Wind-driven Coastal Upwelling Along South of Sulawesi Island

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Abstrak

Perairan di sekitar selatan Pulau Sulawesi dipengaruhi angin monsoon. Observasi menunjukkan bahwa upwelling pantai di perairan tersebut merupakan proses dominan yang menyebabkan meningkatnya konsentrasi klorofil-a selama musim monsoon tenggara. Tujuan penelitian ini adalah menggambarkan kejadian wind-driven upwelling. Angin monsoon dari tenggara adalah penyebab terbentuknya upwelling. Konsentrasi klorofil-a naik secara bertahap, dimulai di bulan Mei dan mencapai maksimum (1.1 mg/m3) di bulan Agustus, kemudian berkurang di bulan September. Menggunakan kombinasi data satelit dari angin permukaan laut, suhu permukaan laut, Chl-a permukaan, mekanisme fisik dari upwelling pantai di perairan di selatan Pulau Sulawesi

Kata kunci : *upwelling pantai, satelit penginderaan jauh, kecepatan angin, suhu permukaan laut, klorofil-a, selatan Pulau Sulawesi.*

Abstract

The sea in the vicinity of south of Sulawesi Island (SSI) is influenced by monsoon winds. The present observation shows that coastal upwelling in the region is a dominant process leading to high chlorophyll-a (Chl-a) concentration during southeast (SE) monsoon season. Southeasterly monsoon winds are responsible for the upwelling formation.The objective of the reseach was to describe the wind-driven upwelling occurrence. The bloom increases gradually, starting in May and climbing up to peak value (1.1 mg/m^3) in August, then weakens in September. By utilizing a combination of satellite data of sea surface wind vector, sea surface temperature (SST), and surface Chl-a, the physical mechanism of the coastal upwelling in the SSI is investigated.

Key words : *coastal upwelling, satellite remote sensing, wind speed, SST, Chl-a, south of Sulawesi island.*

Introduction

The south of the Sulawesi Island (hereafter SSI) is one of the major coastal upwelling regions in Indonesia. Like other major upwelling areas in the world, the vigorous winds play a dominant role in determining the distribution and duration of upwelling events. The prominent characteristic of the SSI waters is the appearance of strong sea surface temperature (SST) gradient during southeast (SE) monsoon (June-August), reflecting the influence of persistent upwelling of cold waters. During this season, strong monsoon wind blows easterly with a large component parallel to the coast as prerequisite for the development of wind-induced coastal upwelling.

Wind-driven coastal upwelling supplies nutrients to the euphotic zone near the coast. Nutrients fuel the growth of phytoplankton, the base of a very productive coastal marine ecosystem (Barth *et al.*, 2007). The physical connection between wind and upwelling occurs through Ekman transport, which is responsible for the transport of deep, nutrient-rich waters to the surface. The present results show a high correlation between phytoplankton bloom, SST cooling events and high southeasterly winds in the SSI region. Satellite chlorophyll-a (Chl-a) observations reveal offshore phytoplankton bloom events with high chl-a spreading off the coasts in the SSI during the SE monsoon. This surface concentration is directly related to the rate of primary production (Ware & Thomson, 2005). The bloom entails high wind and SST cooling, suggesting that it brings nutrients to the surface and thereby enhanced biological productivity. However, phytoplankton or alga blooms can lead to anoxic condition and the subsequent collapse of the local marine ecosystems (Forde, 2005). A better knowledge concerning the spatial and temporal evolution of the phytoplankton blooms is an essential factor for local marine realm management.

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The objective of this paper is to address the spatial and temporal variability of Chl-a bloom along SSI coast. By far, there is no published report and/or paper about the wind driven upwelling in the SSI using satellite measurement. For the first time, by using a set of several satellite products with high spatial resolution, i.e., SST, surface Chl-a concentrations, and sea surface winds, this work examines the response of chlorophyll fields to SE monsoon wind as well as changes in SST. This study provides new insights about upwelling system and lays the foundation for future research in this location.

Material and Methods

Surface Chl-a concentrations used here are SeaWiFS 4-km GAC (Global Area Coverage), obtained from NASA's Goddard Space Flight Center Distributed Active Archive Center (GSFC DAAC; http://oceancolor. gsfc.nasa. gov/cgi/browse.pl). Daily data are used in order to capture upwelling events. The semi-monthly climatology means are calculated from May 1999 to September 2004.

The SeaWinds scatterometer on the QuikSCAT satellite is a scanning microwave radar that infers the surface wind stress from measurements of radar backscatter from the roughness of the sea surface at multiple antenna look angles (Castelao & Barth, 2006). In this study, the QuikSCAT spatial resolution 25 km and 5-year long period (2000-2004) are used. Wind speeds of semi-month climatology mean are calculated.

Tohoku OISST is a SST product developed by the Satellite Oceanography Laboratory, Center for Atmospheric and Oceanic Studies (CAOS), Tohoku University, Japan. Satellite SST observations from infrared radiometers (NOAA/NASA AVHRR Pathfinder Ver.4.1, Tohoku Univ. TRMM/VIRS SST) and a microwave radiometer (JAXA/EORC TRMM/MI SST, ERS-2/ATSR-2 SST) are objectively merged to generate this SST product, which is quality-controlled, cloud-free, high-spatial resolution (0.1 degree-gridded), global coverage, and daily SST digital map. Detailed explanations of the Tohoku OISST are given by Kawai *et al.* (2006). The period of Tohoku OISST used in this study is 1999-2004. We generate semi-monthly SST maps for the analysis.

Results and Discussion

Southeast (SE) monsoon chl-a bloom in the SSI

In general, the surface wind blows northwestward during SE monsoon. The images show the gradual increased of the wind speeds from May to August and the winds are parallel to the coastline. The southeasterly winds begin to intensify in June (Figure 2a). In this month, the strong surface winds spread and cooled the SST (Figure 2b) in the SSI region, after passing the corner of the Sulawesi peninsula. However, in the 2^{nd} half of June until early July, the wind speeds slightly decrease, denoting relaxation of the monsoon winds. In the end of July, very strong winds of about 7 m/s (Figure 6a) occupy and intensify the region - (Figure 3a), marking the peak of SE monsoon (Gordon & Susanto, 2001; Susanto *et al.*, 2006). The presence of high land topography in the Sulawesi Island (white star in Figure 1a) creates a wind wake region (black box in Figure 3a), i.e. leeward of the island. The phenomenon of island-induced wind wakes has not been documented in this region. Toward to August and September, high wind speeds remain clearly seen in the corner. In October, wind conditions no longer favor upwelling.

SST fronts and chlorophyll-a fronts are strongly correlated. Upwelling events observed in the satellite-derived SSTs begin as a narrow band of cold water along the SSI coast that initially only a few kilometers wide (Figure 1b-5b). The Chl-a area evolves following severe SST cooling event. In the 1^{st} half-month of May, the SSI waters are covered uniformly by SST ~29°C (Figure 1b) and characterized by low wind speed of 4 m/s (Figure 6a). Sea surface heating due to solar radiation occurs in this period. These conditions lead to the well-stratified water column. However, small changes in SST start in the 2^{nd} half-month of May. A faint "Cold Pool" appears, concurrent with the appearance of the moderate wind speed (3-4 m/s) in the region. The Cold Pool is clearly seen in late June (Figure 2b) and persists until August. In July, the Cold Pool area size becomes larger and its SST becomes lower than those in the previous months (Figure 3b). The lowest SST of ~27.2°C (Figure 6b) appears in August after the mature monsoon wind (July). The August cooling is most likely a product of stronger winds during July (Figure 6a). Then, the SST starts to increase in September, indicating the weakened of SE monsoon (Figure 5b). Nevertheless, the SST cooling core ~27°C is still recognizable.

Chl-a distributions in the SSI waters demonstrate high spatial and temporal variability. Figure 1c-5c are semi-monthly maps which depicted the detailed development of the chl-a bloom. The maps exhibit high Chl-a concentrations in the SSI upwelling region during SE monsoon, indicating an increase in phytoplankton biomass in the area. In May, the concentrations are relatively low (~0.3 mg/m^3) in the SSI waters, and somewhat higher along the coastal waters of Sulawesi and south of Borneo (Figure 1c). In early June, the high chl-a area starts to develop southwestward from the southern tip of Sulawesi peninsula (Figure 2c and 6c), concurrent with the development of wind speed (Figure 2a and 6a). This month denotes the starting point of Chl-a bloom event in the region. In addition, the concentration is increased significantly from late May (0.3 mg/m^3) to early July (0.7 mg/m^3). It is pronounced that the southwestward bloom evolution enhances in July (Figure 3c). From late July to August, the surface Chl-a concentration jumps from 0.6 to 1.1 mg/m^3 (Figure 6c). The Chl-a bloom area reaches maximum in both width and length in late August (Figure 4c). The highest concentration is also attained in this month. In September, this offshore bloom weakened (Figure 5c and 6c).

Possible mechanism for the chl-a bloom

Surface winds affect the underlying upper ocean by three important processes: mixing of the surface layer, coastal upwelling (or downwelling) due to offshore Ekman transport, and offshore upwelling (or downwelling) due to Ekman pumping resulting from divergence (or convergence) of Ekman transport due to inhomogeneous wind fields (Huyer *et al.*, 2005). The amount of energy available for mixing the surface layer is proportional to the cube of the wind speed (Husby & Nelson, 1982). Coastal upwelling carries deeper water into the surface in an amount that balances the Ekman transport.

Present findings suggest that the mean July wind speed magnitude of 7.3 m/s is the greatest at the southwest Sulawesi Island waters. It seems that the presence of high topography of the southern peninsula of Sulawesi caused local perturbation on the direction and the intensity of the monsoon wind and hence responsible for the strength and location of the Chl-a bloom. Due to the high mountain of Lombobatang (white star in Figure 1a) and sharp southwest corner in the tip, the surface winds can be considered to experience corner and wall effect. In the present study, this jet is referred as the Southern Sulawesi peninsula tip jet. Under the strong wind jet, the cooling is induced by intensified surface turbulent heat flux from the ocean and enhanced mixing across the base of the ocean mixed layer. The later entrainment process creates nutrient-rich and eventually causes the high Chl-a concentration in the region. This is considered to be a typical case of atmosphere-land-ocean interactions (Isoguchi *et al.*, 2005). The detailed mechanism and necessary conditions for the wind jet formation will be investigated in the future study.

The strong winds at the Sulawesi tip may also lead to the estuarine discharges in the SSI waters, which carry significant amounts of organic and inorganic matter as well as dissolved substances that help support a rich coastal environment. The rivers around the Southern Sulawesi Peninsula tip are originated from the Lombobatang Mt. During SE monsoon, the winds hit the east side of the mountain and then generate cloud and cause heavy rainfall there. In the end, it causes fresh water discharges from the rivers to open bay. Due to lack of *in situ* observations, this study cannot give further explanation.

Conclusion

Several satellite data (SeaWiFS, QuikSCAT, and Tohoku OISST) have been examined to study the seasonal variations of wind-driven upwelling in the south of Sulawesi Island waters. The present work suggests that the phytoplankton biomass and low SST in the region are enhanced during SE monsoon season (dry summer). Southeasterly wind forcing presents a well-defined semiannual signal, which is suggested to be the main driving agent of the upwelling. Moreover, the upwelling is strongly associated with the existence of high land topography, and could also be associated with river discharge and bathymetry. Further studies on these matters are highly needed.

Southeast (SE) monsoon chl-a bloom in the SSI

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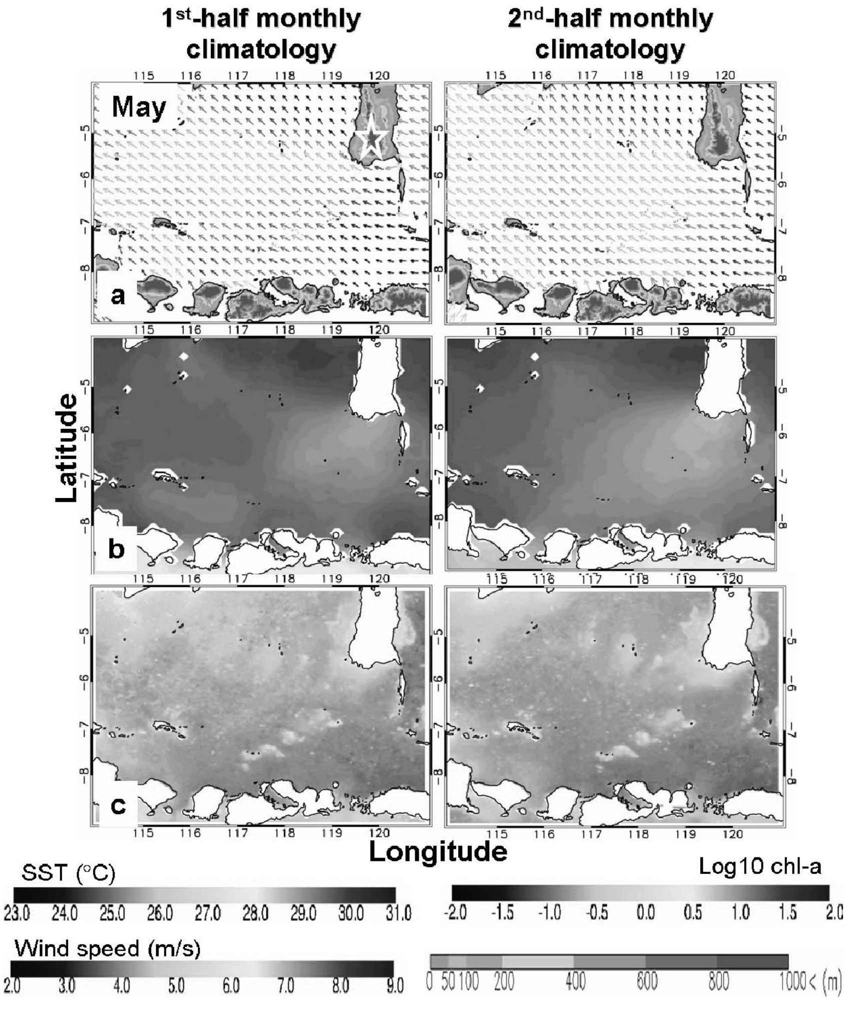

Figure 1. May half-monthly climatology of wind speed, SST, and Chl-a.

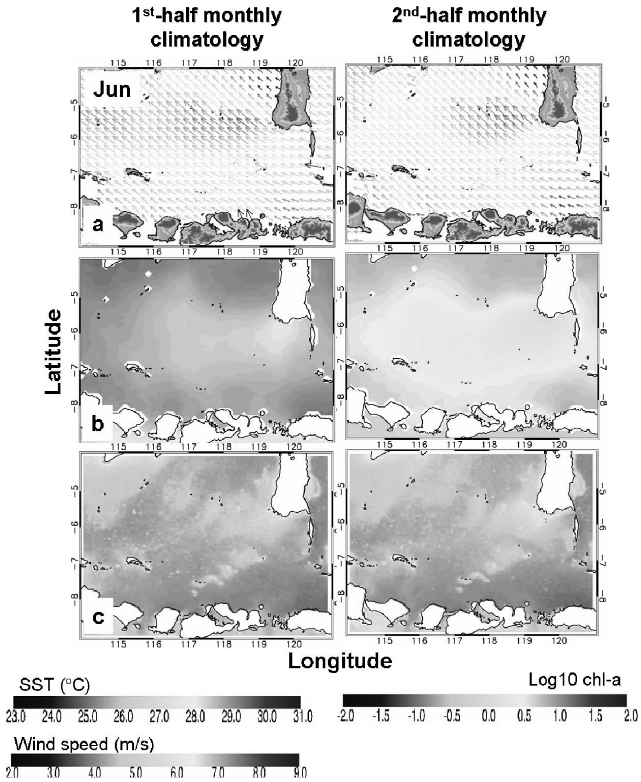

Figure 2. Jun half-monthly climatology of wind speed, SST, and Chl-a.

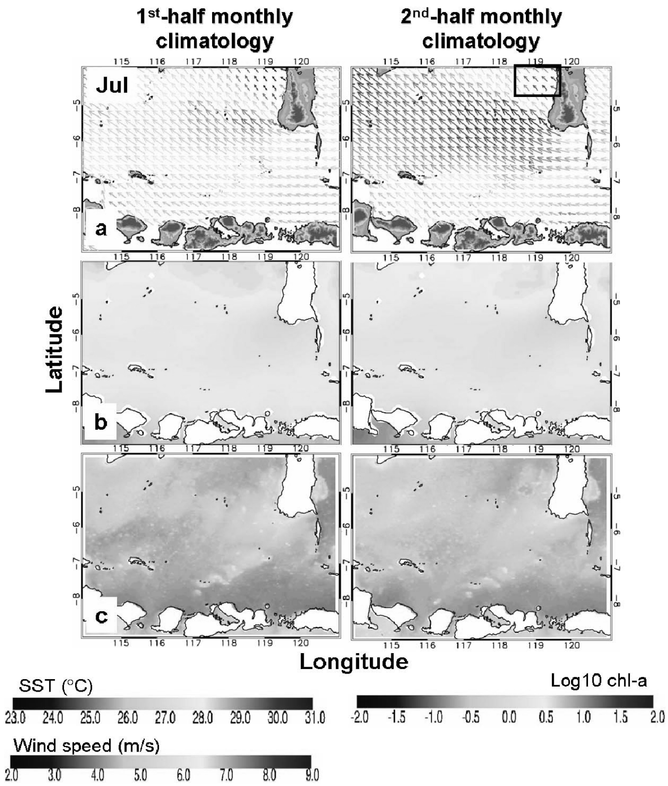

Figure 3. July half-monthly climatology of wind speed, SST, and Chl-a.

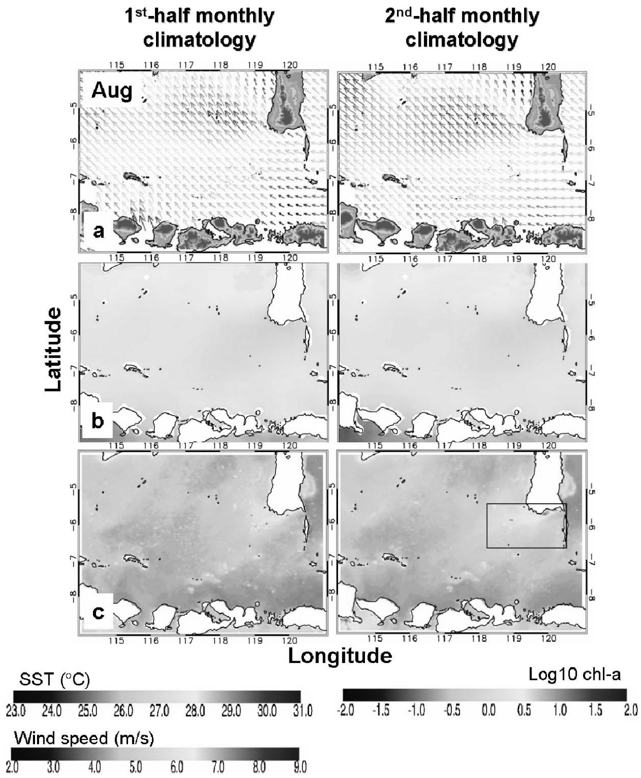

Figure 4. August half-monthly climatology of wind speed, SST, and Chl-a.

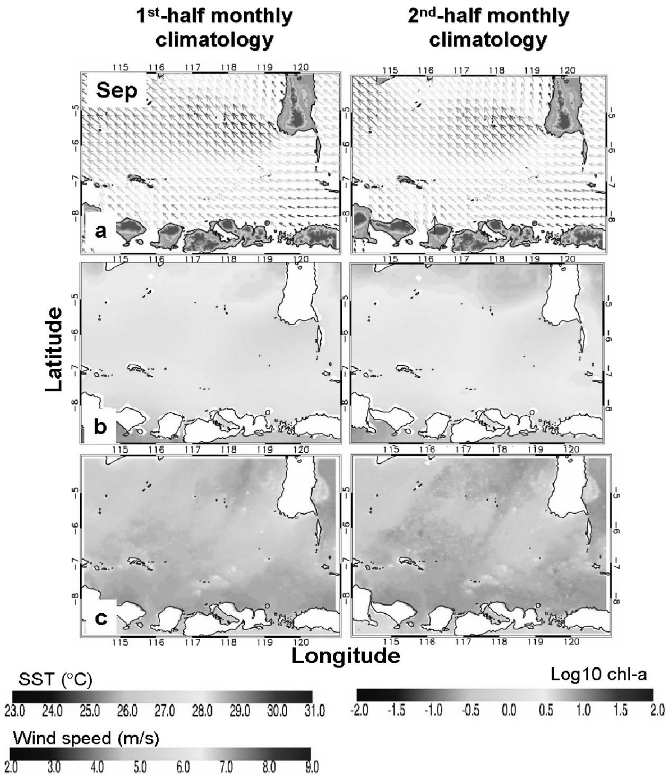

Figure 5. Sep half-monthly climatology of wind speed, SST, and Chl-a.

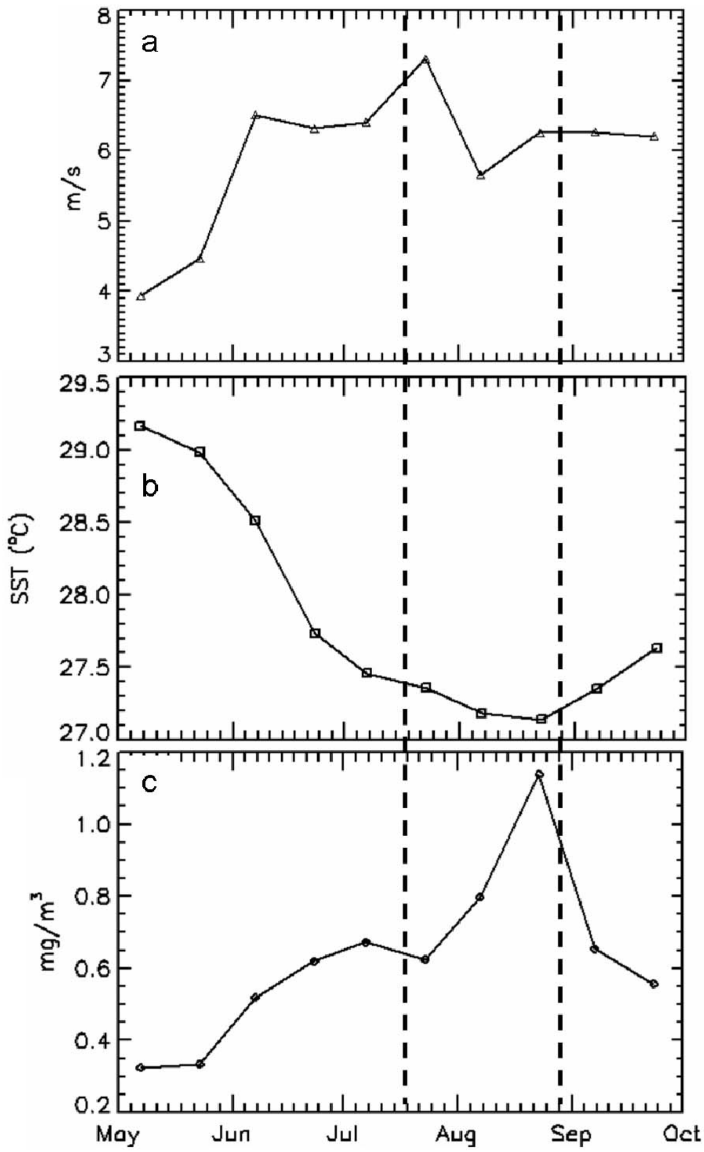

Figure 6. Semi-monthly climatology time series for (a) wind speed, (b) SST, and (c) Chl-a.