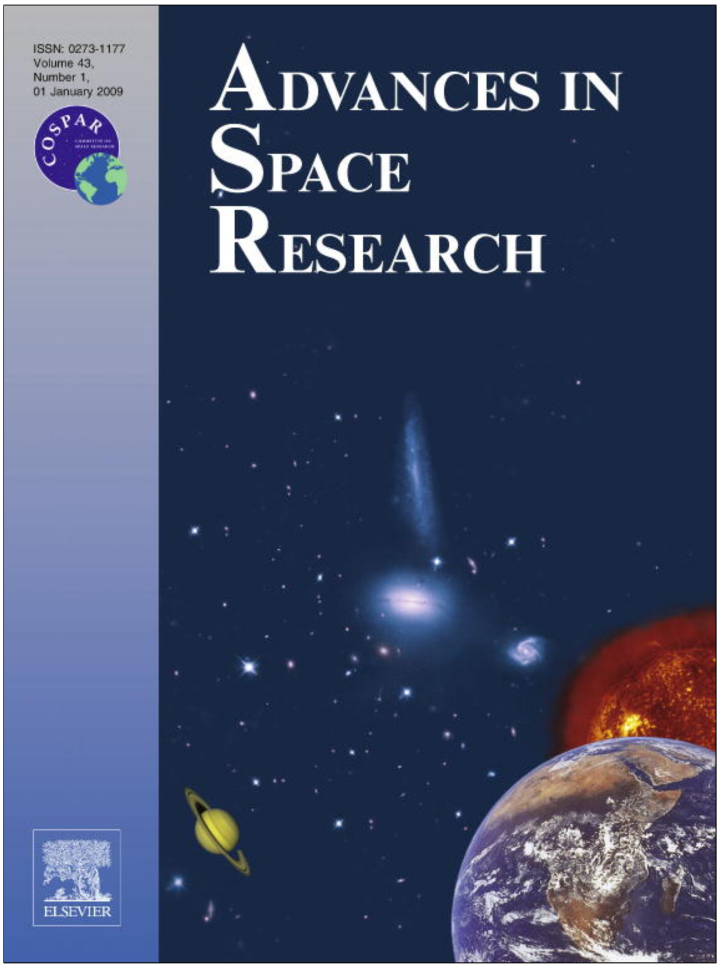
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Changes in suspended sediments associated with 2004 Indian Ocean tsunami

Zhongzheng Yan [1], Danling Tang *

Research Center of Remote Sensing and Marine Ecology Environment (RSMEE), LED, South China Sea Institute of Oceanology, Chinese Academy of Sciences, 164 West Xingang Road, Guangzhou 510301, PR China
Graduate University of Chinese Academy of Sciences, Beijing 100049, PR China

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Abstract

The Sumatra tsunami on 26 December, 2004 in the Indian Ocean was generated by one of the largest earthquakes of the past 100 years. The present study investigated spatial and temporal changes of suspended sediment concentration (SSC) in North-East Indian Ocean (NEIO) after the Sumatra tsunami used satellite remote sensing data. The nLw551 products of MODIS-aqua data (using as indexing SSC) were analyzed for 5 years (2002–2006). Result shows SSC notably increased (55.6–200%) in large river estuaries along coast of the Bay of Bengal (BOB) in a short time (4 weeks) after the tsunami, especially the northwest coast of Indonesia, southeast coast of Myanmar, as well as the north offshore of BOB. Those increases were mainly caused by the re-suspension function induced by the initial surge of the tsunami. Monthly analysis indicates increases (4.26%) of SSC of the entire North-East Indian Ocean area in 2005; especially in November 2005 when increase of SSC increased by about 6.19% compared with other years; those may mainly be caused by the destruction of coastal vegetation and modifying of estuaries or wetlands by the 2004 tsunami. The increases of SSC have different mechanism in different region and period after the tsunami.

Keywords: Suspended sediments; Tsunami; Remote sensing; Indian Ocean

1. Introduction

The Sumatra tsunami on 26 December 2004 was generated by one of the largest earthquakes of the past 100 years, and its epicenter located near 3.3°N and 95.95°E (Fig. 1) with a magnitude of 9.0 and focal depth of 10 km (Lay et al., 2005). The giant waves of the tsunami wrecked the coastal area in its initial surge that destroyed most of the coastal ecosystems. Field survey found that the coastal ecosystems such as coastal vegetation (including Mangroves), sea grass and coral reefs were badly destroyed (UNEP, 2005). Beside, this tsunami also modified most of the coastal estuaries and wetlands, which were fed by numerous rivers or streams. The waves of tsunami may also scour out the riverbank and thereafter change the drainage patterns of the river, as an aftermath, the water and soil conservation ability may also be changed and discharge more sediments to the coastal water. Further more, the ensued tsunami backwash also introduced debris and sediments from land to marine ecosystem (Roberta, 2005), which may also increased suspended sediments concentration (SSC).

Besides tsunami, sediments can be introduced to marine ecosystem via many other different ways, such as runoff of rivers (Islam et al., 1999), re-suspension of sand and silt from the bottom by tides, waves and storms (Zheng and Tang, 2007) and a number of other substances, which may fertilize the ocean water that provide food source for

* Corresponding author. Tel./fax: +86 20 89023203.
E-mail addresses: yanzz.gz@gmail.com (Z. Yan), lingzistdl@126.com (D. Tang).
URL: http://lingzis.51.net/ (D. Tang).
[1] Tel.: +86 20 89023009.

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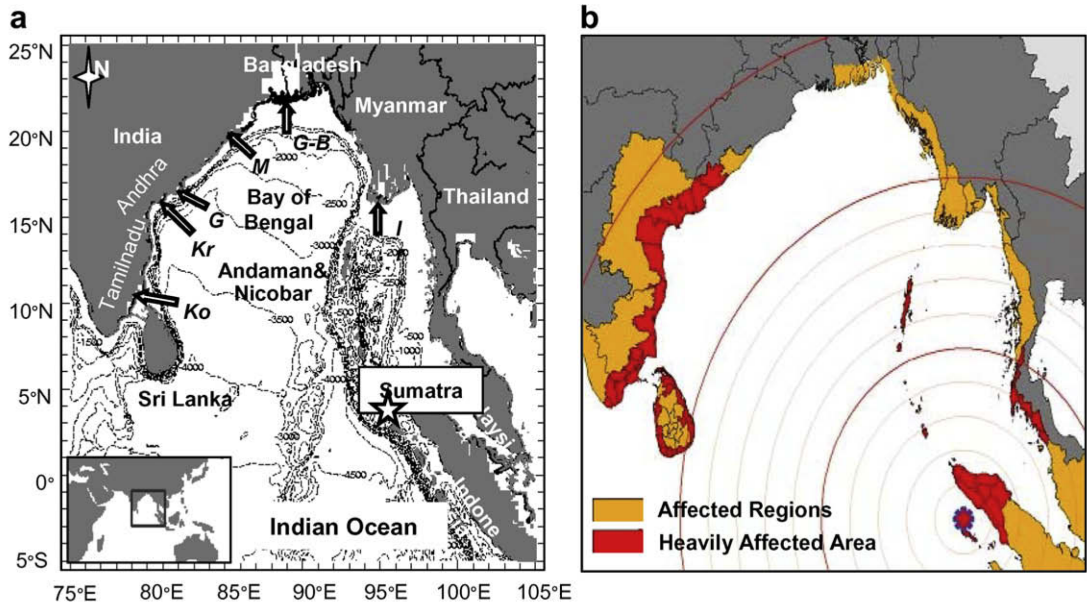

Fig. 1. (a) Geographic location and bathometry of the study area, the star denotes the epicenter of the earthquake; arrows indicate the estuaries of that are potential high discharge areas. *Ko*, *Kr*, *Go*, *Ma*, *G–B*, *Ir* are refer to the river mouths of Kollida, Krishna, Godavari, Mahanad, Ganges–Brahmaputra and Irrawaddy, respectively. (b) Map of tsunami-affected areas (source: United Nations World Food Programme).

bacteria and zooplankton and play a very important role in the marine carbon and carbonate cycles. Increase of SSC can also affect the scattering of light, which in turn reduces the primary production (Tang et al., 2006a,b). The latent affection of introduced suspended sediment on marine ecosystem seems to be a very interesting question that has attracted more and more scientific concerns.

Satellite remote sensing has been applied for studying this tsunami (Singh et al., 2007). By analyzing IRS-P4 OCM digital data, Singh et al. (2001) reported that the suspended sediments and chlorophyll concentration increased after earthquake, resulting from intense shaking due to earthquake along the west coast of India in 2001 (Singh et al., 2001). Previous studies also reported that suspended sediments and chlorophyll concentration changed in east coast of USA and east coast of India after cyclone (Kundu et al., 2001; Gautam et al., 2005). But till now, after this Sumatra tsunami, very few articles report the influences of tsunami on SSC; some researchers hold that the tsunami likely generated suspended sediment (Pennish, 2005) on the upslope and shallow water and transported finer sediment compositions to the surface (Santek and Winguth, 2005). Remote sensing imagery has been applied to study suspended sediments concentration in oceans (Ruddick et al., 2000; Zheng and Tang, 2007). Analysis of OCM (Ocean Color Monitor)data showed considerably increase of SSC along the Andhra and Tamilnadu coasts of Indian after the tsunami (Anilkumar et al., 2006). However, the research area was only restricted to the east coast of the Bay of Bengal (BOB), the changes of SSC in the whole region of North-East Indian Ocean (NEIO) is still unknown. With the strong destroying of the coastal vegetation and modification of drainage patterns in estuaries and wetlands, some problems may arise spontaneously: Have SSC increased after tsunami? How, where and when did SSC change? What relation was between the changes of SSC and tsunami? In present study, we have made an attempt to address some of these concerns using satellite data.

2. Materials and methods

2.1. Study area

Our studied area extends between 5°N and 25°N and 75°E to 105°E (Fig. 1). The bathymetry in this area decreases gradually from more than 4000 m south of Sri Lanka to 2000 m and less at 18°N (Fig. 1). Monsoonal climate dominates the area and its effects are felt far into the subtropics of the southern hemisphere. The Bay of Bengal (BOB) is the arm of the Indian Ocean and receives many large rivers, including the Kollida, Krishna, Godavari, Mahanad, Ganges–Brahmaputra (Subramanian, 1979; Islam et al., 1999, 2002) and Irrawaddy (arrows in Fig. 1), all forming fertile, heavily populated deltas and wetlands.

2.2. MODIS derived SS data

MODIS (Moderate Resolution Imaging Spectroradiometer) is a key instrument aboard the Terra (EOS AM) and Aqua (EOS PM) satellites. Its Aqua's orbit passes south to north over the equator in the afternoon, and viewing the entire Earth's surface every 1–2 days, acquiring data in 36 spectral bands, or groups of wavelengths.

Variations of sediment type (grain size and refractive index) and changing illumination conditions affect the reflectance signal of coastal waters and limit the accuracy of sediment concentration estimations from remote sensing measurements (Doxaran et al., 2002). MODIS nLw551 nm channel is found to be in a good correlation with SSC, which has been applied on study of suspended sediment distribution for the east coast of China, west coast of Africa, Arabian Sea, Mississippi Delta and west coast of Florida (Li et al., 2003; Mobasheri et al., 2004).

In the present study, we apply MODIS nLw551 nm products to study changes of relative suspended sediments concentration for the Indian Ocean after 2004 tsunami. MODIS nLw551 nm data was obtained from the Ocean Color Web (http://oceancolor.gsfc.nasa.gov) monthly and 8-day intervals (spatial resolution 9 km) for 5 years (2002–2006).

2.3. Data analysis

The tsunami-affected areas are derived from the reports of United Nations World Food Programme, Preparedness and Response Unit (http://www.pdc.org/PDCNewsWebArticles/2004SouthAsiaTsunami/InformationProducts/). True color Spot 5 images were obtained from the Centre for Remote Imaging, Sensing and Processing (CRISP), National University of Singapore (http://www.crisp.nus.edu.sg/tsunami/tsunami_browse.html). The distribution of the river mouths in the study area is derived from the Online Map Creation (OMC) (http://www.aquarius.geomar.de/omc_intro.html).

Average SSC images have been processed for two periods of 4 weeks ((i) 24 November–25 December, 2004; (ii) 26 December, 2004–24 January, 2005) before and after tsunami of December 26. Four weeks SSC anomaly was made using average of December 26, 2004–January 24, 2005 minus the average of the same times for the other 3 years (2002, 2003 and 2005). January–March and September–November SSC anomaly images were made using average of January–March and September–November in 2005 minus that of the same months of all the 4 years (2002–2006).

3. Results and discussion

3.1. SSC increased short time after tsunami

Comparison between pre- (Fig. 2A-a) and post-tsunami (Fig. 2A-b) indicates that, SSC increased in the

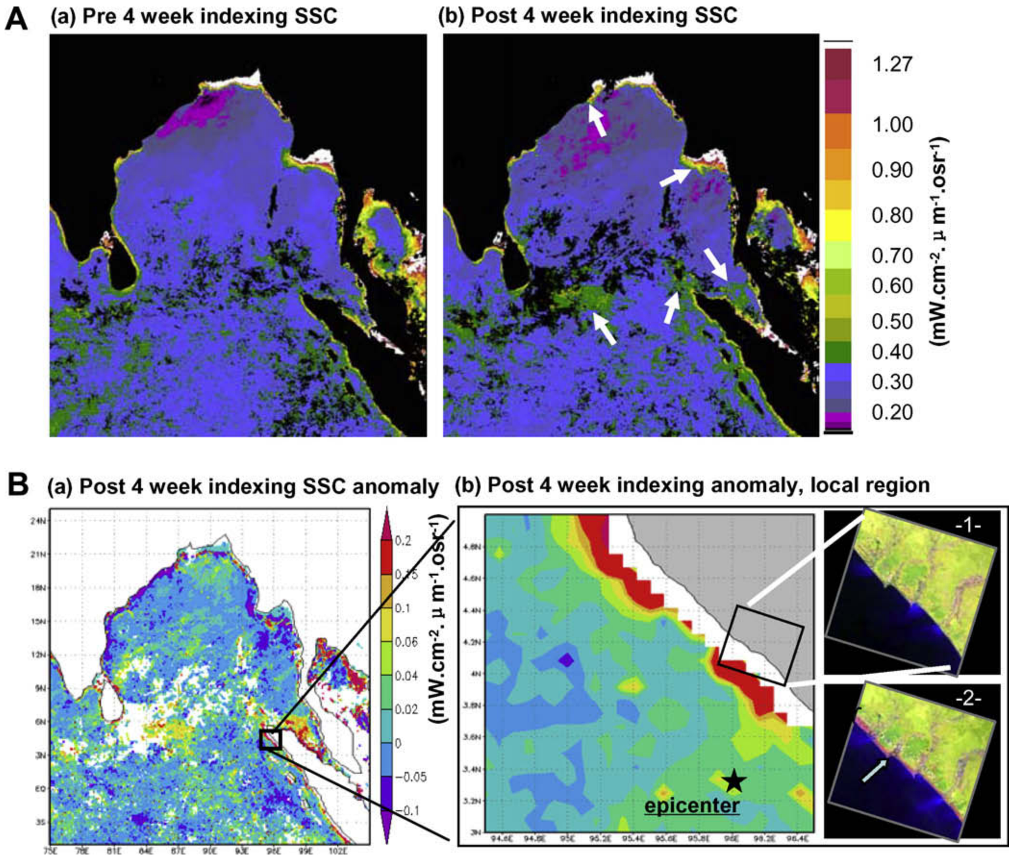

Fig. 2. MODIS-aqua nLw551 derived images, manifest the ocean water suspended sediments relative concentration. (A-a) Indexing SSC's distribution before (24 November, 2004–25 December, 2004) and (b) after (26 December, 2004–24 January, 2005) the tsunami. (B) Anomaly indexing SSC distribution: (a) 4 weeks after the tsunami (26 December, 2004–24 January, 2005), the little rect. denote the area of (B-b); (b) Anomaly indexing SSC in North Sumatra (December 26, 2004–24 January, 2005). Rect. denotes the location of the area of the RGB Spot 5 images. Star indicates the epicenter of the earthquake: (1) true color images before tsunami; (2) true color images after tsunami, arrows indicate changes of coast.

coastal areas (arrows, Fig. 2B-a) 4 weeks after the tsunami, where were badly destroyed with the increasing of turbidity, an example as shown in Fig. 2B-b in coastal region of the north Sumatra, which is near the epicenter of the earthquake. The coordinate Spot 5 true color images are also consistent with the anomaly SSC distribution in this area (Fig. 2B-b). Four weeks after the tsunami SSC increased 55.6–200% compared with the average value of the other 3 years (2002, 2003 and 2005) in coastal areas of northeast coast of Sri Lanka, Northwest coast of Indonesia, southeast coast of Myanmar and the north offshore of the Bengal Bay (see arrows in Fig. 2B-a). Those areas are coincident with high tsunami-affected area (Fig. 1b). Those SS increasing areas are small and displaying in jet-shape straightly off the shore (Fig. 2B), which seems mainly caused by the re-suspension function of initial surge of the tsunami. The results are consistent with survey observation conducted on 3rd January 2005, 9 days after the tsunami (DOD, 2005) showing that SSC were increased on 27 December, 2004 near the coastal regions of Chennai, India (Fig. 1a), and the area of high SSC had also extended from 15 km (50 m depth) to 45 km (1000 m depth) away from the north of Chennai coast. Records of historical sediment also show that tsunamis can transport sediments about 10 km even assuming the maximum wave height (Goto et al., 2002).

It is known that the initial surge of the tsunami badly damaged coastal area, and ensuing backwash carried sediments and debris from land to the ocean can contribute to the increasing of the SSC (Roberta, 2005). Storm waves are known to cause sediment re-suspension to depths greater than 50 m on open shelves (Kineke et al., 1996). When the killer wave arrived at the shallow water, it may agitate the bottom of the shelf, and mix round the shallow water to turbidity plume. The sediment re-suspension can also result from a variety of other causes such as bottom currents, tidal currents and turbidity flows. It explains why we found SSC also lightly increased in the other years. The mixing function of the tsunami is much higher than those other factors, so SSC increased markedly after tsunami.

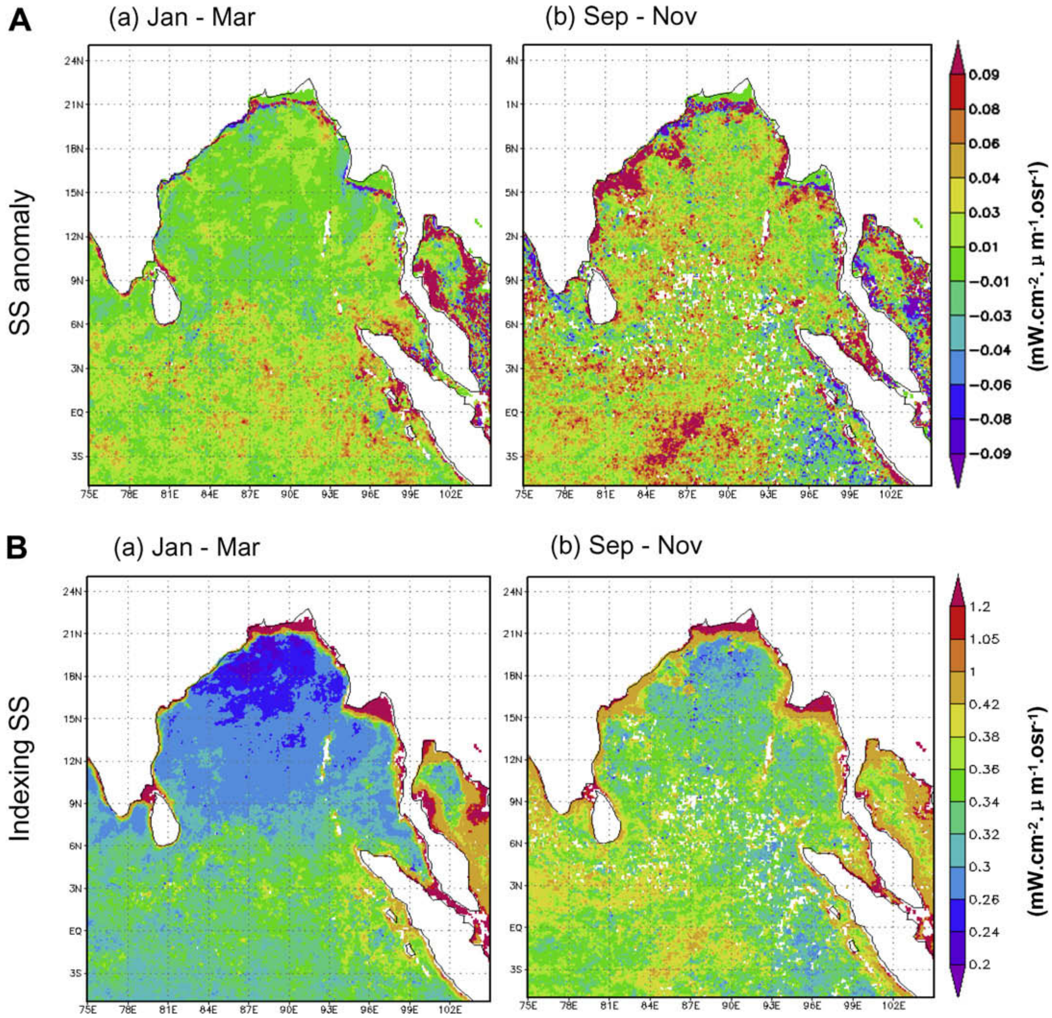

Fig. 3. (A) Anomaly indexing SSC distribution: (a) January–March, 2005 and (b) September–November, 2005. (B) Three-month mean distribution of indexing SSC images of (a) January–March (2003–2006) and (b) September–November (2002–2005).

3.2. Anomaly high SSC in September–November, 2005

For the entire BOB area, SSC increased by 4.26% in 2005 compared with the other years (2002–2004) (Fig. 4B), and it reached 6.19% in November, 2005. Those high SSC areas usually located at the coastal regions (Fig. 2B) and most are near large river estuaries (Fig. 1a). Besides counteracted the waves of the tsunami and protected the hamlets near them (IUCN, 2005; Fernando et al., 2005; Liu et al., 2005), coastal ecosystems can also split and decrease the surged waves, then decrease the wave velocity and increase sedimentation. Coastal vegetation like mangroves and sea grass can absorb nutrients and trap sediments which in turn reduce turbidity of coastal waters (Mazda et al., 1997; Wolanski et al., 1997; Williams, 2005). Whereas, the coastal ecosystems were suffered a badly destruction during the tsunami (UNEP, 2005), which can be also seen from Spot 5 Images of January 14, 2005 in Fig. 2B-b, the coast water may risk increasing SSC as an aftermath.

The BOB receives many large rivers inflows including Kollida, Krishna, Godavari, Mahanad, Ganges–Brahmaputra, Irrawaddy, all forming fertile, heavily populated deltas and wetlands (Fig. 1). In comparing with anomaly SSC distribution in 4 weeks after tsunami (Fig. 2B-a), January–March and September–November (Fig. 3A), we noticed that most of the high SSC areas are all closed to the estuaries of the above rivers, especially in September–November, 2005 (Fig. 3A-b). After the tsunami, SSC off the river mouth in ocean water seemed to be enhanced. Coastal ocean regions with large freshwater inflows are major gateways for the transfer of materials from continents to oceans. The Ganges–Brahmaputra discharges about 525,106 tons of suspended sediment to the bay through the Meghna estuary every year, this amount of suspended sediment load could generate on average 300 mg/l of SSC in the estuarine and coastal (Islam et al., 1999). SSC were found always highest in October–November (Fig. 4A), correlating with the river discharge around the BOB. Many rivers do not carry a large amount of sediments to the ocean except under special conditions, such as floods. And this discharge of high SS seemed to enlarge its quantity in the year 2005, especially at the months of September–November. It may indicate the coastal estuaries and wetlands drainage patterns were changed by the 2004 tsunami. This is revealed again by a closer investigation on a small area including the epicenter (small box in Fig. 2B-b): increase of SSC in the coastal water coincident with the changes of coastal vegetation (arrow in Fig. 2B-b) destroyed by the tsunami.

3.3. Time series analysis for 2002–2006

Detailed analysis of weekly normalized SSC data for 5 years (July 4, 2002–June 10, 2006) shows that, 4 weeks later after the tsunami, SSC climbed up step by step in 2004–

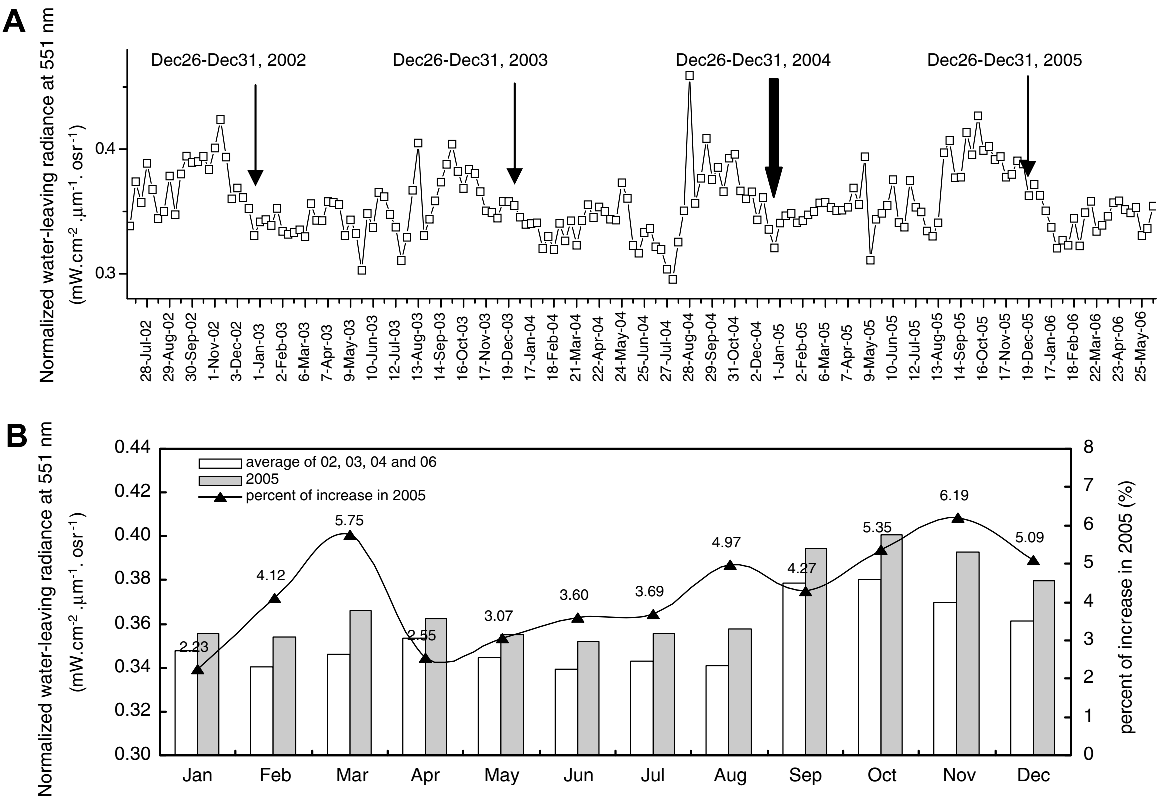

Fig. 4. Time series analysis for 5 years (2002–2006). (A) Time series of weekly indexing SSC (July 4, 2002–June 10, 2006). (B) Comparison of monthly indexing SSC values between 4 years average (2002–2004 and 2006) and 2005; the percentage of net increase of Indexing SSC in 2005.

2005 (Fig. 4A), keeping a relatively high level in 1 January–19 December, 2005 compared with the same period of the other years (bold arrow in Fig. 4A). The increasing of SSC can be also easily found in the anomaly image of SSC 4 weeks after the tsunami (Fig. 2B-a). The re-suspension function and the sediments from the land caused the coastal water turbidity. The SSC increased all the year round of 2005 (Fig. 4B), especially in months of September–December; the largest increase of SSC were observed in November, 2005 (Fig. 4B), with increases of 6.18%. This may correlate with the high runoff and discharge pattern change of the rivers around BOB, which may be affected by the tsunami waves.

Large natural variations in the quantity and timing of river discharge, winds, rainfall, ocean current and other factors may lead to great variability in the quantity and distribution of ocean water suspended sediment. A thoroughly study combined with multi-factors should be carried out to disclose the inner mechanisms. The effect of the increased SSC on marine lives such as phytoplankton is also an interesting question, that calls for further study.

4. Summaries

The present study, analyzing MODIS-aqua derived SSC images and anomaly time series SSC data, show the increases of SSC in the Indian Ocean after the 2004 Sumatra tsunami with different mechanism in different locations during different periods. (1) Just 4 weeks after the tsunami, SSC markedly increased in coastal area located at the estuaries of some large rivers, the increasing quantity was as much as about 55.6–200% of the average value. This increase caused mainly by the re-suspension function of the initial surge of the tsunami. (2) For a long period among 5 years (2002–2006), high SSC were observed in 2005, especially in November. Those increases may mainly caused by the heavy runoff of the coastal area, and may also result from the heavy destruction of the coastal vegetation in the tsunami. (3) In 2005, relatively high increase of SSC was observed near the locations where the coastal areas were destroyed by the tsunami. The effect of the increased SSC on marine lives such as phytoplankton is also an interesting question, which calls for further studies.

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