



Differences between spatial patterns of climate variability and large marine ecosystems in the western South Atlantic

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Abstract. Despite their importance for environmental management, the response of Large Marine Ecosystems (LMEs) to climate changes is unlikely to be controlled by the ecological criteria used to define them. This is because productivity and trophic relations are endmembers of a chain effect that starts with physical processes not necessarily bounded by LMEs. Correlation fields were calculated for climate indices and sea surface temperature anomalies (SSTA) for the southwest Atlantic to identify interannual correlation patterns. Significant correlations indicate that the influence of El Niño/Southern Oscillation (ENSO) along the north and east coasts of Brazil is not coincident with the boundaries of LMEs. The antisymmetric (opposed signs) correlation pattern of the Tropical South Atlantic (TSA) observed in the South Brazil (SB) LME, during the warm PDO phase, may be related with the northeast-southeast SST dipole. It is possible that both the TSA and the Antarctic Oscillation Index (AAO) have distinct influences on the Brazilian LMEs depending on the geographic location and time scale. The PDO multidecadal and the ENSO interannual induced SSTA variability along the Brazilian coast exhibit a complex spatial dynamics against which ecosystem functioning should be tested to provide clues as to how the LMEs might respond to these climate forcings.

Keywords: Ecosystems, Tropical South Atlantic, climate indices, global changes

Resumo. Diferenças entre os padrões espaciais de variabilidade climática e dos grandes ecossistemas marinhos no oeste do Atlântico sul. Apesar de sua importância para o gerenciamento ambiental, é improvável que a resposta dos grandes ecossistemas marinhos (GEMs) às mudanças climáticas seja regida pelos critérios ecológicos usados em sua definição. Isto acontece porque a sua produtividade e relações tróficas são o resultado de uma cadeia de eventos que começa nos processos físicos que não seguem, necessariamente, os contornos dos GEMs. Campos de correlação foram calculados para índices climáticos e temperatura da superfície do mar (TSM) para o oeste do Atlântico sul para a identificação dos padrões interanuais. Correlações significativas indicam que a influência do El Niño Oscilação Sul (ENOS) ao longo da costa brasileira não é coincidente com os limites espaciais dos GEMs. Os padrões antisimétricos de correlação do índice do Atlântico Tropical Sul (ATS) no sul do Brasil durante a fase quente da Oscilação Decenal do Pacífico (ODP) pode estar relacionada com o dipolo de TSM. É possível que tanto o ATS quanto a Oscilação Antártica (OA) apresentem influências distintas nos GEMs do leste e do sul do Brasil. A variabilidade interanual da TSM ao longo dos GEMs no Brasil, induzida tanto pela ODP quanto pelo ENOS, exibe uma dinâmica espacial complexa contra a qual o funcionamento dos ecossistemas devem ser testados.

Palavras-chave: Atlântico Tropical Sul, índices climáticos, mudanças globais

Introduction

Large Marine Ecosystems (LMEs) have been used as a framework for the assessment and management of marine resources and they are defined according to four ecological criteria:

bathymetry, hydrography, productivity, and trophically related populations (Sherman 1991). It is assumed that ecosystem variability in LMEs can be captured by indicators grouped into five modules:

productivity, fish and fisheries, pollution and ecosystem health, socioeconomics and governance (Duda & Sherman 2002). Recent efforts to relate large scale climatic changes to ecological processes such as fisheries biomass yields in LMEs have indicated the presence of emergent trends induced by global warming (Sherman *et al.* 2009). It has been suggested that increasing sea surface temperature (SST) exceeding the levels expected from the warm phase of the Atlantic Multidecadal Oscillation affected the Icelandic Shelf, Norwegian Sea and Faroe Plateau, a region responsible for 5% of the global fisheries yields. The perceived increase in fisheries yields in these regions is a result of increased availability of zooplankton leading to improved feeding conditions of zooplanktivorous species in the Northeast Atlantic. Similarly, fisheries biomass yields are increasing in the proposed North Brazil (NB) and East Brazil (EB) LMEs (Fig. 1), where changes in production seem to be responding predominantly to overexploitation rather than climate warming (Sherman *et al.* 2009).

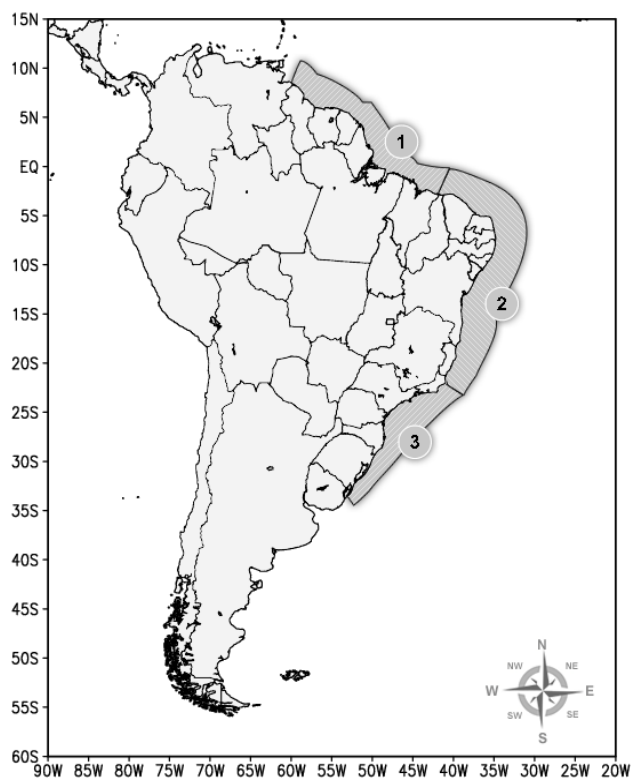


Figure 1. Map of South America showing the location of Large Marine Ecosystems in Brazil. 1) North Brazil LME, 2) East Brazil LME, 3) South Brazil LME.

Integrative research tackling the influence of large and mesoscale processes on biological systems of the western south Atlantic has gained momentum in the last years. Variations in mean SST, cloud cover and turbidity in Bahia State, eastern Brazil, induced by the 1997-98 ENSO

caused partial mortality of octocorals and actinarians, but had limited impact on scleractinian communities in coral reefs (Kelmo *et al.* 2003). ENSO is also known to have caused increased precipitation and reduced salinity of the Patos Lagoon estuary (southern Brazil), driving away euryhaline species (Garcia *et al.* 2001). Remote sensing data show that cold-core eddies form at the Brazil-Malvinas Confluence (BMC) region and rapidly separate from the mean flow with chlorophyll concentration in their cores higher than the surrounding waters (Garcia *et al.* 2004). The western boundary Brazil Current (BC) also produces warm core rings that can be expelled to the shelf (Souza & Robinson 2004). The interannual variability in the number of warm core rings shed in the BMC may be forced by the Antarctic Circumpolar Current (Lentini *et al.* 2002), which helps propagating Pacific ENSO signals to the Atlantic ocean (Peterson & White 1998).

Despite increasing evidences that point to the importance of large geographical areas as target units for ecosystem-based management (Belkin 2009), the response of these areas to climate changes is unlikely to be controlled by the ecological criteria used to define the LMEs. The reason for that is very simple, climate changes can act directly on physiology, behaviour, mortality and distribution, and indirectly on productivity, structure and composition of the ecosystem (Brander 2007). Productivity and trophic relations are endmembers of a chain effect that starts with physical processes not necessarily bounded by LMEs as they are defined today. The response of the tropical Atlantic to climate variability depends on atmospheric teleconnection mechanisms and on basin-scale SST gradients acting on different time scales (Lanzante 1996, Enfield & Mayer 1997, Alexander *et al.* 2002, Giannini *et al.* 2004, Hastenrath 2006). 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). It is clear that the interplay of local dynamics and remote forcing, including the ENSO, is responsible for the observed SST anomalies over the tropical Atlantic (Nobre & Shukla 1996).

It is plausible to assume that if the spatial extent of SST anomalies can only partially affect a LME, the resulting changes in fisheries biomass yields or geographical distribution of species within it may not be statistically detectable. As a result, unbiased assessment of climate change impacts could be hampered and national governments would

face too many uncertainties regarding the effectiveness of response policy measures. Also, managers responsible for mitigation programmes and action plans aimed at dealing with climate change impacts on marine and coastal ecosystems may find it difficult to envisage the necessary site-specific management strategies for multiple stressors (Higgason & Brown 2009). This is an important issue because the reduction in carrying capacity can be coupled with density-dependence effects on biomass changes of small pelagic fish species, such as observed with the Japanese sardine (Yatsu *et al.* 2008). As large-scale climatic-induced regime shifts are modulated by local physical conditions, this will most likely impose time-lagged changes on biological production at lower trophic levels (*e. g.* mesozooplankton). Recently, Gigliotti *et al.* (2010) showed that the interannual variability of egg concentration of the Brazilian sardine can be related to the expansion and contraction of the spawning habitat. The Brazilian sardine is capable of exploring suitable spawning sites provided by the entrainment of the colder and less saline South Atlantic Central Water (SACW) onto the shelf due to the combined effect of coastal wind-driven and meander induced upwelling.

The purpose of this paper is to present some exploratory results that point to important differences between the spatial patterns of correlation of climate indices and SST anomalies (SSTA), and the geographic arrangement of LMEs for Brazil (North Brazil, East Brazil, and South Brazil Shelf), as recently discussed in Sherman *et al.* (2009). The consequences of such differences to the study of the impacts of climate variability in these

LMEs are discussed.

Materials and Methods

Climate indices calculated as SST anomaly averages were obtained for three different areas: Niño 3 limited at 5° S, 5° N and 150° W, 90° W; Tropical North Atlantic (TNA) bounded at 5.5° N, 23.5° N and 15° W 57.5° W; and Tropical South Atlantic (TSA) at 0°, 20° S and 10° E 30° W (Fig. 2). These indices are the same used in other studies of tropical Atlantic climate variability (Enfield *et al.* 1999, Kayano *et al.* 2009) and are available at <http://www.esrl.noaa.gov/psd/>. The SST data used in this work are the monthly gridded series from 1948 to 2008, with a spatial resolution of 2° in latitude and longitude, derived from the version 3 of the reconstructed SST data set, described by Smith *et al.* (2008). These data can be freely downloaded from <http://migre.me/3Hy49>. The Antarctic Oscillation Index (AAO), also known as the Southern Hemisphere Annular Mode (Kidson 1988, Thompson & Wallace 2000) is calculated by projecting the monthly mean 700 hPa geopotential height (normalized) anomalies poleward of 20°S onto the leading Empirical Orthogonal Function (EOF) mode of these anomalies from 1979 to 2000. The AAO describes a mass seesaw between the southern mid and high latitudes, with positive (negative) values representing above (below) normal geopotential height in the midlatitudes and below (above) normal geopotential height in the high latitudes. The monthly AAO dataset corresponds to the period from 1979 to 2007, available at http://www.cpc.noaa.gov/products/precip/CWlink/daily_ao_index/aao/aao.shtml.

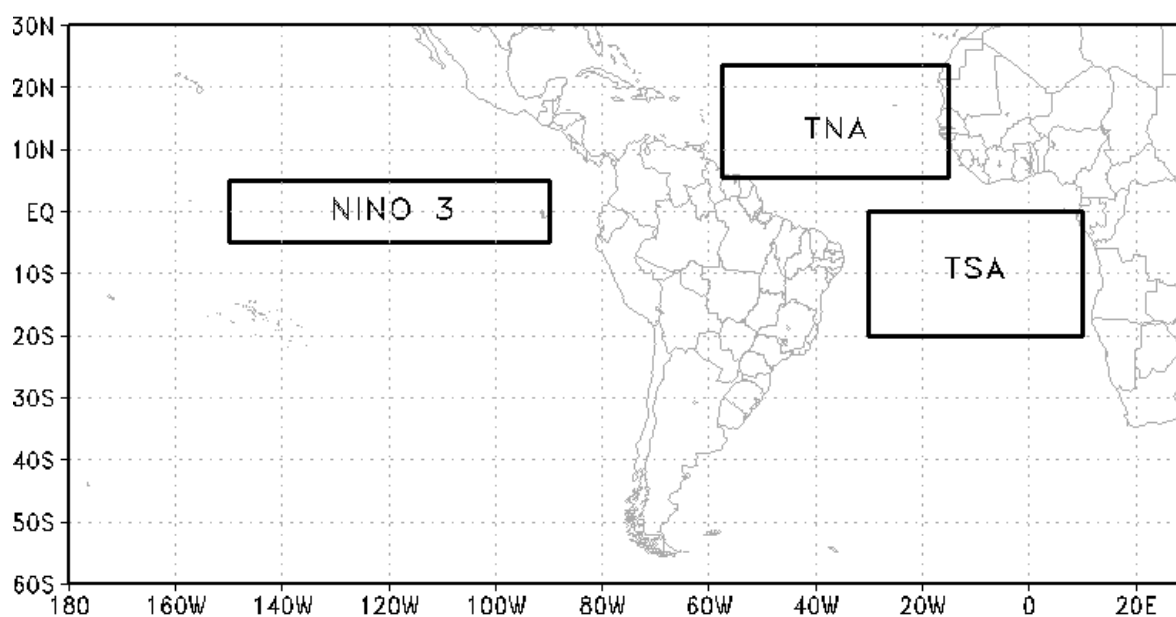


Figure 2. Location of areas from which the climate indices have been calculated.

In order to determine the spatial patterns of interannual SSTA variability along the Brazilian coast associated with global climate change, correlations between Niño 3, TNA, TSA and AAO indices and the SST anomaly field were calculated for the area between 10°N to 40°S and 62°W to 26°W. The influence of the Pacific Decadal Oscillation (PDO) shift on correlations was investigated by dividing the complete time series (1948 to 2008) in the cold PDO phase from 1948 to 1976, and the warm PDO phase from 1977 to 2008 (Mantua *et al.* 1997). Correlations were carried out for each grid point in the study area using linearly detrended, standardized and filtered data. Filtering procedure made use of a Morlet wavelet as a bandpass filter (Torrence & Compo 1998) to retain only the interannual variability between 2 and 7 years. The cross correlation time lags used in the analyses apply to all grid points and were selected based on the higher significance value obtained for each climate index. The statistical significance of all correlations has been assessed by Student's t-test at a 95% confidence level and only significant correlations are presented in the results section. The number of degrees of freedom (DOF) was determined by dividing the total time length of the series by the time lag needed to achieve decorrelation time closest to zero (Servain *et al.* 2000, Kayano *et al.* 2009). Only the lower values for the number of DOFs were adopted, so that the test is the most severe.

Results

For the sake of simplicity, all correlations between the climate indices and SSTAs along the Brazilian coast will be referred to only in terms of the indices used in each case. Maximum positive correlations of 0.7 with the Niño 3 are found along the eastern coast and offshore the northern coast of Brazil and to the north of the equator after a time lag of eight months (Fig. 3). This time lag has been also reported by Lanzante (1996) and indicates that under an El Niño (La Niña) the surface waters in these areas of the tropical Atlantic are anomalously warmed (cooled) eight months later. Possibly, the most striking aspect of the correlation fields is the marked spatial differences between the cold and warm PDO phases, namely the lack of positive correlation in the South Brazil (SB) LME during the warm PDO. Positive correlations with values up to 0.6 appear at the SB LME and up to 0.7 offshore for the cold phase only. It is also important to note that during the warm PDO, correlations in the EB LME are mostly located in its southern half, characterized by high (up to 0.7) values. This suggests a separation

between the two halves of the EB LME, in terms of the decadal SSTA variability. It is worth noting that to the north of the equator correlations are significantly lower for the warm phase of the PDO than for the cold phase.

The TNA achieves higher positive correlations after one month lag but has a limited impact on the SSTA along the Brazilian coast (Fig. 3). During the cold phase of the PDO the north Brazil coast experienced the highest correlations, but these are greatly reduced moving offshore in the following warm phase. In fact, there is no significant correlation for the TNA along the north Brazilian coast during the warm phase. On the other hand, significant correlation of 0.5, restricted to a small area in the eastern coast in the cold phase, evolves into a wide northwest-southeast correlation band. This extends towards the subtropical portion of the central south Atlantic in the subsequent warm phase. So, for the warm PDO, an anomalous warmed (cooled) TNA relates to an anomalous warmed (cooled) subtropical South Atlantic.

Not surprisingly, the TSA achieves the highest correlation (with zero lag) in the northern and eastern portions of Brazilian coast, with the latter being more developed during the warm PDO phase (Fig. 3). This appears to be the result of the proximity with the area of the tropical Atlantic where the TSA is calculated. Furthermore, the positive correlation pattern also resembles the SST equatorial mode previously detected by Zebiak (1993) and Wagner & da Silva (1994). These authors showed that a significant part of the observed SST interannual variability in the tropical Atlantic is related to an internal Atlantic equatorial mode similar to the ENSO in the Pacific. A new feature, however, emerges for the warm phase characterized by negative correlation values as high as -0.6 along the southern limit of the SB LME. For the warm PDO phase, anomalously warm (cold) surface waters in the TSA relate to cold (warm) than normal surface waters in the South Atlantic to the south of 35°S. It is worth noting the lack of significant correlations in the area under the influence of the South Atlantic Convergence Zone (SACZ), similar to the observed pattern for the Niño 3 and TNA indices. The SACZ is an elongated convective band that originates in the Amazon basin extending to the southeastern Atlantic Ocean, responsible for extreme precipitation events and strongly influenced by warm ENSO events that favors its persistence over the Atlantic (Carvalho *et al.* 2004).

It takes six months for the AAO to develop the highest positive correlations along the SB LME

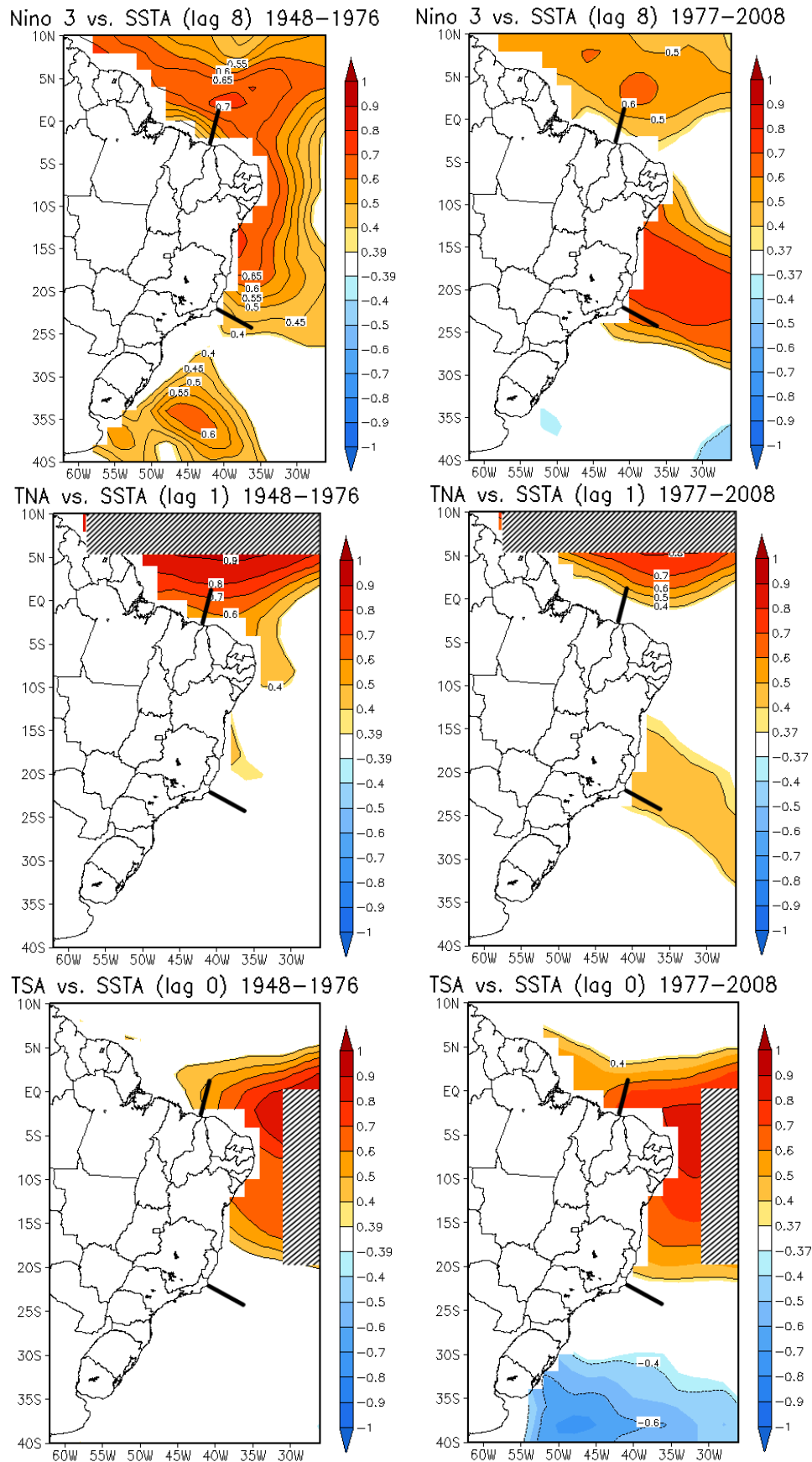


Figure 3. Significant correlation maps for Niño 3, TNA and TSA during the cold (left) and warm (right) PDO phase and their respective time lags. Hatched rectangles indicate areas of spurious correlation. Black straight lines correspond to the limits between LMEs in Brazil and were added for reference. Color bar is in (nondimensional) units of correlation.

and two years (24 months) to develop negative correlations along the NB and EB LMEs, as well as positive correlations restricted to the southern coast (Fig. 4). The most relevant aspect of these correlations is that this is the only index to present some relation with the interannual variability of SSTA within the SACZ region. The fact that significant correlations also developed with a 24 months delay with inverted signals in tropical and southern Atlantic deserves further attention. This aspect is analyzed through the sequential lagged correlation maps from lag 0 to 24 months (Fig. 4). Significant positive correlations appear offshore the southern coast between 25°S and 30°S at lag 1 month. Gradually, these correlations intensify and occupy a large area between 25°S and 35°S from lag 1 to 9 months. Significant negative correlations develop along the NB LME by lag 9 months. As these negative correlations intensify, significant (negative) correlations start to develop between 15° S and 20° S in the South Atlantic, and the positive correlation center between 25° S and 40° S splits into two centers by lag 17 months. With time, all correlations intensify, with the strongest values being settled by lag 24 months. This pattern shows, indeed, three main centers with the largest magnitude of correlation: two negative centers, one along the NB LME and another along the EB LME, and one positive center along the SB LME.

Discussion

There are striking differences between the correlation fields for Niño 3 and the proposed separation of LMEs along the Brazilian coast. This is also the case when the correlation fields for the cold and warm PDO phases are projected onto these LMEs. We have found that the time lag necessary for maximum correlations to be reached is the same (eight months) for both PDO phases, suggesting that the mechanisms connecting the Pacific and the Atlantic Ocean are comparable. During the cold PDO phase the boundary between the NB and the EB LMEs intersects a large region where SSTAs are highly correlated with the tropical Pacific variability (Fig. 3). It is striking, however, the coincidence between the significant correlations and the southern limit of the EB LME. High correlations between Niño 3 and SSTA cover the SB LME only partially and are mostly centered offshore (at 35°S, 45°W). This contrasts with our results for the NB and EB LMEs, where high correlations are found close to the coastline. This gives a strong indication that marine organisms living on the continental shelf of the SB LME, which are sensitive to SSTAs, may

take longer to react the impact of ENSO events. We do know, however, that ENSO induced increase in precipitation in the Patos Lagoon estuary has a negative impact on euryhaline species (Garcia *et al.* 2001). Looking at the warm PDO phase, the EB LME includes areas with high and medium positive correlations and also a large area where no significant correlation was detected. This means that trophically related populations in the EB LME may not respond consistently to a remote climatic forcing such as the El Niño because environmental conditions expressed as SSTAs co-vary differently inside this region. This spatial discontinuity of correlations within the EB LME can pose some threat on pelagic species that rely on the thermal structure of the west tropical Atlantic, such as the albacore *Thunnus alalunga* during their reproductive phase (Frédou *et al.* 2007). Two other emblematic examples of the spatial and temporal effects of climate on marine pelagic ecosystems are provided by Stenseth *et al.* (2002), the Peruvian anchovy crash in 1972 and the zonal displacement of the Pacific skipjack tuna following the eastward displacement of the warm pool during ENSO events.

A further complicating factor is that ecological processes sensitive to long term (e.g. decadal) environmental changes are likely to be submitted to different regimes (see North *et al.* 2009) within the EB LME. The same complicating factor is even more evident in the South Brazil (SB) LME, where high positive correlation with El Niño has been detected during the PDO cold phase, but no significant relation was found in the subsequent warm phase (Fig. 3). So, the PDO-related multi-decadal and ENSO-related interannual SSTA variability along the Brazilian coast exhibit a complex dynamics against which ecosystem functioning should be tested to provide clues as to how NB, EB and SB LMEs might respond to these climate forcings. Besides, if one considers the hypothesis that the PDO can be represented as a red noise process, then extreme values or rapid shifts might occur when fortuitous random phasing combine contributions of different frequencies (Overland *et al.* 2010).

The TNA and TSA indices are long known as indicators of the principal modes of Tropical Atlantic Variability (TAV), namely meridional SSTA gradients, which are important for the climate of the tropical Atlantic and the surrounding land masses (Enfield *et al.* 1999). The reason to include these indices in our analyses is to portray a balanced view of the inter-basin and within-basin influence on the SSTA of the Brazilian LMEs. The extent to which the TNA and TSA interact with SSTA along

the Brazilian LME can be explored in the correlation maps of Fig. 3. These maps show a scenario where correlations with TNA are limited to the southern half of the EB LME during the warm PDO phase, with a single correlation area between 15° and 25° S, and points to a possible indirect influence via ENSO teleconnection over the region. In fact, the TNA itself is forced by the ENSO and is likely to be of marginal importance to the NB and EB LME if compared to the meridional propagations of SSTAs in the tropical Atlantic (Andreoli & Kayano 2004). It is worth mentioning the significant differences between cold and warm PDO correlations for the TNA. This is a recurrent feature that highlights the importance of decadal variability in shaping spatial patterns of LME vulnerability to climate change.

Interpretations regarding the TSA should be made with caution due to the proximity of the EB LME with the region from which the index has been calculated. However, the antisymmetric (opposed signs) correlation pattern observed in the SB LME, during the warm PDO phase, may be related with the northeast-southeast SST dipole suggested by Grodsky & Carton (2006). It is beyond the scope of the present work to discuss the applicability of the term dipole but our results point to a basin scale interannual relation between the SB LME SSTA and the so-called TAV. It is important to highlight that not only TAV may have an impact in SB LME but it strengthened after 1977, since it was absent during the PDO cold phase. Again, the negative correlations of TSA found only for the southern half of the SB

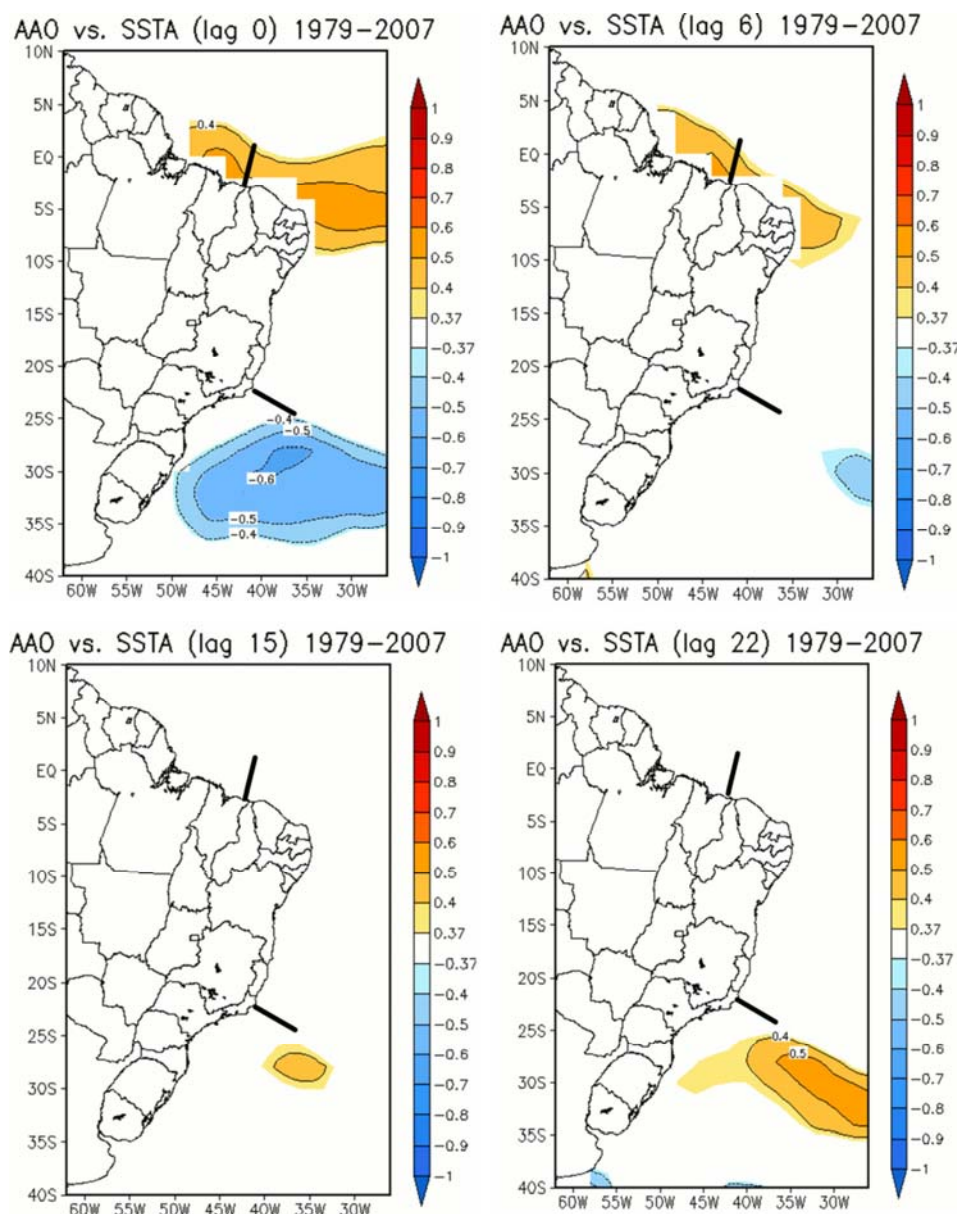


Figure 4. Significant correlation maps for AAO (warm PDO phase only) indicating the time and space evolution of correlation fields along four time lags (from zero to 22 months). Black lines correspond to the limits between LMEs in Brazil and were added for reference. Color bar is in (nondimensional) units of correlation.

LME suggest that possible random phasing with remote forcing of SSTA is likely to produce mixed effects in this LME.

The leading EOF of monthly sea surface height anomalies (SSHA) shown by Grodsky and Carton (2006), indicates a region of shallow thermocline in the southwest Atlantic between 25° and 35° S coincident with negative SST EOF scores. They interpreted the westward 10 cm interannual SSHAs as Rossby waves produced by thermocline anomalies due to local and equatorial air-sea interactions. These waves would propagate along the Agulhas Eddy Corridor (AEC). The region of shallow thermocline is coincident with a field of negative correlations with the AAO without time lag that dominates the northern half of the SB LME (Figure 4). This means that positive AAO indices are correlated with cold of SSTAs and stronger westerly circumpolar flow (positive mid-latitude pressure anomalies) as previously indicated by Thompson and Wallace (2000). Coupled ocean-atmosphere model results suggest that much of the variability of the south Atlantic poleward of 30° S has a direct relation with the Southern Hemisphere Annular Mode (hence, the AAO; Hall & Visbeck, 2002). Positive AAO is related with increased poleward ocean heat transport at 30° S and a reduction at 50° S, with associated 0.05° C increase in SSTA in the subtropics. The importance of AAO as a source of large-scale interannual variability in the tropical and Southern Atlantic Ocean can be also inferred from positive correlation centers along the northern and eastern coast and positive correlations observed between 25° S and 35° S, 15 and 22 months ahead of the AAO for the warm PDO phase (Figure 4). Whether this is a result of enhanced Ekman drift and convergence of heat it is not possible to ascertain, but the observed correlations indicate that the AAO exerts a strong influence on the environmental conditions along the LMEs.

It is possible that both TSA and AAO have an influence on the EB and SB LME acting in different ways depending on the geographic location and time scale. This influence seems to be particularly conspicuous during the warm PDO phase. In this preliminary report, we can only be speculative, but this is not to say that there are no evidences for the influence of the spatial scale. Indeed, it is quite the opposite, looking at the interplays among population dynamics, climate change and fisheries throughout the Atlantic, it is seen that at the basin scale patterns of variations are spatially structured (Rouyer *et al.* 2008).

The current knowledge on coupled ocean-

atmosphere dynamics tells us that LMEs are tied together by wind stress forcing, Ekman drift and heat transport. All of these are important agents that control the pelagic food-web structure, including primary productivity, mesozooplankton biomass and the position of spawning habitats of pelagic fishes (Kiorboe 2008). Changes in surface currents, wind stress and heat flux can have an impact on the long-term dynamics of zooplankton functional groups, leading to regime shifts in the ecosystem functioning from bottom-up to top-down control (Molinero *et al.* 2008). If monitoring and management of LMEs are to become an effective means to respond to climatic impacts on marine biodiversity and productivity, then the physical linkages between ocean-atmosphere dynamics and the pelagic ecosystem on a regional and basin scale have to be explicitly considered.

Conclusions

The above results are preliminary findings that aim at exploring the spatial patterns of correlation between climate indices and the SSTA along the Brazilian LMEs at the interannual time scale. Significant correlations indicate that there is a separation between the north and east Brazil coasts located halfway between the boundaries of the EB LME. The SSTAs in the SACZ region showed no significant correlation with Niño 3, TNA and TSA, but are correlated with the AAO during the warm PDO phase. Possibly, the most evident pattern that surfaced from the results is the influence of the PDO phase shift causing dramatic changes in the spatial distribution of correlations. The correlation patterns for the TSA and AAO seem to have a better fit with Brazilian LME during the warm PDO phase (1977-2007). During this phase of the PDO, while the largest magnitude correlations are found in the EB and SB LME for the TSA, they are centered in the three LME areas for the AAO. It is, strongly recommended the combined use of coupled ocean-climate and ecological models as a means to elaborate the possible mechanisms linking climate change and the functioning of LMEs in Brazil. The assumption that LMEs delimited along the Brazilian coast coherently respond to global climate changes, and that these can be used to monitor their impacts should be taken with caution. It is clear that, as far as their dependence on SSTA is concerned, productivity and trophic relations in each of the Brazilian LMEs are likely to generate mixed responses at the ecosystem level. This would, in turn, induce policy makers to react to a confounded scenario of environmental change.

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