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Patterns of interannual climate variability in large marine ecosystems

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ABSTRACT

The purpose of this study is to investigate the vulnerability of the Brazilian and western African Large Marine Ecosystems (LMEs) to local and remote forcing, including the Pacific Decadal Oscillation (PDO) regime shift. The analyses are based on the total and partial correlation between climate indices (Niño3, tropical South Atlantic (TSA), tropical North Atlantic (TNA) and Antarctic oscillation (AAO) and oceanic and atmospheric variables (sea surface temperature (SST), wind stress, Ekman transport, sea level pressure and outgoing longwave radiation). Differences in the correlation fields between the cold and warm PDO indicate that this mode exerts a significant impact on the thermodynamic balance of the ocean–atmosphere system on the South Atlantic ocean, mainly in the South Brazil and Benguela LMEs. The PDO regime shift also resulted in an increase in the spatial variability of SST and wind stress anomalies, mainly along the western African LMEs. Another important finding is the strong AAO influence on the SST anomalies (SSTA) in the South Brazil LME. It is also striking that TSA modulates the relation between El Niño–Southern Oscillation (ENSO) and SSTA, by reducing the influence of ENSO on SSTA during the warm PDO period in the North and East Brazil LMEs and in the Guinea Current LME. The relation between AAO and SSTA on the tropical area is also influenced by the TSA. The results shown here give a clear indication that future ecosystem-based management actions aimed at the conservation of marine resources under climate change need to consider the high complexity of basin-scale interactions between local and remote climate forcings, including their effects on the ocean-atmosphere system of the South Atlantic ocean.

1. Introduction

Warming trends reported for the world's Large Marine Ecosystems (LMEs) have been associated with contrasting impacts on zooplankton and fisheries biomass, even for close geographic locations within an ocean basin (Sherman et al., 2009). The inferred warming rate (measured as a linear trend) is not the same everywhere, instead, it may vary from slow (over 0.05 °C/decade) to super-fast (over 0.45 °C/decade) (Belkin, 2009). The effects of these warming trends are not uniform, the fast-warming scenario for the northern Northeast Atlantic LMEs resulted in an increase in fisheries biomass due to increased zooplankton biomass while southern areas of these LMEs experienced fisheries biomass declines (Sherman et al., 2009). The response of fisheries biomass to remote and local climate forcing tend to be diverse as a result of amplifications, time lags and feedbacks inducing abrupt and discontinuous shifts (Overland et al., 2010), leading to contrasting biomass yields (Soares et al., 2011). So, before the actual influence of environmental trends (*e.g.*, increase in sea surface temperature) on the functioning of LMEs can be accurately quantified, the relative influence of local and remote forcings on environmental conditions needs to be assessed.

The sensitivity of the South Atlantic to climate variability at interannual, decadal and multidecadal timescales is closely related to changes in basin-scale sea surface temperature (SST) and sea level pressure (SLP) (Wainer and Venegas, 2002). The most important examples of the interplay between local and remote forcing of the SST variability in the tropical Atlantic are the coupled local ocean–atmospheric interaction and the El Niño–Southern Oscillation (ENSO), respectively (Nobre and Shukla, 1996; Wu et al., 2007). Kayano et al. (2012) showed that there is a SST mode in the South Atlantic, which they called the southwest South Atlantic mode. This is characterized by a dipolar structure with a strong negative center at (30°S, 40°W) that extends between 15°S and 45°S, and a less extensive positive center in the southern mid-latitudes, which is strongly modulated by the ENSO. They showed that an El Niño (La Niña) event precedes by up to 12 months the sea surface warming (cooling) in the South Atlantic between 15°S and 45°S. They also found that the South Atlantic SST dipole mode with centers at (15°S, 0° longitude) and (37.5°S, 25°W) leads or lags ENSO depending on the period of analysis.

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Clearly, the response of the tropical Atlantic to remote forcing depends on atmospheric teleconnection mechanisms and on basin-scale SST gradients acting on different time scales (Alexander et al., 2002; Enfield and Mayer, 1997; Giannini et al., 2004; Hastenrath, 2006; Lanzante, 1996). Mechanisms include the upper-tropospheric Rossby-wave train that extends from the equatorial eastern Pacific to the northern tropical Atlantic and the east-west displacement of the Walker circulation during El Niño years (Hastenrath, 1976; Kayano et al., 1988). Alternatively, Chiang and Lintner (2005) suggested that the anomalous warming signal produced in the eastern tropical Pacific during an El Niño episode propagates eastwards in the troposphere as an equatorial Kelvin wave. This tropospheric warming originated from the ocean surface acts to reduce moist convection, causing the latent heat to accumulate at the boundary layer. So, as a result of the reduced evaporation the heat content builds up and warms the ocean mixed layer. In any case, there is still an acute lack of research on the response of the South Atlantic to remote and local forcing of the interannual time scale and their possible effects on the functioning of LMEs.

There are a number of forcing factors affecting the oceanic and atmospheric conditions along the South Atlantic LMEs. An important local forcing in the tropical Atlantic is the inter-hemispheric SST gradient (Andreoli and Kayano, 2003; Enfield and Mayer, 1997; Enfield et al., 1999; Giannini et al., 2004; Moura and Shukla, 1981; Nobre and Shukla, 1996; Pezzi and Cavalcanti, 2001; Servain et al., 2000; Wang, 2002). Simulations with a coupled ocean and atmosphere numerical model (Xie, 1999) indicate that the interactions between wind, SST and evaporation determine the growth and oscillation of the SST inter-hemispheric gradient (see also Chang et al., 2006). Enfield et al. (1999) summarized the temporal variability of the meridional SSTAs in the Atlantic using two climate indices that represent local modes: the Tropical South Atlantic (TSA) and the Tropical North Atlantic (TNA).

Another Atlantic local mode is the Antarctic Oscillation (AAO), also known as the Southern Hemisphere Annular Mode, and it represents the differences in surface pressure between middle and high south latitudes (Gong and Wang, 1999; Hall and Visbeck, 2002; Thompson and Wallace, 2000). Hall and Visbeck (2002) showed that this mode is associated with changes in the surface westerlies as a result of the poleward movement and intensification (weakening) of the atmospheric jet stream around 55°S (35°S). The oceanic linkage is through frictional transfer of momentum, causing Ekman flow anomalies as high as two-thirds of the mean value. It has been suggested (L'Heureux and Thompson, 2005) that the ENSO affects the AAO through changes in the zonal wind anomalies in the subtropical latitudes, accounting for 25% of AAO variability during austral summer.

Besides ENSO, another important remote forcing acting on the Atlantic basin is the Pacific Decadal Oscillation (PDO) (Mantua et al., 1997; Zhang et al., 1997). The PDO is best understood as the leading mode of interdecadal variability in SST of the extratropical North Pacific with characteristic cold and warm phases (MacDonald and Case, 2005). These cold and warm phases are known to trigger significant climate and biological regime shifts with impacts on important fish stocks (Chavez et al., 2003; Mantua and Hare, 2002). It has been shown that the amplitude and dominant period of ENSO in the Pacific have increased after 1976, concurrent with the Pacific shift driven by decadal changes in the background equatorial winds and associated upwelling (Wang and An, 2002). Although the PDO-induced regime shift is well documented for the biota of the North Pacific with a significant change between 1976 and 1977 (see Mantua and Hare, 2002), there is no information available so far as to how the cold and warm phases of the PDO could impact the physical environments along the South Atlantic LMEs. It is also unclear how PDO and ENSO would interact in a basin scale to generate spatial patterns of variations in SST, wind stress and Ekman transport that could be biologically relevant.

Here, we demonstrate for the first time the effects of local and remote forcing on the oceanic and atmospheric conditions along the Brazilian and western African coast LMEs, including the PDO regime shift. We highlight that the geographical boundaries of these LMEs are largely offset from the spatial patterns of climate-induced variations that emerge from our analyses. Therefore, productivity and trophic relations in each of the LMEs are likely to generate mixed responses at the ecosystem level. If not taken into consideration by the environmental-based management policies, this has the potential to induce policy makers to react to a confounded scenario of environmental change. Maps of total and partial linear correlations between climate indices and oceanic-atmospheric variables in the South Atlantic are used to assess the vulnerability of the LMEs in this oceanic sector (Fig. 1) to climate variability.

2. Data and methodology

The SST data used here were the monthly gridded series for the period from 1948 to 2008, with a spatial resolution of 2° in latitude and longitude, derived from the version 3 of the reconstructed SST dataset, described by Smith et al. (2008). These data can be downloaded from http://migre.me/3Hy49. Wind stress data were obtained from the Simple Ocean Data Assimilation (SODA), which are in a spatial resolution of 0.5° in latitude and longitude and the period used in the analyses ranges from 1958 to 2001. The wind stress information was used to derive the Ekman transport ($\vec{E}$, kg m^{-1} s^{-1}) using the follow equation:

$$\vec{E} = \frac{\vec{k} \times \vec{\tau}}{f} \qquad (1)$$

where $\vec{k}$ is a unit vector directed vertically upward, $\vec{\tau}$ (kg m^{-1} s^{-2}) is the wind stress vector and f is the Coriolis parameter (s^{-1}).

The outgoing longwave radiation (OLR) data employed in this work were derived from the polar-orbiting National Oceanic and Atmospheric Administration (NOAA) satellites that have a spatial resolution of 2.5° latitude–longitude over the period from 1979 to 2008. OLR can be used to distinguish deep convection processes and to estimate the radiation balance of the Earth (Liebmann and Smith, 1996). These data were downloaded from: http://www.esrl.noaa.gov/psd/data/gridded/data.interp_OLR.html. The SLP data used have a spatial resolution of 2.5° and were obtained from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) Reanalysis Project version 1 (Kalnay et al., 1996) for the period from 1948 to 2008. Monthly anomalies of the variables were computed at each grid point as the departures from the climatologies based on the period with available data (Table 1). Hereinafter, the anomalies of SST, SLP,

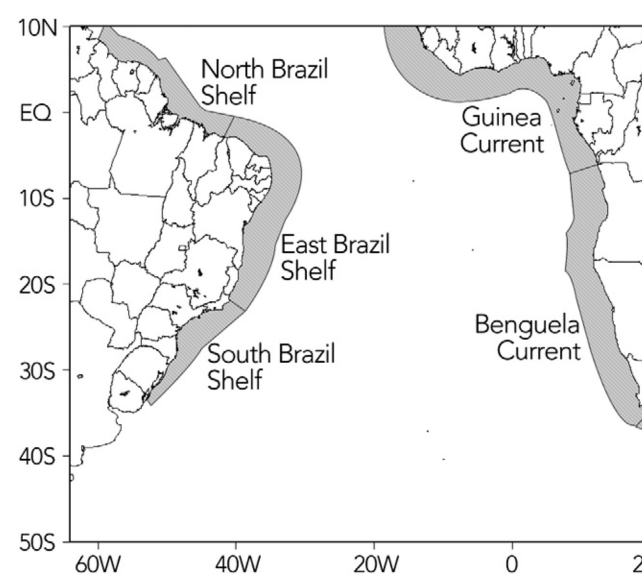

Fig. 1. Location of the South Atlantic LMEs in the region of interest.