Biogeosciences Discuss., 12, 13193–13213, 2015
www.biogeosciences-discuss.net/12/13193/2015/
doi:10.5194/bgd-12-13193-2015

Biogeosciences Discussions
Open Access

Southwestern Tropical Atlantic coral growth response to atmospheric circulation changes induced by ozone depletion in Antarctica

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Received: 17 May 2015 – Accepted: 19 July 2015 – Published: 17 August 2015

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Climate changes induced by stratospheric ozone depletion over Antarctica have been recognized as an important consequence of the recently observed Southern Hemisphere atmospheric circulation. Here we present evidences that the Brazilian coast (Southwestern Atlantic) may have been impacted from both winds and sea surface temperature changes derived from this process. Skeleton analysis of massive coral species living in shallow waters off Brazil are very sensitive to air–sea interactions, and seem to record this impact. Growth rates of Brazilian corals show a trend reversal that fits the ozone depletion evolution, confirming that ozone impacts are far reaching and potentially affect coastal ecosystems in tropical environments.

1 Introduction

Sensitivity of coral species to change in sea surface temperature (SST) has become a focus of attention in the context of modern climate change (Coles and Jokiel, 1978; Howe and Marshall, 2002; Marshall, 2003; Cantin et al., 2010). Response to thermal stress ranges from growth rate alteration to bleaching and eventually death. SST has long been recognized as an important environmental driver for coral growth pattern and calcification (Lough and Barnes, 1997). In a scenario of a warming planet, it is expected that until 2050, ~ 95 % of global reefs will be under pressure from thermal stress and that only 15 % will remain in areas of adequate aragonite saturation for proper coral growth (Burke, 2011). Brazilian coral species have high level of endemism and are predominantly found in shallow waters, with the scleractinian coral *Siderastrea stellata* (Verril, 1868) being one of the main reef builders. It is a colonial, massive and symbiotic coral (Lins-de-Barros and Pires, 2007) with a spatial distribution that encloses all Brazilian reefs and coral communities from nearly 0 to 23° S (Castro and Pires, 2001). For *Siderastrea stellata*, that often grows in shallow water in reef tidal pools (where temperatures normally range between 25 and 31 °C), optimum calcification has been observed at temperatures between 28 and 30 °C. For this particular species, the aragonite saturation seems to play a less relevant role than SST for calcification, especially when SST reach ∼ 26 °C (da Silva et al., 2009).

Several factors can induce change in SST, that will ultimately impact coral communities. One of them is the change in wind circulation patterns. Several authors have reported a close relationship between wind-stress and SST (Lindzen and Nigam, 1987; Hashizume et al., 2001; Chelton et al., 2007) through modulation of surface heat flux and upper ocean mixing. In general, warmer SST can be associated with deeper boundary layers and higher wind stress (Cayan, 1992; O'Neill et al., 2010). The Southern Hemisphere mid-to-high latitude circulation has undergone marked changes in wind dynamics over the past few decades. One of the most pronounced changes is the poleward displacement of the Southern Hemisphere westerly jet, which has been accompanied by a poleward shift and intensification of oceanic circulation (Thompson et al., 2000; Hartmann et al., 2000). These changes have been attributed to external factors such as increased air temperature due to greenhouse gases (GHG) and the Antarctic ozone depletion. The polar stratospheric ozone depletion is believed to affect not only the polar temperature and the latitudinal position of the mid-latitude jet, but also the entire Southern Hemisphere, resulting in a broadening of the Hadley cell and a poleward extension of the subtropical dry zone (Polvani et al., 2011). Trends in the Southern Hemisphere tropospheric circulation have been shown to indicate that the strengthening of the westerly winds was linked to ozone loss (Zazulie et al., 2010). Earlier studies (Sexton, 2001; Thompson and Solomon, 2002) postulated that the Antarctic ozone depletion was the primary cause for tropospheric circulation changes in the Southern Hemisphere that occurred in the late 1970s. Another impact of polar ozone depletion on subtropical regions was examined by The Canadian Middle Atmosphere Model (CMAM) and the National Center for Atmospheric Research (NCAR) Community Atmospheric Model (CAM3). They showed that the ozone depletion area evolution has caused a poleward shift of the extratropical circulation (Kang et al., 2011), resulting in substantially increase in subtropical precipitation in austral summer. According

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to Thompson et al. (2011), the influence of the ozone hole on the Southern Annular Mode has led to a range of significant summertime surface climate changes not only over Antarctica and the Southern Ocean, but also over New Zealand, Patagonia and southern regions of Australia. All in all, ozone depletion appears to have large and far-reaching impacts and to potentially be an important player in the Southern Hemisphere climate system.

One question arising is whether changes in surface winds and SST, triggered in the South Polar region could affect the Tropical South Atlantic coastal ecosystems. Taking into account that warming of surface waters may have implications over coral metabolism and health, potentially compromising the sustainability of coral reefs, we combined here measurements of coral growth rate and climate-oceanography modeled data to investigate wind driven impacts in costal environments, especially over the highly sensitive coral communities living in Abrolhos National Park of Brazil, the most important coral-reef site in the Southwestern Atlantic.

2 Materials and methods

2.1 Coral sampling

Massive coral skeleton cores were retrieved within the scope of the Brazil-France projects RECORD (REconstructing the Climate from cORal Drilling), LMI PALEO-TRACES and the IRD-CNPq (CLIMPAST). Corals were drilled using a custom-made pneumatic corer with a ~ 5 cm diameter barrel. Samples were collected in the National Park of Abrolhos, State of Bahia/Brazil. A *Siderastrea stellata*, labelled CS1, was sampled at Chapeirão do Sueste (17°57′ S; 038°38′ W) on 5 March 2007. Water depth was 8.5 m and core length is 53 cm. A *Favia leptophylla*, labelled P1, was sampled in the vicinity of CS1, at Chapeirão do Pierre, on 4 March 2007. The core length is 51 cm. The third sample, labeled UFBA, was retrieved from a colony of *Favia leptophylla*, at Abrolhos (17°52′ S; 039°38′ W) in the winter of 1977 at approximately 5 m water depth.

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The core was 28.5 cm long, and was hosted at the Department of Geology of the Universidade Federal da Bahia. The chronology of this third core is completed described in Evangelista et al. (2007). In the laboratory, CS1 and P1 cores were washed with Milli-Q water by sonication and then cut in half with a circular saw. One half was sectioned to produce a 1 cm thick slab that was washed again before drying at 40 °C.

2.2 Coral skeleton chronology

Sections of coral cores were X-rayed to generate a chronology based on yearly density band counting (Knutson et al., 1972). X-ray images were digitalized and their original contrast was slightly improved in order to enhance the recognition of high and low density growth bands. Band counting took the year (and the season) of sampling as reference for chronology. In order to validate the chronology based on X-ray radiography, we dated the CS1 core with the U/Th technique, as proposed by Shen et al. (2008). The U/Th dating method is a robust absolute chronological tool for calcitic or aragonitic marine organisms due to the high precision mass spectrometric technology and to the commonly high uranium levels (in the order of ppm) in coral skeletons. Four sub-samples of ∼ 0.1 g were taken from the core with approximately equal spacing from the top to the base. Age corrections were calculated using an estimated radionuclide $^{230}Th/^{232}Th$ ratio of 4 ± 2 ppm. All radiometric analyses were carried out using a SF-ICP-MS at the High-precision Mass Spectrometry and Environmental Change Laboratory (HISPEC), Department of Geosciences, National Taiwan University (NTU) (Shen et al., 2008, 2010). Figure 1 show the comparison of both methods.

2.3 Instrumental data and model outputs

Coral growth data were compared to the extent of the ozone depleted area, the wind stress, the zonal wind, the SST and the PDO (Pacific Decadal Oscillation). The extent of the ozone depleted area over Antarctica (in million km^2) is defined as the maximum daily area in October of each year between 1979 and 2008. Data were obtained from

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NASA Ozone Watch (ozonewatch.gsfc.nasa.gov). Ozone depletion over Antarctica was discovered in the mid 80's (Farman et al., 1985) and was attributed to the positive trend in atmospheric halogenated hydrocarbons released by human activities (Albritton and Kuijpers, 1999; Solomon, 1999). This "ozone hole" has been gradually recovering since the implementation in 1989 of the Montreal Protocol that controls emissions of ozone depleting substances. Annual mean wind stress data used here is from ERA-40 (Uppala et al., 2005) and zonal wind by NCEP-NCAR reanalysis. SST and sea level were provided by NCEP-NCAR reanalysis and the Simple Ocean Data Assimilation – SODA (Carton and Giese, 2008) product. PDO data is available at http://research.jisao.washington.edu/pdo/.

3 Results

The three coral cores collected in Abrolhos exhibit a decline in annual growth rate (Fig. 2) towards the present. Corals used in this study were found in a healthy condition, with no sign of bleaching at the time of sampling. To blend data from the 3 coral cores, we used a simple Gaussian z score transformation (Fig. 2d). Growth anomaly (i.e. annual growth compared to the average growth for each coral) from individual coral cores exhibited a transition from positive to negative approximately after the mid-60's and the 70's, a trend highlighted by the z score compilation. Changes in growth patterns were quite coincident with SST anomaly observed for Abrolhos. It has been suggested that mean annual SSTs throughout the tropics and subtropics have increased between 0.4 and 1 °C in the past four decades (Kleypas et al., 2008). For Abrolhos NCEP-NCAR reanalysis estimated an increase in mean annual SST from ~ 24.8 to ~ 25.8 °C between 1948 and 2006. Figure 2 indicates that the decline in coral growth may have started before the 70's.

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4 Conclusions

The 70's was a decade when major climatic processes largely involving the ocean shifted phases. For example, there was a negative to positive phase transition of the Pacific Decadal Oscillation (PDO), which is associated with more frequent El Niño events (Miller et al., 1994); the Atlantic Multidecadal Oscillation (AMO) index became negative and continued to be throughout the end of the 90's, reflecting a warming trend of the Northern Atlantic SST (Grossmann and Klotzbach, 2009). The atmospheric dynamics around the Antarctic continent also experienced important changes. The westerly winds increased significantly by the end of the 70's (Polvani et al., 2011). This intensification was coeval with the positive trend of the Antarctic Oscillation (evidenced by the AAO Index) that is the dominant pattern of non-seasonal tropospheric circulation variations south of 20° S. The AAO index data is an observation-based Southern Hemisphere Annular Mode index (http://www.antarctica.ac.uk/met/gjma/sam.html – last revised in October 2011) derived from 12 stations around Antarctica to derive the zonal means from 40 to 65° S (Marshall, 2003). The positive phase of AAO is generally associated with stronger cyclones at high southern latitudes (Pezza and Ambrizzi, 2003). The intensification of the westerlies in conjunction with the positive trend of the AAO has been documented in observations, reanalysis and climate models simulations from the mid-1960's to present (Thompson and Solomon, 2002; Gillett and Thompson, 2003; Baldwin and Dameris, 2007). New climatic observations have provided consistent information on the influence of the Antarctic Ozone depletion in the intensification of the westerlies (Albritton and Kuijpers, 1999; Solomon, 1999). Since ozone in the stratosphere is associated to exothermal chemical reactions, its depletion in the Southern Hemisphere high latitudes triggers the decrease of the Antarctic air temperature in the lower stratosphere. Atmospheric temperature shifts concomitant with ozone depletion have been measured at several seaside Antarctic stations from meteorological balloon profiles (Randel and Wu, 1999). One consequence of this lowering in temperature is an increase of the cold-core low pressure area over Antarctica, the Antarctic circumpolar

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vortex – ACV. The intensification of the ACV may contribute to strengthening the polar-to-subtropics pressure and temperature gradient that affects surface winds. Known impacts are the poleward shift of the mid-latitudes jet and of the Hadley cell that ultimately will affect tropical SST. Figure 3 shows our calculations based on NCEP-NCAR of main parameters related to ozone induced climatology and oceanography.

Southern tropospheric wind changes associated with ozone depletion have been largely discussed in the literature (Gillett and Thompson, 2003; Shindell and Schmidt, 2004; Baldwin and Dameris, 2007; Son et al., 2008, 2009; Purich and Son, 2012). What is new here is the way winds and the Tropical Atlantic SSTs are impacted by this phenomenon. Based on the NCEP-NCAR reanalysis, since 1979 the tropical Brazilian coast presumably experienced increased zonal winds (from East to West) as depicted in Fig. 3e. Taking into account the positive correlations observed between ozone depletion area and wind stress (represented here by the length of the arrows at Fig. 3c), it points to a response of winds in the latitudinal band that encloses the tropical South Atlantic sector, from Africa to the Brazilian coast, reaching the Abrolhos site. A potential impact of that is the piling up of warm waters from the Brazil current against the continental shelf that would increase the SST. Based on the UK Meteorological Office Hadley Centre SST climatology (the best spatial and temporal resolved database which dates back to 1870), it shows a clear moderate stepwise positive change of SST since 1980 on the Brazilian continental shelf (Belking, 2009). An average SST change of $\sim 1\,^{\circ}$C was found for the period 1981–2006 with respect to 1957–1980. Long tide gauge time series (calibrated with satellite altimetry) at Cananéia (25° S) and Ilha Fiscal Stations (22° S) both on the Brazilian tropical coast exhibit sea level shifts of ~ 100 mm between 1976 and 2005 with respect to 1954–1975 and ~ 160 mm between 1971 and 2004 with respect to 1963–1970, respectively (Dalazoana et al., 2005). These instrumental data combined with the high positive correlation found between ozone depletion area and SST in the Southwestern Atlantic sector, as shown in Fig. 4, indicate that a mechanism linking Antarctica and the tropics is active.

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In addition, the PDO is a significant parametrization when considering the 1970's climate shift. Several studies postulate a great contribution of the PDO to this climate shift, particularly in the Northern Hemisphere (e.g.: Mantua et al., 1997). Nevertheless, according to Agosta and Compagnucci (2008), in the regional context of Southern South America and adjacent Southern Atlantic, changes in the basic atmospheric circulation of the late 1970's climate transition cannot be solely attributed to the PDO or associated El Niño-like variability. In Fig. 5 we show the correlation map between SST and PDO. The result indeed shows an impact of the PDO in the South Atlantic with significant correlation coefficients mostly occurring at a latitude band from ~ 35 to 65° S. The fact here is that significant correlation coefficients found in Fig. 4 (ozone depletion area and SST) are observed where coral communities live in the Brazilian coastal line, while the higher correlations with PDO is confined to subtropics and central Atlantic. Since r Pearson values between SST and ozone at the Brazilian coral site varied from +0.6 to +0.7, the explained variance of SST (~ 40 %) due to the climate induced effects (changes in atmospheric circulation) of the ozone depletion is much higher compared with the PDO influence at that site.

Both processes (depletion of stratospheric ozone in Antarctica and GHG – Greenhouse Gases emissions) account for reduced surface pressure over the high latitudes accompanying increase of surface pressure at mid-latitudes. This is associated with the meridional temperature gradient and the position of mid-latitude upper level jet that modulates the tropospheric circulation (winds) and ultimately impact the SST spatial distribution. The near-surface ocean temperature is forced by winds, radiation and freshwater fluxes. The ocean then impacts the atmosphere via latent, sensible and radiative heat losses that are dependent on SST and fundamentally on the wind-stress. Since SST is closely related to the mixing layer variability, SST variations are intimately connected with the heat budget of the mixed layer (McPhaden and Hayes, 1991; Chen et al., 1994; Wang and McPhaden, 2000; Foltz et al., 2003). Furthermore, atmospheric circulation anomalies have been shown to precede the development of basin-wide SST patterns for the tropical Atlantic (Nobre and Shukla, 1996). Taking into account the

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present database of coral growth anomaly for Abrolhos site/Brazil (Fig. 2), it is (first) the timing of the registered change (dominantly positive to dominantly negative growth rate anomaly) with respect to ozone area evolution and (second) the high SST and ozone correlation, that points the ozone depletion area as the most probable causal parameter. If ozone depletion triggers changes in wind structure at the Southern Atlantic with consequences to SST elevation at the Brazilian coral sites it is a factor of great concern to the coastal environments, since it would constitute an additional SST increase on a scenario of expected global warming due to GHG. Evidence of sharp decline in growth rate since the late 1970's can also be noted in comparable latitudes away from South America, e.g. by examining the trends of growth rates in the genus Porites from 44 reefs in Australia (Lough et al., 2002). In a subsequent work these authors have expanded their database to include 5 other reef sites (Lough, 2008). Their average time series depicts a sharp drop in the calcification rate ($\mathrm{g\,cm^{-2}\,yr^{-1}}$) starting in the late 1970's.

Ozone levels in the stratosphere are expected to recover by the end of the century (Perlwitz et al., 2008), and that should theoretically weaken westerly winds (Arblaster and Meehl, 2006; Turner et al., 2009) and contribute to a trend reversal in zonal wind and SST anomalies. However, GHG concentrations will continue to rise and that could override the trend reversal due to the ozone recovery.

Author contributions. All co-authors provided significant contributions to the discussions and the final version of the text. Heitor Evangelista, Abdelfettah Sifeddine and Bruno Turcq were the leaders of the RECORD project that generated the coral database. Ilana Wainer provided the modeling in the manuscript. Thierry Corrège, Daniely Godiva and Renato Campello Cordeiro made the coral drillings at the Brazilian coast. Thierry Corrège made the final revision of the text and significatively improved that. Florence Le Cornec and Claire E. Lazareth were responsible by Sr/Ca and U/Ca measurements at IRD-France and comments in the text. Chuan-Chou Shen and Ching-Yi Hu made the radioisotope analysis for dating. Luiza Oliveira provided data of coral growth.

Acknowledgements. We thank IBAMA for coral sampling licenses (no. 283/2006 and 040/2007CGREP); Fundação de Amparo à Pesquisa do Estado de São Paulo-FAPESP; Co-

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ordenação de Aperfeiçoamento de Pessoal de Nível Superior-CAPES, Conselho Nacional de Pesquisa-CNPq grant 300223/93-5 and CNPq-MCTI/INCT-Criosfera 573720/2008 grant. The Brazil-France scientific programs LMI PALEOTRACES and the IRD-CNPq (PRIMO). U-Th dating was supported by the Taiwan ROC Ministry of Science and Technology (MOST) (103-2119-M-002-022).

Authors declare not exist any competing financial interests in this work.

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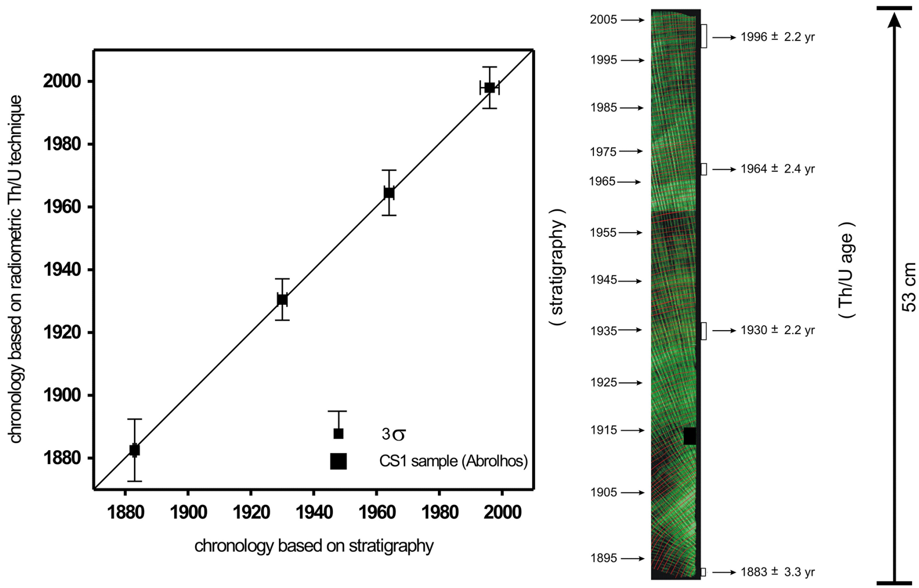

Figure 1. Comparison of chronologies obtained from X-ray radiography (right) and U/Th radiometry (left) for a coral core of *Siderastrea stellate* (CS1) from Abrolhos National Park/Brazil.

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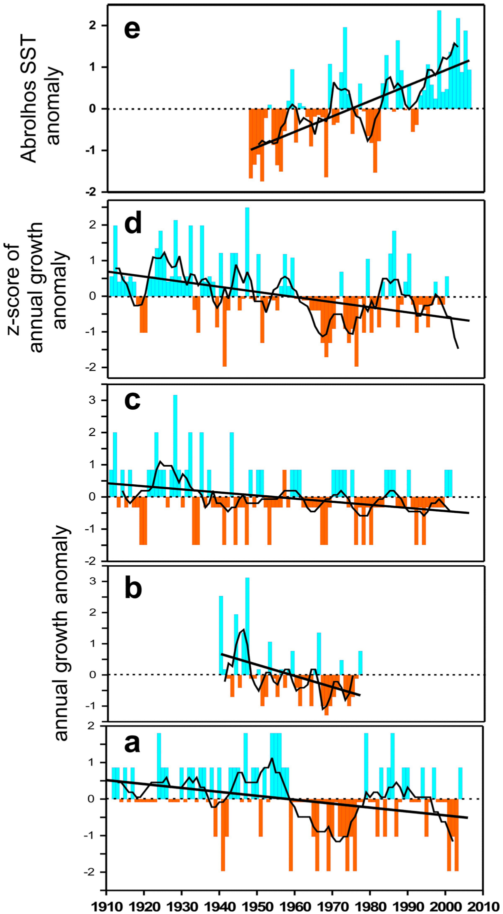

Figure 2. Time variability and linear trends of annual coral growth anomaly for samples **(a)** (CS1), **(b)** (Abrolhos/UFBA) and **(c)** (P1); **(d)** *z* score for **(a)**, **(b)** and **(c)**; **(e)** SST anomaly for Abrolhos National Park/Brazil based on NCEP-NCAR reanalysis.

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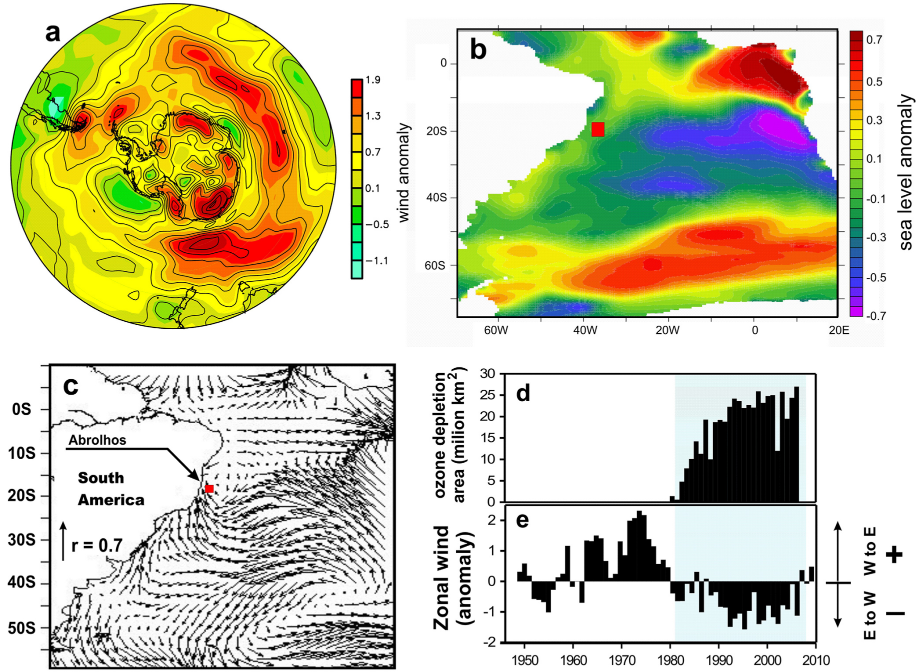

Figure 3. Figure 3 shows our calculations based on NCEP-NCAR reanalysis for: **(a)** the zonal winds around Antarctica (before and after 1979), previously published in 2012 (Cataldo et al. 2012); **(b)** sea level pressure difference (also before and after 1979, but with emphasis to the Southern Atlantic); **(c)** correlation of wind stress and the ozone depletion area (arrow lengths correspond to *r* Pearson values); **(d)** ozone depletion area; and **(e)** the zonal wind anomalies calculated to Abrolhos site.

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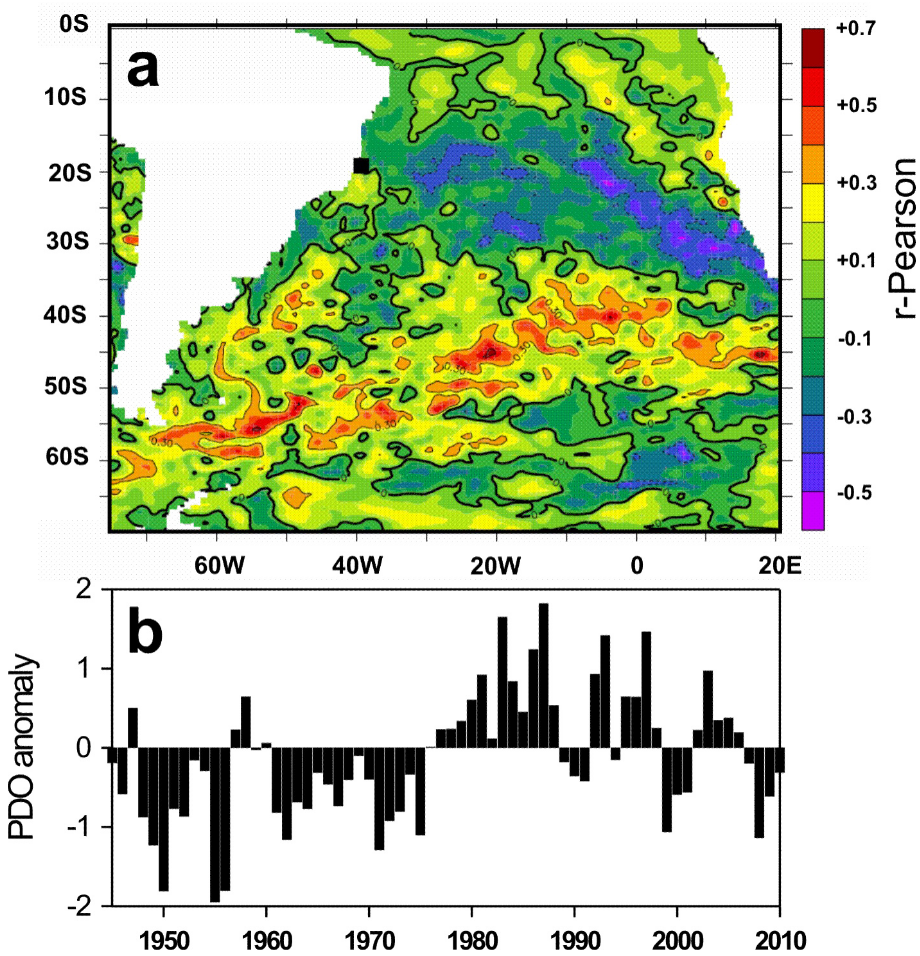

Figure 4. (a) Correlation map (SST × PDO) and; **(b)** PDO (Pacific Decadal Oscillation) anomaly since 1948.

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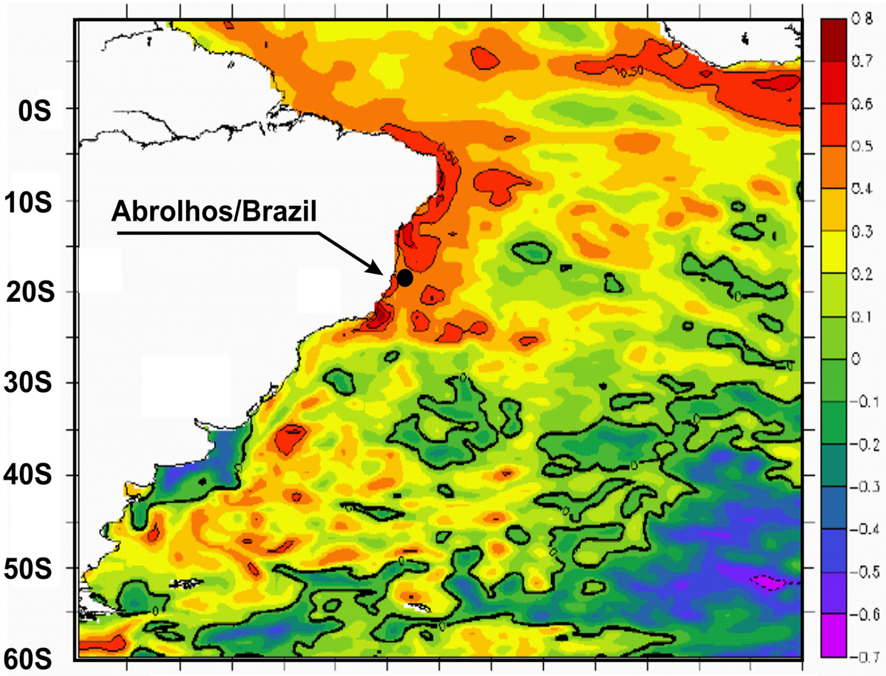

Figure 5. Correlation map between ozone depletion area in Antarctica and Southwestern Atlantic SST.

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