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Review and suggestions for estimating particulate organic carbon and dissolved organic carbon inventories in the ocean using remote sensing data

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Abstract
Dissolved organic carbon (DOC) and particulate organic carbon (POC) are basic variables for the ocean carbon cycle. Knowledge of the distribution and inventory of these variables is important for a better estimation and understanding of the global carbon cycle. Owing to its considerable advantages in spatial and temporal coverage, remote sensing data provide estimates of DOC and POC inventories, which are able to give a synthetic view for the distribution and transportation of carbon pools. To estimate organic carbon inventories using remote sensing involves integration of the surface concentration and vertical profile models, and the development of these models is critical to the accuracy of estimates. Hence, the distribution and control factors of DOC and POC in the ocean first are briefly summarized, and then studies of DOC and POC inventories and flux estimations are reviewed, most of which are based on field data and few of which consider the vertical distributions of POC or DOC. There is some research on the estimation of POC inventory by remote sensing, mainly in the open ocean, in which three kinds of vertical profile models have been proposed: the uniform, exponential decay, and Gauss models. However, research on remote-sensing estimation of the DOC inventory remains lacking. A synthetic review of approaches used to estimate the organic carbon inventories is offered and the future development of methods is discussed for such estimates using remote sensing data in coastal waters.

Key words: ocean carbon inventory, dissolved organic carbon, particulate organic carbon, remote sensing

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1 Introduction

Both land and ocean observations made to date have demonstrated that the ecosystems on earth are being affected by changes in the climate system (Parry et al., 2007). According to the global carbon project (GCP), the carbon cycle is central to the earth's climate system, being inextricably coupled to the climate, water cycle, nutrient cycle, and production of biomass by photosynthesis on land and in the oceans (Canadel et al., 2003). This cycle can be divided into three main parts: the atmosphere cycle, the terrestrial cycle, and the ocean cycle. According to the GCP, there is a great need to estimate the carbon inventories and fluxes of all three pools.

As one of the main greenhouse gases, carbon dioxide (CO_2) is estimated to be about 780 Pg in the atmosphere (Houghton, 2007). CO_2 measurements from over 100 sites run by 14 countries and remote sensing data have been used to calculate regional and global carbon budgets to quantitatively analyze the carbon flux between the atmosphere and underlying surface (Canadel et al., 2003). The terrestrial carbon pool is divided into two parts: the above-ground biomass carbon (AGBC) and soil carbon pools. The forest, grassland, agricultural, and wetland ecosystems are a greater part of the AGBC pool, with the forest ecosystem alone accounting for about 86% of the biomass carbons (Lal, 2003). The soil carbon pool is the largest carbon pool (about 2 500 Pg) in the terrestrial carbon system, 60% of which is organic, and is 2.8 times larger than the AGBC pool (Lal, 2004). The use of remote sensing data to estimate the forest carbon pool allows the establishment of empirical regression models using the band ratios or normalized difference vegetation index (NDVI) (Foody et al., 2001) and the retrieval of such forest carbon pool parameters as tree height and leaf layer height, after which this pool can be calculated on the basis of theoretical models (Patenaude et al., 2004). Although many researchers have focused on the terrestrial carbon pool, their monitoring results are insufficiently accurate (Holmgren et al., 2007).

The ocean carbon inventory and the ocean carbon transport play critical roles in the carbon cycle (Fig. 1), with approximately (118±19) Pg anthropogenic CO_2 absorbed in the nearly 200 a between 1800 and 1994 (Sabine et al., 2004), which is high-

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ly significant for regulating the level of CO_2 in the atmosphere (Joos et al., 1999). However, the estimation of the ocean carbon inventory remains highly uncertain because of the dynamic and large-scale nature of the ocean and the scarcity of the data. More observational data and further study are needed.

Satellite remote sensing data are widely used in ocean research because of its spatial and temporal coverage. With the development of ocean color research, the product of surface POC distribution has become available from the NASA's ocean color website (http://oceancolor.gsfc.nasa.gov/). Some researchers have estimated the POC inventory in open oceans by integrating the surface distribution and a vertical profile model of POC (Stramska, 2009; Duforêt-Gaurier et al., 2010). However, research on the remote sensing of surface DOC distribution remains under-developed and limited in coastal areas. Several studies showed estimation of the DOC inventory on the basis of *in-situ* data (Hung et al., 2000; Vlahos et al., 2002; Hung et al., 2003; Johannessen et al., 2008), but none used remote sensing data. The estimation of the organic carbon inventories by remote sensing thus constitutes a relatively new research area. Satellite observations of the ocean organic carbon inventories still suffer from a large degree of uncertainty owing to the inaccuracy of remote sensing algorithms and oversimplification of vertical profile models. There is thus an urgent need to develop accurate remote sensing algorithms for ocean organic carbon because of the significant role it plays in the ocean carbon cycle (Platt et al., 2008). Furthermore, most studies on the ocean organic carbon pool focus on the open ocean, partly because the biogeochemical conditions in coastal waters are rather complex. The coastal ocean constitutes only 7% of the global ocean in area; however it contributes more than 25% of the primary productivity (Longhurst et al., 1995). Hence, it would be desirable to develop organic carbon inventory estimation methods using satellite remote sensing in coastal waters.

In this paper, our primary focus is to provide a review of the methods for estimating ocean organic carbon (including POC and DOC) using satellite remote sensing and to give suggestions to future development of the estimation methods. Section 2 briefly discusses the typical biogeochemical behaviors of POC and DOC for the mechanistic bases of the satellite algorithms. Section 3 describes current estimation methods based on field data and analyzes the sources of uncertainty therein. Section 4 reviews and analyzes the previous studies on estimation methods utilizing remote sensing data, and includes several suggestions for the future development of ocean carbon inventory estimation by satellite remote sensing in coastal waters. Section 5 concludes the paper.

2 General distribution of organic carbon

In devising a more reasonable and accurate model for estimating ocean organic carbon, it is essential to understand the general distribution of POC and DOC variations. According to the joint global ocean flux study (JGOFS) sampling protocols, POC and DOC are separated by a 0.45 μm pore size filter. In fact, particles of 0.5–1.0 μm in size are just able to settle with no obvious Brownian movement, which supports the separation of particulate and dissolved matter by a 0.45 μm pore size filter (Parsons and Strickland, 1962). Owing to their distinct composition and sources, POC and DOC differ significantly in biogeochemical behavior, which has an effect on the final distribution of their inventories.

About 97% of the organic carbon (over 685 Pg) in the ocean is DOC, which is 200 times greater than the biomass of ocean creatures (Hansell and Carlson, 2001). Recent studies show DOC is closely related to microorganism activities. Photosynthesis, sloppy feeding by zooplankton, and virus lysis processes are important labile DOC sources in the ocean (Keller and Hood, 2011), and bacterial respirations usually take labile DOC as their food source. The concentration of POC is much smaller than that of DOC, although most marine organisms, including phytoplankton, zooplankton, and bacteria, are important components of particulate organic matter. As the foundation of ocean ecosystem, POC is an important carrier of carbon settling from the surface ocean to the seafloor (Bauer et al., 2002), taking CO_2 away from the atmosphere in a long term. Accordingly, many researchers have focused their attentions on POC flux in the ocean in recent years.

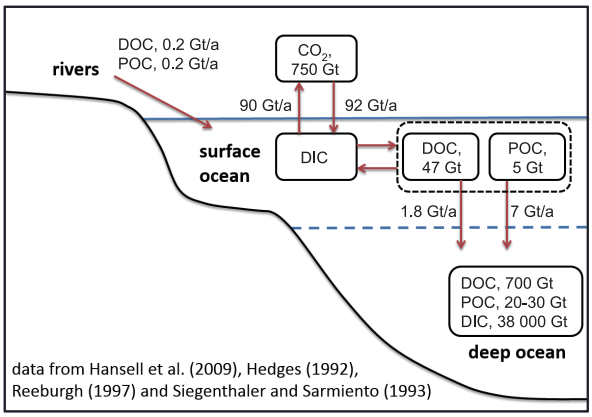

Fig.1. Carbon pools in the ocean.

2.1 *POC distribution*

POC can be divided into living and non-living components: the living component (bio-POC) contains phytoplankton, zooplankton, bacteria, fungus, viruses, fish, and so on, whereas the non-living component (organic detritus) is mainly constituted by wreckage and pellets from biological activities (Parsons, 1975).

Consistent with the distribution of chlorophyll *a* (Chl *a*) and nutrients, the horizontal distribution of POC usually exhibits a decreasing pattern from nearshore to the open ocean (Hung et al., 2000). In the open ocean, the POC concentration is relatively low, with a significant seasonal variation but no interannual variation (Loisel et al., 2002). For instance, the concentration has been reported to range from 5 to 40 μg/dm^3 in the North Pacific subtropical gyre (Hebel and Karl, 2001), whereas in a high primary production area, such as the northeast subarctic Pacific Ocean, the surface POC concentration ranges from 18 to 164 μg/dm^3 (Bishop et al., 1999) . In the Indian sector of the Southern Ocean, it ranges from 19 to 224 μg/dm^3 (Pasquer et al., 2010).

The POC concentration is often much higher in the coastal ocean than in the open ocean because of terrestrial input. Every year, more than 0.43 Pg of POC is transported to the coastal ocean by world's rivers (Meybeck, 1982). For example, the POC concentration reaches as high as (1 836±636) μg/dm^3 in the Chesapeake Bay (Fisher et al., 1998), and ranges from 48 to 960

μg/dm^3 in the western Mediterranean Sea (Cauwet et al., 1997). Another external source of POC is organic particles settling from the atmosphere, with approximately 0.22 Pg settling in the sea every year (Zhang et al. (2006) and the references therein). Biological activities, particularly those in open ocean areas, are also significant POC sources. The living component of POC comes primarily from phytoplankton production and the ocean food chain, whereas the non-living component is generated primarily by life metabolism and dead processes.

The vertical distribution of POC is closely associated with its vertical flux, and has received considerable attention to date. The composition of POC implies that biological activities have a strong influence on its distribution. Phytoplankton blooms can directly increase the concentration of POC, as evidenced by the good linear relationship between POC and Chl *a* concentration seen in most *in-situ* observations (Legendre and Michaud, 1999). When POC settles down from the surface layer, it is usually broken into dissolved form (becoming DOC) and is then consumed by bacteria and other microorganisms (Hedges, 1987). Owing to this process, most POC is consumed to support the respiration of bacteria and other microorganisms, with only a small part reaching the seafloor (Honjo et al., 2008). At the same time, such respiration consumes much of the dissolved oxygen in the seawater, resulting in low concentrations of dissolved oxygen and even hypoxia in the middle and bottom layers (Garnier et al., 2001). Some zooplankton remain below the euphotic layer during the day and swim to the surface layer at night to feed; this behavior has significant effects on POC distributions (Ducklow et al., 2001). In many coastal regions, the resuspension of sediments is also an important source of POC. Bottom POC concentration in a shallow sea can rise up to three times under the influence of resuspension when the wind speed increases (Hung et al., 2000). Furthermore, physical mechanisms constitute important control factors for POC distribution. For example, convective mixing induced by decreasing temperature is the main reason for POC to exhibit a uniform vertical profile in the water column (Zhao et al., 2003).

2.2 *DOC distribution*

DOC consists of a mixture of compounds, most of which have not yet to be identified. The previous studies showed that DOC contains amino acids, carbohydrates, lipids, aromatic hydrocarbon, humic acid, and the like (Otto and Balzer (1998) and the references therein). The complex components of DOC may originate from its complex sources: phytoplankton production, sloppy feeding by zooplankton, bacterial degradation, and terrestrial input (Carlson, 2002).

DOC concentrations in the open ocean are much lower than those in the coastal ocean. For example, they range from 40 to 80 μmol/dm^3 in the Southern Ocean and the equatorial Pacific Ocean (Carlson and Ducklow, 1995; Wiebinga and de Baar, 1998; Loh and Bauer, 2000), whereas in the costal ocean, particularly in the areas with abundant terrestrial input such as the Baltic Sea, the Chesapeake Bay, and the West Florida shelf, they can reach more than 300 μmol/dm^3 (Pan et al. (2012) and the references therein). In the coastal areas of the East China Sea (ECS), DOC concentrations are influenced primarily by the input of the Changjiang River, ranging from 80 to 119 μmol/dm^3 (Hung et al., 2000). In the outer shelf region, which is not subject to the influence of terrestrial input, DOC concentrations are very low, ranging from 65 to 75 μmol/dm^3 (Ogawa et al., 2003). As DOC is a type of dissolved matter, its distribution is easily influenced by the physical processes of seawater. A significant relationship between DOC and the salinity has been observed in many major river estuaries and their adjacent coastal seas (Del Vecchio and Blough, 2004; Del Castillo and Miller, 2008; Hessen et al., 2010), which results from the conservative mixing process of seawater and fresh water.

The vertical distribution of DOC concentration varies greatly, ranging from 34 μmol/dm^3 in the deep ocean to more than 90 μmol/dm^3 in the surface ocean. The primary cause of this large variation is due to phytoplankton production in the euphotic layer and microbial consumption at all depths (Hansell, 2002). In the euphotic layer, phytoplankton excrete DOC as part of primary production during photosynthesis. This excreted DOC accounts for about 20% of the primary production on average (Marañón et al., 2004). The sloppy feeding of zooplankton often leads to the leakage of DOC from the breaking up of plankton cells (Møller, 2005), which accounts for, at most, 30% of DOC from the phytoplankton production (Keller and Hood, 2011). Furthermore, the virus lysis process can also break up plankton cells and release DOC, although it has little influence on the vertical DOC distribution (Keller and Hood, 2011). Bacteria are the most important consumers of DOC (Benner et al., 1995; Amon and Benner, 1996). The excreted DOC released by the phytoplankton production, most of it labile, is essential to the microbial carbon cycle. It accounts for up to 70% of the bacterial and microbial food sources (Peterson, 1984). This consumption often leads to a significant correlation between the DOC concentration and apparent oxygen utilization (AOU) below the euphotic layer (Arístegui et al., 2002; Santinelli et al., 2010), which suggests that bacterial consumption exerts a dominant influence over the vertical distribution of DOC. Hung et al. (2000) found a significant relationship between the DOC concentration and the temperature in the southern ECS, suggesting that the distribution of DOC be controlled primarily by the mixing of shelf water and Kuroshio water. In the northern ECS, Ogawa et al. (2003) observed a good correlation between the DOC concentration and the water density, but a scattered relationship between that concentration and the chlorophyll concentration. Above all, it is the mixing process, rather than any biological processes, that accounts for the vertical distribution of DOC in shelf areas.

3 Estimation of organic carbon inventories through field measurements

The estimation of inventories using remote sensing data involves lots of parameters and complicated mechanisms, hence there is a great need to review these estimation methods. Little research specifically examines the distribution of the organic carbon inventory, while most studies in this area are simple estimations based on the *in-situ* data. As the vertical fluxes of POC and DOC can directly reflect the carbon-sequestration ability of the ocean, many studies have focused on these fluxes, particularly POC flux. In the meantime, an organic carbon flux is closely related to the organic carbon inventory and the primary production in the surface layer (Koeve, 2002; Reigstad et al., 2008; Forest et al., 2010). We review studies of POC and DOC inventories, together with their vertical fluxes, in the following section.

3.1 *POC inventory*

Following the implementation of the JGOFS program, many researchers turned their attentions to the vertical flux and

transformation of POC in the ocean (Tolosa et al., 2005; Honjo et al., 2008; Ma et al., 2011). During gravity settling over a long distance, the majority of POC is consumed by degradation of heterotrophic microorganisms or feeding process of mesozooplankton until the bottom is reached. For example, in the north Pacific Ocean, only 6%–10% of POC reaches the depth of 2 000 m (Schlitzer, 2002; Forest et al., 2010).

The data on the POC flux were traditionally collected via sediment traps (Knauer et al., 1979; Martin et al., 1987). Newer methods employing natural radioactive isotopes (such as the $^{234}Th/^{238}U$ disequilibrium) to estimate POC export rate have obtained higher resolutions in both space and time, and are thus widely used internationally (Waples et al., 2006; Yang et al., 2009). According to the review by Honjo et al. (2008), the lowest reported POC flux is 25 mmol/(m^2·a) (in the warm pool of the Pacific Ocean) and the highest is 459 mmol/(m^2·a) (in the Arabian Sea). The North Pacific subarctic Gyre (in the Bering Sea), on a significantly large scale, exhibits the highest POC flux of 213 mmol/(m^2·a) on average, whereas the North Pacific subtropical and tropical gyres exhibit the lowest of 39 mmol/(m^2·a) on average. Globally, the POC flux is about 36.2 Tmol/a.

Several studies have focused on the POC inventory, with most estimating the POC inventory of the water column by integrating the profile data from *in-situ* measurements. For example, Pasquer et al. (2010) estimated the POC inventory of the surface layer (0–150 m) in the Indian sector of the Southern Ocean based on summer 2006's cruise data. The results ranged from 270 to 1 580 mmol/m^2, which are smaller values than those recorded in the adjacent Ross Sea. Forest et al. (2011) used the same method to estimate the POC inventory of the surface layer (0–100 m) in the Amundsen Gulf in the Arctic Ocean. Their estimates were 420 mmol/m^2 on average and displayed a similar spatial pattern as the Chl *a* concentration.

Some researchers have used the beam attenuation coefficient (c_p) profile to estimate the POC inventory of the water column based on the significant linear relationship between POC concentration and c_p. Based on the c_p profile data collected with a transmissometer, Bishop (1999) estimated the POC inventory in the 0–100 m layer in the northeast subarctic Pacific Ocean, and found it to range from 106 to 238 mmol/m^2. Gardner et al. (2000) used the c_p profile data to estimate the POC inventory over the 0–100 m layer in the Ross Sea. Their estimates ranged from 200 to 5 600 mmol/m^2, which show large variations over space and time.

Other studies proposed simple POC vertical distribution models based on field observations, and estimated the POC inventory by integrating the surface POC concentrations using these models. Working on the global scale, Duforêt-Gaurier et al. (2010) classified POC vertical profiles into two types under different water conditions, and established an empirical power function relationship between the surface POC concentration and POC inventory. On the basis of that relationship, they obtained a global distribution of the POC inventory in the euphotic layer, which showed the highest value in the polar areas and the lowest value in the equator area. The value of the POC inventory of the euphotic layer in the global ocean was found to be about 1.19 Pg.

To date, three methods have been used to estimate the POC inventory. The first directly integrates discrete field data, the second uses the continuous c_p profile based on the significant linear relationship between POC concentration and c_p, and the third combines the surface POC concentrations with vertical distribution models. The first method is the simplest and easiest to use, but is heavily reliant on the field data available. The uncertainty of this method stems primarily from the sparse sampling of POC and the integration process. The second method is able to provide more detailed profile data and a detailed POC vertical distribution, but it also relies on field data. Its uncertainty arises from both the sparse sampling of POC and the variations of the linear relationship between POC concentration and c_p. The third method requires the establishment of a vertical profile model of the POC concentration based on its real distribution and the ability to use remote sensing data, and is thus independent of field data. Its uncertainty arises primarily from the errors of modeling and the remote sensing products.

Studies of POC flux are relatively mature, and have almost clarified its distribution and variation in the ocean. However, as an important component of the ocean carbon cycle, the distribution of POC and variation in the POC inventory have yet to be fully recognized, particularly in coastal areas. Because of the complexity of biogeochemical control factors involved, POC vertical profiles in the coastal ocean exhibit more complex and variable patterns than those in the open ocean. The combination of *in-situ* measurements and remote sensing data is essential to large scale, long-term monitoring of the POC inventory.

3.2 *DOC inventory*

DOC export to the deep ocean is several times greater than any conventional estimates and is equally important as the POC flux (Hansell et al. (2009) and the references therein). Globally, the entire DOC inventory of the ocean is estimated to be about 662–780 Pg via biogeochemical modeling (Houghton, 2007; Hansell et al., 2009). Approximately 47 Pg of DOC is stored in the upper 200 m, accounting for 7% of the total global inventory. Although the majority of DOC is stored in the middle and deep layers of the ocean, the greatest variation is found in the euphotic layer (Hansell, 2002). Through the circulation, the newly produced DOC in the upper layer is taken into the deep ocean and forms recalcitrant DOC over time (Hopkinson and Vallino, 2005). For instance, the formation of mesopelagic ocean water in the north Pacific and deep-ocean water in the North Atlantic constitute important DOC exportation processes to the deep ocean (Hansell, 2002; Carlson et al., 2010). A recently proposed concept, the microbial pump, demonstrates that bacterial respiration consumes labile DOC from the surface layer and releases recalcitrant DOC to the deep ocean (Jiao and Zheng, 2011). The latter is accomplished by the mixing process and the long-term circulation, which ultimately removes CO_2 from the atmosphere.

Relative to the open ocean, the coastal ocean is characterized by a higher rate of the primary production and the higher DOC concentration. Many researchers have observed the CO_2 absorbed in the surface coastal ocean to be transported to the deep ocean in the form of DOC (Frankignoulle and Borges, 2001; Yool and Fasham, 2001; Dai et al., 2009). Hence, the inventory and flux of DOC in the coastal ocean are important for estimating DOC transportation into the deep ocean, although they have only recently begun to attract attention.

Indeed, there is still limited research on the DOC inventory and flux, and most studies in this area rely on the *in-situ* data. The simplest way of estimating the DOC inventory from the field data is to integrate the data in different layers in the

vertical dimension and to interpolate the integration result onto the surface, finally summing up the interpolation result. For instance, using this simple method and the data from JGOFS cruises in 1994, Wiebinga and De Baar (1998) estimated that the DOC inventory of the surface layer (0–100 m) in the Indian sector of the Southern Ocean ranges from 61.8 to 75.9 g/m^2. Vlahos et al. (2002) estimated the total DOC inventory in the top 100 m in the Middle Atlantic Bight using the DOC data collected from three cruises in March, April, and August, and found that the corresponding value of the total DOC inventory in March and April is about 5.88 Tg. Forest et al. (2011) performed a similar calculation for the Amundsen Gulf in the Arctic Ocean, and found that microorganisms are unable to consume the majority of DOC (about 80–95 g/m^2) in the upper 100 m.

Another estimation method requires information on the water masses in the study area. It uses the average DOC concentration of these masses and multiplies the water fluxes or volumes to obtain the DOC flux or water-mass inventory. Hung et al. (2000) used this method to determine that the annual DOC export flux from the southern ECS is 414 Gmol, four times as the annual POC flux (106 Gmol). The average DOC inventory in the euphotic zone was also calculated: about 1.15 mol/m^2 in the coastal waters, 2.54 mol/m^2 in the upwelling region north of Taiwan Island, China, and 6.72 mol/m^2 in the Kuroshio waters. These results demonstrate the strong influence of the euphotic zone on the DOC inventory. Research was carried out to estimate the DOC inventory in the ECS and the DOC export flux to the open ocean, which were found to be about 38.9 Tg and (1.9±1.5) Tg, respectively (the calculation area was approximately 9×10^5 km^2), over the entire water column (Hung et al., 2003). Johannessen et al. (2008) not only divided the Strait of Georgia into three sub-regions, but also partitioned the water column into an upper layer and a deep layer by considering the obvious difference in the DOC concentration with depth. The average DOC inventory in the water column of the Strait of Georgia is about 0.81 Tg over the four seasons.

Several studies have employed numerical models to estimate the DOC flux or inventory on regional scale. For example, Druon et al. (2010) simulated the dissolved organic matter (DOM) cycle by adding a biogeochemical module to the regional oceanic modeling system (ROMS) for the east coast of North America. By taking into account the DOM modules in one test, twin experiments were performed to verify the importance of DOM in the carbon cycle. The simulation results confirmed a DOM's essential role in the carbon cycle. Further, the estimated results of the DOM export flux to the deep ocean suggested an equal contribution of carbon fixation compared with the POC settlement (Druon et al., 2010).

Most research on estimation of the DOC inventory on the global scale is based on field data and the numerical simulation, and its uncertainty stems from errors in the numerical models, the field data, and the interpolation methods. In regional studies, the DOC inventory is usually calculated by integrating the sample data over the ocean depth or averaging the DOC data of the water mass and multiplying its volume. The uncertainty of these calculations arises primarily from the non-uniformity of the DOC distribution and field data and errors of the interpolation method. However, these estimation methods are significantly reliant on the field observations and do not allow monitoring of seasonal and annual variations in the DOC inventory. In addition, they often introduce errors to the surface distribution during the interpolation process.

4 Discussion of estimation methods involving remote sensing data

The use of remote sensing data allows an economic, frequent, and large-scale observation of organic carbon inventories. Changes in the ocean organic carbon inventories often occur below the surface layer, and the estimation of organic carbon by the remote sensing data still poses considerable challenges. A number of researchers have examined the estimation of the POC inventory and flux by the remote sensing data (Gardner et al., 2006; Stramska, 2009; Forest et al., 2010), but none has considered the estimation of the DOC inventory owing to the immature state of the remote sensing algorithm for the surface DOC distribution, particularly in the open ocean. Nevertheless, the estimation of DOC inventory using the remote sensing data could adopt the same approach as the estimation of POC inventory (Fig. 2).

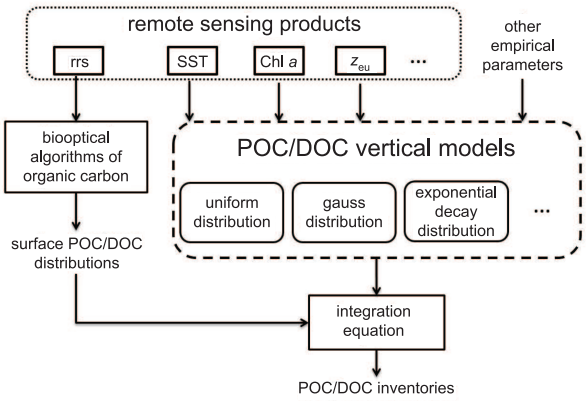

Fig.2. Schematic diagram of methods used to estimate POC/DOC inventories using remote sensing data.

4.1 *Estimation of POC inventory using satellite remote sensing*

Recent studies have demonstrated that the ratio of POC flux to net primary production (NPP) follows an exponential decrease with depth. On the basis of this, several relationship models have been developed to estimate the POC flux by the remote sensing data (Pace et al., 1987; Francois et al., 2002; Lutz et al., 2002). The satellite-derived NPP data can be used to calculate the distribution of POC flux based on the empirical relationship model established by Pace et al. (1987):

$$f_{\mathrm{poc}}(z) = 3.523 p_{\mathrm{np}} z^{-0.734}, \tag{1}$$

where p_{np} is the net primary production and z is water depth. Using Eq. (1), Muller-Karger et al. (2005) found that the POC flux in the coastal ocean accounts for about 40% of the global fluxes, which demonstrates its significance in the ocean carbon cycle.

Similar to the estimation of POC flux, the accurate estimation of the POC inventory also needs to consider the vertical distribution of POC, which often has a close relationship to surface POC concentration. Hence, integrating the surface POC concentration ($c_{\mathrm{poc,s}}$) with a given POC vertical distribution model is the main way to retrieve the POC inventory in the water column by the satellite remote sensing data. One such model is

given below,

$$s_{\mathrm{poc}} = \int_0^{z_{\mathrm{m}}} c_{\mathrm{poc,s}} f(z,\cdots)\mathrm{d}z, \tag{2}$$

where c_{poc} is POC surface concentration, z_{m} is the integration depth of the POC inventory; and $f(z,\cdots)$ is the vertical distribution model (such as Nakajima and Nishizawa (1972), Bishop et al. (1999), Stramska (2009), Duforêt-Gaurier et al. (2010)). Current POC remote sensing algorithms generally use such parameters as reflectance band ratios and the beam attenuation coefficient, and particulate backscattering coefficients to retrieve the POC concentration (Gardner et al., 2006; Stramski et al., 2008; Son et al., 2009). NASA provides a number of standard satellite products (such as MODIS and SeaWiFS) for the surface POC distribution on the global scale. Although the complex environmental conditions of the coastal ocean, such as the optical disparity and different carbon ratios of particles, make the remote sensing of its POC distribution more difficult, it also has received considerable attention lately.

In contrast, no review of the vertical profile models of the POC concentration has been carried out to date. In this paper, we collect three main models of the vertical profile distribution of POC from the literature (Table 1). The simplest profile is the uniform distribution, which is often observed in the well mixing coastal waters. In this case, the POC inventory is the product of the value of the surface POC concentration and a given depth, such as the mixed layer depth or 100 m. Stramska and Stramski (2005) retrieved the surface POC distribution using blue-red band ratio algorithm. Based on the uniform profile, they obtained the global distribution of the POC inventory over the mixed layer depth, one optical attenuation depth, and a depth of 200 m, respectively.

Table 1. Vertical profile models of POC collected from the literature

Vertical profile model	Equation[1)]	Applicable region	study
Uniform model	$c_{\mathrm{poc},z} = c_{\mathrm{poc,s}}$	well mixed water and mixed layer	Stramska (2009)
Exponential decay model	$c_{\mathrm{poc},z} = c_{\mathrm{poc,s}}\mathrm{e}^{-k(z_0-z)}$	high primary production area	Nakajima and Nishizawa (1972), Bishop et al. (1999)
Gauss model	$c_{\mathrm{poc},z} = c_{\mathrm{poc,s}} + \frac{A}{\sigma\sqrt{2\pi}}\mathrm{e}^{\frac{-2(Z-Z_{\max})^2}{\sigma^2}}$	stratified water	Duforêt-Gaurier et al. (2010)

Notes: 1) $c_{\mathrm{poc},z}$ is the POC concentration at depth z; $c_{\mathrm{poc,s}}$ is the surface POC concentration at depth z_0; k denotes the decreasing rate of POC with depth; $z_{\max}$ is the depth of the subsurface maximum peak; and A and σ are the amplitude and width of the subsurface maximum peak, respectively.

The second type of the POC vertical profile distribution is the exponential decay distribution, which often occurs in open ocean waters with weak or no stratification in which the photosynthesis process is limited only by light. Nakajima and Nishizawa (1972) proposed this profile model, which describes a similar distribution of POC in the open ocean. Gardner et al. (2006) established the linear relationship between the POC concentration and c_{p} for the global ocean based on a large amount of data from the world ocean circulation experiment (WOCE), the JGOFS, and the South Atlantic ventilation experiment, and then established an exponential decay model of POC based on the continuous c_{p} profile data. Finally, they integrated the surface POC concentration and the second type of the profile model to obtain the POC inventory at an optical attenuation depth.

The third type of the vertical POC profile is consistent with the subsurface chlorophyll concentration maximum and exhibits Gaussian distribution in the euphotic layer. It is often observed in clean and stratified waters, where phytoplankton production is the major influential factor in the POC profile. Taking the water structure and chlorophyll concentrations in the surface layer into consideration, Duforêt-Gaurier et al. (2010) established two POC profile models: a uniform profile in mixed water and a Gauss profile in stratified water. They then built up power law relationships between surface POC concentration and POC inventory in the euphotic layer, on the basis of which they were able to retrieve a reasonable distribution of the POC inventory via satellite remote sensing data.

Featuring a high primary production rate, the coastal ocean is one of the most important ecosystems in the global carbon cycle, in which the CO_2 in the atmosphere is often fixed by the POC settling and the DOC exportation to the deep ocean. Because of complex vertical distributions of POC, few studies focused on the remote sensing estimation of the POC inventory in the coastal ocean. Neither a simple uniform profile nor a power law simulation is able to present a reasonable POC profile in this complex body of water, in which the terrestrial input, the phytoplankton production, and the resuspension may be the principal control factors in the POC distributions. Duforêt-Gaurier et al. (2010) recommended partitioning the complex coastal region by such influential factors as chlorophyll concentration. However, the terrestrial input and water structure are also important control factors in the coastal ocean, and should be taken into account in future research by adding such parameters as total suspended matter and surface temperature. Furthermore, under different conditions, corresponding vertical profile models (such as the uniform model, exponential decay model, Gauss model) of POC could be established on the basis of the biogeochemical mechanism of the POC distribution, which would produce a more accurate POC inventory estimate.

4.2 *Estimation of DOC inventory by satellite remote sensing data*

As noted above, owing to the limitation of remote sensing algorithm for surface DOC distribution, there is very little specific research on estimating the DOC inventory using the satellite remote sensing data. However, the use of such remote sensing data to monitor the distribution of and variation in DOC inventory would be very helpful in carbon cycle research. Here, we discuss several possible methods of estimating the DOC inventory using the satellite remote sensing data.

Similar to estimation of the POC inventory, the estimation of the DOC inventory using the satellite remote sensing data can be achieved by integrating surface concentration and vertical

profile model. In previous studies, the surface distribution of DOC is usually retrieved from the satellite-derived colored dissolved organic matter (CDOM) products based on the significant linear relationship between DOC and CDOM observed in many coastal ocean areas (Vodacek et al., 1995; Ferrari, 2000; Del Vecchio and Blough, 2004). These linear relationships have been applied to retrieving the surface DOC distribution in the Middle Atlantic Bight and the Mississippi Estuary (Del Castillo and Miller, 2008; Mannino et al., 2008; Fichot and Benner, 2011). However, the relationship relies on the conservative mixing of the terrestrial end member and seawater end member of DOC and CDOM. Influenced by all kinds of biogeochemical processes, particularly phytoplankton production (Pan et al. (2012) and the references therein), DOC often exhibits non-conservative mixing behavior in the coastal ocean. Liu et al. (2013) considered biological influences on the DOC distribution, and established an improved DOC reversion algorithm for the ECS by including such parameters as the chlorophyll concentration to denote the biological effect.

Although there is no specific research on the vertical distribution of DOC, there have been some relevant discussions. Using the field data collected from the Gulf of Mexico and the Middle Atlantic Bight, Guo et al. (1995) found a significant relationship between DOC concentration and the water density, which suggests that the water structure is the major control factor of DOC profile. Ogawa et al. (2003) observed a significant but negative relationship between DOC concentration and the water density in the northern ECS (r^2=0.927; P<0.001). Although the maximum distribution of DOC concentration was consistent with the subsurface chlorophyll maximum concentration at some stations, the Chl *a* and DOC concentrations did not exhibit any significant relationship on the whole (r^2=0.08; n=112). Below the euphotic layer, the DOC profile often exhibits a negative trend with AOU because of bacterial consumption (Arístegui et al., 2002; Santinelli, 2010). However, in most situations, the physical processes are the main control factors of these profiles, with phytoplankton production and bacterial consumption being the minor influential factors. Hence, the information on a density profile could be used to establish the DOC profile, and a corresponding DOC profile model is then established according to the water structures.

4.3 *Uncertainty and suggestions*

So far we have discussed the existing studies on the estimation of organic carbon inventories using the remote sensing data. It is believed that these remote sensing estimation methods will facilitate the clarification of carbon inventories and fluxes in the ocean. However, we still face some problems and uncertainties with these methods.

The uncertainty involved in the estimation of organic carbon via the satellite remote sensing data stems largely from errors in satellite-derived surface concentrations, which are subject to spatial and seasonal variations. For example, the average relative error of the standard satellite-derived POC products in the open oceans is around 20% (Stramska, 2009). DuforÍžt-Gaurier et al. (2010) found a relative error of about 21% in the coastal ocean, accounting for 18.5% of the error in the final satellite-derived POC inventory. An empirical model describing the vertical distribution of organic carbon is essential to accurate estimation of the organic carbon inventory by the remote sensing data. Since the establishment of a vertical profile model requires a huge amount of field data, the sampling strategy and measurement precision of the field data would propagate their errors into the model. Indeed, no empirical model can fully simulate the ever-changing vertical profile of organic carbon, and such a model is likely to cause estimation errors. The numerical simulation offers great advantages in the simulation of physical processes in the ocean. Using such simulation to establish vertical profile models is likely to produce more accurate empirical model parameters and significantly reduce estimation errors.

Confronting the above mentioned problems and uncertainties, we propose some suggestions for future research on POC/DOC inventory estimations based on remote sensing data. Multiple utilization of optical proxies and an insight understanding of biogeochemical mechanisms of carbon cycle may improve the accuracy of remote sensing algorithms of the surface POC and DOC distributions. More *in-situ* data are needed to establish more accurate vertical models. For example, the combination of continuous observations by in situ optical instrument for CDOM or c_p, etc. The structure of water-mass is also an important control factor of organic carbon in the ocean, which could be derived from the numerical simulation or data assimilation products. In addition, the use of such satellite-derived products as chlorophyll concentration and surface temperature to establish a vertical profile model of organic carbon will be even more critical. Hence, an all-around observation system including the *in-situ* data, the numerical simulation, the data assimilation products and the remote sensing data probably will be essential for future work on the estimation of organic inventories using the remote sensing data.

5 Conclusions

Recent studies showed that both DOC and POC in the ocean are important carriers of CO_2 absorbed from the atmosphere, which suggests that organic carbon plays a significant role in the ocean carbon cycle. As the basic variables of this cycle, the DOC and POC inventories are closely related to the downward flux of organic carbon, the annual and seasonal variations of which provide the information on the ocean's carbon-sequestration ability to some extent. In this paper, we reviewed several studies on the estimation of the DOC and POC inventories. Because of the critical role that POC plays in carbon sequestration, considerable research attention has been paid to the POC flux, and there are connections between its flux and the POC inventory. Studies on the DOC inventory remain scarce. The estimation of the global DOC inventory is generally inaccurate, as no accurate model has been proposed to calculate the DOC inventory on either the global or regional scale.

We are still on the frontiers of research into the remote sensing of the ocean organic carbon inventory. Although, having benefited from the remote sensing algorithms of the surface POC concentration, the POC inventory of the open ocean has recently been retrieved from the satellite remote sensing data. However, there is little research on estimating the POC inventory of the coastal ocean in this manner, as more accurate and detailed profile models are required owing to the complex conditions involved. At present, there are no studies on the remote sensing estimation of the DOC inventory, although there have been promising developments in the remote sensing of the DOC distribution in the coastal ocean. As with the remote sensing estimation of the POC inventory, the vertical profile of DOC will be the emphasis of the carbon inventory estimations in the future research.

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