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A VARIABILIDADE DAS ONDAS DE CALOR E DE FRIO OCEÂNICAS NA COSTA LESTE DA AMÉRICA DO SUL

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Esta Dissertação foi julgada adequada para obtenção do Título de Mestre e aprovada em sua forma final pelo Programa de Oceanografia.

Florianópolis, 14 de maio de 2019.

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Dedico este trabalho aos meus pais
e a todos os colegas de laboratório,
entre professores e funcionários.

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“The science of today is the technology of tomorrow”
Edward Teller

RESUMO

O objetivo deste trabalho é avaliar a ocorrência de ondas de calor e ondas de frio oceânicas na costa leste da América do Sul, avaliando o padrão de variação espacial e temporal dos eventos. Para alcançar tal objetivo, foram utilizadas séries temporais diárias de temperatura oceânica estimadas por satélite na resolução de 0,25°. Considerando-se que perto da costa a temperatura do mar é mais fortemente influenciada por fatores topográficos, oceanográficos e atmosféricos do que pelas massas de água, hipotetizamos (1) um aumento geral das ondas de calor e ondas de frio nos locais costeiros do que no oceano aberto. Considerando-se as características oceanográficas e climáticas ao longo da costa, esperamos (2) um aumento dos eventos no norte e no sul da área de estudo. Considerando-se a tendência global de aumento da temperatura da superfície do mar, esperamos (3) que as séries temporais mostrem um aumento geral na tendência de todos os parâmetros para as ondas de calor e uma diminuição geral para as ondas de frio e (4) que esse padrão vai acontecer em toda a região costeira. As análises espaciais mostraram que as anomalias de temperatura são mais intensas (mas não persistentes e freqüentes) próximo à costa leste da América do Sul do que no oceano aberto e mais intensas e persistentes no sul da região costeira e mais frequentes no norte. As análises temporais mostraram que o número de eventos, a duração e a intensidade média das ondas de calor aumentaram e das ondas de frio diminuíram no leste da América do Sul, e que as tendências temporais dos parâmetros de ondas de calor não variaram ao longo da região costeira e somente para as ondas de frio o número de eventos foi maior no sul e menor no norte da região costeira. Estes resultados confirmam a maior predominância da influência das massas de água no oceano aberto impactando mais na duração dos eventos anômalos, e da topografia e dos processos atmosféricos e oceanográficos nos locais costeiros impactando na intensidade, principalmente no norte e no sul, e que as anomalias quentes dos eventos têm aumentado em toda a àrea de estudo devido à tendência global de aumento da temperatura dos oceanos.

Palavras-chave: Ondas de calor marinhas. Ondas de frio marinhas. Oceano aberto. Costa. Anomalias de temperatura. Temperatura da superfície do mar.

ABSTRACT

The objective of this work is to evaluate the occurrence of marine heat waves and cold spells in the eastern coast of South America assessing the spatial and temporal pattern of variation of the events. From this purpose, were used daily time series of ocean temperature measured by satellite at the resolution of 0.25°. Considering that near the coast the temperature of the sea is more strongly influenced by topographic, oceanographic and atmospheric factors than by the masses of water, we hypothesized (1) a general increase of heat waves and cold spells in coastal sites than at offshore sites. Considering the oceanographic and climatic characteristics along the coast, we expected (2) an increase of events in the north and south of the study area. Considering the global trend of increasing sea surface temperature, we expect (3) the time series to show a general increase in the trend of all parameters for the heat waves and a general decrease for cold spells, and (4) that this pattern will happen in all coastal region. The spatial analyses showed that the temperature anomalies are more intense (but not persistent and frequent) on the eastern coast of South America than offshore and more intense and persistent in the south of the coastal area and more frequent in the north. The temporal analyses showed that the number of events, duration and mean intensity of heat waves increased and of cold spells decreased in the eastern of South America, and that the temporal trends of heat waves parameters did not vary along the coastal region, and only for cold spells the number of events was higher in the south and lower in the north of coastal region. These results confirm the greater predominance of the influence of the water masses in offshore sites impacting more in the duration of the anomalous events, and of the topography and the atmospheric and oceanographic processes in the coastal sites impacting in the intensity, mainly in the north and the south, and that the warm anomalies of events have been increasing in all study area in accordance with the global trend of increase in the sea surface temperature.

Keywords: Marine heat waves. Marine cold spells. Offshore. Coast. Temperature anomalies. Sea surface temperature.

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1 INTRODUÇÃO

O aumento da produção de gases de efeito estufa antropogênicos e as mudanças no uso da terra levaram a mudanças significativas no clima global (XU et al., 2018). Os ecossistemas marinhos são fortemente influenciados por eventos climáticos extremos, incluindo ondas de calor (GARRABOU et al., 2009; WERNBERG et al., 2013) e ondas de frio (FIRTH et al., 2011), que são conduzidas por processos físicos complexos interligados no sistema climático e que interagem através de uma hierarquia de escalas espaciais e temporais (TRENBERTH, 2012; FENG et al., 2013). Impactos de eventos extremos de ondas de calor e ondas de frio são muitas vezes repentinos e podem ter consequências catastróficas nesses ecossistemas, causando a mortalidade ou migração de espécies marinhas para outras áreas oceânicas cujas condições sejam mais adequadas à sua sobrevivência (FRÖLICHER e LAUFKÖTTER, 2018). Além disso, eventos extremos de ondas de calor ou de frio têm um impacto negativo mais acentuado nos ecossistemas costeiros do que aqueles no oceano aberto, pois suas temperaturas podem mudar mais rapidamente. Devido a este fato, é importante investigar a ocorrência de eventos extremos de temperatura do oceano - ondas de calor marinhas (MHWs) e ondas de frio marinhas (MCSs) - não só no oceano aberto (*offshore*, termo em inglês) como também no ambiente costeiro (SCHLEGEL et al., 2017).

Ondas de calor marinhas, em qualquer escala, originam-se diretamente de processos atmosféricos como ocorreu no Mar Mediterrâneo em 2003 (SCHAR et al., 2004; MARULLO e GUARRACINO, 2003; SPARNOCCHIA et al., 2006) ou pelo transporte de águas quentes devido às correntes oceânicas como ocorreu na Austrália Ocidental em 2011 (FENG et al., 2013), no Atlântico Noroeste em 2012 (MILLS et al., 2013, CHEN et al., 2014), no nordeste do Oceano Pacífico entre 2013-2015 e na maior parte dos oceanos tropicais e extratropicais em 2015-2016 (FROLICHER et al., 2018). Por outro lado, algumas das ondas de frio marinhas conhecidas foram causadas por fenômenos de frio atmosférico extremo (FIRTH et al., 2011), como a onda de frio marinha que ocorreu na costa do Texas em 1940 (GUNTER, 1941). As tendências, em geral, são de redução da frequência de ondas de frio marinhas em cenários climáticos futuros, mas há exemplos delas se tornando mais frequentes em algumas localidades (GERSHUNOV e DOUVILLE, 2008; MATTHES et al., 2015). Embora os estudos envolvendo ondas de frio marinhas ainda estejam em seus estágios iniciais (HOBDAY et al., 2016; SCHLEGEL et al., 2017), as ondas de calor marinhas estão se tornando cada vez mais conhecidas no mundo devido a sua crescente frequência e intensidade, e essa tendência acelerará sob aquecimento global. Nos últimos 38 anos, foi detectado o dobro do número de dias de ondas de calor marinhas em relação ao período anterior (FRÖLICHER et al., 2018), e este número deverá aumentar em média 41 vezes mais até o final do século XXI para um aquecimento global de 3,5°C (HULME, 2016; MITCHELL et al., 2016). As mudanças na ocorrência de ondas de calor marinhas são impulsionadas principalmente pela mudança da escala global na temperatura média dos oceanos. Tendências no aumento da temperatura média global dos oceanos têm sido relatadas em vários estudos científicos (XU et al., 2018; FRÖLICHER e LAUFKÖTTER, 2018; FRÖLICHER et al., 2018; LIMA e WETHEY, 2012), e essa tendência é maior no hemisfério sul do que no hemisfério norte (WIJFFELS et al., 2016). No entanto, esta tendência de aumento da temperatura dos oceanos não é uniforme espacialmente, apresentando algumas variações entre a região costeira e a região *offshore*. Simulações numéricas de mesoescala realizadas em estudos científicos mostram que a temperatura do mar é mais estática na região offshore (LOMBARDO et al., 2017) do que na região costeira devido à grande profundidade e capacidade térmica do oceano que impactam na mudança mais lenta da temperatura (WIJFFELS et al., 2016). No entanto, as tendências globais são de aumento da temperatura na região offshore, com mais de 75% das anomalias de temperatura do mar detectadas no sul do Equador, principalmente no Oceano Atlântico Sul (JOHNSON e DONEY, 2006). Na região costeira, o padrão de anomalias de temperatura e as tendências de aumento de eventos extremos são ainda mais pronunciados que na região offshore, devido à maior variabilidade térmica relacionada às influências costeiras, atmosféricas e topográficas locais (PALMEIRA et al., 2015; SCHAR et al., 2004; MARULLO e GUARRACINO, 2003; SPARNOCCHIA et al., 2006; MILLS et al., 2013; CHEN et al., 2014; FIRTH et al., 2011). Estudos científicos mostraram que três quartos das áreas costeiras do mundo estão aquecendo e que metade experimentou uma grande diminuição na frequência de eventos marinhos extremamente frios, com taxas de mudança heterogêneas espacialmente. No leste da América do Sul, o número de dias quentes aumentou e o número de dias frios diminuiu em todas as regiões costeiras, principalmente na região equatorial (LIMA e WETHEY, 2012).

Na porção norte da costa leste da América do Sul, predomina um intenso processo oceanográfico devido à influência da Corrente Norte do Brasil, que é uma massa de água tipicamente quente e com variabilidade sazonal em seu transporte de calor, e que se origina do encontro da Corrente Sul-Equatorial com o continente (STRAMMA, 1991; SILVEIRA et al., 1994) e flui para noroeste ao longo do quebra da plataforma sul-americana (RICHARDSON e WALSH, 1986; OLSON et al., 1988; GORDON, 1986). Além disso, nesta mesma região ocorrem intensas atividades de ressurgência ao longo da borda da plataforma (LME, 2004), além da formação de anomalias quentes e frias de temperatura da superfície do mar ao longo do ano (MOURA e SHUKLA, 1981; HASTENRATH e HELLLER 1977; HASTENRATH, 1984). Estudos recentes indicam o aumento da temperatura do mar no Atlântico Sul Equatorial impactando diretamente na frequência de eventos quentes (LIMA e WETHEY, 2012). Na porção central da costa leste da América do Sul, predomina a influência da Corrente do Brasil, que é quente e possui pouca variação sazonal e flui para sul ao longo da margem continental, sendo mais rasa próximo ao Equador e mais profunda na porção sul (CATALDI et al., 2010; RICHARDSON e WALSH, 1986; OLSON et al. 1988; STRAMMA, 1991; DA SILVEIRA et al., 1994). Nesta região, as anomalias quentes e frias de temperatura da superfície do mar são mais persistentes do que na porção norte da costa leste da América do Sul (MOURA et al., 1998; MOURA e SHUKLA, 1981; NOBRE e SHUKLA, 1996; UVO et al. 1998). Estudos recentes indicam que o enfraquecimento da circulação termohalina global tende a diminuir o aquecimento do Atlântico Sul Tropical a longo prazo (MACHADO, 2009), deslocando as anomalias quentes de temperatura do mar para o extremo sul da região. Por outro lado, na porção sul da costa leste da América do Sul predomina a forte influência de duas correntes oceânicas diferentes: a Corrente do Brasil (quente) durante a maior parte do ano, e a Corrente das Malvinas (fria) (OLSON et al., 1988). Além disso, um dos principais processos oceanográficos observados nessa região é a penetração de águas pouco salinas e frias do estuário do Rio de la Plata (PARISE, 2005), que estão associadas a eventos persistentes de ventos de sudoeste e possuem relação direta com a Corrente das Malvinas (PIMENTA et al., 2005). Estudos recentes mostram que um aquecimento do Oceano Atlântico Sul Extratropical tem sido registrado nos últimos anos, principalmente próximo à latitude de 30°S, devido ao enfraquecimento da circulação termohalina global (MACHADO, 2009; MACHADO e JUSTINO, 2011), que tende a causar redução dos processos que envolvem a Corrente das Malvinas a longo prazo.

1.1 OBJETIVOS

1.1.1 Objetivo geral

O objetivo deste trabalho é avaliar a ocorrência de ondas de calor e ondas de frio na costa leste da América do Sul, avaliando o padrão de variação espacial e temporal dos eventos.

1.1.2 Objetivos específicos

São objetivos específicos deste trabalho:

- Fazer um levantamento de séries de temperatura do oceano medidas por satélite da costa leste da América do Sul;
- Calcular as ondas de calor e ondas de frio oceânicas;
- Fazer a análise espacial do padrão de variabilidade das ondas de calor e de frio oceânicas entre a região *offshore* e a costa leste da América do Sul, e testar se o padrão encontrado na região costeira varia espacialmente;
- Fazer a análise temporal do padrão de variabilidade das ondas de calor e de frio oceânicas no leste da América do Sul e comparar as tendências temporais dos eventos ao longo da costa.

1.2 HIPÓTESES

Considerando-se que perto da costa a temperatura do mar é mais fortemente influenciada por outros fatores do que pelas massas de água, hipotetiza-se (1) um aumento geral das ondas de calor e ondas de frio nos locais costeiros do que no oceano aberto. Considerando-se as características oceanográficas e climáticas ao longo da costa, espera-se (2) um aumento dos eventos no norte e no sul da área de estudo. Considerando-se a tendência global de aumento da temperatura da superfície do mar, espera-se (3) que as séries temporais mostrem um aumento geral na tendência de todos os parâmetros para as ondas de calor e uma diminuição geral para as ondas de frio e (4) que esse padrão vai acontecer em toda a região costeira.

2 CAPÍTULO 1: ARTIGO

Este capítulo apresenta o conteúdo do artigo que compõe esta dissertação e foi submetido à revista *Journal of Marine Systems* em 25/04/2019. O conteúdo apresentado a seguir segue na íntegra, mudando a formatação do texto.

The Variability of Ocean Heat Waves and Cold Spells in the Eastern Coast of South America

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ABSTRACT

The objective of this work is to evaluate the occurrence of marine heat waves and cold spells in the eastern coast of South America assessing the spatial and temporal pattern of variation of the events. From this purpose, were used daily time series of ocean temperature measured by satellite at the resolution of 0.25°. Considering that near the coast the temperature of the sea is more strongly influenced by topographic, oceanographic and atmospheric factors than by the masses of water, we hypothesized (1) a general increase of heat waves and cold spells in coastal sites than at offshore sites. Considering the oceanographic and climatic characteristics along the coast, we expected (2) an increase of events in the north and south of the study area. Considering the global trend of increasing sea surface temperature, we expect (3) the time series to show a general increase in the trend of all parameters for the heat waves and a general decrease for cold spells, and (4) that this pattern will happen in all coastal region. The spatial analyses showed that the temperature anomalies are more intense (but not persistent and frequent) on the eastern coast of South America than offshore and more intense and persistent in the south of the coastal area and more frequent in the north. The temporal analyses showed that the number of events, duration and mean intensity of heat waves increased and of cold spells decreased in the eastern of South America, and that the temporal trends of heat waves parameters did not vary along the coastal region, and only for cold spells the number of events was higher in the south and lower in the north of coastal region. These results confirm the greater predominance of the influence of the water masses in offshore sites impacting more in the duration of the anomalous events, and of the topography and the atmospheric and oceanographic processes in the coastal sites impacting in the intensity, mainly in the north and the south, and that the warm anomalies of events have been increasing in all study area due in accordance with the global trend of increase in sea surface temperature.

Keywords: Marine heat waves. Marine cold spells. Offshore. Coast. Temperature anomalies. Sea surface temperature.

1. Introduction

The increased production of anthropogenic greenhouse gases and changes in land use have led to significant changes in global climate (XU et al., 2018). Marine ecosystems are strongly influenced by extreme climatic events, including heat waves (GARRABOU et al., 2009; WERNBERG et al., 2013) and cold spells (FIRTH et al., 2011), which are driven by complex physical processes interconnected in the climate system and that interact through a hierarchy of spatial and temporal scales (TRENBERTH, 2012; FENG et al., 2013). The heat waves and cold spells events are often sudden and may have catastrophic consequences in the marine ecosystem, causing mortality or migration of species to other oceanic areas whose conditions are more suitable for their survival (FRÖLICHER and LAUFKÖTTER, 2018). In addition, extreme events of heat waves or cold spells are more intense and have a more pronounced negative impact on coastal ecosystems than offshore because their temperatures may change more rapidly. Due to this fact, it is important to investigate the occurrence of extreme events of ocean temperature - marine heat waves (MHWs) and marine cold spells (MCSs) - not only in the offshore as in the coastal environment (SCHLEGEL et al., 2017).

Marine heat waves, at any scale, originate directly by atmospheric process as occurred in the Mediterranean Sea in 2003 (SCHAR et al., 2004; MARULLO and GUARRACINO, 2003; SPARNOCCHIA et al., 2006) or by the transport of warm waters due to ocean currents as occurred in Western Australia in 2011 (FENG et al., 2013), in the Northwest Atlantic in 2012 (MILLS et al., 2013, CHEN et al., 2014), in the northeast of Pacific between 2013-2015 and most of the tropical and extratropical oceans in 2015-2016 (FROLICHER et al., 2018). On the other hand, some of the known marine cold spells were caused by phenomena of extreme atmospheric cold (FIRTH et al., 2011), such as the marine cold spell that occurred on the coast of Texas in 1940 (GUNTER, 1941). The trends, in general, are to reduce the frequency of marine cold spells in future climate scenarios, but there are examples of them becoming more frequent in some localities (GERSHUNOV and DOUVILLE, 2008; MATTHES et al., 2015). Although studies involving marine cold spells are still in their early stages (HOBDAY et al., 2016; SCHLEGEL et al., 2017), marine heat waves are becoming more known in the world because of their increasing frequency and intensity, and this trend will accelerate under global warming. In the last 38 years, a doubling of the number of days of marine heat waves were detected than previous period (FRÖLICHER et al., 2018), and this number is expected to increase by an average of 41 times by the end of the 21st century under the global warming of 3.5 degrees Celsius (HULME, 2016; MITCHELL et al., 2016). The changes in the occurrence of marine heat waves are mainly driven by the global scale change in the average temperature of the oceans. Trends in increase of global average ocean temperature have been reported in several scientific studies (XU et al., 2018; FRÖLICHER and LAUFKÖTTER, 2018; FRÖLICHER et al., 2018; LIMA and WETHEY, 2012), and this trend is higher in the southern hemisphere than in the northern hemisphere (WIJFFELS et al., 2016). However, this trend in increase of the temperature of ocean is not uniform spatially, presenting some variations between the coastal region and the offshore. Numerical mesoscale simulations carried out in scientific studies show that sea temperature is more static in the offshore ocean (LOMBARDO et al., 2017) than in the coastal region, due to the great depth and thermal capacity that impacts in the slower change of the temperature (WIJFFELS et al., 2016). However, the global trends are increasing in the temperature of the offshore ocean, with more than 75% of the anomalies detected in the south of Ecuador, mainly in the South Atlantic Ocean (JOHNSON and DONEY, 2006). In the coastal region, the pattern of temperature anomalies and the trends of increase extreme events are even more pronounced than offshore, due to higher thermal variability related to local coastal, atmospheric and topographical influences (PALMEIRA et al., 2015; SCHAR et al., 2004; MARULLO and GUARRACINO, 2003; SPARNOCCHIA et al., 2006; MILLS et al., 2013; CHEN et al., 2014; FIRTH et al., 2011). Scientific studies have shown that three folds of the world's coastal areas are warming and that half have experienced a great decrease in the frequency of extremely cold marine events, with spatially heterogeneous rates of change. In the east of South America, the number of warm days increased and the number of cold days decreased in all coastal region, mainly in the equatorial region (LIMA and WETHEY, 2012).

In the north portion of the eastern coast of South America an intense oceanographic process predominate due to the influence of the Northern Brazil Current, which is a typically warm water mass with seasonal variability in your transport of heat, and that originates from the encounter of the South-Equatorial Current with the continent (STRAMMA, 1991; SILVEIRA et al., 1994) and flows to northwest along the break of the South American platform (RICHARDSON and WALSH, 1986; OLSON et al., 1988; GORDON, 1986). In addition, in this same region there are intense resurgence activities along the edge of the platform (LME, 2004), as well as the formation of warm and cold sea surface temperature anomalies throughout the year (MOURA e SHUKLA, 1981; HASTENRATH e HELLLER, 1977; HASTENRATH, 1984). Recent studies indicate the increase of sea temperature in the Equatorial South Atlantic directly impacting the frequency of warm events (LIMA and WETHEY, 2012). In the central portion of the eastern coast of South America, predominate the influence of the Brazil Current, which is warm and has little seasonal variability and flows to the south along the continental margin, being shallower near the equator and deeper in the southern portion (CATALDI et al., 2010; RICHARDSON and WALSH, 1986; OLSON et al. 1988; STRAMMA, 1991; DA SILVEIRA et al., 1994). In this region, warm and cold anomalies of sea surface temperature are more persistent than in the north of eastern coast of South America (MOURA et al., 1998; MOURA and SHUKLA, 1981; NOBRE and SHUKLA, 1996; UVO et al., 1998). Recent studies indicate that the weakening of the global thermohaline circulation tends to decrease the warming of the Tropical South Atlantic (MACHADO, 2009), shifting the warm temperature anomalies to the extreme south of the region. On the other hand, in the south of the eastern coast of South America predominate the strong influence of two different oceanic currents: the warm Brazil Current, during most of the year, and the cold Falkland Current (OLSON et al., 1988). In addition, one of the main oceanographic processes observed in this coastal region is the penetration of low salt and cold waters from the estuary of the Río de la Plata (PARISE, 2005), that are associated with persistent events of southwestern winds and having directly relation with the Falkland Current (PIMENTA et al., 2005). Recent studies showed that a warming of the Extratropical South Atlantic Ocean has been recorded in the last few years, mainly near 30°S latitude, due to the weakening of the global thermohaline circulation (MACHADO, 2009; MACHADO and JUSTINO, 2011), which tends to cause reduction of the processes that involve that Falkland Current in the long term.

The aim of this work is to evaluate the occurrence of marine heat waves and cold spells in the eastern coast of South America assessing the spatial and temporal pattern of variation of the events. Considering that near the coast the sea temperature is influenced by other factors than the water masses, we hypothesize (1) a general increase of heat waves and cold spells at coastal sites than at offshore sites. Considering the oceanographic and climate characteristics along the coast we expect (2) an increasing of events forward the north and south of the study area. Considering the global trend of increase in the sea surface temperature we expect the time series will show a (3) general increase in the temporal trend of all parameters for the heat waves and a general decrease for the cold spells, and (4) this pattern will happen in all coastal region.

2. Materials and methods

2.1 Study area

The study area was the eastern coast of South America delimited by the latitudes 10° and -40.5° and the longitudes -60° and -30° decimal degrees (Fig. 1).

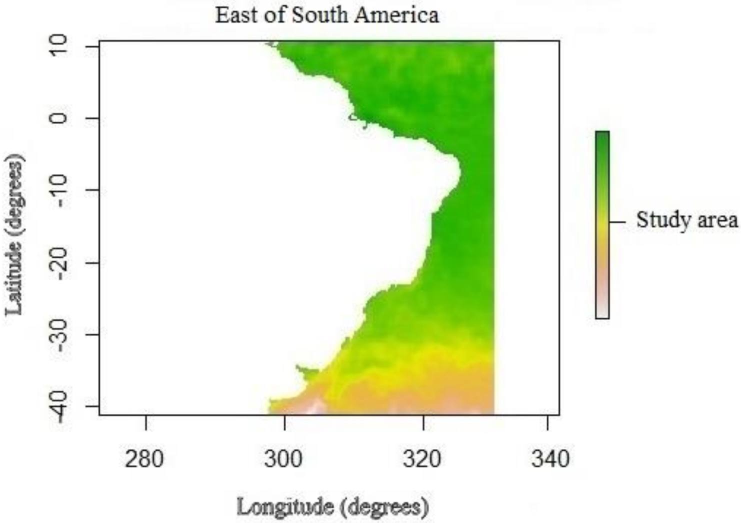


Figure 1. Raster in large-scale of east of South America bounded by the latitudes 10° and -40.5° and the longitudes -60° and -30° decimal degrees.

The area cover a wide range of the water masses influencing the coastal waters that embrace three marine provinces (North Brazil Shelf, Tropical Southwestern Atlantic, and Warm Temperate Southwestern Atlantic; SPALDING et al., 2007), each one formed by distinctive geomorphological features, hydrographic features, geochemical influences and biodiversity (Fig. 2)(BRIGGS, 1974, 1995; HAYDEN et al., 1984; SEALEY and BUSTAMANTE, 1999). The North Brazil Shelf (NBS) is a tropical environment dominated by tides and warm currents, which extends from the Caribbean Sea in Central America (10°N) to the

Parnaiba River in Northeastern Brazil (0°; SMITH and SANDWELL, 1997), including marine environments of six countries (Brazil, French Guiana, Suriname, Guyana, Trinidad and Tobago and Venezuela) (ISAAC and FERRARI, 2016). The Tropical Southwestern Atlantic (TSA) is dominated by temperate ocean realms and warmer waters that extends since the north by the equatorial region (~0°) to the south in 20 °S, including São Pedro and São Paulo Islands, Fernando de Noronha and Atol das Rocas, Northeastern Brazil, Eastern Brazil and Trindade and Martin Vaz Islands (SPALDING et al., 2007). The Warm Temperate Southwestern Atlantic (WTSA), that constitutes a transition between the cold temperate South America Province and the Tropical Southwestern Atlantic, is a biogeographic province bounded to the north by Cabo Frio (Brazil, 23 °S) and to the south by the Valdes Peninsula (41 ºS; SEALEY and BUSTAMANTE, 1999), including marine environments of the Southeastern Brazil, Rio Grande, Rio de La Plata and Uruguay-Buenos Aires Shelf (DEFEO and MCLACHLAN, 2011; LERCARI and DEFEO, 2006).

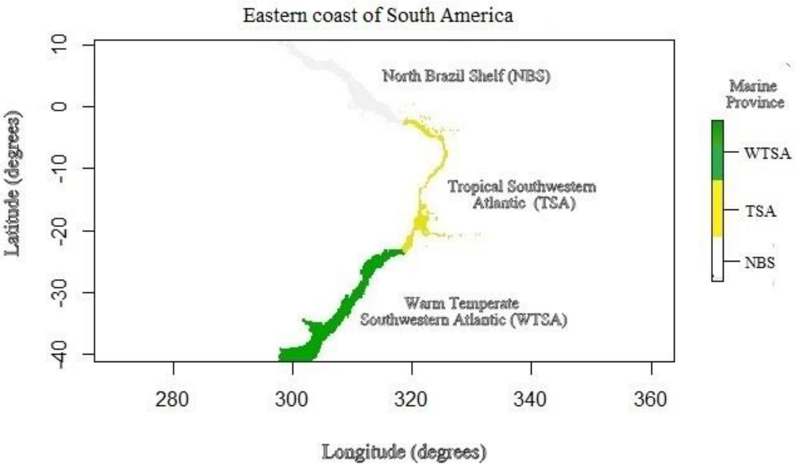


Figure 2. Raster of the eastern coast of South America in the area of the three marine provinces (North Brazil Shelf, Tropical Southwestern Atlantic and Warm Temperate Southwestern Atlantic).

2.2 Heat waves and cold spells

In order to generate the climatology a time series of the average daily sea surface temperature, from January 1982 to December 2017, were obtained from the National Oceanic and Atmospheric Administration (https://www.ncdc.noaa.gov/oisst) in a 0.25° resolution. The data is produce by Advanced Very High Resolution Radiometer satellite sensors using Optimized Interpolation. To make a large-scale polarization adjustment of the incoming infrared temperatures of the satellite data, observations made by buoys and ships are use as reference (REYNOLDS et al., 2007; BANZON et al., 2016). The detection of the marine temperature anomalies were made in relation to the climatological normal of the studied range-time for each one of the pixels/sites of the studied area (total of 17,358 sites). We recognized a sea temperature anomaly when it remained above the thresholds of percentile 90 for the heat waves and below the thresholds of percentile 10 for the cold spells, and that last for a period equal to or greater than five days (HOBDAY et al., 2016). After defining each events, a set of metrics were estimated under an annual base, including the number of events (n), mean intensity (°C) and duration (days). The intensities of the cold spells were presented as negative values.

2.3 Strategies of the analysis

We used a bulk of strategies to analyze the parameters calculated for both heat waves and cold spells based on the entire dataset and two subsets of its. The coastal subset was delimited from the shore to 200 m depth (2,075 pixels/sites), while the offshore subset was the remaining sites (15,283 pixel/sites). At the coastal sites we could discriminate marine provinces. The physical delimitation of the marine provinces is possible and supported mainly by the distinctive geomorphological features, hydrographic features, geochemical influences, and biodiversity (SPALDING et al., 2007).

For the entire dataset we generate for each of the three parameters (number of event, duration and mean intensity) an average value for the entire time series and for the two halves of the data, period 1982-1999 and period 2000-2017. Additionally, an annual trend in each parameter was assessed. The trends were calculated fitting a linear model to the annual data for each site separated. Then, the slope of each model was used as the trend and they were multiplied by 10 to present the data as a decadal trend in the graphics. Those procedures allowed assessing the behavior of the parameters along the last 36 years and contrast the parameters between the current period and the preceding period. These temporal analyses were supported given that the climate change has increased the anomalous events over the past few decades (STOCKER et al., 2013).

Thus, we made spatial and temporal analyses of the events. The spatial analyses consisted of the comparisons of the heat waves and colds spells events between offshore data and coastal data, and among the marine provinces only for the coastal data. With these procedures we intent to assess if the main signal of the events identified in the offshore are detected in the coast area too and if they are consistent along the coastal region. The temporal analyses of the events were made comparing different periods of the time series using the entire dataset, and contrasting the temporal trends among the marine provinces using only the coastal data. To all analyses we applied the generalized linear models (Poisson with link-log) (HOTHORN et al., 2008). All calculations were made with the heatwaveR (SCHLEGEL and SMIT, 2018), raster (HIJMANS, 2016), dplyr (WICKHAM et al., 2017) and stats (R CORE TEAM, 2017) packages in the R platform.

3. Results

The parameters that characterize the marine heat waves and cold spells varied spatially among offshore and coastal data, and among the marine provinces (Figs 3, 4 and Table 1).

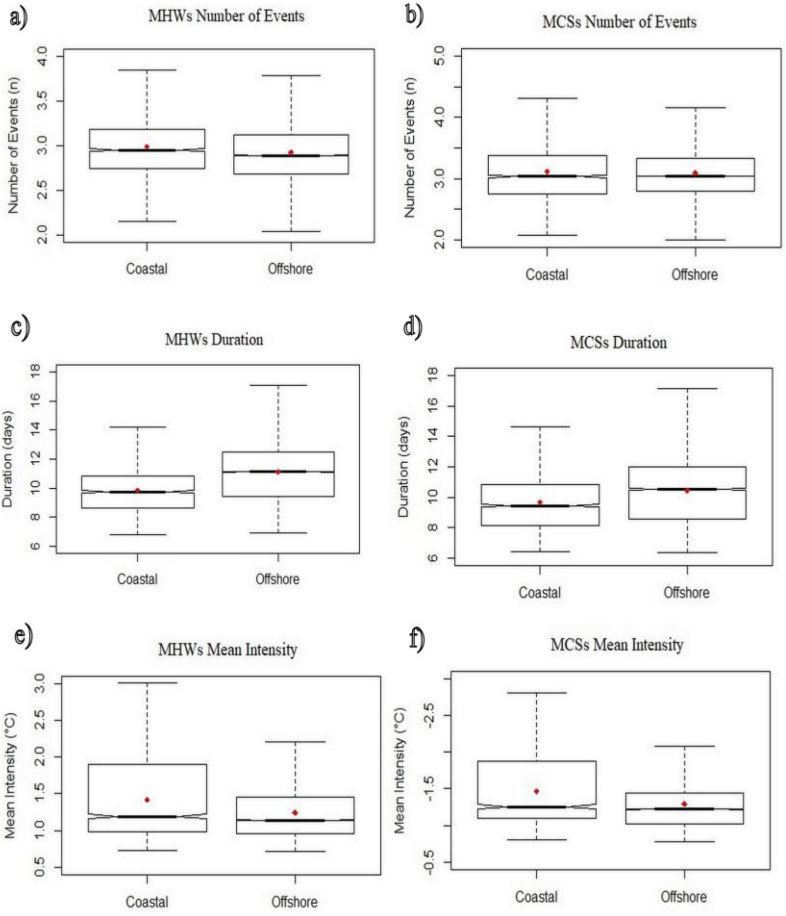


Figure 3. Boxplot of MHWs (first column) and MCSs (second column) parameters calculated from the coastal sites and offshore sites for the entire time series. The parameters calculated were the number of events per year (letters a and b), the duration (letters c and d) and the mean intensity (letters e and f) of events in the eastern coast South America. The lozenges painted in red represent the mean values of the metrics.

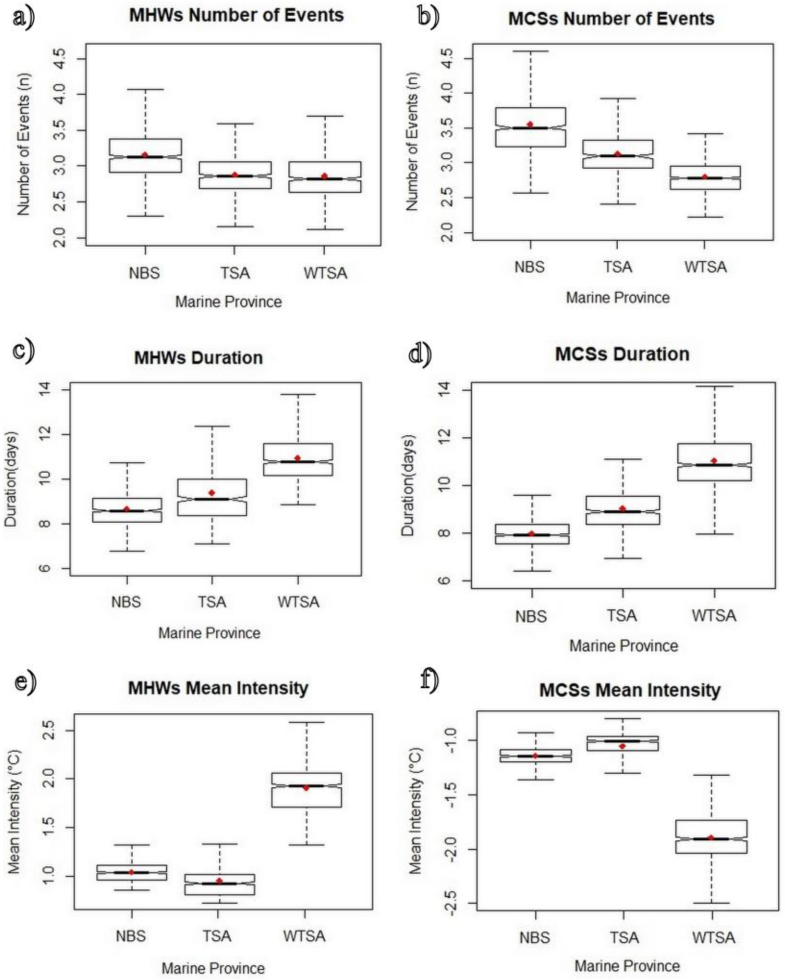


Figure 4. Boxplot of MHWs (first column) and MCSs (second column) parameters calculated from the marine provinces in coastal section for the entire time series. The parameters calculated were the number of events per year (letters a and b), the duration (letters c and d) and the mean intensity (letters e and f) of events. The lozenges painted in red represent the mean values of the metrics.

Table 1. Mean (+-SD) range (Min-Max) and results of the Generalized linear models with Poisson distribution for the number of events, duration and mean intensity of the marine heat waves and marine cold spells between the offshore and coast data and among marine provinces in the eastern coast of South America. R² coefficient of determination; Int interpretation of the significance.

(to be continue)

Area	Parameter	Factor	MHWs						MCSs					
			Mean	SD	Min	Max	R²	Int	MV	SD	Min	Max	R²	Int
Offshore and coastal pixels														
	Number of events	Offshore	2.92	0.34	1.80	4.90	0.00	Coast=Offshore	3.08	0.42	2	5.33	0.00	Coast=Offshore
	Number of events	Coast	2.98	0.35	2.10	4.80			3.11	0.48	2.06	5.2		
	Duration	Offshore	11.10	2.06	6.91	22.2	0.04	Coast<Offshore	10.45	2.12	6.35	21.9	0.01	Coast<Offshore
	Duration	Coast	9.83	1.50	6.70	16.2			9.63	1.74	6.40	15.7		
	Mean Intensity	Offshore	1.24	0.40	0.71	4.17	0.03	Coast>Offshore	-1.29	0.39	-0.7	-3.82	0.02	Coast>Offshore
	Mean Intensity	Coast	1.42	0.50	0.70	3.01			-1.46	0.43	-0.80	-2.81		

(continuation)

Area	Parameter	Factor	MHWs						MCSs					
			Mean	SD	Min	Max	R²	Int	MV	SD	Min	Max	R²	Int
Marine Province														
	Number of events	NBS	3.16	0.36	2.30	4.61			3.55	0.44	2.57	5.2		
	Number of events	TSA	2.90	0.26	2.18	3.95	0.13	NBS>(TSA=WTSA)	3.11	0.33	2.4	4.46	0.5	NBS>TSA>WTSA
	Number of events	WTSA	2.88	0.32	2.14	4.8			2.78	0.24	2.06	3.57		
	Duration	NBS	8.65	0.82	6.77	11.33			7.98	0.67	6.40	11.13		
	Duration	TSA	9.38	1.44	7.09	16.23	0.48	NBS<TSA<WTSA	9.1	1.03	6.99	14.25	0.66	NBS<TSA<WTSA
	Duration	WTSA	10.9	1.07	8.83	15.06			11.11	1.23	8.03	15.79		
	Mean Intensity	NBS	1.04	0.09	0.85	1.31			-1.14	0.07	-0.9	-1.4		
	Mean Intensity	TSA	0.96	0.18	0.73	1.66	0.83	(NBS=TSA)<WTSA	-1.05	0.15	-0.8	-1.6	0.82	(NBS=TSA)<WTSA
	Mean Intensity	WTSA	1.91	0.28	1.33	3.01			-1.89	0.25	-1.3	-2.81		

The spatial analyses showed that duration of events were higher at the offshore sites than at the coastal sites (mean from 11.1 and 9.83 days, respectively) while the intensity of events were higher at the coastal sites than offshore (mean from 1.42 °C and 1.24 °C, respectively), and only the number of events was similar between places (mean from 2.92 and 2.98 events per year). The comparisons among the marine provinces showed the number of events of the heat waves and cold spells were significantly higher in the northward province (North Brazil Shelf; mean from 3.16 events per year for MHWs and 3.55 events per year for MCSs) than in the others provinces, and only for cold spells the number of events were significantly lower in the southward province (Warm Temperate Southwestern Atlantic; mean from 2.78 events per year). On the contrary, the duration and intensity of the events for both the heat waves and cold spells were higher in the southward province (mean from 10.9 days and 1.91 °C for MHWs and 11.11 days and -1.89 °C for MCSs) and only for duration they were significantly lower in the northward province (mean from 8.65 days for MHWs and 7.98 days from MCSs).

The temporal analyses (Figs. 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16 and Table 2) showed an increased value for the number and duration of events between previous period and current period for the heat waves (mean from 2.19 events per year and 8.49 days in 1982-1999 to 3.35 events and 12.5 days in 2000-2017; $p<0.05$) and a decreased value for the cold spells (mean from 3.62 events per year and 10.63 days in 1982-1999 to 1.94 events and 9.82 days in 2000-2017; $p<0.05$). The intensity of the events decreased for the cold spells (mean from -1.32 °C in 1982-1999 to -1.28 °C in 2000-2017; $p<0.05$) and did not differ between periods for the heat waves. The temporal trends of the number of events, duration and mean intensity of heat waves did not vary significantly among provinces (0.03.decade-^{1}, 0.01 days.decade-^{1} and -0.002 °C.decade-^{1} in North Brazil Shelf; 0.01.decade-^{1}, 0.01 days.decade-^{1} and -0.001°C.decade-^{1} in Tropical Southwestern Atlantic and 0.03.decade-^{1}, 0.01 days.decade-^{1} and 0.003°C.decade-^{1} in Warm Temperate Southwestern Atlantic; $p>0.05$). The temporal behavior of the cold spells parameters were contrary to the heat waves not only for the period comparisons but for the provinces too. The temporal trends were higher in the Warm Temperate Southwestern Atlantic and Tropical Southwestern Atlantic provinces (0.03.decade-^{1} for both) and lower in the North Brazil Shelf for the number of events (-0.01.decade-^{1}; $p<0.05$). The duration and mean intensity did not differ among provinces for cold spells events.

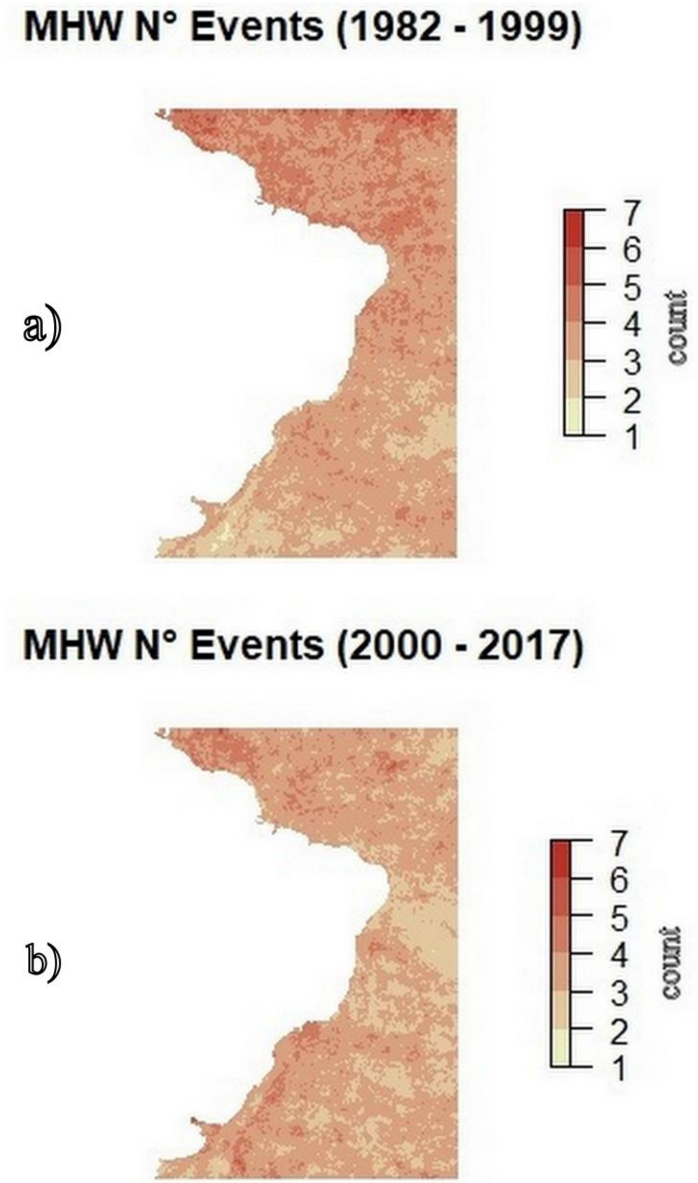


Figure 5. Mean values for the number of events per year of the marine heat waves for each period (a, 1982-1999; b, 2000-2017) for each site in the eastern of South America.

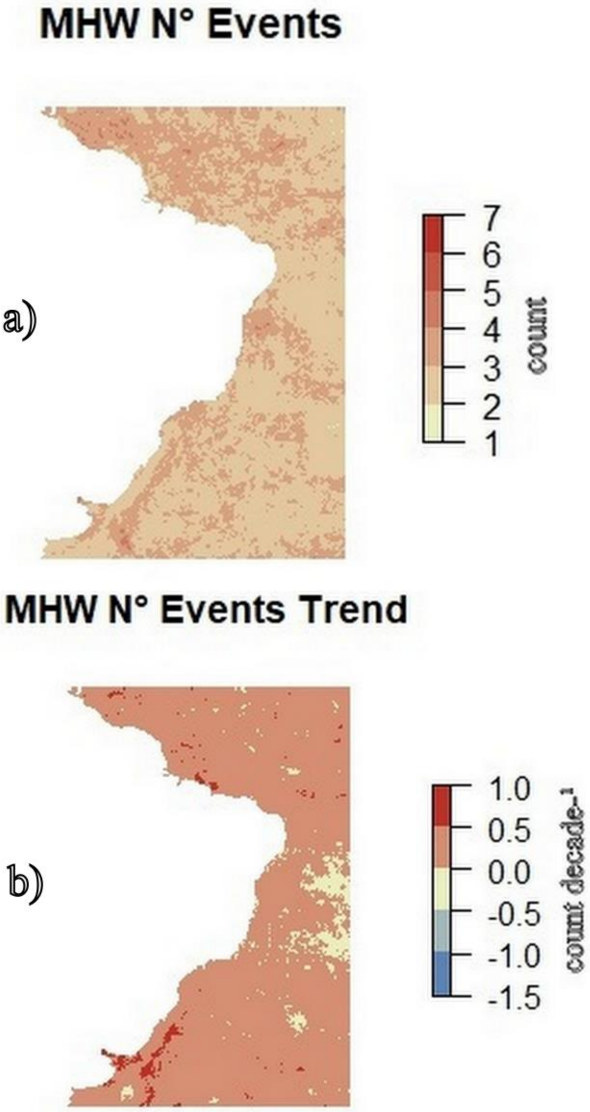


Figure 6. Mean values for the number of events per year of the marine heat waves for the 36 years (a) and the temporal trends (b) for each site in the eastern of South America.

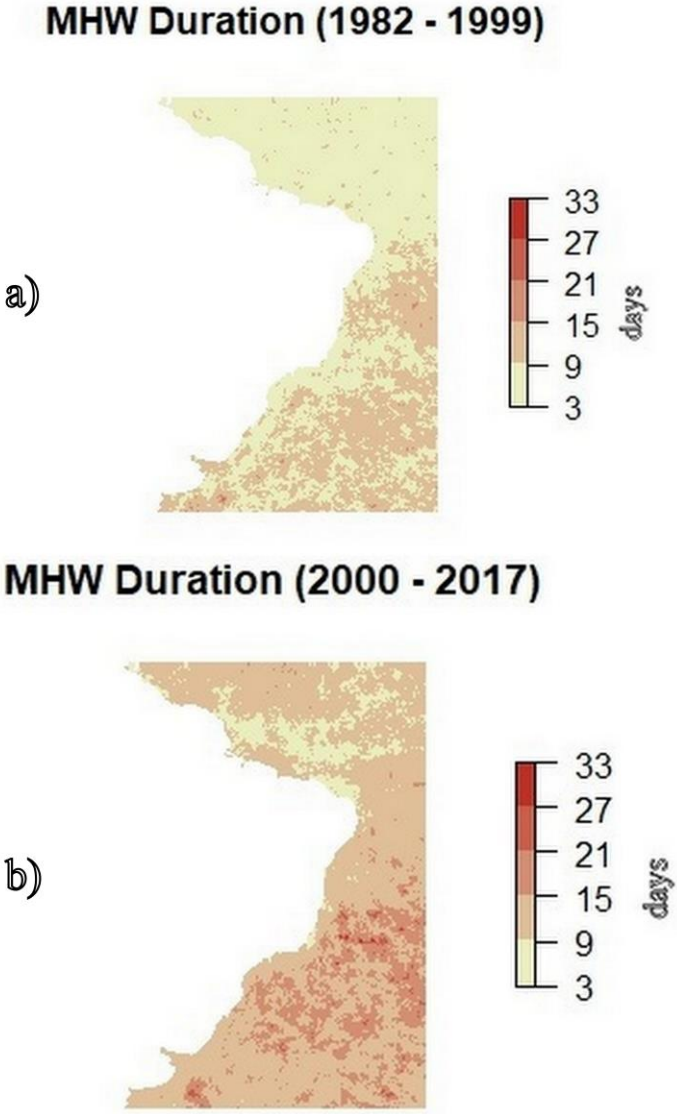


Figure 7. Mean values for the duration of the marine heat waves for each period (a, 1982-1999; b, 2000-2017) for each site in the eastern of South America.

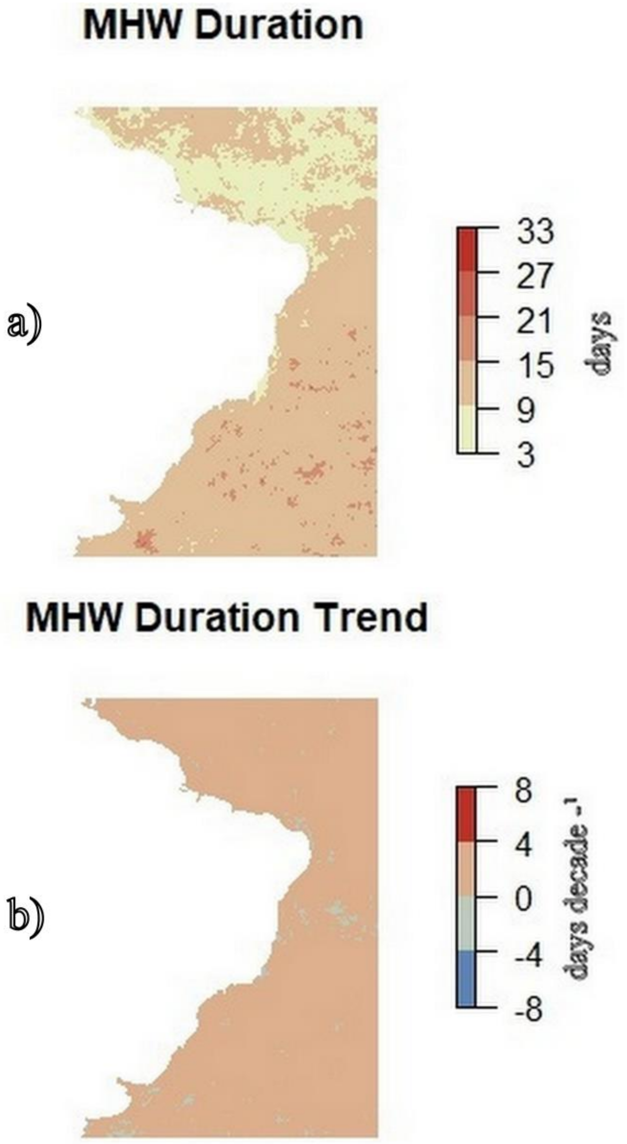


Figure 8. Mean values for the duration of the marine heat waves for the 36 years (a) and the temporal trends (b) for each site in the eastern of South America.

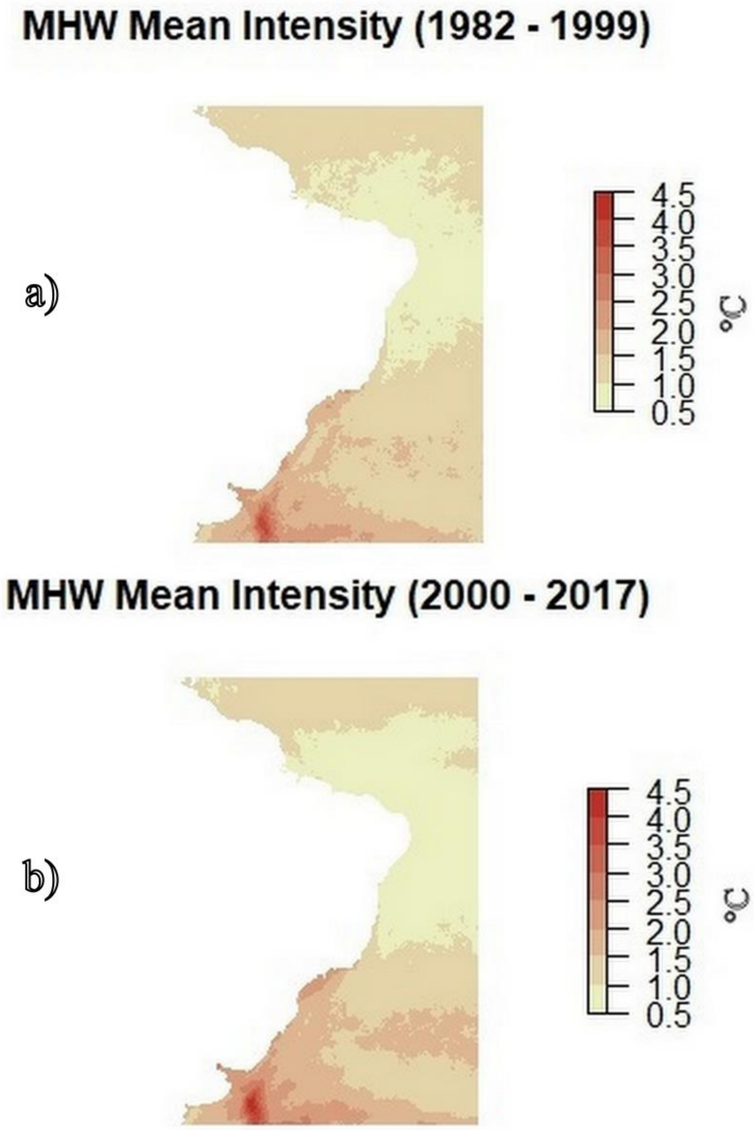


Figure 9. Mean values for the mean intensity of the marine heat waves for each period (a, 1982-1999; b, 2000-2017) for each site in the eastern of South America.

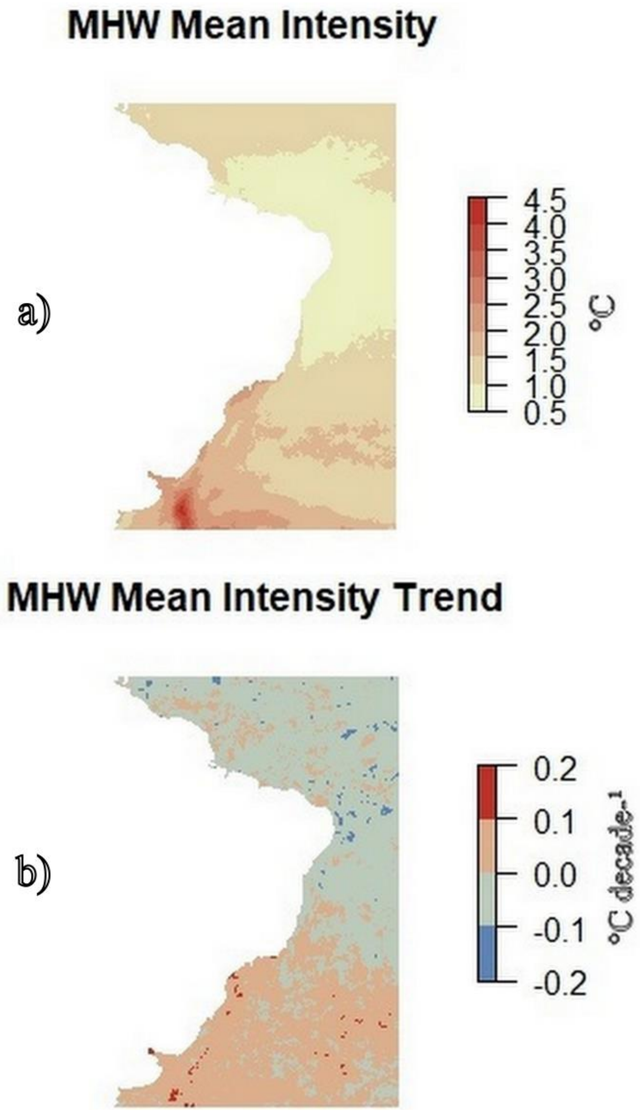


Figure 10. Mean values for the mean intensity of the marine heat waves for the 36 years (a) and the temporal trends (b) for each site in the eastern of South America.

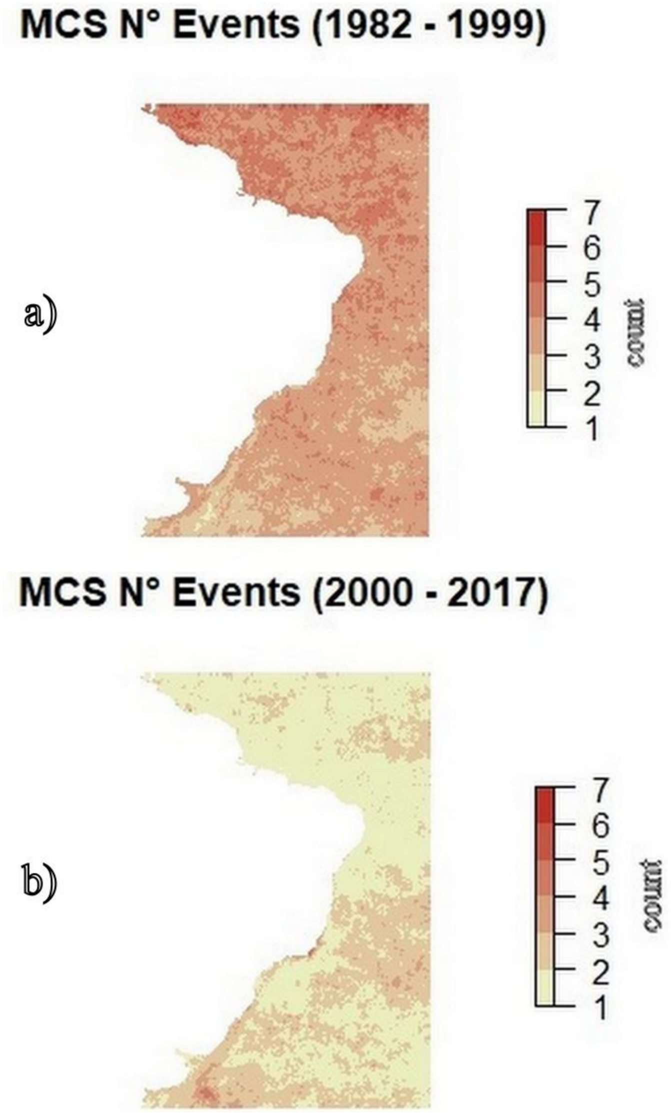
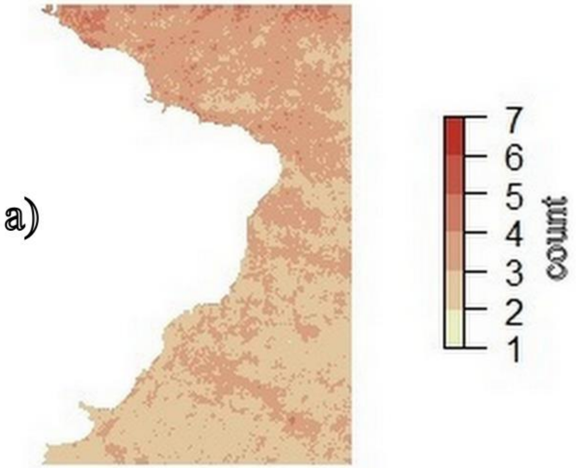


Figure 11. Mean values for the number of events per year of the marine cold spells for each period (a, 1982-1999; b, 2000-2017) for each site in the eastern of South America.

MCS N° Events



MCS N° Events Trend

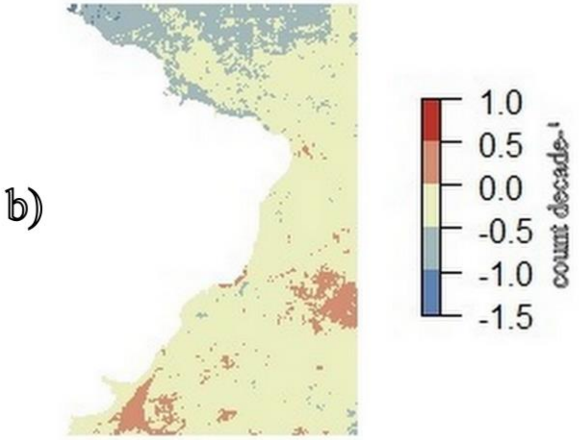


Figure 12. Mean values for the number of events per year of the marine cold spells for the 36 years (a) and the temporal trends (b) for each site in the eastern of South America.

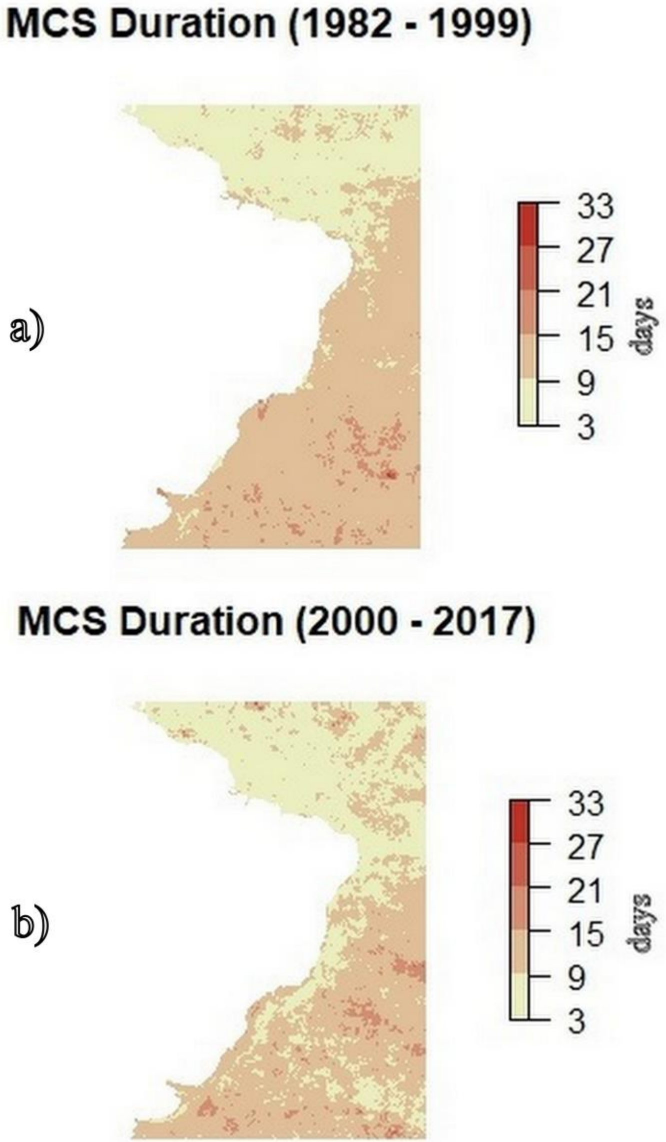


Figure 13. Mean values for the duration of the marine cold spells for each period (a, 1982-1999; b, 2000-2017) for each site in the eastern of South America.

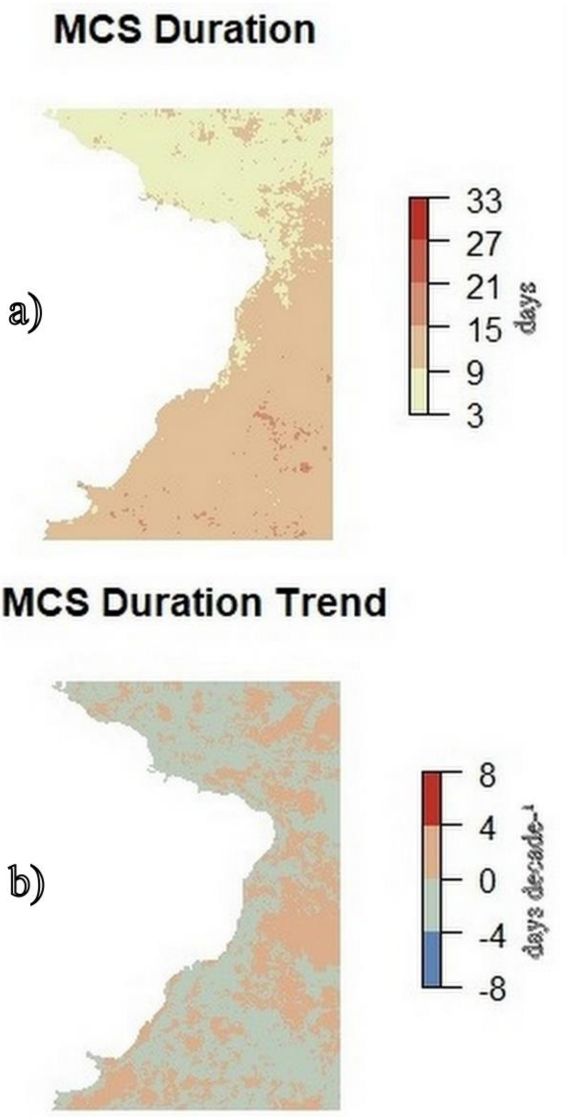


Figure 14. Mean values for the duration of the marine cold spells for the 36 years (a) and the temporal trends (b) for each site in the eastern of South America.

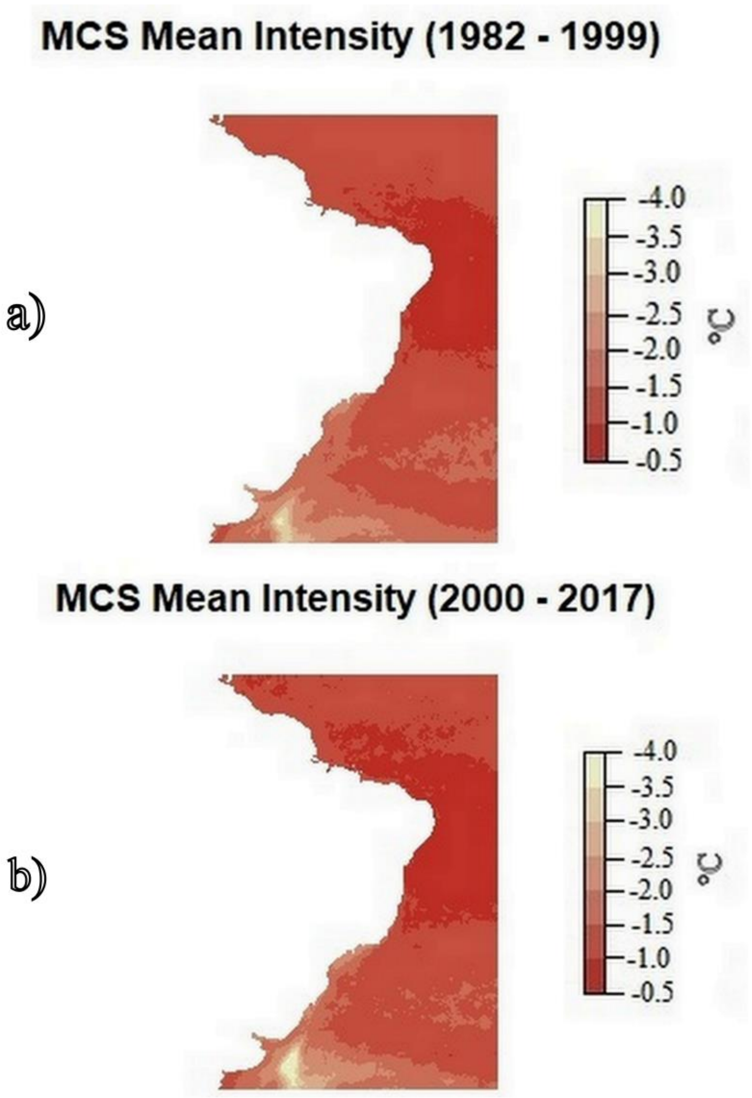


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Figure 15. Mean values for the mean intensity of the marine cold spells for each period (a, 1982-1999; b, 2000-2017) for each site in the eastern of South America.

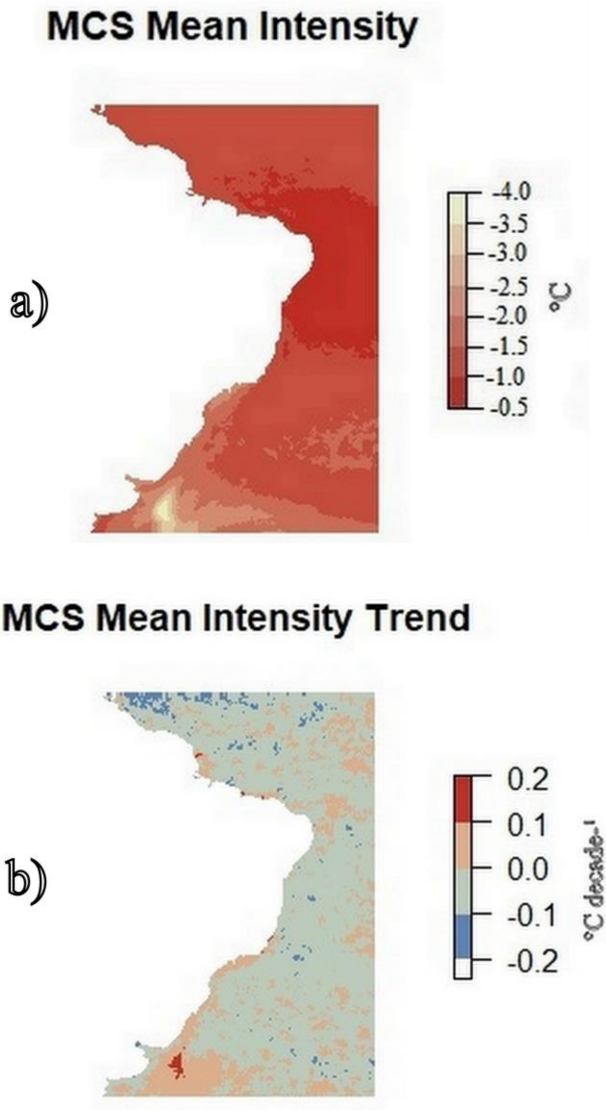

Figure 16. Mean values for the mean intensity of the marine cold spells for the 36 years (a) and the temporal trends (b) for each site in the eastern of South America.

Table 2. Mean (+-SD) range (Min-Max) and results of the Generalized linear models with Poisson distribution for the number of events, duration, mean intensity and the decadal trends of all parameters of the marine heat waves and marine cold spells between the previous period (1982-1999) and current period (2000-2017) and among marine provinces in the eastern coast of South America. R² coefficient of determination; Int interpretation of the significance.

(to be continue)

Area	Parameter	Factor	MHWs						MCSs					
			Mean	SD	Min	Max	R²	Int	MV	SD	Min	Max	R²	Int
Offshore and coastal pixels														
	Number of events	Previous period	2.19	0.47	1.00	4.66	0.59	Previous period< current period	3.62	0.57	1.66	6.9	0.69	Previous period> current period
	Number of events	Current period	3.35	0.47	2.00	5.8			1.94	0.51	1.00	5.00		
	Duration	Previous period	8.49	1.77	5.07	21.1	0.43	Previous period< current period	10.63	2.32	6.16	28.22	0.02	Previous period> current period
	Duration	Current period	12.50	2.87	7.19	32.7			9.82	2.63	5.0	26.93		
	Mean intensity	Previous period	1.26	0.37	0.68	3.89	0.001	Previous period= current period	-1.32	0.37	-0.7	-3.61	0.002	Previous period> current period
	Mean intensity	Current period	1.26	0.45	0.68	4.31			-1.28	0.43	-0.6	-4.0		

(continuation)

Area	Parameter	Factor	MHWs						MCSs					
			Mean	SD	Min	Max	R²	Int	MV	SD	Min	Max	R²	Int
Marine Province														
	Decadal trends of number of events	NBS	0.03	0.01	-0.00	0.07			-0.05	0.01	-0.13	-0.01		
	Decadal trends of number of events	TSA	0.01	0.01	-0.02	0.04	0.28	NBS=TSA= WTSA	-0.02	0.01	-0.07	0.03	0.55	NBS< (TSA=WTSA)
	Decadal trends of number of events	WTSA	0.03	0.01	-0.01	0.09			-0.01	0.01	-0.05	0.03		
	Decadal trends of duration	NBS	0.01	0.00	-0.01	0.04			-0.009	0.01	-0.07	0.03		
	Decadal trends of duration	TSA	0.01	0.01	-0.02	0.05	0.01	NBS=TSA= WTSA	-0.004	0.00	-0.02	0.03	0.09	NBS=TSA= WTSA

(continuation)

Area	Parameter	Factor	MHWs						MCSs					
			Mean	SD	Min	Max	R^2	Int	MV	SD	Min	Max	R^2	Int
	Decadal trends of duration	WTSA	0.01	0.01	-0.03	0.05			-0.001	0.01	-0.03	0.05		
	Decadal trends of mean intensity	NBS	-0.00	0.00	-0.01	0.00			-0.002	0.00	-0.01	0.01		
	Decadal trends of mean intensity	TSA	-0.00	0.00	-0.01	0.006	0.47	NBS=TSA= WTSA	-0.002	0.00	-0.01	0.01	0.12	NBS=TSA= WTSA
	Decadal trends of mean intensity	WTSA	0.00	0.002	-0.006	0.01			0.0001	0.00	-0.01	0.01		

4. Discussion

The spatial analyzes showed that the marine heat waves and cold spells detected offshore and near the coast in the eastern of South America generally exhibited spatially different signals in the behavior of their occurrence. This difference in the pattern observed in temperature anomalies in the two oceanic sections seems to be related to the nature and variability of physical oceanographic processes at large and local scales (SCHLEGEL et al., 2017) and to the change of some properties of the offshore thermal signal in coastal waters due to local modifications of coastal circulation patterns by influences of oceanic topography and atmospheric processes, as well as changes in the properties of the thermocline (OKUBO, 1973, PINGREE and MADDOCK, 1979, GRAHAM and LARGIER 1997; OORT and VONDER HAAR, 1976). Evaluating each parameter of anomalous events separately, it was detected that only the number of marine heat waves and marine cold spells events did not change between offshore and near the coast, while the duration and intensity showed some changes spatially. For the duration, the increase of this parameter was registered for both the marine heat waves and cold spells events far the coast that could be related to the greater response time of the offshore ocean, serving as reservoir of large amounts of energy that are stored (and released), causing impacts more reflected in the duration of events (WIJFFELS et al., 2016; TRENBERTH and SOLOMON, 1993; OORT and VONDER HAAR, 1976; SANTOS, 2006). The coastal sites generated more intense heat waves and cold spells than offshore sites, which could be explained by the interactions of the ocean topography of the continental shelf and mainly by the reduction in the thickness of the oceanic layer, causing it to warm up or to cool faster (PALMEIRA et al., 2015), in addition to the atmospheric forcing caused by coastal heating or cooling (SCHAR et al., 2004; MARULLO and GUARRACINO, 2003; SPARNOCCHIA et al., 2006; MILLS et al., 2013; CHEN et al., 2014; FIRTH et al., 2011; GUNTER, 1941). However, what occurs in the coastal region is not uniform. The number of marine heat waves events was higher in North Brazil Shelf than in Tropical Southwestern Atlantic and Warm Temperate Southwestern Atlantic marine provinces that could be explicated for the strong influence of the warm North Brazil Current in the coastal region (JOHNS et al., 1998), in addition, the formation of warm anomalies of sea temperature in the Equatorial South Atlantic together with the increase of sea temperature in the equatorial coastal region (LIMA and WETHEY, 2012). It was also verified that the number of events of cold spells is greater in the northward province than in the other provinces that could be related for the formation of cold anomalies from sea temperature in the Equatorial South Atlantic (HASTENRATH, 1984) combined with resurgence events along the platform edge (LME, 2004), and the weakening of the global thermohaline circulation that tends to shifting the warm temperature anomalies typical to the extreme south of tropical region (MACHADO, 2009). However, a contrary behavior signal was detected for the duration and mean intensity for both marine heat waves and cold spells because they were higher in the southward province than in the others and, in the case of duration, lower in northward province. As the Warm Temperate Southwestern Atlantic and the Tropical Southwestern Atlantic provinces are more influenced by atmospheric process with greater variability than in the North Brazil Shelf, and in the north the warm (and cold) anomalies of sea temperature have a short duration, these could be among the causes of higher durations and intensities for both events in the south than north province, besides the region of the continental shelf break in low latitudes is closer to the coastline (KNOPPERS et al., 1999; MOURA et al., 1998; MOURA and SHUKLA, 1981; NOBRE and SHUKLA, 1996; UVO et al., 1998; ROBERSON and MECHOSO, 2000, GRIMM, 2009).

The temporal analyzes showed that the number of events and the duration of marine heat waves increased while the same parameters decreased for marine cold spells, in agreement with the South Atlantic warming trends presented (MCGREGOR et al., 2014; JOHNSON and DONEY, 2006). However, only for the intensity of the events, marine heat waves not increased while marine cold spells decreased between 1982-1999 and 2000-2017. These parameters may be related to macroscale ocean dynamics, whose impacts on anomalous warming are easier to detect in the durability and frequency than in intensity of heat waves due to the higher ocean thermal capacity (WIJFFELS et al., 2016) and the low interference of the oceanic topography and atmosphere process in large-scale, when compared to the only coastal region (OORT and VONDER HAAR, 1976). The temporal trends of the number of events, duration and mean intensity of heat waves did not vary among marine provinces, which can be explained by the greater influence of warm waters carried by warm currents during most of the year and by the increase of sea temperature throughout the coastal region in the last three decades with trends of increase of warm events (LIMA and WETHEY, 2012). The decadal trends of marine cold spells were contrary to heat waves, with higher temporal trends in the Tropical Southwestern Atlantic and Warm Temperate Southwestern Atlantic provinces than in the North Brazil Shelf for the number of events, and not differing between the provinces for duration and intensity. These tendencies may be related to atmospheric influences of cold events (ROPELEWSKI and HALPERT, 1987; KOUSKY, 1979), cold oceanic currents and the Subantarctic Water Platform influence (MENDONÇA et al., 2018) together the increase of frequencies of resurgence events (GARCÍA-REYES et al., 2015) in this area.

5. Conclusion

Our experience working with ocean temperature dataset in the east of South America showed that the signal found in the anomalies of heat waves and cold spells differs spatially between the coastal region and the offshore region in eastern South America. In the offshore region, the temperature anomalies were more intense (but not persistent and frequent) than in near the coast. The spatial behavior of the anomalies of warm and cold events along the coastal region is not uniform, with accentuation of the parameters of anomalous events in the south and north, with more intense and persistent heat waves and cold spells in the southern province and more frequent in the northern province. The time series showed a general increase in the temporal trend of all parameters for heat waves and a general decrease for cold spells, and this pattern occurs in all coastal region independently of the marine provinces, in agreement with the global trend of increase in sea surface temperature.

3 CONSIDERAÇÕES FINAIS

Este estudo mostrou que o sinal verificado nas anomalias de ondas de calor e ondas de frio difere espacialmente entre a região costeira e a região offshore no leste da América do Sul. Na região offshore, a temperatura do mar é mais influenciada pelas massas de água enquanto que na região costeira é mais influenciada por processos oceanográficos, atmosféricos e pela topografia oceânica, que tiveram impacto em anomalias de temperatura mais intensas (mas não persistentes e frequentes) na costa. O comportamento espacial das anomalias dos eventos quentes e frios ao longo da região costeira não é uniforme, com acentuação dos parâmetros de eventos anômalos no sul e no norte devido à maior variabilidade dos processos climáticos e oceanográficos nestas áreas, com ondas de calor e de frio mais intensas e persistentes detectadas na província do sul e mais frequentes na província do norte. As séries temporais mostraram um aumento geral na tendência temporal de todos os parâmetros para as ondas de calor e uma diminuição geral para as ondas de frio, e este padrão ocorre em toda a região costeira independentemente das províncias marinhas, em concordância com a tendência global de aumento da temperatura da superfície do mar.

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