT region (light blue region, AOT~0.2) is found in the eastern half of the SCS. In March and April, Asian desert dust episodes are at the peak. During this period, desert dust aerosols are mixed with the eastern China anthropogenic aerosols and carried down together by the northeast monsoon to the northern part of the SCS.

As in Figure 3, May is the transitional month between the northeast and southwest monsoon. Though the aerosol source strength in the eastern China and Asian deserts is still high, due to the change in wind direction, only the very northern part of the SCS is loaded by these terrestrial aerosols (i.e. AOT ~ 0.2). In June and July, SCS is dominant by the southwest monsoon and the AOT loading is the lowest. In August and September, biomass burning in Sumatra and Borneo peaks and biomass burning aerosols from these southern sources are transported by the monsoon to the southern part of the SCS. September is another transitional month between northeast and southwest monsoon. One can see that though the biomass burning in the southern Borneo is still active, due to the change in the wind direction, these aerosols are confined in the very southern part of the SCS. During October – December, SCS is again dominant by the northeast monsoon. As in Figure 3, the influence from the southern biomass burning sources from Borneo and Sumatra is minimised. The aerosol loading in the SCS is again dominant by the anthropogenic aerosol loading from the Eastern China transported south by the Northeast monsoon.

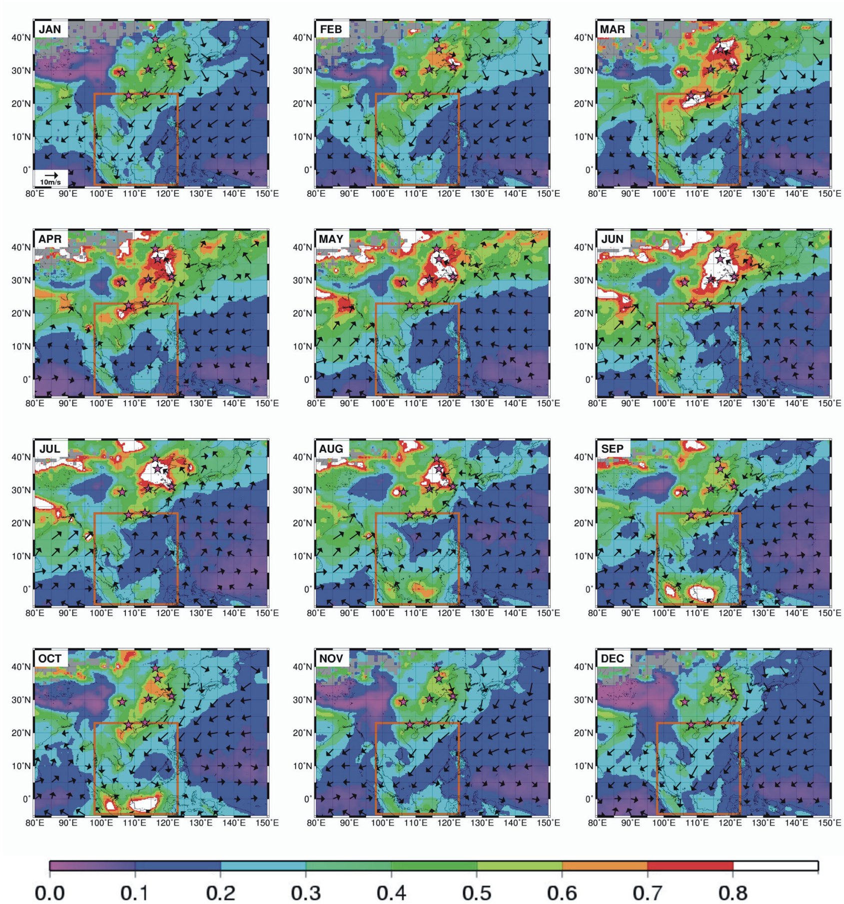

Figure 3. 3-year (2002-2004) averaged total AOT from MODIS for each month in the South China Sea (boxed region) and neighbouring regions. QuikSCAT ocean surface wind vectors are overlaid. Major Chinese cities are annotated in stars.

4. Outlook

Episodic atmospheric forcing to the biogeochemistry and carbon cycle of the South China Sea is an important issue which has been little investigated. In this chapter, possible impact of typhoon and atmospheric aerosol loading is introduced. It can be seen that the situation is highly complex. Each year there are many typhoons (on average 14 per year) of different strength passing by the SCS. Furthermore, multiple terrestrial aerosol sources, including anthropogenic aerosols from the eastern China, Asian desert dust, and biomass burning from Sumatra and Borneo are carried to the SCS by the prevailing monsoon wind and exhibit large spatial and temporal variability. A systematic and integrated approach with multiple satellite observations will be critical to further understand these highly dynamic atmospheric–ocean biogeochemical interaction processes.

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