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Detection and variability of the Congo River plume from satellite derived sea surface temperature, salinity, ocean colour and sea level

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ABSTRACT

Despite its size and importance the dispersal, variability and dynamics of the Congo River plume have until recently been minimally documented. In this paper we analyse remotely sensed sea surface temperature, sea level anomaly, salinity and chlorophyll concentration from 2010 to describe and quantify the extent, strength and seasonality of the plume and to explain its behaviour in relation to winds, ocean currents and fresh water discharge. Empirical Orthogonal Function (EOF) analysis reveals strong seasonal and coastal upwelling signals, potential bimodal seasonality and responses to fresh water discharge peaks in all data sets. Salinity and chlorophyll are significantly negatively correlated (-0.4 to -0.9) across a 500 km^2 zone west of the river mouth. Lagged correlations with river discharge show the westward translation, dispersal and strengthening of a similar sized region of positive chlorophyll-discharge and negative salinity-discharge correlations. Peaks in chlorophyll lag the discharge by 1–4 months, although it is not possible from ocean colour alone to distinguish increases in chlorophyll resulting from the dispersal of nutrient rich river discharge from other physical and biological mechanisms that promote changes in surface chlorophyll, or indeed have confidence that the signal has not been contaminated by other optically active substances. The strongest plume-like signatures from EOF analysis are found in the salinity and colour data sets, which are then also analysed using a statistically based water mass detection technique to isolate the behaviour of the plume. The validity of the technique is checked against ARGO profiles. Throughout the year the main axis of the fresh water plume extends between 400 and 1000 km, northwest along the coastline, or west–southwest out into the open south Atlantic. Changes in the magnitude and direction of wind stress and hence wind driven surface currents are the principal driving force behind this far-field variability, although the strength and direction of the Angola and Benguela Coastal currents may also play a role. The mean surface salinity within the plume and its surface area have qualitative links to the seasonal cycle in river discharge and wind stress.

1. Introduction

Approximately 40% of the fresh water entering the oceans is transported by the world's ten largest rivers (Dagg, Benner, Lohrenz, & Lawrence, 2004). This discharge, reducing the surface ocean density and carrying large inputs of suspended sediment, particulate and dissolved carbon and nutrients has a major impact on the geochemical and biological processes of the surrounding continental margin (Gattuso, Frankignoulle, & Wollast, 1998). After the Amazon, the river with the second highest annual mean daily discharge (39,866 $m^3\ s^{-1}$) is the Congo in Africa (Fig. 1). It is also the world's second largest exporter of terrestrial organic carbon into the oceans (Coynel, Seyler, Etcheber, Meybeck, & Orange, 2005; Spencer et al., 2012). The outflow of such a large volume of water into the southeast Atlantic produces a vast fresh water plume, whose signature has been traced 700–800 km from the river mouth (Braga et al., 2004; Van Bennekom & Berger, 1984). This Eastern Atlantic low salinity pool and its high seasonal range (>1.5 pss (practical salinity scale)) are now detectable from the new SMOS (Soil Moisture and Ocean Salinity) satellite (Tzortzi, Josey, Srokosz, & Gommenginger, 2013).

The river discharge at Kinshasa, 500 km upstream of the river mouth, has a stable bimodal cycle; the main maximum is in November/December (56,880 $m^3\ s^{-1}$) and a second peak occurs in May (38,890 $m^3\ s^{-1}$). Periods of minimum discharge occur in August and March. The river channel is narrow and predominately surrounded by high and steep terrain. There are few potential areas of significant storage or diversion along its route, and no major adjoining tributaries, so flow characteristics at Kinshasa are likely conserved further downstream, albeit with a time delay (Lucas, Etienne, & Mercier, 2012).

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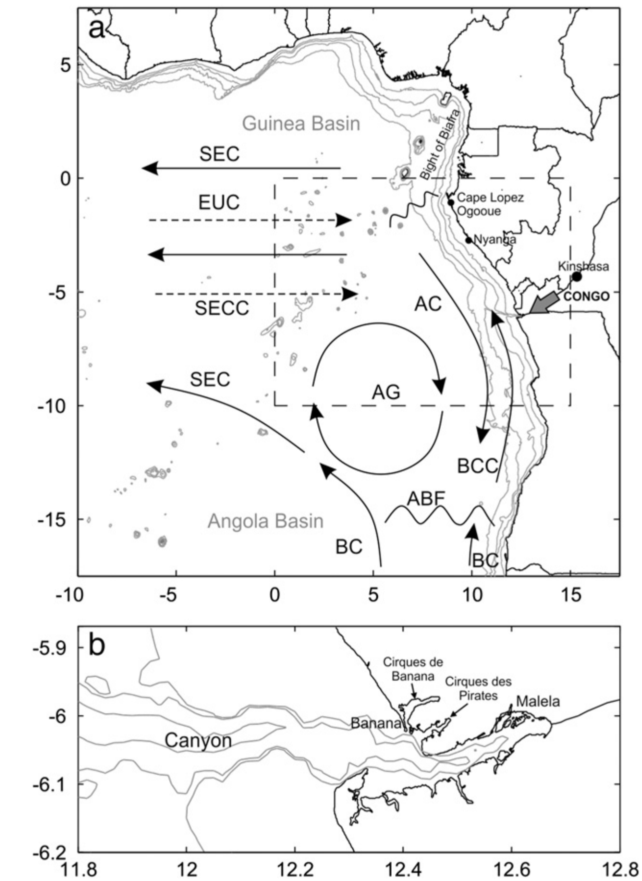

Fig. 1. (a) Surface (solid arrows) and subsurface (dashed arrows) circulation patterns and frontal zones in the Angola and Guinea Basins: South Equatorial Current (SEC), Angola Current (AC), Benguela Current (BC), Benguela Coast Current (BCC), South Equatorial Counter Current (SECC), Equatorial Under Current (EUC), Angola–Benguela Front (ABF), Angola Gyre (AG). Bathymetric contours are 100 m (shelf edge), 1000 m, 2000 m, and 3000 m. Dashed box marks the analysis area. (b) Congo River mouth and canyon. Contours are 600 m, 100 m and 50 m.

The Congo River plume may be classified as surface-advected (Yankovsky & Chapman, 1997); buoyant river inflow remains on top of shelf water forming a thin layer that, decoupled from bottom stress, spreads many hundreds of kilometres offshore. As for other buoyant plumes, estuarine, near- and far-field regions may be identified.

The plume forms initially at Malela (Fig. 1b) as a 10 m layer of fresh water (salinity 0–15 pss). An estuarine type circulation has been identified here, where surface outflow is compensated at depth by a residual up-canyon transport of saline water (Denamiel, Budgell, & Toumi, 2013; Eisma & Van Bennekom, 1978). As the plume approaches the near-field, which spans the river mouth at Banana and the continental shelf (salinity = 15–25 pss), it thins into a 3 m layer and is ejected WNW as a narrow jet. The direction of this initially buoyancy driven flow is determined by the speed of outflow (~2.5 m s^{-1}), the orientation of the estuary mouth and the local coastal currents (Denamiel et al., 2013; Eisma & Van Bennekom, 1978).

Offshore, in the far-field (salinity > 25 pss), the thickness of the plume increases to 10–20 m and mixing by vertical entrainment of subsurface oceanic water, most likely driven by the wind (Fong & Geyer, 2001; Hetland, 2005), gradually reduces its salinity. The offshore dynamics of surface-advected plumes are in general controlled by surface processes such as Coriolis, wind stress, ocean circulation patterns and strong tidal currents (O'Donnell, 1990; Yankovsky & Chapman, 1997). The Amazon River plume for example is swept north–west by the North Brazil Current, but also responds to variability in trade winds and tidal currents (Hu, Montgomery, Schmitt, & Muller-Karger, 2004; Nikiema, Devenon, & Baklouti, 2007; Salisbury et al., 2011). Further smaller scale examples include the discharge of the Niagara River into Lake Ontario (Masse & Murthy, 1992), and the Columbia River plume (Orton & Jay, 2005). Until a recent study presenting the first numerical simulation (Denamiel et al., 2013), the dynamics of the Congo River plume had been minimally documented. Consequently there is little detailed information from observations on the spatial and temporal variability of its dispersal. In this paper we take advantage of remote sensing products to better understand and document the dispersal of the Congo plume throughout the year.

The Congo River enters the southeast Atlantic at 6°S, 12.3°E, north of the Angola–Benguela front (Fig. 1a), the confluence between the Angola Current, a fast and narrow southward geostrophic flow of warm, saline water, and the Benguela Current, a cold and less-saline northward flow (Stramma & England, 1999). The Angola Current forms the eastern side of a cyclonic gyre, the Angola Dome (centred on 10°S, 5°E). The dome is primarily maintained by dynamic uplift of the thermocline on its western side driven by the Benguela–South Equatorial Current system and is thought to be responsible for much of the upwelling in the area (Signorini et al., 1999). North of the Congo at Cape Lopez another front separates warm waters in the Bight of Biafra from the colder waters of the Equatorial Under Current. The broad westward South Equatorial Current (SEC) is the northern limb of the large southern subtropical gyre. This zonal geostrophic current is driven by meridional gradients in the strength of the trade winds and Coriolis force. Meteorological conditions in the area are dominated by seasonal changes in the position of the intertropical convergence zone and the West Africa monsoon.

Owing to the economic potential of oil reserves in the area recent observational research has been focused on the sedimentary transport system in the deep canyon, and the biogeochemistry of deep ocean waters (e.g. Savoye, Babonneau, Dennielou, & Bez, 2009; Vangriesheim et al., 2009). Little effort since Eisma and Van Bennekom (1978) and other works from the 1970s–1980s has gone into studying the surface-advected plume. Large river plumes such as the Amazon, Mississippi and Congo however play an important role in the ocean carbon cycle, often functioning as carbon sinks. An understanding of their extent and seasonality is therefore essential if they are to be realistically accounted for in global assessments of the carbon cycle. Within large plumes a suite of biogeochemical and physical processes drive the uptake of terrestrial inputs of inorganic nutrients, the recycling of organic carbon and nutrients, and nitrogen fixation. These processes stimulate production and the synthesis, export and potential deep sea burial of organic carbon (Liu, Atkinson, Quiñones, & Talaue-McManus, 2010). River plumes can also be sinks for atmospheric CO_2 (Lohrenz & Cai, 2006); Bakker, de Baar, and de Jong (1999) report a reduction in pCO_2 in the outer Congo plume suggesting that it too may uptake CO_2.

The objective of this paper is twofold. First, to assess the utility of different remote sensing data sets in identifying the dispersal and behaviour of the Congo plume, and to develop a method to automate this process. The analysis of large, dynamic plumes is difficult, particularly from in-situ observations. Satellite data products however, although only a surface measurement, provide a snapshot of the whole plume and are the only really viable approach to monitoring the dispersal of waters over synoptic scales. Second, we aim to describe and quantify the extent, strength and variability of the plume and to explain its behaviour in relation to the main physical forcing processes. The paper is split into two parts. In the first (Section 3), we examine four data sets: satellite sea surface temperature, salinity, chlorophyll concentration, and mean sea level anomaly and assess whether coherent plume signatures can be extracted from them. We identify the dominant modes of variability in the Angola Basin from Empirical Orthogonal Function (EOF) analysis, and significant correlations between variables that reveal the persistence of plume waters. In the second part (Section 4), we apply a statistically based water mass detection technique to identify the plume in salinity and chlorophyll images. The results of this analysis, yielding estimates of the extent and orientation of the plume throughout 2010, are validated against in-situ data, and are discussed