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Mesoscale and intraseasonal air–sea CO_2 exchanges in the western Arabian Sea during boreal summer

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ABSTRACT

Intraseasonal variability, considered a coupled phenomenon, typically occurs in the 20-to-90 day-band and is seen in several of the air–sea interaction parameters over the Indian Ocean. The corresponding variability in the air–sea CO_2 exchanges and oceanic pCO_2 are not widely studied. In this study, we focus on the boreal summer season to find that there is a strong air–sea interaction of carbon cycle over the Somali region of the western Arabian Sea where the intraseasonal variability during this season is clearly evident in the intense variability in winds, the strength of the upwelling and the evolution of meso-scale eddies. The oceanic pCO_2 variability in this intraseasonal band over the Somali region is also remarkably consistent with the other variables and is found to be driven by sea surface temperatures (SST) albeit with a counteracting but relatively minor influence from the dynamics of dissolved inorganic carbon (DIC). The 20-to-90 day-band in pCO_2 accounts for about 40% of the monthly mean variability of the sea-to-air CO_2 fluxes of this region in boreal summer. Ocean dynamic control on the atmospheric wind response at these mesoscales has been reported before and this study demonstrates that the ocean dynamics also control the seawater pCO_2 and the air–sea CO_2 fluxes in this region. Other regions with similar meso-scale dynamics must be analyzed for processes that determine air–sea CO_2 exchanges and to determine whether the mesoscale fluxes contribute to the low-frequency CO_2 fluxes. The role of the intraseasonal variability in atmospheric pCO_2 in this exchange is not quantified here due to the lack of data at such high resolutions and needs to be considered in further observational and modeling efforts.

1. Introduction

During boreal summer (June–September, JJAS hereinafter) the atmospheric circulation of the tropical Indian Ocean (north of 10°S) is characterized by a strong anti-cyclonic vorticity over the ocean which drives a clockwise oceanic circulation. This circulation is composed of an eastward flowing summer monsoon current in the north equatorial Indian Ocean and westward flowing south equatorial current (SEC) to the south. To the west and east, these circulations are connected through cross-equatorial flows; northward along the western boundary known as Somali current and southward as a surface trapped return flow between a broad band of longitudes from 60°E to 100°E (Schott and McCreary, 2001). The Somali current is a narrow and intense western boundary current along the coast of Somalia due north in boreal summer with a vertical structure extending from surface to ~2000 m, delivering nearly 40 Sv of water to the northern Indian Ocean (Schott et al., 1990, 1997; Beal and Chereskin, 2003). The strong upwelling, genesis of intense eddies, presence of high salinity, high nutrient and carbon rich water in the surface are distinct properties along the Somali coast during this season (Sharada et al., 2008; Kawamiya and Oschlies, 2003; Wiggert et al., 2006). The surface waters along the Somali coast are thus some of the coldest in the tropical Indian Ocean during boreal summer and they create a venue for intense air–sea interactions and play a key role in the Indian summer monsoon variability (Vecchi et al., 2004; Seo et al., 2008; Izumo et al., 2008).

One conspicuous nature of the Somali coastal circulation during boreal summer is the systematic formation of two intense and semi-permanent anti-cyclonic eddies known as the Great Whirl (GW) and the Southern Gyre (SG; see Fig. 1). Observations of sea surface height show that the GW and the SG are part of the mean circulation of the Indian Ocean. The onset of these eddies can be seen in as early as April–May when the annual Rossby wave arrives at the western boundary (Beal and Donohue, 2013). GW grows and matures in order to maintain vorticity balance in the northward flowing western boundary currents crossing the

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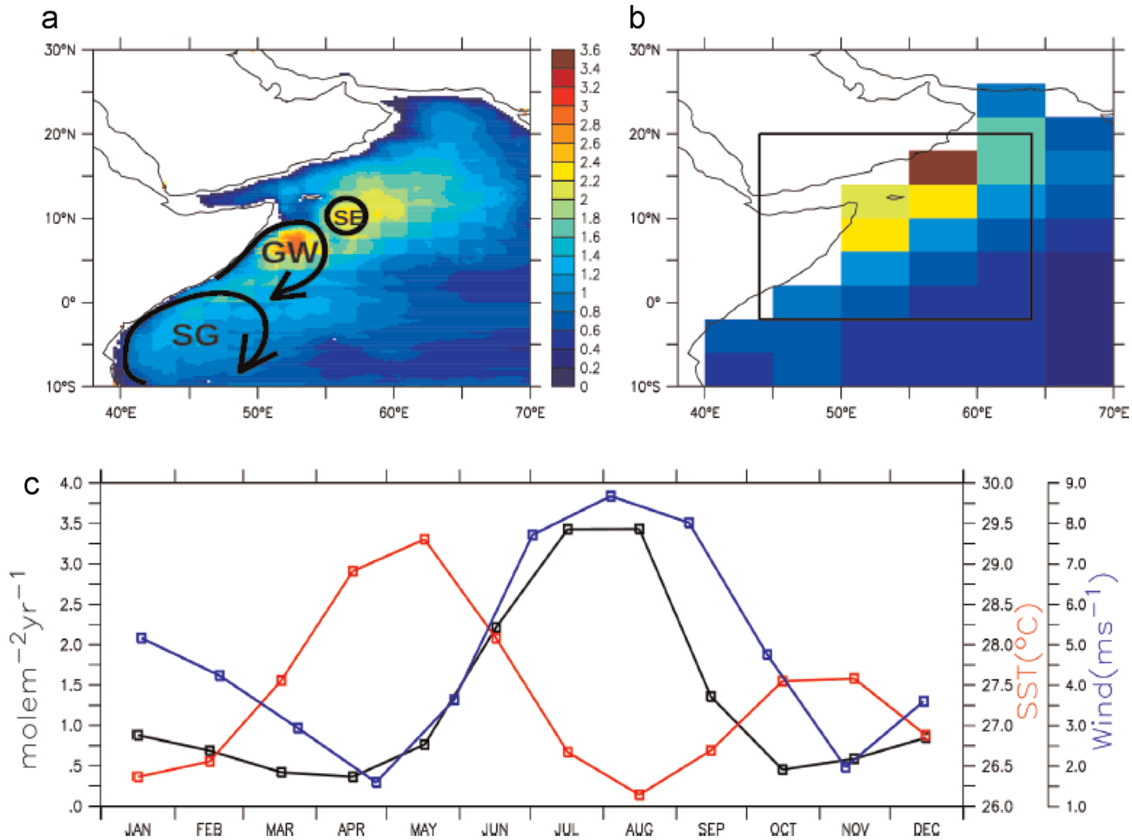

Fig. 1. (a) Annual mean sea-to-air CO_2 fluxes from the model (1992–1997) and (b) from the observations of Takahashi et al. (2009). Units are in mole m^{-2} yr^{-1}. (c) The area averaged sea–air CO_2 fluxes (black-line) over a box shown in 'b' and area averaged SST (red-line), wind speed (blue-line) from the same box shown as climatological monthly values. Locations where major anti-cyclonic eddies form during the boreal summer are schematically shown in (a). SG: Southern Gyre, GW: Great Whirl, SE: Socotra Eddy. Red (blue) colors indicate a positive (negative) pCO_2. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

equator (Jensen, 1991). The generation of GW and SG can be reproduced numerically by linear dynamics involving western boundary currents forced by interior wind driven ocean circulations (Shankar and Shetye, 1997). The sharp SST fronts generated by ocean dynamics are known to induce an atmospheric response that involve vertical entrainment of momentum that lead to a counter-intuitive pattern of accelerating winds over warm SSTs and weak winds over cold SSTs (Hayes et al., 1989; Vecchi et al., 2004, Seo et al., 2008).

The intense upwelling, the formation of strong anti-cyclonic eddies and the Ekman pumping at the northern flanks of the eddies cause the Somali region to be biogeochemically active. During the boreal summer the chlorophyll concentrations of the Somali region increase. Simultaneously, the dissolved inorganic carbon (DIC), nutrients, partial pressure of carbon dioxide (pCO_2) and carbon emission also ramp up (Takahashi et al., 2009; Valsala and Maksyutov, 2013). Despites it is highly visible biogeochemically activity, very few observational or modeling studies are performed in this region to date.

The western Arabian Sea (including the Somali region) is a perennial source of CO_2 (Sarma, 2003; Sarma et al., 2013). Interestingly, the evolution of SST, wind speed, and CO_2 emission are seasonally coupled over this region (Fig. 1). The SST starts to cool from its peak value in April–May, as soon as the wind speed increases due to the summer or the Southwest monsoon circulation (Murtugudde and Busalacchi, 1999). The subsequent upwelling and latent heat release cool the western Arabian Sea (Fig. 1c). The spreading of upwelled cold, salty water causes a sudden drop in SST in this region (Valsala, 2009). Simultaneously, the CO_2 emissions increase and that correlates positively with the wind speed as well as upwelling and negatively with the SST at seasonal timescales. Therefore, the seasonal cycle of CO_2 fluxes from the western Arabian Sea is easily explained by the wind speed variability and the DIC dynamics.

Apart from the above interactions in the seasonal mean and at mesoscales, there can be short-time scale variability of SST, winds, pCO_2, DIC and CO_2 fluxes in the western Arabian Sea, a topic that is not explored in previous studies on ecosystem and carbon cycle variability. The idea stems from the fact that the mean atmospheric circulation and air–sea interactions over the Arabian Sea exhibit strong intra-seasonal variability (ISV) during boreal summer (Goswami, 2005; Roxy and Tanimoto, 2007; Waliser et al., 2004) including in ecosystem signatures such as chlorophyll (Waliser et al., 2005). The summer ISV is generally referred to as the 20-to-90 day oscillations in the various oceanic and atmospheric parameters involved in the Indian summer monsoon variability. The variance of such short-term oscillations contributes about 40–60% of the year to year changes in the mean state of the Indian monsoon system (Goswami and Ajayamohan, 2001). The seasonal cycles of SST and wind of the western Arabian Sea are negatively correlated with each other while a positive correlation is found between these variables in their short-term intraseasonal cycles (Vecchi et al., 2004). Therefore it is natural to ask whether such intrinsic short-term variability of atmosphere–ocean coupled system has any signatures in the underlying carbon cycle of the western Arabian Sea. In this study, we address this question over a region close to the Somali coast to highlight the robust carbon cycle signatures associated with the significant ISV of SST observed during JJAS. Moreover, the intense eddies during the summer monsoon season and the related upwelling, as well as the Ekman