Innovative Indonesia:

Facing the Challenges of the Twenty First Century

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Study on Carbon Cycling in The Indonesian Seas: Present Status and Future Direction

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Abstract

Role of the Indonesian seas in regulating global climate system has been investigating intensively, particularly the physical processes and the Indonesian throughflow. However, little is yet known about the Indonesian seas' role in the global carbon cycle. In addition, the gap of knowledge whether the coastal seas act as a source or sink for atmospheric is still relevant for scientific question. This paper aims to evaluate carbon cycling processes in the coastal and open seas in global ocean level and to present a preliminary result and future direction for the Indonesian seas study. The fate of organic carbon input from rivers to coastal seas and its transport mechanism from the shallow to deep seas is the main issue in this paper, including vertical mixing as a physical forcing.

Keywords: marine carbon cycle, the Indonesian seas

1. Background

The role of ocean in absorbing and transporting heat that able to control climate change has been progressively investigating since 1980s by several international research institutes. During the period, geochemist and marine biologist started to consider the role of physical processes, particularly modeling material transport in the sea, including air-sea boundary layer interaction related to atmospheric carbon dioxide budget. Therefore, it is possible to predict the climate change as a response of increasing greenhouse gas concentrations in atmosphere. Concerning with this issue, research on global carbon cycle has been started in US through Global Ocean Flux Study (GOFS) program on 1984 and then extended in the international level on 1987 became Joint Global Ocean Flux Study (JGOFS).

The aims of JGOFS as follow:

- To determine and understand on a global scale the processes controlling the time-varying fluxes of carbon and associated biogenic elements in the ocean, and to evaluate the related exchanges with the atmosphere, sea floor, and continental boundaries.
- To develop a capability to predict on a global scale the response of oceanic biogeochemical processes to anthropogenic perturbations, in particular those related to climate change.

Recently, the topic of marine carbon cycle has been considered by Indonesian scientists, particularly triggered by a question "Do the Indonesian seas act as a source or sink for atmospheric carbon dioxide?" The initial opinion was released by official government of Indonesia, said that the Indonesian seas can be a sink for atmospheric carbon dioxide. The statement was based on the speculation related with phytoplankton ability in absorbing atmospheric carbon dioxide through biological activity, without valid scientific data. Therefore, the research activities are needed to develop carefully dealing with marine biogeochemical processes over the Indonesian seas, including physical forcing that control dynamic of the seas. The dynamic is depended on the specific characteristic for particular region, where the Indonesian seas can be divided into two regions: shallow seas (small islands and coastal seas affected by land activities, mostly in the western part) and deep sea (open seas in the eastern part and Economic Exclusive Zone region).

The present paper aims to review a carbon cycle in the coastal and open seas for the global ocean as well as preliminary result for the Indonesian seas study. What is lacking in the previous studies will be also summarized for the development of research in future.

2. Carbon cycle study of the coastal seas

The coastal seas receive an amount of carbon in organic and inorganic forms through river discharges. Nutrient supply from the rivers contributes also for biological productivity. Those riverine inputs bring an increase of complexity in carbonate system interactions in the coastal seas. Land use changes due to human activities also affect material supply (including carbon) to the sea. As yet, there is no consensus on the simple question noted by Land-Ocean Interactions in the Coastal Zone (LOICZ) program in its first report: Are the coastal seas carbon sources or sinks to the atmosphere? (Kempe, 1995). Recent studies have made contradicting suggestions regarding this question. For example, Mackenzie *et al.* (2000) concluded that the continental margin is a source of CO_2 to the atmosphere in spite of increased invasion of anthropogenic CO_2 from the atmosphere. In contrast, studies by Chen (2004) and Frankignoulle and Borges (2001) suggested that the coastal seas represent largest sink fluxes.

On the other hand, the role of continental margin in the global ocean carbon cycle has been synthesized by the Continental Margins Task Team, a co-sponsor of JGOFS-Joint Global Ocean Flux Study and LOICZ-Land Ocean Interaction in the Coastal Zone (Liu et al., 2000). Their findings demonstrate that continental margins are complicated systems with highly active physical and biogeochemical processes that affect the global carbon cycle. Within the world oceans, these margins are likely the most vulnerable to perturbations from human activities. Continental margins are much more heterogeneous than the open ocean, so that, continental margin carbon fluxes cannot be adequately represented by coarsely gridded maps of the current global ocean carbon fluxes.

Of the estimated annual increase of 2.2 Pg C/yr (1 Pg = 10^{15} g) oceanic carbon inventory, 40% enters the ocean via continental margins where the two-third by riverine input and the remains by air-sea exchange. In their estimation, the global continental margins serve as a net weak sink for atmospheric CO_2 (- 0.3 Pg C/yr). In addition, they estimated that the global continental margins which occupy 12% of total area of the global ocean can produce 20% of global ocean net primary production and 22% of global export production. The continental margins also accounts for 19% of net oceanic CO_2 uptake and more than 90% of oceanic denitrification.

Although the global synthesis of carbon fluxes in continental margins has been established, but there are three aspects that should be considered for improvement: air-sea exchange of CO_2, cross-shelf export of carbon to the open ocean and river fluxes. Cai et al. (2006) suggested another view in estimating the air-sea exchange of CO_2 in the continental margins using a province base-synthesis. They found that the mid-high latitude continental margins serve a net sink (- 0.33 Pg C/yr), but the low latitude acts as a source (0.11 Pg C/yr) for the atmospheric CO_2. Therefore, according to their result, the global continental margins can serve as a net weak of 0.22 Pg C/yr.

The river fluxes itself is one of the difficulty problems for the global carbon cycle since there is no consensus in determining the natural content for carbon riverine input. The current estimate of the total flux of riverine carbon discharged from land is about 0.8 Pg C/yr, of which 45% is organic (0.36 Pg C/yr) and the rest inorganic (Liu et al., 2000). On the other hand, Sabine et al. (2004) suggested that the river flux of carbon accounts for 1.1 Pg C/ yr. Particularly the organic carbon, Schlünz and Schneider (2000) estimated the river flux to be 0.43 Pg C/yr where Baum et al. (2007) suggested a total Indonesian riverine DOC (Dissolved Organic Carbon) export to the ocean of 21 Tg C/yr (1 Pg = 10^{12} g), representing about 5% of the global riverine DOC input. Recent observational data of the Brantas River – ranks number 17 among the top 20 rivers that originate at elevations above 3000 m in Indonesia – shows that the riverine DOC export to the ocean of 0.2 Tg C/yr or totally the riverine carbon input (overall carbon material) is 0.5 Tg C/yr (Aldrian et al., 2008).

Concerning the cross-shelf export of carbon to the open ocean, Tsunogai et al. (1999) proposed a theory that imply a significant sink of continental shelves or coastal seas for atmospheric carbon dioxide. The authors used measurements of temperature and salinity in the East China Sea during late fall/early winter to demonstrate the existence of down-sloping isopycnals from the surface of the shelf region to the intermediate depths of the open ocean Kuroshio region. They suggest that dense waters formed near shore by rapid winter cooling at the surface are transported to the open ocean along the down-sloping isopycnals. They showed that these waters have high CO_2 content because cooling enhances the gas solubility. In other words, the transport of this dense, high CO_2 waters originating from the coastal surface region into the interior of the open ocean represents a net transfer of carbon from the atmosphere to the ocean. Described as the "continental shelf pump" theory, it paves the way for the coastal oceans to play a possibly important role in the global ocean carbon budget.

However, ocean mixing in coastal margins is often unique, and the lessons from the East China Sea are not immediately applicable to other shelf regions. In tropical seas, such as the Indonesian seas, there is no winter cooling, because solar radiation is relatively constant over the whole year. Ocean mixing is instead generated by external forces such as winds, tides and fresh water fluxes. Therefore, unlike the East China Sea, mixing is typically more diapycnal than isopycnal in the Indonesian seas.

3. Carbon cycle study of the open seas

Sabine et al. (2004) reported that the global ocean was naturally a source for atmospheric carbon dioxide during pre-industrial era. Since the industrial revolution, carbon dioxide emissions have been increasing year by year. Global Carbon Project presented that the annual growth of atmospheric carbon dioxide was 1.8 ppm in 2008 while the mean growth rate for the last 20 years was about 1.5 ppm per year. This increase brought the atmospheric CO_2 concentration to 385 ppm in 2008, 38% above the concentration at the start of the industrial revolution (about 280 ppm in 1750). The present concentration is the highest during at least the last 2 million years. The carbon dioxide before industrial era is then called natural carbon and carbon dioxide emissions is called anthropogenic carbon.

Global Carbon Project 2007 reported that a total amount of carbon dioxide emissions to atmosphere is 9.1 Pg C/year due to fossil fuel consumptions and deforestation. The fate of carbon dioxide emissions is absorbed by ocean of 26%, terrestrial (forest) sinks of 29% and remain in atmosphere is around 45% from the total carbon dioxide emissions. In this case, the total anthropogenic carbon remained in atmosphere has been increasing from 40% on 1960 to present accumulation of 45%. The variability of terrestrial sinks is quite steady, but the efficiency rate of ocean sinks rate has decreased since 1960 until present. Part of the decline is attributed to up to a 30% decrease in the efficiency of the Southern Ocean sink over the last 20 years. The decline is attributed to the strengthening of the winds around Antarctica which enhances ventilation of natural carbon-rich deep waters. The strengthening of the winds is attributed to global warming and the ozone hole.

In general, the global ocean has changed from a source became a sink for atmospheric carbon dioxide during industrial era. Therefore, the ocean carbon cycle will always change in order to find a new equilibrium as a response to increased carbon dioxide emissions. However, the present status of global ocean carbon sinks is a net condition for global air-sea carbon dioxide fluxes. Takahashi et al. (2002) on the other hand showed that tropical oceans tend to act as a source, but subtropical and temperate regions act as a sink.

For the open ocean, Karl et al (2001) concluded that partial pressure of carbon dioxide (pCO_2) at sea surface is generally 7 μatm lower than atmosphere, so that the global ocean acts as a main sink. However, pCO_2 is depended on characteristics of particular regions where its variability is strong related with marine carbonate system. pCO_2 plays an important role in regulating the direction of air-sea carbon fluxes. Feely *et al.* (2001) summarized that $pCO2$ in mixed-layer waters that exchange CO_2 directly with the atmosphere is affected primarily by temperature, dissolved inorganic carbon (DIC) levels and alkalinity (A_T). While the water temperature is regulated by physical processes, including solar energy input, sea-air heat exchanges and mixed layer thickness, the DIC and A_T are primarily controlled by the biological processes of photosynthesis and respiration and by upwelling of subsurface waters rich in respired CO_2 and nutrients. In a parcel of seawater with constant chemical composition, pCO_2 would increase by a factor of 4 when the water is warmed from polar temperatures of about −1.9 °C to equatorial temperatures of about 30 °C. On the other hand, the DIC in the surface ocean varies from an average value of 2150 μmol/ kg in polar regions to 1850 μmol/kg in the tropics as a result of biological processes. This change should reduce pCO_2 by a factor of 4. On a global scale, therefore, the magnitude of the effect of biological drawdown on surface water pCO_2 is similar in magnitude to the effect of temperature, but the two effects are often compensating. Accordingly, the distribution of pCO_2 in surface waters in space and time, and therefore the oceanic uptake and release of CO_2 , is governed by a balance between the changes in seawater temperature, net biological utilization of CO_2 and the upwelling flux of subsurface waters rich in CO_2.

4. Preliminary study of carbon cycling in the Indonesian seas

The Indonesian seas are uniquely situated between two oceans Pacific and Indian and two continents Eurasia and Australia. The western parts of the Indonesian seas are mainly covered by shallow waters (~ 50 m depth) and known as the Sunda shelf, whereas, the eastern parts are generally deep (> 1000 m). Recently, there has been a focus on the Indonesian Throughflow (ITF), which transports warm waters from the Pacific Ocean to the Indian Ocean and as such is responsible for global climate. The Indonesian seas are also characterized by relatively high biological production over the entire year as well as high biological diversity. However, little is yet known about the Indonesian seas' role in the global carbon cycle.

Physical forcing, particularly vertical mixing is important not just for physical oceanography but also for biogeochemistry as well, since mixing supplies nutrients and relatively high pCO_2 from the ocean interior to the surface ocean. Indeed a physical and biogeochemical modeling study of the Java Sea, situated in the western part of the Indonesian seas, points to the importance of diapycnal mixing regulating the regional biogeochemistry (Koropitan and Matsumoto, 2010). The study shows that the flow pattern in the Java Sea is controlled by monsoon wind with two rigid patterns of water transport: eastward and westward during northwest monsoon (NWM) and southeast monsoon (SEM), respectively. It is likely therefore that the organic carbon-rich waters of the Java Sea will join the southward-flowing ITF to the east in Makassar Strait and Flores Sea and then be exported to the Indian Ocean via Lombok Strait. This export would be pronounced during NWM season. This speculation is supported by a recent study of seasonal variation of the ITF water at the outflow straits based on INSTANT (International Nusantara-Stratification and Transport Program) 2003-2005 surveys (Atmadipoera et al., 2009), which shows a domination of the "fresh layer" of the Java Sea waters in thermocline layer in Ombai and Lombok Straits (major outflows of ITF).

The Java Sea thus appears important to the ITF properties. This in turn illustrates the importance of diapycnal mixing in the regional biogeochemistry and ITF, because there is significant vertical mixing induced by internal waves (baroclinic tide) in the eastern part of the Java Sea over the Dewakang Sill (Hatayama, 2004). This vertical mixing mixes down surface water properties including carbon into the intermediate layer in a manner similar to the continental shelf pump. Finally, the solubility pump is a major mechanism which controls the air-sea carbon exchange over the Indonesian seas. Recent study (Koropitan, unpublished data) shows that the Indonesian seas are still a source for atmospheric CO_2 due to higher SST.

5. Future direction

Given the gap in knowledge related with question whether the Indonesian seas act as a source or sink and in order to gain a fundamental understanding of the role of physical processes in the carbon cycle of a tropical coastal setting, future research needs to evaluate the following central hypothesis: Ocean mixing is a primary mechanism of the continental shelf pump and driver of the carbon fluxes in the Indonesian seas. Several scientific questions related with physical and biogeochemical processes of the Indonesian seas, including the following:

1. How does baroclinic tide (internal wave) interact with local topography and contribute to the continental shelf pump?
2. How does monsoon wind-driven Ekman transport interact with tides and contribute to the continental shelf pump?
3. What is the relative importance of the physical and biological processes in regulating the Indonesian seas carbon budget?
4. What is the role of Indonesian seas in the global continental margins carbon budget?

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