



## Aerosol impact on the South China Sea biogeochemistry: An early assessment from remote sensing

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[1] Using 4 years' of aerosol optical thickness (AOT) and chlorophyll-a (Chl-a) concentration data from the NASA/MODIS and SeaWiFS sensors, this work systematically explores the role that atmospheric aerosols play in the biogeochemistry of the South China Sea (SCS). The results suggest that the further away from the coastline, the greater the potential role for atmospheric aerosols would be as a nutrient source to stimulate the biological activities because the chances of having other sources of nutrient inputs (e.g., river run-off or upwelling) are lower. It is found that the highest correlated area ( $R \sim 0.7$ ) of the Chl-a and AOT time series is in the southern centre of the SCS basin, typically between 111–113°E and 8–10°N. Away from the basin centre, the correlation between the two time series is typically low, with  $R \sim 0.2$ –0.3. It is found that since there are other more prominent nutrient sources (e.g., monsoon-induced upwelling and convective-overturn) to support the biological activities, atmospheric aerosols become less critical as a nutrient source in regions away from the basin centre. **Citation:** Lin, I.-I., G. T. F. Wong, C.-C. Lien, C.-Y. Chien, C.-W. Huang, and J.-P. Chen (2009), Aerosol impact on the South China Sea biogeochemistry: An early assessment from remote sensing, *Geophys. Res. Lett.*, *36*, L17605, doi:10.1029/2009GL037484.

### 1. Introduction

[2] Aerosol impact on the biogeochemistry [Duce *et al.*, 1991; Karl *et al.*, 1997; Fung *et al.*, 2000; Jickells *et al.*, 2005; Hsu *et al.*, 2008] of the South China Sea (SCS) is an intriguing research issue about which much has been speculated [Wu *et al.*, 2001, 2003; Wong *et al.*, 2002, 2007; Lin *et al.*, 2007]. Presumably because of its oligotrophic nature and strategic location, i.e., in the vicinity of the Asian continent where land aerosol input like desert dust can be made available, it has been hypothesized that atmospheric aerosol may be an important nutrient source to stimulate biogeochemical activities in the South China Sea [Wu *et al.*, 2001, 2003; Wong *et al.*, 2002, 2007; Lin *et al.*, 2007]. However, observations are scarce and there exists little systematic study on the subject. As such, it remains unclear whether indeed the South China Sea is sensitive to such terrestrial aerosol biogeochemical forcing and how it

responds. For example, which region within the SCS is sensitive to such forcing? What is the impact of different aerosol types? In particular, recent study has found that besides Asian desert dust, fossil fuel burning from the Eastern China and biomass burning in Borneo, Sumatra, and Indo China can play an even more significant role in the aerosol loading to the SCS [Lin *et al.*, 2007]. Using satellite derived aerosol optical thickness (AOT) and chlorophyll-a (Chl-a) concentration data spanning 4 years, this work aims to systematically explore the role that atmospheric aerosols may play in the biogeochemistry of the SCS. In Section 2, data and method are introduced. Section 3 is for results and discussion and conclusions are presented in Section 4.

### 2. Data and Method

[3] Two remote sensing data sets, i.e., the AOT data from the NASA/MODIS (MODerate Resolution Imaging Spectro-radiometer) sensor [Kaufman *et al.*, 2002; Remer *et al.*, 2005] and the Chl-a data from the NASA/SeaWiFS (Sea-viewing Wide Field-of-View Sensor) sensor [O'Reilly *et al.*, 1998] are used in this work. First the SCS is gridded into 1° by 1° boxes. For each grid, averaged AOT and Chl-a data are first obtained. A monthly temporal average is used while the spatial average is 1° by 1° from the grid cell centre. Monthly time series data for AOT and Chl-a over the four-year period starting from the launch of MODIS in April 2000 is obtained. The correlation between the AOT and the Chl-a time series for each grid is then examined. Thus a correlation map over the entire SCS can be constructed to see whether there exists any regional dependence. The relationship between the AOT and Chl-a time series is subsequently examined at different parts of the SCS except for the coastal regions (here bathymetry <200m is used as a the coastal criteria) because the SeaWiFS Chl-a data in the coastal regions is known to be of much lower accuracy [O'Reilly *et al.*, 1998].

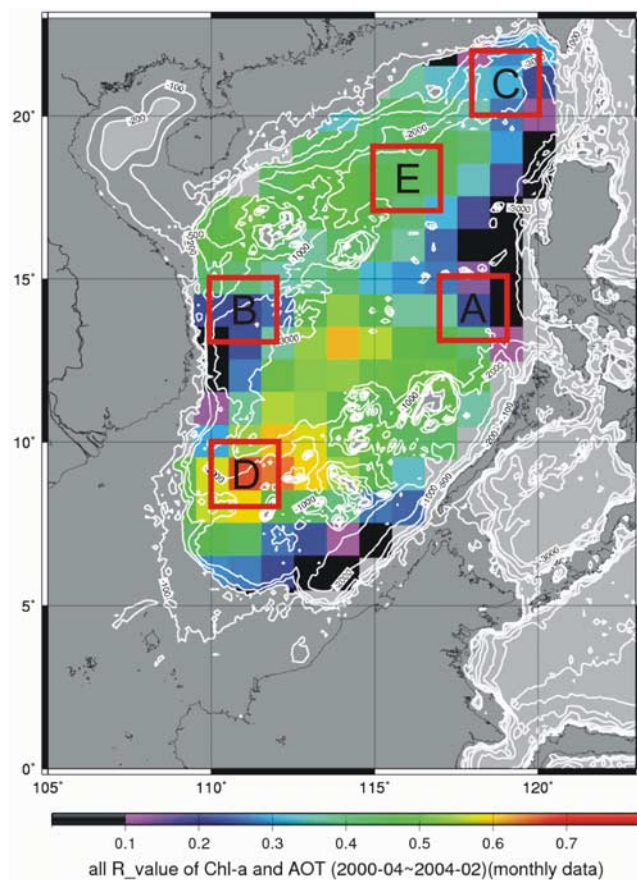
### 3. Results and Discussion

[4] Figure 1 depicts the AOT and Chl-a correlation map over the SCS. It can be seen that a regional dependence exists and that the correlation is evidently higher in the central part of the SCS basin than in the periphery. In the periphery, the correlation coefficient is pre-dominantly low, with coefficient  $R$  typically around 0.1–0.3. Moving towards the basin central,  $R$  increases significantly to around 0.5–0.7 and the highest correlation region is found to be around the southern centre of the SCS basin. In other words, the closer towards the centre of the SCS basin, the higher the correlation between the Chl-a and AOT time series is

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**Figure 1.** The  $1^\circ$  by  $1^\circ$  correlation map based on 4-year time series (starting from April 2000) of MODIS/aerosol optical thickness and SeaWiFS/chlorophyll-a concentration data over the SCS. The locations of the 5 study regions in Section 3 are also depicted.

found. This appears to suggest that the further away from the coastline, the greater the potential role for atmospheric aerosols would be as a nutrient source to stimulate biological activities since the chances of having other sources of nutrient input (e.g., river discharge or coastal upwelling) are lower. For further exploration, the situation is assessed according to the different locations (Table 1) in the SCS as follows.

### 3.1. Region A

[5] First the low correlation region in the eastern periphery (Region A) is examined (Figure 1). Located in the eastern part of the SCS basin around  $116\text{--}118^\circ\text{E}$ ,  $14\text{--}17^\circ\text{N}$ , Region A is an area known to receive the least amount of terrestrial aerosols in the SCS [Lin *et al.*, 2007]. As reported in Lin *et al.* [2007], terrestrial aerosols coming from the northern aerosol source (i.e., fossil fuel burning from Eastern China and Asian desert dust) is pre-dominantly at the north-western part of the SCS (typically at the west of  $115^\circ\text{E}$  and to the north of  $15^\circ\text{N}$ , see Figure S1 in the auxiliary material).<sup>1</sup> Also, aerosols coming from the southern terrestrial source (i.e., biomass burning from Sumatra

and Borneo) usually do not extend beyond  $10^\circ\text{N}$  (see Figure S1 in the auxiliary material). Thus, Region A is out of reach from both terrestrial aerosol sources and is typically loaded only with the marine sea salt aerosols. This situation can be clearly seen in the AOT time series (Figure 2a) that the AOT observed in Region A is low, i.e.,  $\sim 0.13$ , depicting the typical background condition dominated by sea salt aerosols [Lin *et al.*, 2007]. Examining the Chl-a time series, it can be seen that Chl-a is also low, typically around  $0.1\text{ mg/m}^3$ , depicting the typical oligotrophic condition of SCS. Thus, it is understandable why the correlation in this region is low, since there is little terrestrial AOT to stimulate the biological activities in this oligotrophic water and subsequently both AOT and Chl-a are only around the background values.

### 3.2. Region B

[6] Located in the western peripheral of the SCS basin off Vietnam, Region B is a region under the influence of the summer monsoon-induced coastal upwelling [Liu *et al.*, 2002; Xie *et al.*, 2003]. During the summer months in this region, biological activities can be much enhanced due to nutrient supply from the upwelling. As observed in Figure 2b, Chl-a concentration can increase dramatically to around  $0.4\text{ mg/m}^3$  in the summer months, for example in July–August 2000. Observing the AOT time series, the AOT fluctuations are much gentler as compared to the Chl-a fluctuations, with AOT typically only around  $0.1\text{--}0.2$ . Also, little association can be observed between the 2 time series, as depicted in Figure 2b. Thus as in Figure 1, low correlation  $R$  of  $\sim 0.2$  is found in this region since the AOT loading is small and there exists another primary nutrient source, i.e., monsoon-induced upwelling, to support the biological productivity.

### 3.3. Region C

[7] At the northern periphery of the SCS basin, Region C is another region where the correlation between Chl-a and AOT is low ( $R \sim 0.3$ , see Figure 1). However, unlike Region A and B where there is little terrestrial aerosol loading, Region C can receive significant amounts of terrestrial aerosols, especially during the spring season (March and April) where both Asian dust and Eastern China fossil fuel aerosols can be transported to this northern SCS region (see Figure S1 in the auxiliary material and Lin *et al.* [2007]). From Figure 2c, it can be seen that the AOT peaks significantly from  $0.1$  to  $0.4\text{--}0.6$  during the spring season, showing the clear increase in the terrestrial loading. However, observing the correspondent Chl-a time series, no increase associated with such increase in AOT loading during spring is found. The Chl-a in this region shows a clear winter peak (December–January), which is evident of the typical winter bloom found in the northern SCS due to the convective over-turn associated with the sea surface temperature cooling [Tseng *et al.*, 2005; Wong *et al.*, 2007]. Also as in Liu *et al.* [2002], Lin *et al.* [2003], and Chen *et al.* [2007], monsoon-induced upwelling, typhoon, and cold ocean eddies can also contribute to the increased bio-productivity in this region. This suggests that though there is significant atmospheric aerosol loading during the spring season, there are alternative nutrient sources to support the bio-productivity in this region and the primary Chl-a peak is

<sup>1</sup>Auxiliary materials are available in the HTML. doi:10.1029/2009GL037484.

**Table 1.** Geolocation of the 5 Study Regions and the Corresponding Means and Standard Deviations of AOT and Chl-a From the Time Series in Figure 2<sup>a</sup>

	Longitude (°E)	Latitude (°N)	AOT	Chl-a (mg/m <sup>3</sup> )	AOT (Mar.–Sep. only)	Chl-a (mg/m <sup>3</sup> ) (Mar.–Sep. only)
A	117–119	13–15	0.15 ± 0.03	0.12 ± 0.02	0.16 ± 0.04	0.12 ± 0.02
B	110–112	13–15	0.19 ± 0.06	0.16 ± 0.05	0.17 ± 0.06	0.15 ± 0.06
C	118–120	20–22	0.26 ± 0.1	0.22 ± 0.1	0.25 ± 0.13	0.16 ± 0.05
D	110–112	8–10	0.17 ± 0.05	0.16 ± 0.04	0.16 ± 0.05	0.14 ± 0.04
E	115–117	17–19	0.22 ± 0.08	0.16 ± 0.08	0.2 ± 0.08	0.12 ± 0.02

<sup>a</sup>The last 2 columns are the means and standard deviations of AOT and Chl-a excluding the winter months.

associated with the winter convective-overturn. Therefore, in this region the correlation between Chl-a and AOT is low.

### 3.4. Region D

[8] Though low AOT-Chl-a correlations are found in the peripheral regions of the SCS basin, there exists a high correlation region in the basin central. In Region D, i.e., the southern central of the SCS basin, the correlation is the highest, with  $R$  reaching 0.7. Checking the Chl-a and AOT time series of this region (Figure 2d), it can be seen that during the summer months (e.g., July–August), increases in Chl-a concentrations are attended by increases in AOT. Also, from existing literature about the biogeochemistry of the SCS [e.g., Liu *et al.*, 2002; Wong *et al.*, 2007], Region D belongs to the most oligotrophic part of the SCS where other prominent nutrient sources (e.g., upwelling) are absent. This suggests that in the absence of other nutrient sources, AOT input becomes important in this oligotrophic part of the SCS. Also, it can be noted that the amplitude of the Chl-a increase associated with the AOT increase (Figure 2d) is much smaller as compared to the Chl-a increase associated with the convective-overturn or upwelling (see Figures 2b and 2c). For example in Figure 2c, the Chl-a can increase from 0.1 to  $\sim 0.5$  mg/m<sup>3</sup> while the increase in Chl-a associated with AOT is much smaller, from 0.1 to  $\sim 0.25$  mg/m<sup>3</sup> (Figure 2d).

### 3.5. Region E

[9] Located in the northern central of the SCS basin, Region E is the site of the SouthEast Asian Time-series Study (SEATS) [Tseng *et al.*, 2005; Wong *et al.*, 2007]. From Figure 1, it can be seen that the correlation between AOT and Chl-a in this region is somewhere in-between (i.e.,  $R \sim 0.4$  to 0.5), as compared to the other regions. As in Figure 2e, there are clear peaks in the winter months due to the convective over-turn [Tseng *et al.*, 2005; Wong *et al.*, 2007]. However, association between the Chl-a variability and the AOT variability in the non-winter months seems to be present as well. To test this possibility, a correlation map excluding the winter months (from October to February) was generated and is presented as Figure 3. It can be seen in Figure 3 that the correlation coefficient  $R$  in this region increases to  $\sim 0.7$ , comparable to the correlation found in the southern central region of the basin. This suggests that aerosol input may still play a role during the non-winter months in the northern central part of the SCS basin.

[10] Interestingly, it can also be observed in Figure 3 that the low correlation region of  $R \sim 0.1$ –0.2 is found along the belt near 15°N (Figure 3). This is consistent with the boundary where terrestrial aerosols can reach, as reported in Lin *et al.* [2007]. As by Lin *et al.* [2007], there are two main

terrestrial aerosol sources for the SCS, one is the northern source consisting of eastern China fossil fuel aerosols and Asian desert dust while the other is the southern source consisting of aerosols sourced from Sumatra and Borneo attributed to biomass burning. These aerosols are transported by the prevailing NE and SW monsoon winds, respectively. The northern source usually can extend southwards to around 15–16°N while the southern source can extend northwards to around 11–12°N [Lin *et al.*, 2007]. Therefore, the belt along 15°N is where the aerosol loading is the lowest, since it is the region where both sources typically can not reach. As such, the Chl-a – AOT correlation is low since there is little terrestrial aerosol present along this belt.

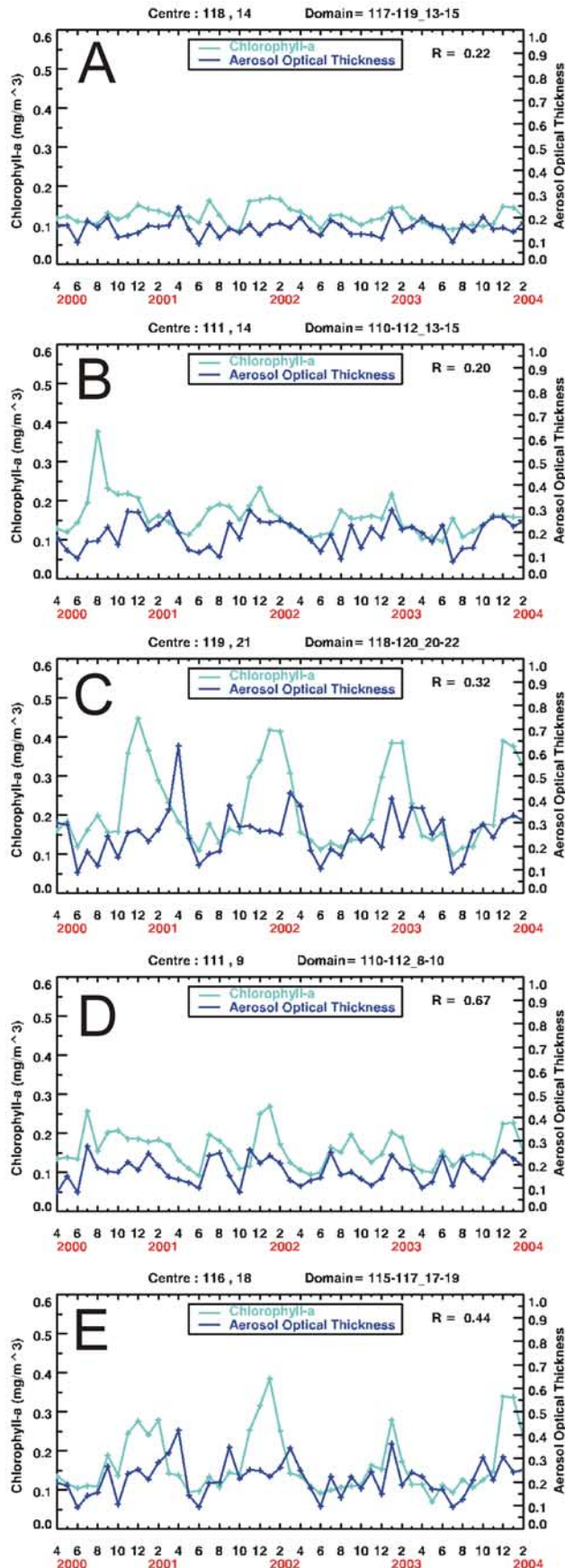
## 4. Conclusion

[11] The role terrestrial atmospheric aerosols play as a nutrient source impacting the biogeochemistry of the SCS has been much speculated upon but only scantily investigated. Using a 4-years' time-series of NASA/MODIS AOT and NASA/SeaWiFS Chl-a data, this work systematically explored the situation. It is found that:

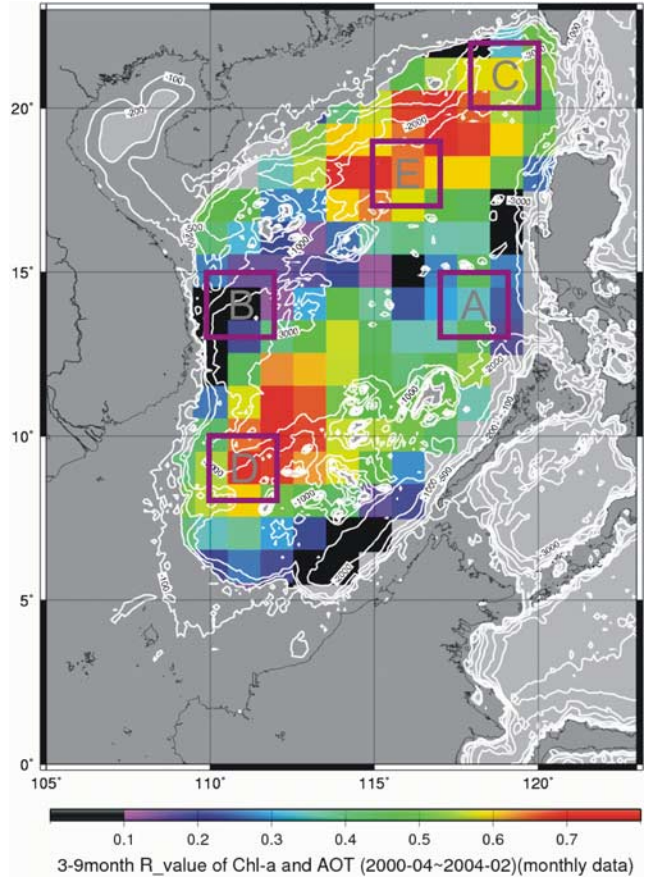
[12] 1. Among the entire SCS basin, the highest correlated area ( $R \sim 0.7$ ) of the Chl-a and AOT time series is found to be the southern central region of the basin, typically between 111–113°E, 8–10°N (i.e., Region D in Section 3). It is suggested that because little other nutrient sources (e.g., upwelling) are present, terrestrial aerosols become an important nutrient source to stimulate the biological activities in this oligotrophic part of the SCS, as supported by the clear correlation found between Chl-a concentration and AOT.

[13] 2. The further away from the centre of the basin, the lower the correlation between the AOT and Chl-a concentration is found. At the periphery of the SCS basin, the correlation coefficient  $R$  is the lowest, typically  $\sim 0.2$ –0.3. Two reasons are identified to cause such low correlation. The first is applicable to regions where other prominent nutrient sources are present (e.g., in the northern and the western peripherals of the basin, i.e., Regions B and C). In these regions, since there exist other prominent nutrient sources such as upwelling and convective-overturn, the role AOT plays becomes minor, as characterised by the low correlation. Second is applicable to region where it is both oligotrophic and in the absence of the terrestrial aerosol loading (e.g., in the eastern peripheral of the Basin at Region A). Since this existing oligotrophic region is also in lack of terrestrial aerosols and is dominant by the marine sea salt aerosols, low correlation is obtained.

[14] 3. In the centre region of the northern basin where the SEATS station is (i.e., Region E), the correlation



**Figure 2.** Four-years’ time series of AOT (right axis) and Chl-a (left axis) at the 5 study regions.



**Figure 3.** As in Figure 1, but excluding the winter months (October–February).

coefficient is somewhere in the middle, i.e.,  $R \sim 0.4-0.5$ . After removing the winter months in the time series where convective over-turn dominates, the correlation coefficient increases to 0.7. This suggests that terrestrial aerosol may still play a role during the non-winter months to stimulate the biological activities in this part of the SCS.

[15] The role of terrestrial aerosols in the biogeochemistry of the SCS is a subject at its infancy. This work serves as an early assessment of the situation based on the remote sensing data. Much more research including *in situ* observations and biogeochemical modelling are deemed necessary to further explore the detailed mechanistic link between terrestrial aerosol input and the biological responses in different parts of the South China Sea.

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