Areas of the global major river plumes

KANG Yan1,2, PAN Delu1,2*, BAI Yan2, HE Xianqiang2, CHEN Xiaoyan1,2, CHEN Chen-Tung Arthur3, WANG Difeng2

1 Department of Earth Sciences, Zhejiang University, Hangzhou 310027, China
2 State Key Laboratory of Satellite Ocean Environment Dynamics, Second Institute of Oceanography, State Oceanic Administration, Hangzhou 310012, China
3 Institute of Marine Geology and Chemistry, National Sun Yat-sen University, Kaohsiung, Taiwan 804, China

Received 1 April 2012; accepted 18 September 2012

Abstract
River plumes are the regions where the most intense river-sea-land interaction occurs, and they are characterized by complex material transport and biogeochemical processes. However, due to their highly dynamic nature, global river plume areas have not yet been determined for use in synthetic studies of global oceanography. Based on global climatological monthly averaged salinity data from the NOAA World Ocean Atlas 2009 (WOA09), and monthly averaged salinity contour maps of the East and South China Seas from the Chinese Marine Atlas, we extract the monthly plume areas of major global rivers using a geographic information system (GIS) technique. Only areas with salinities that are three salinity units lower than the average salinity in each ocean are counted. This conservative estimate shows that the minimum and maximum monthly values of the total plume area of the world’s 19 largest rivers are 1.72×10^6 km^2 in May and 5.38×10^6 km^2 in August. The annual mean area of these river plumes (3.72×10^6 km^2) takes up approximately 14.2% of the total continental shelves area worldwide (26.15×10^6 km^2). This paper also presents river plume areas for different oceans and latitude zones, and analyzes seasonal variations of the plume areas and their relationships with river discharge. These statistics describing the major global river plume areas can now provide the basic data for the various flux calculations in the marginal seas, and therefore will be of useful for many oceanographic studies.

Key words: river plume, World Ocean Atlas, geography information system, Changjiang River, marginal sea


1 Introduction
The global freshwater discharge from rivers into the oceans is about 36 109 km^3/a (GRDC, 2009), and approximately 40% of the freshwater and particulate material transported into the oceans is from the top ten largest rivers (Dagg et al., 2004; Chen et al., 2008). Large rivers generate offshore plumes characterized by high buoyancy and biological productivity because of their low salinities, high levels of nutrients, suspended and dissolved terrestrial materials (Higgins et al., 2006; Kouame et al., 2009). As a result, the chemical, geological, biological and physical environments of adjacent marginal seas are affected (Smith and Demaster, 1996; Shipe et al., 2006).

River plumes are important locations where land and ocean processes meet, but they are not as well understood as other areas of the world’s ocean. River plumes can travel long distances and are known to be high in biological productivity, because of their nutrient input, making the adjacent shelves important fishing grounds. River plumes also transport terrestrial material to the shelves and beyond, and are important in sediment distribution, as well as in affecting the distribution of pollutants and the biogeochemistry of carbon and associated elements. High phytoplankton productions cause eutrophication and may even generate hypoxia, which may lead to the establishment of dead zones in the coastal area (Diaz and Rosenberg, 2008). Many studies show that large river plumes are atmospheric CO₂ sinks due to the combination of biological and physical processes occurring in them, but the air-sea CO₂ fluxes vary significantly with seasons (Cai, 2003; Tan et al., 2004; Green et al., 2006; Cooley et al., 2007; Zhai and Dai, 2009; Zhai et al., 2009). Based on extensive research on air-sea CO₂ exchange in 106 estuaries, Chen et al. (2012) pointed out that estuaries are CO₂ sources, while the large river plumes become a CO₂ sink even many hundred kilometers beyond the river mouth. However, a study of how important these plumes are in terms of the carbon cycle, for instance, has not been possible because of the lack of detailed information on the exact plume areas. Therefore, the determination of major river plume areas is urgently needed for the assessments of the global oceanic carbon budget and other flux estimations. Yet, owing to the highly dynamic nature of plume systems but the limited extent of field investigations in them, even the plume areas of the world’s major rivers are not available, not to mention their spatial and temporal

Foundation item: The National Basic Research Program of China (973 Program) under contract No. 2009CB412102; the Public Science and Technology Research Funds Projects of Ocean under contract No. 200905012; the National Natural Science Foundation of China under contract Nos 41271578, 40976110 and 40706061; the National High Technology Research and Development Program of China (863 Program) under contract No. 2007AA09Z201.

*Corresponding author, E-mail: pandelu@sio.org.cn
characteristics. Recently, two specific microwave satellite sensors (L-band radiometers) were launched to monitor surface water salinity for the global ocean: the SMOS (the Soil Moisture and Ocean Salinity) and Aquarius/SAC-D satellite. These two microwave satellite sensors are good for open ocean observations over a very large scale. Nevertheless, because of their coarse spatial resolution (typically 30–300 km) and long revisiting time (3 d or more) (Koblinsky et al., 2003; Font and Camps, 2010; Kerr et al., 2010), they are still of limited capacity for the observation of salinity in coastal areas. Satellite ocean color data with relatively higher spatial resolution (e.g., ~1–9 km) and revisiting frequency (e.g., less than 1 d) has also been used to detect some larger river plumes based on the difference of water color between plume and ambient waters (Klemas, 2012). Several methods have been used to study the spatial and temporal variations of some large river plumes because there are good relationships between salinity and the absorption coefficients of dissolved organic matter and detritus, which can be retrieved by satellite ocean color data (Binding and Bowers, 2003; D’Sa and Miller, 2003; Hu et al., 2004; Vecchio and Subramaniam, 2004; Chen et al., 2007). Satellite-derived chlorophyll concentration and diffuse attenuation coefficient from MODIS (Moderate Resolution Imaging Spectroradiometer) and SeaWiFS (Sea-viewing Wide-Field-of-view Sensor) were also used to characterize the variability of river plumes, such as the La Plata River plume (Piola et al., 2008), the Chesapeake Bay estuarine outflow (Dzwonkowski and Yan, 2005), the Amazon River plumes (Io et al., 2005; Cooley et al., 2007; Moller et al., 2010), and the Changjiang River (Kim et al., 2009). Meanwhile, the satellite-retrieved normalized water-leaving radiances (Thomas and Weatherbee, 2006; Liihan et al., 2008) and sea surface temperature from NOAA Advanced Very High Resolution Radiometer (AVHRR) data (Walker, 1996) were also used to detect the river plumes. However, all these methods were established based on regional data and specified for local systems, which cannot be extended easily to estimate the global river plume areas because different rivers may have different optical characteristics, and it is difficult to use the same satellite algorithm and criteria to define all river plumes.

In contrast, the available synthesized data sets of global oceanic salinity enable us to obtain the climatological distributions of the global major river plumes. Therefore, the goal of this paper is to use the global in situ salinity data set from the World Ocean Atlas 2009 (WOA09) provided by NOAA (National Oceanic and Atmospheric Administration) (Antonov et al., 2010) and the salinity contour maps of the East and South China Seas from the Chinese Marine Atlas (Chen, 1992; Hon, 2006) to extract the climatological monthly averaged plume areas of major rivers based on the Geographic Information System (GIS) technology. GIS spatial analysis technology has a higher accuracy and credibility for calculating the area of river plumes compared with other methods. It should be pointed out that, although the two ocean atlas data sets we used are climatologies, they are still sufficient to create global statistics, which did not exist for the various plume-related flux calculations and other multidisciplinary oceanographic studies.

In this paper, we present the data acquisition and extraction method for plume areas in Section 2. In Section 3, we provide the plume areas of major rivers and statistical data for different oceans and latitude zones. We also analyze the seasonal variations of plume areas and their relationships with the river discharge. Finally, we discuss the implications of the extracted plume areas for future work in Section 4.

2 Data and methods

2.1 Data acquisition

(1) Basic geographic information data

We obtained basic geographic information data from the Natural Earth data set (http://www.naturalearthdata.com/), including the ocean, land and rivers maps. The Natural Earth dataset is a free, public domain map available in vector and raster formats with 1:10 000 000, 1:50 000 000, and 1:110 000 000 scales. Here, we use the 10 m land, 10 m ocean, 10 m river, lake, centerlines, and 10 m bathymetry datasets, where 10 m equates to a 1:10 000 000 scale of the relative data set.

The total area of the global continental shelves calculated in this paper is 26.15 × 10^6 km^2 (with water depth < 200 m), which is between the minimum value used by Cai et al. (2006) (25.83 × 10^6 km^2) and the maximum value used by Chen and Borges (2009) (30.0 × 10^6 km^2).

(2) Global salinity data

We obtained the NOAA World Ocean Atlas 2009 (WOA09) salinity data from its website (http://www.nodc.noaa.gov/OC5/SELECT/woaselect/woaselect.html) using the WOASelect tool (Antonov et al., 2010). WOASelect is an interactive tool which enables the user to view the climatological monthly averaged data by designating a specific area, depth, resolution, file format and oceanographic variable. The salinity data have a spatial resolution of 0.25° in the GIS point vector file format. The WOA09 salinity data set has 24 layers, and we only use the surface layer of data.

In addition, we used the monthly averaged salinity contour maps from the China Marine Atlas in the East and South China Seas (Chen, 1992; Hon, 2006) to get more detail for the plume areas of the Changjiang River and Zhujiang River (Pearl River). We digitized the Atlas maps to raster images. Then we established their location in terms of map projections using ArcGIS software. In ArcGIS, we used Geo-referencing and Vectorizing processes to obtain salinity contour data.

(3) Global major river information

The discharges of the world’s top 25 largest rivers (ranked in terms of discharge) are taken from McKee et al. (2003), as shown in Table 1. The total discharge of these 25 rivers is about 17 440 km^3/a, and the total accounts for 48.3% of the total freshwater discharge into the oceans from rivers. In this study, we only include the plume areas of 19 rivers since the WOA09 data set lacks the effective salinity data in the other six river estuaries (Mekong, Magdalena, Purari, Indus, Zambezi, and Danube). The locations of these 19 rivers are shown in Fig.1. The total discharge of these 19 rivers is approximately 15 910 km^3/a, and accounts for 44.06% of the total freshwater into the oceans.

2.2 Extraction method of the global major river plume areas

(1) Threshold salinity for identification of river plume area

The threshold salinity values for the identification of river plume areas are different from ocean to ocean, since different ocean basins have different background salinities. Using the WOA09 salinity data set, we determined the monthly mean surface layer salinities for all five oceans, and the results are given in Table 2. Although there are slight monthly variations, the Atlantic Ocean has the highest salinity, and the Pacific Ocean has the lowest mean surface salinity next to the Arctic Ocean. Surface layer salinity is quite low in the Arctic Ocean because of the large freshwater input from rivers, low evaporation, and seasonal ice melt (Lique et al., 2011). The annual-mean surface layer salinities are 34.51, 34.98, 34.77 and 30.00 for the Pacific Ocean, Atlantic Ocean, Indian Ocean and Arctic Ocean, respectively.