Laís Gonçalves Fernandes Duarte

O FENÔMENO EL NIÑO-OSCILAÇÃO SUL E OS EVENTOS EXTREMOS DE PRECIPITAÇÃO EM SANTA CATARINA

Dissertação submetida ao Programa de Pós-Graduação em Oceanografia da Universidade Federal de Santa Catarina para a obtenção do Grau de Mestre em Oceanografia
Orientadora: Prof.ª Dr.ª Regina R. Rodrigues

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

Local, 21 de março de 2017.

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"A tarefa essencial do professor é despertar a alegria de trabalhar e de conhecer."

(Albert Einstein)

RESUMO

O estado de Santa Catarina (SC) apresenta um histórico considerável de registro de eventos extremos de precipitação ao longo das décadas, além de um aumento significativo nas inundações bruscas nos últimos anos. O objetivo deste trabalho é analisar as mudanças na frequência e intensidade dos eventos extremos em SC, entre 1979-1999 e 2000-2015, relacionadas ao fenômeno El Niño Oscilação Sul (ENSO). Os resultados mostram que mudanças no ENSO, devido à influência da Oscilação Interdecadal do Pacífico (IPO), modificam a teleconexão entre o Pacífico e a América do Sul (PSA) que ocasiona alterações nos mecanismos atmosféricos. No primeiro período (1979-1999) os eventos são mais numerosos em episódios de El Niño (EN) e no segundo período (2000-2015), em La Niña (LN) e períodos de neutralidade. Na estação da primavera (SON), entre 1979-1999, os eventos são causados pelo desenvolvimento de Complexos Convectivos de Mesoescala (CCMs), fortalecidos pela atuação dos jatos de altos e baixos níveis. No último período, os eventos estão associados à sistemas frontais e ainda à advecção de umidade do Atlântico subtropical, oriunda da Zona de Convergência do Atlântico Sul (ZCAS). No verão (DJF), os eventos extremos são mais frequentes em episódios de desenvolvimento da ZCAS envolvendo regiões ao sul de sua posição climatológica, principalmente a parte norte e leste de SC. Novamente, no primeiro período, esses eventos acontecem em episódios de EN e no segundo, ficam mais frequentes em LN. Eventos extremos também ocorrem em períodos com bloqueio atmosférico em parte do Sul e Sudeste do Brasil, em anos sem influência do ENSO, ocasionando eventos no interior e no sul de SC.

Palavras-chave: ENSO, Oscilação Interdecadal do Pacífico, eventos extremos de precipitação, variabilidade climática, Santa Catarina.

ABSTRACT

The state of Santa Catarina (SC) presents a considerable record of extreme rainfall events over the last decades, as well as a significant increase in floods events in recent years. The objective of this work is to analyze changes in frequency and intensity of the extreme events in SC, between 1979-1999 and 2000-2015, related to El Niño-Southern Oscillation (ENSO). The results show that changes in ENSO, due to influence of Interdecadal Pacific Oscillation (IPO), modifies the teleconnection between the Pacific and South America (PSA) that causes changes in atmospheric mechanisms. In the first period (1979-1999), events are more numerous in El Niño (EN), while in the second period (2000-2015) in La Niña (LN) and neutral years. In the spring (SON) season of 1979-1999, events are caused by the development of Mesoscale Convective Complexes (MCCs), strengthened by the performance of high and low level jets. In the second period, the events are associated to frontal systems and moisture flux advection of South Atlantic, coming from the South Atlantic Convergence Zone (SACZ). In summer (DJF), extreme events are more frequent in episodes of SACZ embracing regions southern of its climatological position, mainly the north and east part of SC. Again, in the first period, these events occurred in episodes of EN and in the second period, they are more frequent in LN. Extreme events also occur in periods with atmospheric blocking in part of the South and Southeast of Brazil, in years without ENSO influence, causing events in the west and south of SC.

Keywords: ENSO, Interdecadal Pacific Oscillation, extreme rainfall events, climate variability, Santa Catarina.

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Figure 1 - Surface elevation above the mean sea level (shading, in m) for the state of Santa Catarina (SC). Histograms show the annual cycle of precipitation for the seven selected meteorological stations: Chapecó-

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LISTA DE ABREVIATURAS E SIGLAS

B – Sistema de baixa pressão
CW – Campo Novos (Central West)
CCMs – Complexos Convectivos de Mesoescala
DJF – Dezembro, janeiro e fevereiro
E – São José (East)
EN – El Niño
ENC – El Niño Central
ENL – El Niño Leste
ENSO – El Niño-Oscilação Sul (El Niño-Southern Oscillation)
EPAGRI/CIRAM – Empresa de Pesquisa Agropecuária e Extensão Rural de Santa Catarina – Centro de Informações Ambientais e de Hidrometeorologia
ECMWF – European Centre for Medium-Range Weather Forecasts
ERSSTv4 – Extended Reconstructed Sea Surface Temperature v4
FF – Frente Fria
FQ – Frente Quente
INMET – Instituto Nacional de Meteorologia
IPCC – Painel Intergovernamental para as Mudanças Climáticas
IPO – Oscilação Interdecadal do Pacífico (Interdecadal Pacific Oscillation)
JAN – Jato de altos níveis
JBN – Jato de baixos níveis
JS – Jato subtropical
JP – Jato polar
LN – La Niña
LNC – La Niña Central
LNL – La Niña Leste
MCC – Mesoscale Convective Complexes
N – Indaial (North)
NOAA – National Oceanic and Atmospheric Administration
NE – Itajaí (Northeast)
OLR – Outgoing longwave radiation
PSA – Trem de ondas americano do Pacífico Sul (Pacific-South American wave train)
ROL – Radiação de Onda Longa
S – Urussanga (South)
SALLJ – South Atlantic Lower Level Jet
SACZ – South Atlantic Convergence Zone
SAMS – South American Monsoon System

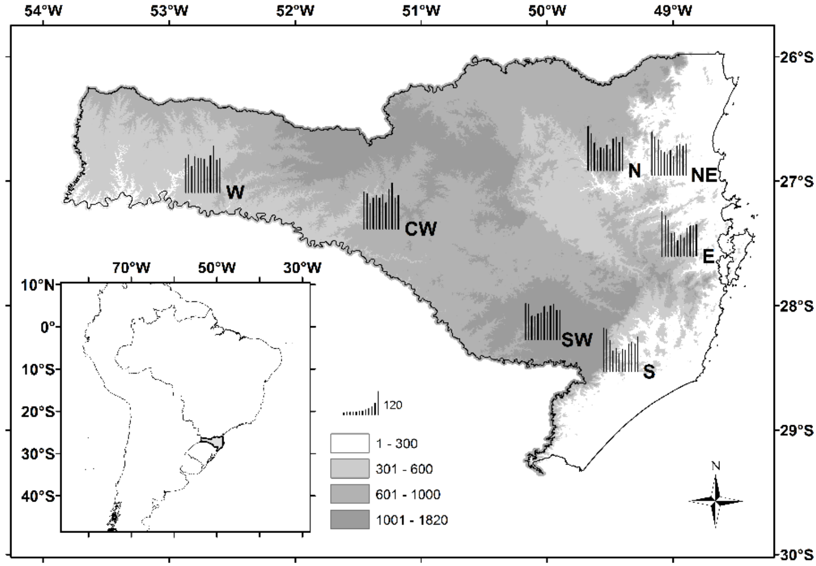
SC – Santa Catarina
SESA – Sudeste da América do Sul (Southeastern South America)
SON – setembro, outubro e novembro
SST – Sea Surface Temperature
SW – São Joaquim (Southwest)
TSM – Temperatura da Superfície do Mar
VCAN – Vórtice ciclônico de altos níveis
W – Chapecó (West)
ZCAS – Zona de Convergência do Atlântico Sul

SUMÁRIO

1 INTRODUÇÃO

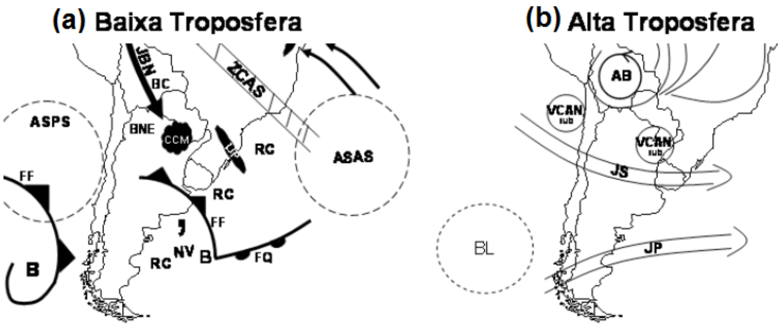
O Estado de Santa Catarina (SC), localizado no Sul do Brasil, está em uma região de transição entre os trópicos e as latitudes médias, com clima subtropical e ocorrência de precipitação em todos os meses do ano. A distribuição ao longo dos meses varia e o pico da estação chuvosa acontece na primavera na região oeste e no verão na região centro-leste (Figura 1). A passagem de sistemas frontais sobre o continente (RODRIGUES et al., 2004) e o desenvolvimento de sistemas de baixa pressão em superfície no interior do Sul do Brasil, denominados Complexos Convectivos de Mesoescala (CCMs) (VELASCO & FRITSCH, 1987) são os principais sistemas meteorológicos que contribuem para a ocorrência de precipitação na primavera. Outro sistema associado à chuva (mas menos frequente que os CCMs e os sistemas frontais) é o chamado Vórtice Ciclônico de Altos Níveis (VCAN) ou cutoff lows, caracterizado por uma circulação ciclônica fechada despreendida do escoamento de oeste, persistente entre os altos e médios níveis da atmosfera (REBOITA et al., 2010a). Nestes casos, a trajetória sinótica dos sistemas é do continente em direção ao oceano (oeste para leste nos CCMs e VCANS, e sudoeste para nordeste nos sistemas frontais).

Figura 1 - Elevação da superfície acima do nível médio do mar (em metros) para o Estado de Santa Catarina (SC). Os histogramas exibem o ciclo anual da precipitação (em milímetros) para as sete estações meteorológicas utilizadas: Chapecó (W), Campos Novos (CW), São Joaquim (SW), Urussanga (S), São José (E), Itajaí (NE) e Indaial (N). À esquerda, localização de SC no Brasil e na América do Sul.



No verão, a instabilidade na atmosfera aumenta, porém, agora os sistemas frontais se deslocam sobre o oceano e sistemas de baixa pressão se formam sobre o continente acompanhando o deslocamento das frentes (OLIVEIRA, 1986). Em alguns casos, esta atividade convectiva em terra evolui para uma extensa banda de nebulosidade, observada entre a região Amazônica, o Sudeste do Brasil e o Atlântico subtropical, chamada de Zona de Convergência do Atlântico Sul (ZCAS), sistema de grande escala responsável pelo regime de chuvas na América do Sul tropical (KODAMA, 1992). A precipitação ainda pode ocorrer devido à circulação marítima, quando um anticiclone apresenta trajetória adjacente à costa do Sul do Brasil e ocasiona a persistência de ventos do quadrante leste que trazem umidade do Atlântico subtropical para o continente (RODRIGUES & YNOUE, 2016). Esta situação é mais favorável de acontecer no verão, quando o número de frentes frias que passam sobre a região é reduzido e os ventos de leste tornam-se mais constantes. Nesta estação do ano a chuva em SC ocorre em regiões desconexas, diferente da precipitação dos sistemas sinóticos da primavera, e sobretudo no litoral, onde a diferença de temperatura entre o continente e o oceano e o efeito da barreira topográfica ocasionam chuvas muito intensas (GRIMM et al., 1998). A Figura 2 exibe a síntese dos principais sistemas atmosféricos atuantes na América do Sul nos altos e baixos níveis da atmosfera, responsáveis pela ocorrência de precipitação.

Figura 2 - Sistemas atmosféricos atuantes no Sul da América do Sul: (a) Baixa troposfera: JBN → jato de baixos níveis; FF (frente fria) + FQ (frente quente) + B (sistema de baixa pressão) → sistema frontal; ZCAS → Zona de Convergência do Atlântico Sul; CCM → Complexo Convectivo de Mesoescala; (b) Alta troposfera: JS (jato subtropical) + JP (jato polar) → jato de altos níveis; VCAN → vórtice ciclônico de altos níveis.



Fonte: Reboita et al. (2010b).

SC possui um amplo território ao nível do mar (530 km de linha de costa) e logo em seguida, altitudes que chegam a 1800 metros nas serras (Figura 1), ou seja, seu relevo contribui para acentuar os contrastes na distribuição da precipitação. Além disso, está em uma região onde diferentes sistemas atmosféricos causam chuvas intensas. Isto mostra o quanto é importante entender como acontecem os eventos extremos de precipitação em SC, chuvas persistentes e intensas em um curto período de tempo que ocasionam, nos piores casos, inundações e deslizamentos de terra. Estes eventos são tão frequentes que este tipo de desastre natural faz parte da história e cultura catarinenses, registrados em diferentes regiões e épocas do ano (Figura 3).

Figura 3 - Inundações em SC associadas aos eventos extremos de precipitação. (a) Blumenau em julho de 1983; (b) Florianópolis em dezembro de 1995; (c) Navegantes e Itajaí em novembro de 2008; (d) Bom Retiro em setembro de 2013.

Fonte: http://diariocatarinense.clicrbs.com.br/ e http://g1.globo.com/.

Estas fortes chuvas estão causando perdas econômicas e humanas cada vez mais expressivas, devido ao aumento populacional e ao maior número de infraestruturas feitas pela sociedade ao longo dos anos, que contribuem para o aumento da vulnerabilidade (EASTERLING et al., 2000). Entre 1980 e 2010 aconteceram 1257 inundações bruscas em SC (Tabela 1), devido à ocorrência de eventos extremos de precipitação, na maioria dos casos na primavera e no verão (HERRMANN & ALVES, 2014). Os dados da Defesa Civil mostram que estas inundações estão se tornando mais frequentes depois dos anos 2000. A maior delas aconteceu em novembro de 2008 (Figura 3c), quando fortes chuvas atingiram o Litoral Catarinense e a Região do Vale do Itajaí, resultando em uma enchente com deslizamentos de terra sem precedentes. A tragédia afetou 20% da população do Estado (~ 1,5 milhões de pessoas) e foram registradas 135 mortes.

Tabela 1 - Número de desastres naturais (inundações e escorregamentos) em SC, entre 1980 e 2010.

Tipos de Desastres Naturais	**1980-2000 (20 anos)**	**2000-2010 (10 anos)**	**1980-2010 (30 anos)**
Inundação gradual	1232	112	1344
Inundação brusca	321	936	1257
Escorregamentos	118	104	222

Fonte: Herrmann & Alves (2014).

Kunkel et al. (1999), Easterling et al. (2000) e Frich et al. (2002) relataram um aumento dos eventos extremos de precipitação nos EUA e em outras partes do mundo, nas últimas décadas do século XX. O último relatório do Painel Intergovernamental para as Mudanças Climáticas (IPCC) lançado em 2013 mostra um aumento na precipitação média e no número de eventos extremos no Sul do Brasil durante o século XXI, porém os dados não são confiáveis como os disponíveis para o Hemisfério Norte.

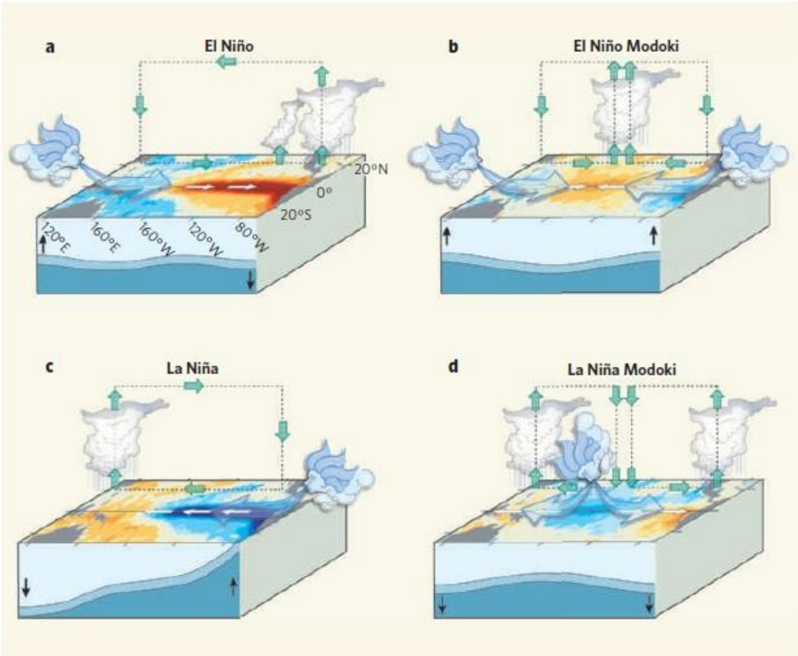
Geralmente eventos extremos estão associados ao fenômeno El Niño Oscilação Sul (ENSO). Alguns estudos foram realizados para a América do Sul, principalmente para o Sudeste da América do Sul (SESA), região a qual SC está inserida, associando a circulação atmosférica e as anomalias de precipitação mensal/sazonal ao ENSO (ACEITUNO, 1988; ACEITUNO, 1989; CAZES-BOEZIO et al., 2003; DIAZ et al., 1998; GRIMM et al., 1998; GRIMM, 2011; HILL et al. 2009; KAYANO et al., 2011; KOUSKY et al.,1984; PEZZI &

CAVALCANTI, 2001; ROPELEWSKI & HALPERT, 1987; TEDESCHI et al., 2013). Porém, são poucos os trabalhos que relacionaram o ENSO com os eventos extremos de precipitação na região Sul do Brasil e na sua vizinhança (GRIMM & TEDESCHI, 2009; PSCHEIDT & GRIMM, 2009, ROBLEDO et al., 2013, TEDESCHI et al., 2014).

O fenômeno ENSO é a principal causa da variabilidade climática interanual global. É uma oscilação do sistema acoplado oceano-atmosfera que altera a Temperatura da Superfície do Mar (TSM), a pressão, o vento e a convecção tropical (TRENBERTH & STEPANIAK, 2001). Tem reflexos em muitos lugares do planeta, inclusive no Sul do Brasil e suas fases opostas são chamadas episódios El Niño (EN) e La Niña (LN). O pico das anomalias de TSM acontece durante o verão, ou seja, em dezembro, janeiro e fevereiro (DJF). Por este motivo, um evento de EN ou LN é referenciado por dois anos, como por exemplo, o EN de 1982/83. Durante o EN, fase positiva ou quente do ENSO, a temperatura das águas superficiais do Oceano Pacífico Equatorial fica mais alta que o normal enquanto que durante a LN, fase negativa ou fria, ocorre o resfriamento anômalo dessas águas.

As anomalias de TSM do ENSO causam fluxos anômalos de calor e vapor d’água do oceano para a atmosfera alterando as circulações divergentes de Walker e Hadley e produzindo Ondas de Rossby (GRIMM, 2003). No Hemisfério Sul, a teleconexão é realizada através do trem de ondas Americano do Pacífico Sul (PSA), o qual está mais ativo entre setembro e dezembro e corresponde ao segundo (PSA1) e terceiro (PSA2) padrão principal da variabilidade atmosférica no Hemisfério Sul (MO 2000; VERA et al. 2004; GRIMM et al. 2007). As mudanças na atmosfera estão relacionadas a estes mecanismos de teleconexões globais distintos que perturbam a circulação do planeta produzindo alterações na precipitação da América do Sul extratropical. Posteriormente, ASHOK & YAMAGATA (2009) concluíram que existem diferentes tipos de EN e LN: eventos com anomalias quentes de TSM no leste do Pacífico Equatorial e aqueles com as anomalias no centro do Pacifico Equatorial (Figura 4). No EN Leste (ENL), ou EN Canônico, as anomalias positivas de TSM se encontram na região mais a leste do Pacífico Equatorial (próximo à costa da América do Sul). O EN Central (ENC) apresenta estas anomalias na região central do Pacífico Equatorial. As modificações notadas nos eventos quentes (EN) podem ser igualmente percebidas nos eventos frios (LN). O ENC difere do ENL também em relação às teleconexões globais nos extratrópicos.

Figura 4 - (a) El Niño Leste (ENL), as anomalias positivas de TSM ocorrem no Pacífico Equatorial Leste; (b) El Niño Central (ENC), as anomalias positivas de TSM se encontram no Pacífico Equatorial Central; (c) La Niña Leste (LNL), as anomalias negativas de TSM ocorrem no Pacífico Equatorial Leste; (d) La Niña Central (LNC), as anomalias negativas de TSM se encontram no Pacífico Equatorial Central.

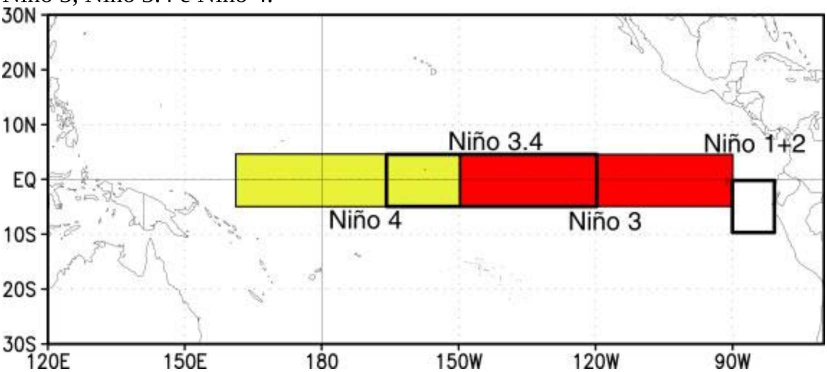


Fonte: Ashok & Yamagata (2009).

Existe ainda um outro modo de variabilidade climática no Oceano Pacífico, conhecido como Oscilação Interdecadal do Pacífico (IPO). Da mesma maneira que o ENSO, ele está relacionado ao padrão das anomalias de TSM no Pacífico, porém apresenta um período de oscilação que varia entre 20 e 30 anos. A sua fase positiva (negativa) está relacionada à uma interferência construtiva em episódios de EN (LN), ressaltando a ocorrência destes, devido ao aquecimento (resfriamento) das águas do Pacífico tropical e ao enfraquecimento (fortalecimento) dos ventos alísios na região (ENGLAND et al., 2014). Até o momento foram identificadas duas fases positivas (1922-1944 e 1978-1998) e duas negativas (1946-1977 e 2001-presente) (SALINGER et al., 2001, ENGLAND et al., 2014). Salinger et al. (2001) revelaram que a IPO modula a variabilidade climática do ENSO alterando a precipitação no Pacífico Sudoeste, entretanto, não existem ainda evidências claras da influência deste fenômeno no clima da América do Sul, pois a IPO é um modo de variabilidade menos compreendido e analisado que o ENSO.

As anomalias de precipitação mensal/sazonal e os eventos extremos no Sul do Brasil apresentam forte conexão com o ENSO, na primavera do ano inicial do fenômeno (setembro, outubro e novembro – SON). Anomalias positivas de TSM na região do Niño 3 (Figura 5) estão relacionadas às anomalias positivas de precipitação (GRIMM et al., 1998, KAYANO et al., 2011) e ao aumento na frequência e intensidade dos eventos (GRIMM & TEDESCHI, 2009; TEDESCHI et al. 2014), especialmente no mês de novembro. Todavia, existe uma maior sensibilidade do ENSO na distribuição dos eventos extremos, quando comparada à influência do fenômeno na distribuição dos totais de chuva mensais e sazonais. (GRIMM & TEDESCHI, 2009; TEDESCHI et al. 2014). Robledo et al. (2013) também encontraram associação entre os eventos extremos que acontecem na primavera no centro-leste da Argentina e a fase positiva do ENSO.

Figura 5 - Áreas no oceano Pacífico Equatorial conhecidas como Niño 1+2, Niño 3, Niño 3.4 e Niño 4.



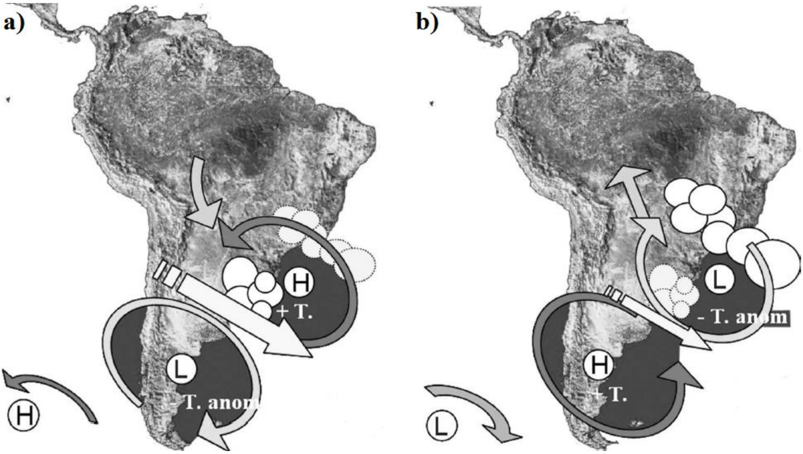
Fonte: NOAA (2014).

Grimm & Tedeschi (2009) e Tedeschi et al. (2014) ainda explicam as anomalias atmosféricas sobre a América do Sul extratropical durante estes eventos extremos: anomalias no trem de ondas de Rossby são observadas em 200 hPa e também diferenças no fluxo de umidade nos baixos níveis. Os eventos extremos em SON de episódios EN acontecem devido à persistência de uma circulação anticiclônica anômala sobre o Sudeste do Brasil em 200 hPa, relacionada ao fortalecimento do jato de altos níveis (JAN) na região subtropical (Figura 2b). Além disto, nos baixos níveis é observado um intenso fluxo de umidade do quadrante noroeste da região Amazônica em direção ao Sul do Brasil, denominado de Jato de Baixos Níveis (JBN) (Figura 2a). A combinação destes dois tipos de jato favorece o aparecimento de CCMs no interior do Sul do Brasil, responsáveis pelas anomalias positivas de precipitação e pelo aumento da frequência e intensidade dos eventos extremos no Sul do Brasil. (GRIMM et al., 1998; GRIMM & TEDESCHI, 2009; PSCHEIDT & GRIMM, 2009). A posição da anomalia anticiclônica nos altos níveis sobre o Sudeste do Brasil e Atlântico subtropical está relacionada ao caminho realizado pelo trem de ondas PSA1, durante os episódios de EN (GRIMM 2003; RODRIGUES et al., 2011; VERA 2004).

Pscheidt & Grimm (2009) examinaram os eventos extremos no Sul do Brasil no mês de novembro durante episódios de ENSO. Os autores mostram que os padrões característicos da circulação atmosférica em episódios de EN são semelhantes aos encontrados durante os eventos extremos favorecendo a ocorrência destes em EN, com aumento na frequência de eventos tanto na região costeira quanto no interior do continente. Episódios de LN mostram a redução do número de eventos nas áreas longínquas da costa.

Diferente da primavera, em alguns verões pode não haver teleconexão através do trem de ondas de Rossby entre o Pacífico e a América do Sul extratropical e processos locais prevalecem sobre as forçantes remotas (GRIMM, 2003, CAZES-BOEZIO et al., 2003, TEDESCHI et al., 2014). Nesta estação do ano, Grimm & Tedeschi (2009) observaram um número maior de eventos extremos no centro-leste do Brasil, associados aos episódios de ZCAS em anos de EN. As anomalias na circulação atmosférica que favorecem a ocorrência de eventos extremos no Sul na primavera e no centro-leste do Brasil no verão são descritas em Vera et al. (2006) (Figura 6).

Figura 6 - Anomalias de circulação regional em 700 hPa caracterizando períodos de (a) aumento e (b) redução da nebulosidade convectiva sobre SESA, durante a primavera e o verão austral. As letras H e L e a circulação vetorial associada representam as anomalias de circulação anticiclônica e ciclônica, respectivamente. O fortalecimento relativo do jato subtropical é representado pelos vetores de diferentes tamanhos. O vetor a leste dos Andes indica a direção da anomalia de vento nos baixos níveis.



Fonte: Vera et al. (2006).

Durante o verão há o desenvolvimento de uma anomalia ciclônica sobre o Sul e Sudeste do Brasil e uma anomalia anticiclônica no Sul da América do Sul (Figura 6b). Esta situação é de desenvolvimento da ZCAS gerando precipitação intensa no Sudeste e pouca chuva no Sul. No período da primavera, a situação se reverte, e uma anomalia anticiclônica se estabelece no sudeste/sul do Brasil acompanhado de uma anomalia ciclônica no Sul da América do Sul (Figura 6a). Há um fortalecimento do JBN que traz umidade da Amazônia e consequentemente, chuvas para o sul do Brasil. Nesta situação, a ZCAS não se estabelece e o Sudeste tem menos precipitação.

Eventos extremos no Sul do Brasil durante episódios de EN apresentam um padrão de anomalias na circulação semelhante ao apresentado na Figura 6a (GRIMM & TEDESCHI, 2009, PSCHEIDT & GRIMM, 2009, TEDESCHI et al., 2014). Contudo, não se sabe ao certo até que ponto a ZCAS pode se estender sobre Atlântico e pelo Sul do Brasil, podendo também estar associada à ocorrência de eventos extremos nas áreas mais ao sul. Barros et al. (2000) revelaram que um aumento na precipitação no nordeste (NE) da Argentina, Uruguai e Sul do Brasil, está associada a fracas manifestações da ZCAS, com deslocamentos ao sul da sua posição climatológica, devido à presença de anomalias positivas de TSM entre 20°S-40°S e oeste de 30°W (BARROS et al., 2000).

Eventos extremos no SE do Brasil estão relacionados à ocorrência de episódios de ZCAS oceânica. Carvalho et al. (2004) afirmaram que alguns episódios de ZCAS oceânica levaram à ocorrência de eventos extremos com inundações e deslizamentos de terra e que esta persistência da ZCAS oceânica acontece com maior frequência associada aos episódios de EN. Carvalho et al. (2002) observaram que a incidência de eventos extremos no Sudeste do Brasil em regiões distintas apresenta relação com diferentes tipos de ZCAS, com variações na intensidade (fraca x forte) e também na área de atuação (continental x oceânica). Cada tipo de ZCAS apresenta um padrão distinto nas anomalias de vento e radiação de onda longa (ROL) (em 850 hPa) e altura geopotencial (em 200 hPa).

1.1 JUSTIFICATIVA

As maiores tragédias naturais que ocorreram em SC são oriundas de eventos extremos de precipitação que ocasionaram enchentes e deslizamentos de terra que, por sua vez, trouxeram grandes impactos sociais e econômicos, inclusive perdas humanas. Além disso, é necessário um estudo mais detalhado destes eventos extremos, primeiro porque os trabalhos anteriores abrangem áreas maiores e diferentes entre si, como toda a América do Sul, ou parte dela (SESA, leste da América do Sul, Sudeste e Sul do Brasil). Segundo, porque estes eventos acontecem tanto em anos de ENSO quanto em anos de neutralidade do Oceano Pacífico, quando outros modos de variabilidade podem influenciar nas chuvas intensas. Uma investigação mais aprofundada dos mecanismos oceânicos e atmosféricos que geram as chuvas intensas pode revelar que outros fatores estão por trás da ocorrência de eventos extremos em SC, além da fase positiva do fenômeno ENSO e da configuração atmosférica associada a este cenário.

1.2 OBJETIVOS

1.2.1 Objetivo geral:

O trabalho tem como objetivo investigar os eventos extremos de precipitação em SC, analisando variações na frequência e intensidade, entre os anos de 1979 e 2015, bem como a relação destes eventos com o fenômeno ENSO. O estudo foca nos eventos da primavera (SON) e do verão (DJF), pois são as estações em que eles mais ocorrem. Uma vez identificados os eventos, foram determinados os padrões oceânicos e atmosféricos associados.

1.2.2 Objetivos específicos:

Os objetivos específicos são:

(1) Determinar os padrões de anomalia de TSM nos Oceanos Pacífico e Atlântico, associados aos eventos extremos de precipitação em SC;

(2) Determinar os padrões de anomalia de pressão e vento (nos baixos níveis – 850 hPa) e anomalia diária de altura geopotencial e vento (nos altos níveis – 200 hPa), sobre o Pacífico Sul, a América do Sul e o Atlântico Sul, associados aos eventos extremos de precipitação em SC;

(3) Determinar os padrões de radiação de onda longa (ROL), no topo da atmosfera, e do fluxo integrado de umidade específica nos baixos níveis, sobre a América do Sul e Atlântico Sul, associados aos eventos extremos de precipitação em SC;

(4) Determinar os padrões do fluxo de atividade da onda de Rossby nos Oceanos Pacífico e Atlântico, e na América do Sul, associados aos eventos extremos de precipitação em SC.

1.3 HIPÓTESES

Serão testadas as seguintes hipóteses:

(1) Eventos extremos de precipitação em SC estão ocorrendo com mais frequência e intensidade;

(2) Mudanças nos padrões de anomalias de TSM em episódios de ENSO, nos últimos anos, estão relacionadas às alterações nos padrões de teleconexão (PSA) entre o Oceano Pacífico e a América do Sul;

(3) A diferença nos padrões de teleconexão, por sua vez, desencadeiam a gênese de mecanismos atmosféricos distintos, que ocasionam os eventos extremos.

CHANGES IN THE PATTERNS OF EXTREME RAINFALL EVENTS IN SOUTHERN BRAZIL

Este capítulo apresenta o conteúdo do artigo que compõe esta dissertação e foi submetido à revista *International Journal of Climatology* em 03/03/2017. O conteúdo apresentado a seguir segue na íntegra o publicado na revista, mudando apenas a formatação do texto. A confirmação da submissão é apresentada na próxima página.

Submission Confirmation

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CHANGES IN THE PATTERNS OF EXTREME RAINFALL EVENTS IN SOUTHERN BRAZIL

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ABSTRACT

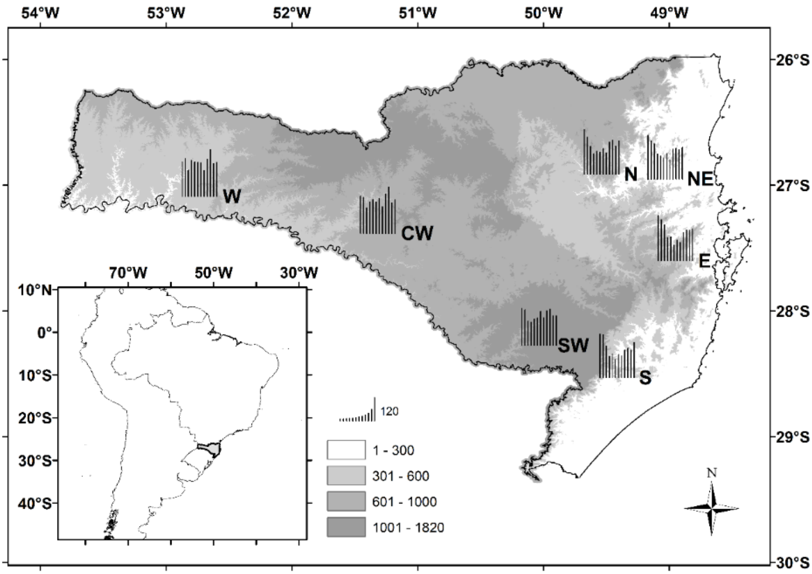
In this study we have examined changes in frequency and intensity of extreme rainfall events for the state of Santa Catarina (SC) in southern Brazil during austral spring and summer. The results show that changes in El Niño-Southern Oscillation (ENSO) between 1979-1999 and 2000-2015 due to different phases of Interdecadal Pacific Oscillation have impact on the teleconnection patterns from the Pacific to South America. As a consequence, precipitation over SC in the late period is less likely to be linked to ENSO. Moreover, there have been changes not only in the frequency and intensity of extreme events between the two periods but also in the mechanisms that cause the extremes affecting the spatial distribution of the extremes. In spring, the extreme events are less likely to occur during El Niño events and more frequent during La Niña and neutral years. The classical mechanism, of an enhanced South Atlantic Lower Level Jet (SALLJ) bringing moisture to SC, is no longer responsible for the extremes in the spring. The current main mechanism is associated with the presence of frontal systems during ENSO years and the presence of the South Atlantic Convergence Zone (SACZ) to the north combined with an anticyclonic system off the South American coast during neutral years. As a consequence the extreme events are currently more frequent at stations in the eastern side of SC. In summer during neutral years, SACZ events have become less frequent at the same time that atmospheric blocking events have become more frequent, explaining the decrease in extremes. On the other hand, SACZ events have become more frequent during La Niña years and so do the extremes in SC, with El Niño events playing a less important role.

Keywords: ENSO, Interdecadal Pacific Oscillation, Extreme rainfall events, South America, Southern Brazil.

2.1 INTRODUCTION

In recent years, many studies reported that there has been a rapid expansion of the tropics in the last decades and areas in the transition zone between the tropics and subtropics are most likely to be affected (Lucas et al., 2014). The state of Santa Catarina (SC) is located in southern Brazil within this transition zone, between the latitudes of 26°S and 29°S (Figure 1). In addition, SC is very important for the Brazilian economy since is responsible for 6% of the gross domestic product and 8% of Brazil’s exports with a population of around 7 million people. Among the main activities are agriculture and the generation of hydroelectric power. Thus, understanding the mechanisms that control the climate variability of SC is important to be able to make accurate seasonal forecasts and future climate projections.

Figure 1 - Surface elevation above the mean sea level (shading, in m) for the state of Santa Catarina (SC). Histograms show the annual cycle of precipitation for the seven selected meteorological stations: Chapecó-West (W), Campos Novos-Central West (CW), São Joaquim-Southwest (SW), São José-East (E), Itajaí-Northeast (NE), Indaial-North (N) and Urussanga-South (S). Box in the left-bottom corner gives the location of SC in relation to Brazil and South America.



The climate of SC is strongly linked to the South American Monsoon System (SAMS; Vera et al., 2006; Marengo et al., 2012). During the mature phase of SAMS, the main convective activity is associated with the South Atlantic Convergence Zone (SACZ). The SACZ is a band of cloudiness that extends from the Amazon to southeastern Brazil and adjacent South Atlantic Ocean. There is a dipole structure in precipitation where enhanced precipitation over the SACZ region is accompanied by decreased precipitation over southern Brazil (see Figure 10d from Vera et al., 2006). The opposite phase is associated with a strengthening of the South American low-level jet (SALLJ), which increases the moisture flux from the Amazon region to southern Brazil (see Figure 10c from Vera et al., 2006). The rainy season peaks in austral summer for most of SC during the mature phase of the SAMS (Figure 1). However, in the western region of SC the peak wet season is during the onset of the SAMS in austral spring (Grimm et al., 1998). The formation of mesoscale convective complexes (MCC) and the passage of frontal systems through SC can also cause extreme events of precipitation (Grimm and Tedeschi, 2009; Kousky et al., 1984). Even though, frontal systems are more likely to occur during winter, they still can occur during early spring. Therefore, SC is subject to a large variability in precipitation and extremes.

As a result of the variety of mechanisms that affects its climate, SC is prone to extreme events of precipitation that have led historically to floods and mudslides with significant impacts on infrastructure, energy, agriculture and water resource management. There were 1257 cases of flashfloods and 222 cases of mudslides between 1980 and 2010 in SC due to extreme rainfall events (Herrmann and Alves, 2014). Most of them occurred during spring and summer and according to the Emergency Services data they have become increasingly more frequent in the last decade: 75% of flashfloods and 50% of mudslides occurred between 2000 and 2010 (Herrmann and Alves, 2014). A recent example is the devastating event of November 2008 during which 200 mm of rain fell in a short period of less than 24 hours causing floods and widespread mudslides in the Itajaí River Valley. This event claimed 135 lives, affected more than 1.5 million people and caused losses of the order of USD$350 million (Marengo, 2009). Therefore, accurate weather and climate prediction for SC are very important to minimize socioeconomic losses, but are rather difficult to attain because of the influence of various physical mechanisms on its precipitation pattern.

Previous studies show that extreme events of precipitation in southern Brazil are associated with the El Niño-Southern Oscillation (ENSO), which is also the main source of interannual variability of precipitation for this region (Grimm et al., 1998; Grimm and Zilli, 2009; Grimm and Tedeschi, 2009; Pscheidt and Grimm, 2009; Hill et al., 2009; Kayano et al., 2011; and references therein). Most of these studies, however, have focused on either the whole South America or southeastern South America (SESA), which encompasses southern Brazil, Uruguay and northern Argentina. Heavy rainfall generally occurs during El Niño events, when a strong SALLJ enhances the moisture flux from the Amazon towards SESA. During La Niña years on the other hand, the SALLJ weakens and rainfall is scarce over this region.

These changes in lower-level circulation over South America are caused by ENSO upper-level teleconnection patterns. In other words, ENSO triggers Rossby wave trains that propagate from central-eastern equatorial Pacific poleward to the tip of South America, then turning equatorward into the Atlantic. They are the second and third leading mode of circulation variability in the Southern Hemisphere, called Pacific-South American wave trains (PSA1 and PSA2, respectively) (Karoly, 1989; Kiladis and Mo, 1998; Mo, 2000; Mo and Hakkinen, 2001). As a result, in El Niño years an anomalous cyclonic circulation establishes over southern South America and an anticyclonic circulation over subtropical South America, enhancing the SALLJ and leading to excess precipitation (Rodrigues et al., 2011). The opposite occurs in La Niña years. The precipitation pattern in response to this ENSO teleconnection is particularly evident in spring before the mature phase of ENSO, which occurs during summer (Grimm, 2011). During summer, however, the relation between ENSO and precipitation over southern Brazil is not clear, suggesting that other mechanisms must play a role (Grimm, 2003, 2004; Grimm and Tedeschi, 2009).Most of the aforementioned studies were inconclusive about the precursors of extreme events in SC particularly in summer because they examined extreme events only during ENSO years. Moreover, they focused either on SESA region or on the whole South America.

For instance, the most comprehensive study for southern Brazil by Pscheidt and Grimm (2009) investigated the frequency of extreme rainfall events only for November during ENSO years. Therefore the objective of this study is to investigate changes in extreme rainfall events specifically for SC, using high quality data from meteorological stations for the period of 1979-2015. This study will focus on spring and summer when most of extreme events occur. We will show that the frequency and intensity of these events, as well as their genesis mechanisms, have changed in the last decades and that many of them happen during neutral ENSO years.

2.2 DATA AND METHODOLOGY

Daily rainfall data are obtained from Empresa de Pesquisa Agropecuária e Extensão Rural de SC - Centro de Informações Ambientais e de Hidrometeorologia (EPAGRI-CIRAM) and Instituto Nacional de Meteorologia (INMET). After a series of quality control procedures, we have selected 7 stations with continuous daily data for the period of 1979-2015. They are spread across the state to represent all main regions (Figure 1). We will refer to them by their approximate geographical location as follows: Chapecó-West (W), Campos Novos-Central West (CW), São Joaquim-Southwest (SW), São José-East (E), Itajaí-Northeast (NE), Indaial-North (N) and Urussanga-South (S).

The extreme rainfall events were determined using a methodology similar to Pscheidt and Grimm (2009) and is summarized here. First, three-day running totals are calculated and ascribed to the middle day. The percentile for each day of spring and summer is calculated and precipitation corresponding to the percentile equal or greater than 95 is considered an extreme episode. To be considered an extreme event, however, it has to occur simultaneously in at least 3 different stations of SC. We then use the definition of ENSO years according to Trenberth (1997) to sort the selected extreme events into three categories: El Niño, La Niña and neutral years. To this end, we use the 2°x2° gridded monthly sea surface temperature (SST) data from the Extended Reconstructed Sea Surface Temperature v4 (ERSSTv4) for the period of 1979–2015 (Huang et al., 2015). NINO3 index is obtained by averaging the SST anomalies within 90°W-150°W and 5°S-5°N.

In order to investigate the general patterns that lead to the extreme events we construct composite of various atmospheric fields, using daily data obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-Interim reanalysis for the period of 1979-2015 (Dee et al., 2011). They are mean sea level pressure, geopotential height, specific humidity, zonal and meridional components of the wind at different levels. We also use interpolated outgoing longwave radiation (OLR) data by Liebmann and Smith (1996) as a proxy for tropical convection for the period of 1979–2015 and the 1/4°x1/4° gridded daily sea surface temperature (SST) data from Optimum Interpolation SST (OISST) for the period of 1982–2015 (Reynolds et al. 2007). The statistical significance for the composites of the aforementioned fields is computed using the Student t-test at the 95% confidence level. The same test is used for the correlation analysis, however, at the 99% confidence level.

2.3 PRECIPITATION PATTERNS OVER SC

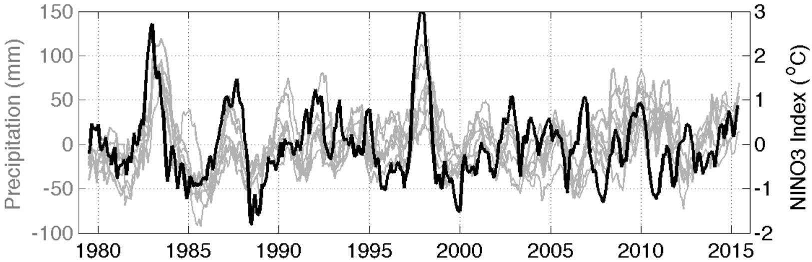
Before analyzing the results related to the extreme events, it is important to discuss some important aspects of the precipitation over SC. First, we look at the spatial coherence in precipitation between the different regions in SC by cross-correlating the time series of precipitation for all 7 stations (Table 1, see also Figure 1 for their location). The correlation coefficients among all of them are statistically significant. However, the strongest correlations are found within two clusters of stations: one consisting of stations Chapecó (W), Campos Novos (CW) and São Joaquim (SW) located in the western side of the hills; another comprising the coastal stations São José (E), Itajaí (NE) and Indaial (N), located in the northeastern side of the hills. The southernmost station Urussanga (S) is highly correlated to the nearby São Joaquim (SW) and Indaial (N). This spatial pattern in southern Brazil, in which precipitation over inland stations differs slightly from that over coastal stations, has been described in the literature (Pscheidt and Grimm, 2009). Generally, inland stations in the western side of the hills have their precipitation dictated by the moisture flux associated with the SALLJ, whereas coastal stations in the eastern side of the hills can also be affected by moisture flux from the Atlantic Ocean (see orography in Figure 1).

Table 1 - Correlation coefficient among time series of precipitation for all stations in SC. All coefficients are statistically significant at 99% confidence level. Locations of the stations are depicted in Figure 1.

	CW	N	NE	E	SW	S
Chapecó (W)	0.87	0.58	0.51	0.33	0.61	0.49
Campos Novos (CW)	-	0.75	0.63	0.40	0.76	0.61
Indaial (N)	-	-	0.79	0.63	0.70	0.71
Itajaí (NE)	-	-	-	0.68	0.64	0.67
São José (E)	-	-	-	-	0.48	0.55
São Joaquim (SW)	-	-	-	-	-	0.74
Urussanga (S)	-	-	-	-	-	-

As previously mentioned, over southern Brazil the interannual variability is associated with ENSO. Even though the objective of this study is to investigate extreme events, it is important to understand the interannual variability since previous works have shown that the ENSO-related changes in the frequency of extreme rainfall events are coherent with changes in total monthly rainfall quantities (Grimm and Tedeschi, 2009). Figure 2 shows time series of the monthly precipitation anomalies for the seven meteorological stations in SC and NINO3 index. Table 2 depicts the correlation coefficient between them and NINO3. We find that they are all statically correlated with NINO3, except the coastal station of São José (E). Above-average precipitation generally occurs during the positive phase of ENSO, i.e., El Niño years, hence positive correlations. Moreover, the stronger correlations with NINO3 are found for the western cluster of stations, also consistent with the fact that El Niño events enhance the SALLJ bringing more moisture from the Amazon to southern Brazil. Thus excess precipitation tends to occur in athe western side of the hills (see orography in Figure 1).

Figure 2 - Time series of monthly precipitation anomalies (mm) for the seven selected meteorological stations in SC (gray solid lines, see their location in Figure 1) and NINO3 index (black solid line), which is obtained by averaging the SST anomalies within 90°W-150°W and 5°S-5°N.



One aspect that stands out from Figure 2 is the decrease of ENSO variability in the 2000's (from 0.83 to 0.49°C²). This has been attributed to the negative phase of the Interdecadal Pacific Oscillation (IPO) and is believed to be, at least partially, responsible for the warming hiatus of the 2000's (England et al., 2014). There has been a strengthening of the trade winds over the Pacific since 2000 that has led to more frequent occurrence of La Niñas with few weak central El Niños. The first strong El Niño since the 1997/98 event occurred recently in 2015/16. A careful inspection of Figure 2 and the correlations between precipitation for all 7 stations and NINO3 shows that they are only statically significant correlated with NINO3 from 1979 to 1999 (Table 2). From 2000 to 2015, there is no relationship between them and ENSO. Hence no statistically significant correlation coefficients were found for the late period (Table 2).

Table 2 - Correlation coefficients between NINO3 index and precipitation time series for different stations over SC. The location of each station is given in Figure 1. Bold values represent the coefficients that are statistically significant at 99% confidence level.

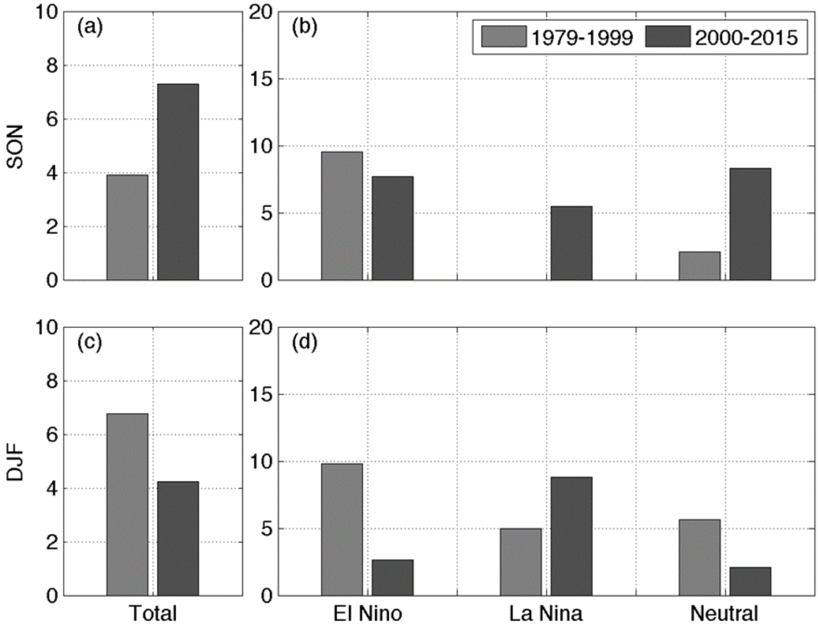
	1979-2015	**1979-1999**	**2000-2015**
Chapecó (W)	**0.48**	**0.58**	0.18
Campos Novos (CW)	**0.49**	**0.62**	0.11
Indaial (N)	**0.34**	**0.54**	-0.06
Itajaí (NE)	**0.28**	**0.42**	-0.12
São José (E)	0.07	**0.23**	-0.17
São Joaquim (SW)	**0.38**	**0.65**	-0.07
Urussanga (S)	**0.32**	**0.43**	0.07

This finding has guided us to investigate if there has been any change in the occurrence of extreme events for the two periods, namely 1979-1999 and 2000-2015, once we know from previous studies that frequency of extreme rainfall events are associated with changes in total monthly rainfall. We will show in the next sections that: 1) the frequency and intensity of extreme events has increased in SC during spring for the late period, but has decreased during summer; and 2) most of the late events are caused by other mechanisms unrelated to the strengthening of SALLJ, which is a hallmark of ENSO teleconnection.

2.4 CHANGES IN FREQUENCY AND INTENSITY OF EXTREME RAINFALL EVENTS

Based on previous discussions and using the methodology described in section 2, we have computed the frequency of extreme rainfall events during spring and summer for two periods 1979-1999 and 2000-2015 (Figure 3). There has been an increase in the frequency of extreme rainfall events during spring, from 4% for 1979-1999 to 8% for 2000-2015, considering the total number of the days during the corresponded period (Figure 3a). However, a decrease from 7% to 4% was observed during summer (Figure 3c).

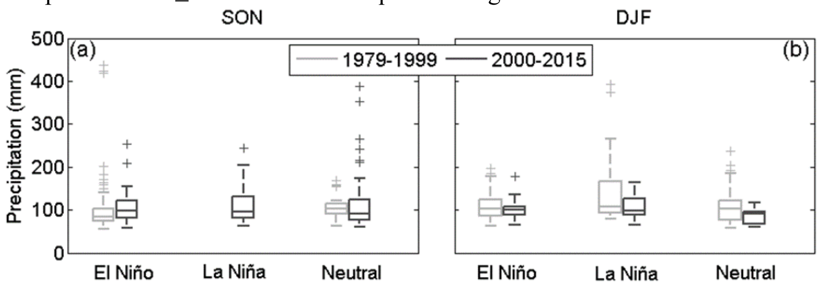
Figure 3 - Histograms of frequency (%) of extreme rainfall events (see definition in the text) during (a)-(b) austral spring and (c)-(d) austral summer, for two periods 1979-1999 and 2000-2015. (a) And (c) are the total frequencies (total number of extreme event days per total number of the days during the corresponded period). (b) And (d) are the frequencies of extreme events by category: El Niño, La Niña and neutral years (the number of extreme events in each category per number of days in the respective category, for each period).



We also look at the changes in frequency of extreme events by category, i.e., during El Niño, La Niña and neutral years. During spring, the number of extreme events has slightly decreased from 10% to 8% for El Niño years, but increased during La Niña and neutral years for 2000-2015, respectively from 0% to 5% and from 2% to 8% (Figure 3b). One could argue that this is due to the fact that there were more La Niña and neutral years in the late period. However, in this case the frequencies were calculated dividing the number of extreme event by the number of days with El Niño, La Niña or neutral conditions for each period. During summer, the number of extreme events decreases during El Niños from 10% to 3% and neutral years from 6% to 2%, but increases for La Niña years from 5% to 9% (Figure 3d). Thus, extreme events are more likely to occur during La Niña years in the late period for both spring and summer. On the other hand, El Niño events in the late period are less likely to cause an extreme event in both spring and summer. During neutral years, an increase in extreme events during spring is accompanied by a decrease during summer. To evaluate the statistical significance of the aforementioned changes, we use a Kolmogorov–Smirnov test and find that all changes from 1979-1999 to 2000-2015 are statistically significant at 99% confidence level, except for the decrease in frequency during summer for El Niño years.

It is also important to investigate the changes in the intensity of the extreme events. Figure 4 shows the box plot diagram of extreme events per category. Looking at the median, there has been an increase in the intensity of the extreme events during El Niño years and a decrease during neutral years in spring for the late period (Figure 4a). (Note that there is no La Niña extreme event for the first period.) However, analyzing the outliers, there has been a decrease in intensity of the most extreme events during El Niño years for the late period, but an increase for neutral years. During summer (Figure 4b), the median and extreme values consistently decreased in the late period for all cases. The changes in median are statistically significant to the 99% confidence level using Wilcoxon test.

Figure 4 - Box-plot diagram of daily accumulated precipitation considering only extreme events above the 95% percentile for El Niño (red), La Niña (blue) and neutral years (black) during (a) spring and (b) summer. Outliers (crosses) are data point values ≥1.5 times the interquartile range.



2.5 CIRCULATION PATTERNS ASSOCIATED WITH EXTREME RAINFALL EVENTS

We have a good understanding of the teleconnection patterns that cause extreme events during El Niño years, but we need to learn more about the conditions that lead to extreme events during La Niña and neutral years, since they became more frequent in the last decades. The focus of this section is the atmospheric circulation patters while changes in the ENSO teleconnections will be addressed in more detail in the next section.

2.5.1 Spring

We start with composites of daily anomalies of geopotential height at 200 hPa, mean sea level pressure, wind at 200 hPa and 850 hPa for extreme events during El Niño years (Figure 5). Comparing the first period 1979-1999 with the second period 2000-2015 in the spring, the atmospheric circulation pattern at the upper troposphere has changed over the Pacific and South America. In the first period (Figure 5a), the Rossby wave train is weak and places an upper-level cyclonic circulation over the southern South America (negative geopotential height anomalies) and an anticyclonic circulation over eastern South America (positive geopotential height anomalies). The latter enhances the SALLJ that brings moisture from the Amazon to SC (vectors in Figure 5b and middle panel of Figure 6a). This pattern is associated with the development of low-pressure systems (MCC) and has been previously described in the literature (Grimm et al., 1998; Grimm and Tedeschi, 2009). The MCC signature can be seen as low values of OLR in Figure 6a. Moreover, the intensification of the upper-level jet (Figure 5a) contributes to the advection of cyclonic vorticity and hence to the formation of MCC (Velasco and Fritsch, 1987). (The ageostrophic component of the upper-level jet favors divergence at the upper level and convergence at the lower level.)

For the late period, alternated positive and negative geopotential anomalies appear more elongated over South America (Figure 5c). As a consequence, the SALLJ is not enhanced. The lower-level circulation pattern resembles the passage of frontal systems with winds blowing from southeast over the SC coast (Figure 5d). The OLR minimum presents a more elongated shape that propagates off the coast of SC consistent with the passage of frontal systems (panels in Figure 6b). The advection of moisture comes from the ocean (vectors in the middle panel of Figure 6b). This explains why most of the extreme events occur at stations in the western side of SC for the first period (with SALLJ) and at stations in the eastern side of SC for the late period (without SALLJ).

Figure 5 - Composites of (a) geopotential height anomalies at 200 hPa (shading; m) and wind anomalies at 200 hPa (vectors; m s-1) and (b) mean sea level pressure anomalies (shading, hPa) and wind anomalies at 850 hPa (vectors, m s-1) for extreme events during El Niño years in SON for the period of 1979-1999. (c)-(d) As in (a)-(b), but for 2000-2015. Solid lines in (c) and (f) encompass areas where the composites are statistically significant different from the climatology at 95% confidence level given by a standard two-tailed t test.

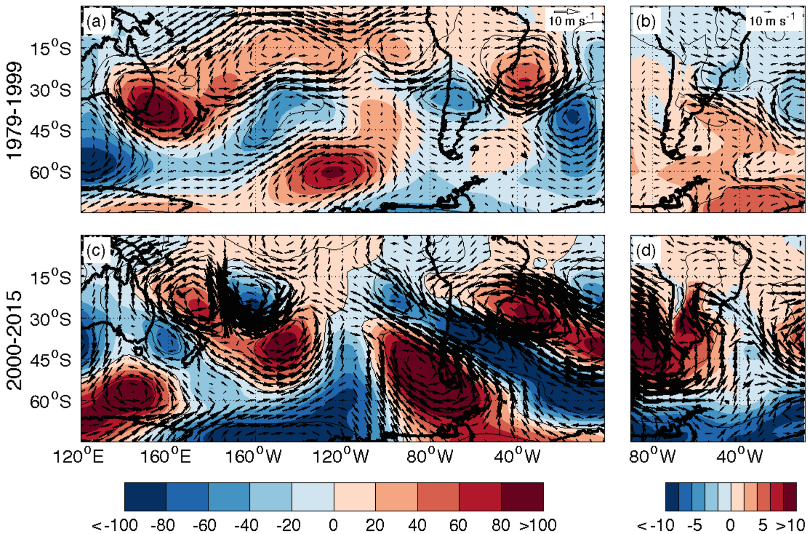
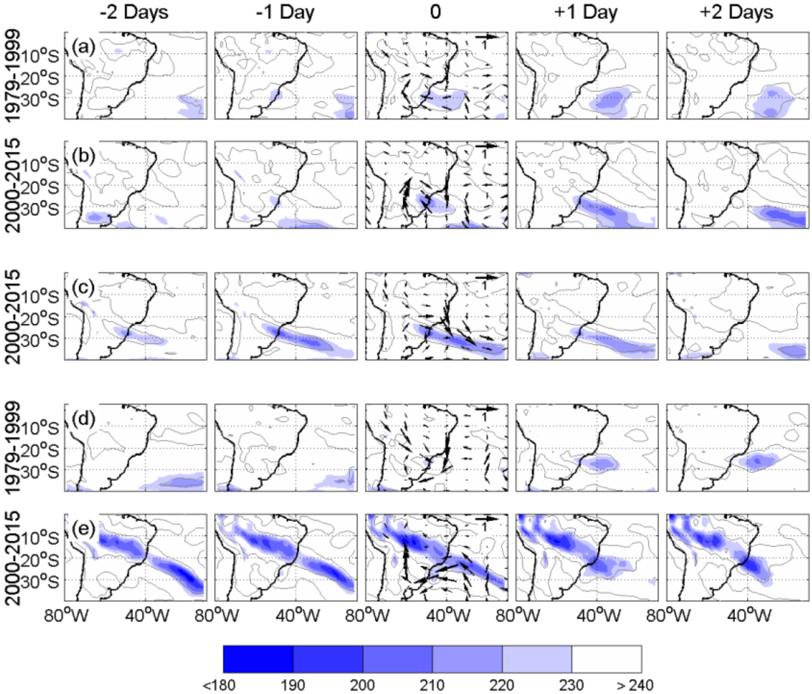
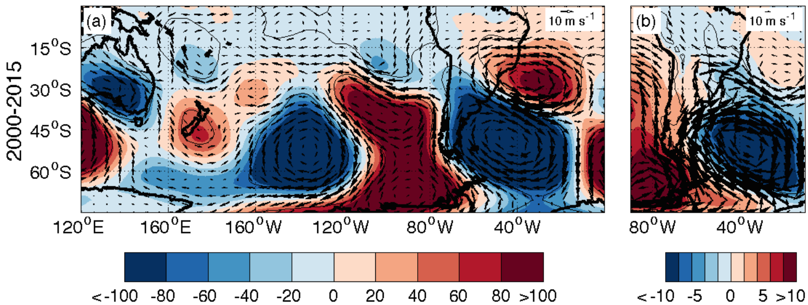


Figure 6 - Composites of OLR (in W m-2) for extreme events in SON during: (a) El Niño years for 1979-1999, (b) El Niño years for 2000-2015, (c) La Niña years for 2000-2015, (d) neutral years for 1979-1999, (e) neutral years for 2000-2015. Panels from left to right show the temporal evolution of OLR, from 2 days before the onset, 1 day before the onset, on the onset day, 1 day after the onset and 2 days after the onset, respectively. Vectors in the middle panels represent moisture flux integrated between 850 and 1000 hPa (×10 kg m-1 s-1). Solid lines in (c) and (f) encompass areas where the composites are statistically significant different from the climatology at 95% confidence level given by a standard two-tailed t test.



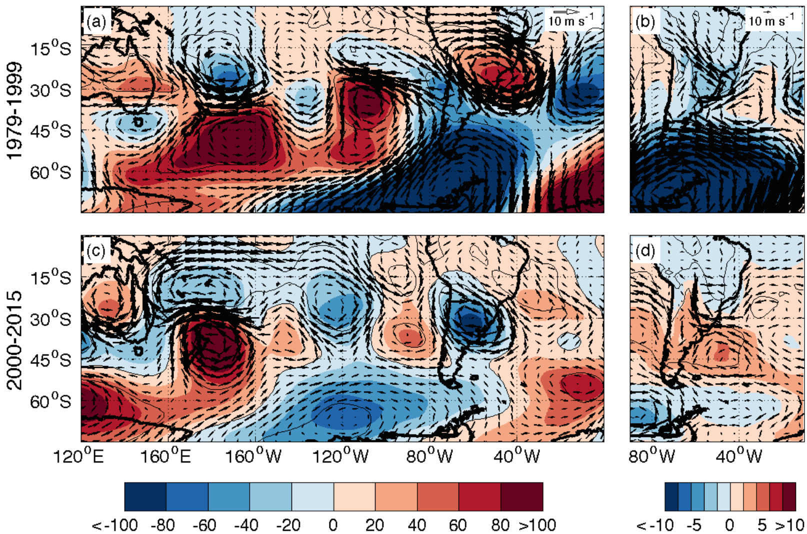
Extreme events of rainfall only occur during La Nina years for the late period. The traditional known pattern of La Niña teleconnection is the opposite of that related to El Niños and for this reason used to cause droughts in SC (Grimm, 2004). That is for the first period. For the late period, however, the Rossby wave train places an anomalous cyclonic circulation over southern South America and an anticyclonic over subtropical South America (Figure 7a). As a consequence, the SALLJ is enhanced bringing moisture from the Amazon to SC (Figure 7b). Moreover, for the La Nina cases there is an intense cyclonic circulation off the coast of Argentina (southern South America), which also brings moisture from the ocean to SC. The OLR signature resembles the passage of frontal systems with convergence of moisture flux over SC (Figure 6c). As a consequence, extreme events are more frequent at stations in the eastern side of SC.

Figure 7 - As in Figure 5, but for extreme events during La Niña years for the period of 2000-2015.



For neutral years, we do not expect necessarily a teleconnection pattern from the Pacific Ocean. Nevertheless, we show the geopotential height anomalies at the upper troposphere over the Pacific for consistency (Figure 8). For the first period, there is an upper-level anomalous anticyclonic circulation associated with a lower-level anomalous cyclonic circulation over eastern South America and enhanced SALLJ similar to those during El Niños years, albeit stronger (cf. Figures 8a,b and 5a,b). In this case, however the anomalies are shifted to the west, but the mechanisms are comparable. The OLR composites show the MCC signature with moisture flux coming from the Amazon (Figure 6d). For the late period, in contrast to previous cases, there is a cyclonic circulation at the upper troposphere instead (Figure 8c). A cyclonic circulation is also present at lower level with strong eastward wind anomalies (Figure 8d). These events are associated with the establishment of the SACZ, which can be identified by a band of low values of OLR (below 200 W m-2) extending from the Amazon to western South Atlantic (Figure 6e). The SACZ is located to the north of SC; however, the anticyclonic circulation to the south advects the moisture from the SACZ to SC (vectors in the middle panel of Figure 6e). Most of the extreme events occurred in November, including the devastating event of 2008. The onset of the SAMS is generally in November when episodes of SACZ become more frequent. It is worth noting that for neutral years, the Rossby wave train pattern has a higher wave number and in this case we speculate that could be related to tropical convection, i.e., Madden-Julian Oscillation (MJO). Carvalho et al. (2002, 2004) and Rodrigues and Woollings (2017) that have shown the link between SACZ and MJO corroborate this. The spatial distribution of the extreme events reflect the different mechanisms by which they are caused: for the first period, the extreme events occur in all stations, but mainly in the west; for the late period, 75% of the extremes occur at stations in the eastern side of SC.

Figure 8 - As in Figure 5, but for extreme events during neutral years.



2.5.2 Summer

The extreme events during El Niño years are less frequent in summer than in spring. This might be due to the fact that the teleconnection between ENSO and South America is stronger during spring (Vera et al., 2004). For the first period, there is an anomalous upper-level cyclonic circulation over eastern South America and an anticyclonic circulation to the south over western South Atlantic (Figure 9a). The wind anomalies at lower levels show an anomalous anticyclonic circulation near the southeast coast, with dominant northeasterly anomalies over SC. According to Vera et al. (2006), this pattern is related to the occurrence of SACZ with heavy precipitation over eastern Brazil. Though the anomalies shown here are slightly shifted to the south and thus the SACZ encompasses SC to the south (Figure 10a). The circulation pattern at upper and lower levels (Figure 9a,b) is similar to that reported by Carvalho et al. (2002) as being related to a weak-oceanic SACZ (their Figure 6e,f). This is corroborated by the composites of OLR, which show weak convection (lower OLR values) across South America with a core over SC where the moisture flux converges (Figure 10a). For the late period, there is a tripole with negative geopotential height anomalies over the tip of South America, positive anomalies over southeastern South America and negative anomalies along the eastern coast of South America. At lower levels, a strong cyclonic circulation over the western South Atlantic leads to an increase of the westerlies there, extending the deep convection toward the Atlantic. This case resembles the intense-oceanic category by Carvalho et al. (2002) with a well-developed SACZ with the SALLJ advecting moisture to the SACZ and SC (Figure 10b). For both periods, the extreme events are well distributed spatially over SC, occurring slightly more at stations in the eastern side.

Figure 9 - As in Figure 5, but for extreme events during El Niño years in DJF.

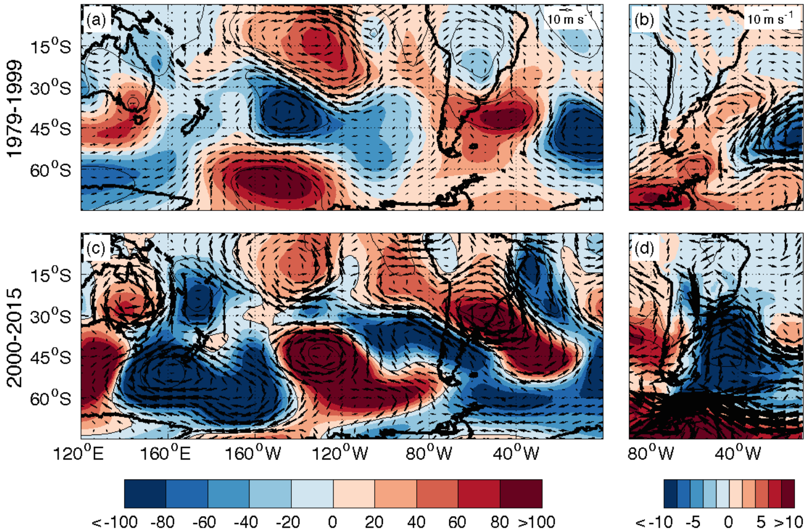
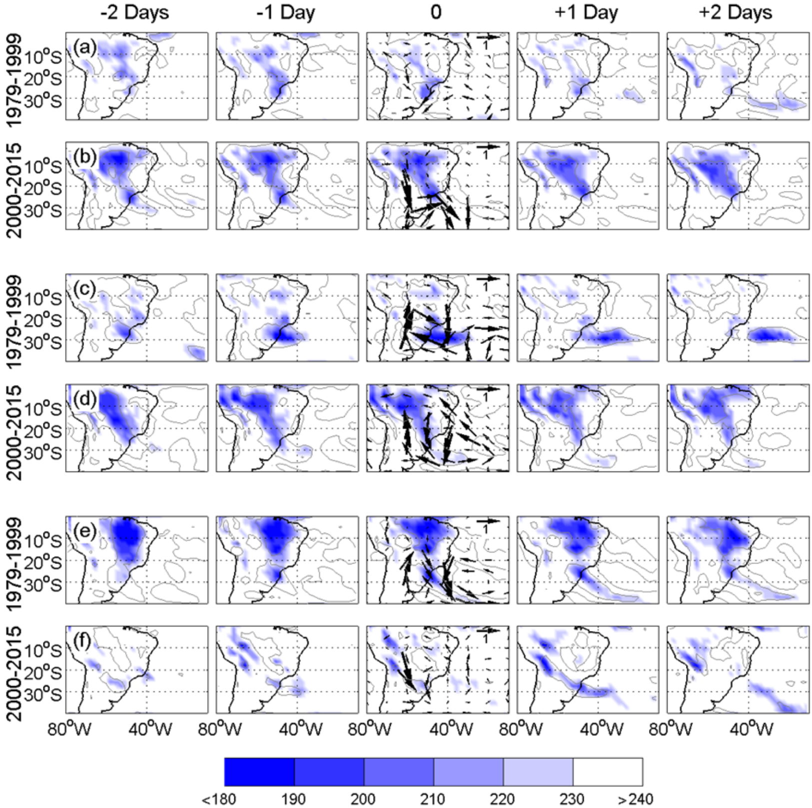
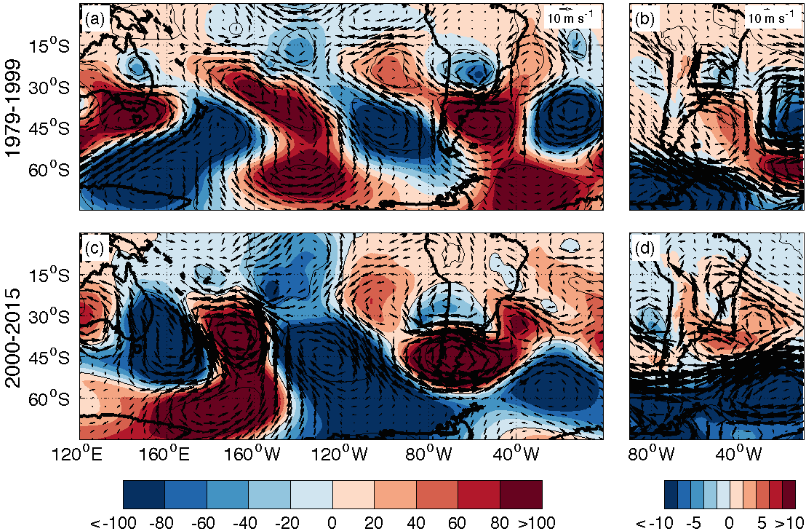


Figure 10 - As in Figure 6, but for extreme events in DJF during: (a) El Niño years for 1979-1999, (b) El Niño years for 2000-2015, (c) La Niña years for 1979-1999, (d) La Niña years for 2000-2015, (e) neutral years for 1979-1999, (f) neutral years for 2000-2015.



During La Niña years, the ENSO teleconnection is similar between the two periods (Figure 11a,c). In both cases, there is an upper-level cyclonic circulation over South America between 15-30°S, flanked by positive geopotential height anomalies. The anomalous cyclonic circulation is also present at mid (not shown) and lower levels (Figure 11b,d). Though this pattern is stronger for the first period leading to wind anomalies from the east over SC. The moisture flux comes from the South Atlantic (Figure 10c) and low values of OLR develop over SC extending to the South Atlantic (Figure 10c). This is a typical case of cut-off lows reported by Reboita et al. (2010), where the cyclonic anomalies are strong at upper and middle levels. In only 10% of the cases, these cyclonic anomalies reach the surface like those shown here (Palmén and Newton, 1969); they cause the most extreme rainfall events (Fuenzalida et al., 2005). All extreme events occur at stations in the eastern side of SC, reflecting the genesis mechanism. For the late period, the anomalous cyclonic circulation is weak and shifted to the west. As a consequence the wind anomalies are from the northwest over SC and this is less conducive to extreme precipitation, hence the weaker intensity of the extreme events for the late period (Figure 4b); but they are more likely to occur (Figure 3d). The OLR and lower-level wind patterns resemble those of a continental SACZ based on Carvalho et al. (2004) with less precipitation along the South American coast (cf. Figures 10d, 11d and their Figure 8d). As a consequence, extreme events are spatially well distributed.

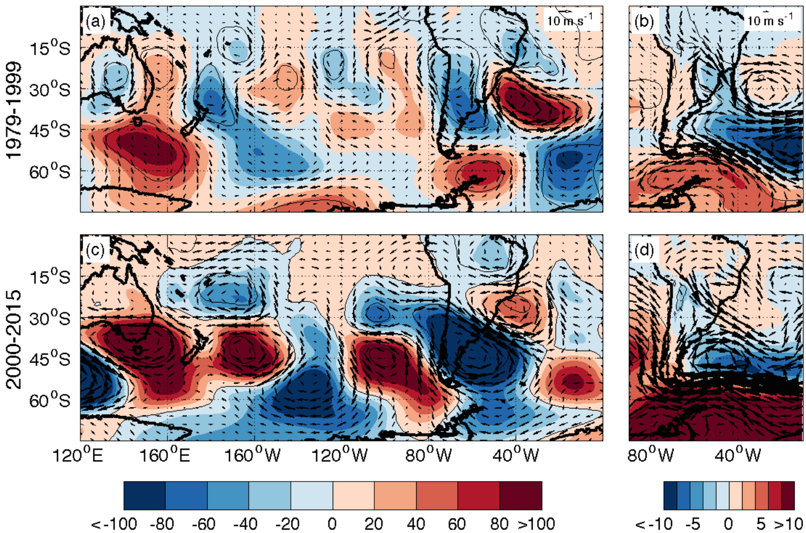
Figure 11 - As in Figure 5, but for extreme events during La Niña years in DJF.



During neutral years, for the period of 1979-1999 the circulation at both upper and lower levels resembles that of a typical intense-oceanic SACZ (Figure 12a.b). When compared to Carvalho et al. (2002) fields (their Figure 8e,f), the patterns are slightly shifted to the south. As consequence the main core of the oceanic SACZ and moisture flux convergence are over SC, hence the extreme events there. In contrast for the period of 2000-2015, the circulation pattern at both upper and lower levels resembles that of an atmospheric blocking reported by Rodrigues and Woollings (2017). At the upper level, there is a strong anomalous cyclonic circulation over the tip of South America and an anticyclonic circulation over eastern South America (cf. Figure 12c and their Figure 11d). The anticyclonic circulation is also present at the lower level leading to the intensification of the SALLJ (Figure 12d), which brings moisture from the Amazon to SC (middle panel in Figure 10f). The excess precipitation over SC might also be due to the fact that the anticyclonic system blocks the equatorward propagation of cold fronts that would help the establishment of the SACZ over eastern South America (Nieto-Ferreira et al., 2011). The cold fronts stall and become stationary over SC, causing the excess precipitation there. Rodrigues and Woollings (2017) corroborate this result (cf. Figure 10f and their Figures 7b and 9b). Though, the extremes associated with blocking are less intense (Figure 4b).

Once again, the different mechanisms for both periods reflect the spatial distribution of the extreme events: for the first period associated with the SACZ, they occur at all stations; for the late period associated with blocking, they occur only at stations in the western side and south of SC. In summary, both mechanisms, southward SACZ and blocking, can lead to extreme events in SC in summer during neutral years. They are the two poles of the dipole precipitation pattern reported in the literature (Vera et al., 2006). This highlights the difficulty of predicting extreme events and precipitation for regions of regime transition such as SC.

Figure 12 - As in Figure 5, but for extreme events during neutral years in DJF.



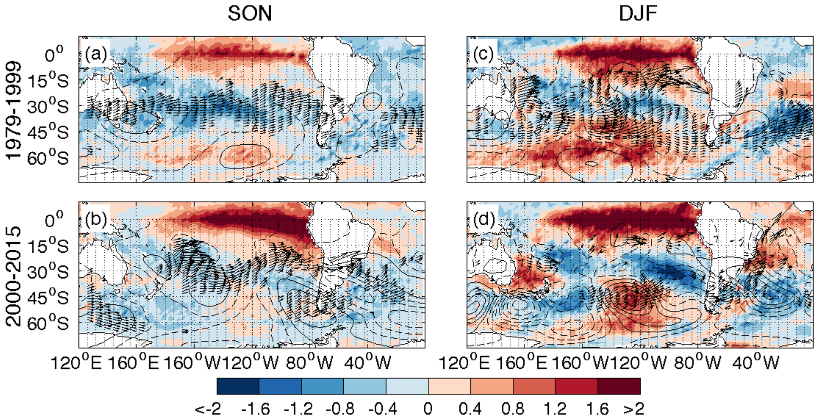
2.6 CHANGES IN ENSO TELCONNECTIONS

Now we investigate if changes in ENSO between 1979-1999 and 2000-2015 due to different phases of IPO have an impact on the teleconnection patterns from the Pacific to South America. It has been reported in the literature that during the positive phase of IPO (first period), ENSO diversity was higher with strong eastern Pacific El Niño events as well as central Pacific El Niños and La Niñas (Chen et al., 2015). On the other hand, during negative phase of IPO (late period), there has been a strengthening of the trades over the tropical Pacific that has led to more La Niña events and less El Niño events, without the occurrence of strong eastern Pacific El Niños (England et al., 2014). One would expect that the extreme events during El Niño years are associated with canonical eastern Pacific El Niños and that the decrease in frequency and intensity of extremes for the late period is a simple result of a reduction in the occurrence of such strong El Niños. However, a close inspection of the daily composites of geopotential height anomalies at 200 hPa for extreme events during El Niños (Figure 5a) has show that for the first period the Rossby wave train resembles the PSA2 with the wave train trapped equatorward, typical of central Pacific El Niños. And for the late period, the wave train propagates more poleward, similar to the teleconnection caused by eastern Pacific El Niños (PSA1).

This is corroborated by composites of daily SST anomalies and Rossby wave activity flux for El Niño cases in both periods during spring (Figure 13a,b). We compute Rossby wave activity flux using Takaya and Nakamura (2001) formulation, which is an extension of the zonally averaged Eliassen–Palm flux (Andrews and McIntyre, 1976). The wave activity flux is parallel to the local group velocity and hence shows the direction of Rossby wave ray paths. For the first period, the strong positive SST anomalies are in the central Pacific with the Rossby wave activity flux similar to the PSA2.

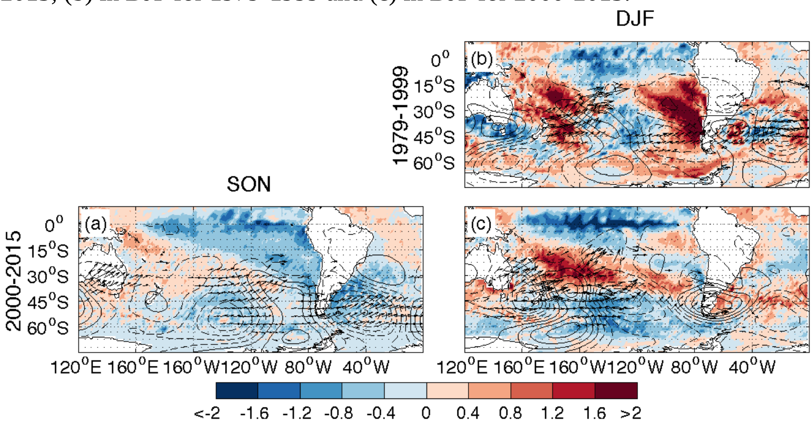
For the late period, the SST pattern resembles that of eastern Pacific El Niño. The wave train extends farther poleward in the South Pacific, splits into two and turns equatorward near the tip of South America, similar to the PSA1 reported by Rodrigues et al. (2015). This is consistent with the basic Rossby wave theory (Ambrizzi and Hoskins, 1997), which shows that zonal elongation of the forcing (eastern Pacific El Niño) enhances meridional propagation. During summer, according to Vera et al. (2004) the PSA patterns are less evident and as a consequence the Rossby wave activity flux for both periods is incoherent (Figure 13c,d). Nonetheless, the results are similar to those during spring. The SST anomalies are stronger for the late period and the wave train propagates more poleward, veering towards South America. In contrast for the first period, the Rossby wave activity flux shows propagation across lower latitudes over the Pacific and towards the South Atlantic. The impact of these different wave patterns is on the atmospheric circulation over South America that lead to the extremes described in the previous section.

Figure 13 - Composites of SST anomalies (shading, °C), geopotential height anomalies at 200 hPa (contours, m) and Rossby wave activity flux (vectors, m2 s-2) for extreme events during El Niño year in SON for (a) 1979-1999 and (b) 2000-2015. (c)-(d) As in (a)-(b), but in DJF. Contour interval is every 25 hPa. Zero contours are omitted and solid (dashed) lines represent positive (negative) values. Only vectors where the composites are statistically significant different from the climatology at 95% confidence level given by a standard two-tailed t test are plotted.



During La Niña years in spring (Figure 14a), the extreme events occur only for the late period. Colder waters are widespread along the coast of South America with the strongest anomalies in the eastern Pacific. In this case, the wave train propagates poleward towards the middle of South Pacific placing a cyclonic circulation over southern South America and an anticyclonic over eastern South America. These anomalous circulations are responsible for the enhanced SALLJ and the extremes. During summer for the first period (Figure 14b), the cold anomalies are already fading along the equatorial Pacific with strong warm anomalies off the coast of South America and western South Pacific where the Rossby wave activity flux is intense. In contrast for the late period (Figure 14c), strong cold anomalies are still present along the equatorial Pacific with the intense Rossby wave activity flux shifted to the west, near Australia. As a consequence, the anomalous cyclonic circulation over South America between 15-30°S flanked by anticyclonic circulations is also shifted to the west for the later period, leading to different wind anomalies and moisture flux over SC.

Figure 14 - As in Figure 13, but during La Niña years: (a) in SON for 2000-2015, (b) in DJF for 1979-1999 and (c) in DJF for 2000-2015.



The analyses of SST and Rossby wave activity flux described here for El Niño events are unexpected and the composites using daily data differ from those using monthly data (not show). Within the days with extreme event, the Pacific seems to present characteristic of central Pacific El Niño for the first period and that of eastern Pacific El Niño for the late period. A close inspection of the exact days of extreme events for the first period reveal that during spring half of the extremes happened during eastern Pacific El Niños (1982 and 1997) early in the season (when the El Niño is developing) and the other half occurred during central Pacific El Niños later in the season (when the El Niño is mature). This is consistent with the central Pacific El Niño teleconnection described here for the first period. For the late period, all extreme events happened in 2009 (strong central Pacific El Niño) and 2015 (eastern Pacific El Niño). For instance, the daily evolution of SST anomalies during the 2009/2010 El Niño reveals that pulses of warm waters extend to the eastern Pacific for days (see animation at https://podaac.jpl.nasa.gov/node/594), given the nature of this phenomenon which involves ocean wave dynamics. This occurs in spite of the fact that most of the time the strongest warm anomalies are in the central Pacific, reflecting on the monthly mean. The La Niña results are more consistent with what we expect from ENSO-IPO diversity, in which extreme events are associated with weaker La Niñas in the first period and with stronger La Niñas in the late period.

2.7 SUMMARY AND CONCLUSIONS

In this study we have examined changes in frequency and intensity of extreme rainfall events for the state of SC (southern Brazil) during austral spring and summer. The results show that changes in ENSO between 1979-1999 and 2000-2015 due to different phases of IPO have an impact on the teleconnection patterns from the Pacific to South America. As a consequence, precipitation over SC in the late period is less likely to be linked to ENSO. Moreover, there have been changes not only in the frequency and intensity of extreme events between the two periods but also in the mechanisms that cause the extremes affecting the spatial distribution of the extremes. The main conclusions of this study can be summarized as follow:

•In spring, the frequency and intensity of the extreme events have decreased during El Niño years between the two periods. For the first period, the ENSO teleconnection pattern causes an intensification of the SALLJ advecting moisture from the Amazon to SC and favoring the development of MCC over SC. This is the typical known El Niño teleconnection mechanism. For the late period, the SALLJ is weak and upper-level jet is strong, hence the extremes are associated with the passage of frontal systems along the coast of SC. As a consequence, for the first period the extremes occur everywhere in SC whereas for the late period most of the extremes occur at stations in the eastern side of SC.

•La Niña events used to cause droughts in SC in spring therefore no extreme events of rainfall were identified for the first period. For the late period, the teleconnection pattern has changed and extreme events are associated with a strong upper-level jet and the passage of frontal systems through the coast of SC. Hence, most of these extreme events occur in the eastern side of SC.

•During neutral years, the frequency and intensity of the extreme events have increased. The mechanism associated with extreme events is similar to that of El Niño years (strong SALLJ and occurrence of MCC) for the first period. For the late period is associated with the presence of SACZ to the north and an anticyclonic circulation over SC that advects the moisture from the SACZ in the South Atlantic to SC. The spatial distribution of the extreme events also changed with more events occurring at stations in the western side for the first period and at the eastern side of SC for the late period.

•During summer, again the frequency and intensity of the extreme events have decreased during El Niño years between the two periods. The mechanisms are similar for both periods, i.e., the extremes are associated with the establishment of the SACZ with the SALLJ advecting moisture to the SACZ and SC. For both periods, the extreme events are more frequent at stations in the eastern side of SC.

•In La Niña years, extreme events are more frequent but less intense for the late period. They are associated with the presence of cutoff lows for the first period and with the SACZ for the late period. For the first period, the moisture flux is from the South Atlantic hence the extremes occurs at stations in the eastern side of SC. For the late period, the moisture flux is from the north and the extreme occurs everywhere in SC.

•During neutral years, the extreme events are less frequent and weaker for the late period. For the first period, extremes are related to the presence of a more southward SACZ that encompasses SC, whereas for the late period they are associated with blocking events to the north. Hence, the extreme events are more frequent at stations in the eastern side of SC for the first period and in the western side and south of SC for the late period.

We recognize that the changes between the two periods are not consistent for all situations analyzed here, i.e., El Niño, La Niña, neutral years, spring and summer, and that there is not a simple mechanism that explains the changes and/or causes of the extreme events of precipitation in SC. This is due to the climate complexity of this transition zone. Nonetheless, we can conclude that in spring, the extreme events are less likely to occur during El Niño events and more likely during La Niña and neutral years. The classical mechanism, of an enhanced SALLJ bringing moisture to SC, is no longer responsible for the extremes in SC in the spring. The current main mechanism is associated with the presence of frontal systems during ENSO years and the presence of the SACZ to north combined with an anticyclonic system to the south off the South America coast during neutral years. In summer, SC is in the transition between the two poles of the dipole structure of the SAMS and as a consequence precipitation in SC can be associated with both phases of the dipole, i.e., rainfall can occur either when the SACZ is active and located southward to its mean position or when the SACZ is absent and the SALLJ is enhanced (caused by atmospheric blocking). In neutral years, SACZ events have become less frequent at the same time that atmospheric blocking events have become more frequent, explaining the decrease in frequency and intensity of the extremes. On the other hand, SACZ events have become more frequent during La Niña years and so do the extremes. Once again, El Niño events play a less important role on causing extremes in SC. The aforementioned changes are reflected at the spatial distribution of the extreme events in SC.

Finally, during El Niño years the extreme events are associated with central Pacific El Niños for the first period and with eastern Pacific El Niños for the late period. This result is only evident by analyzing daily fields and explains the decrease in extreme events between the two periods. During La Niña years, extreme events are associated with weaker La Niñas in the first period and with stronger La Niñas in the late period. Stronger La Niñas are more frequent in the late period and so do the extremes

More work needs to be done to identify the precursors of the extreme events in SC during neutral years, with MJO being a strong candidate. The impact of the South Atlantic SST, Antarctic Oscillation and the poleward shift of the westerlies in the Southern Hemisphere have not been addressed and could also be linked to the changes reported here. These will be the focus of future research.

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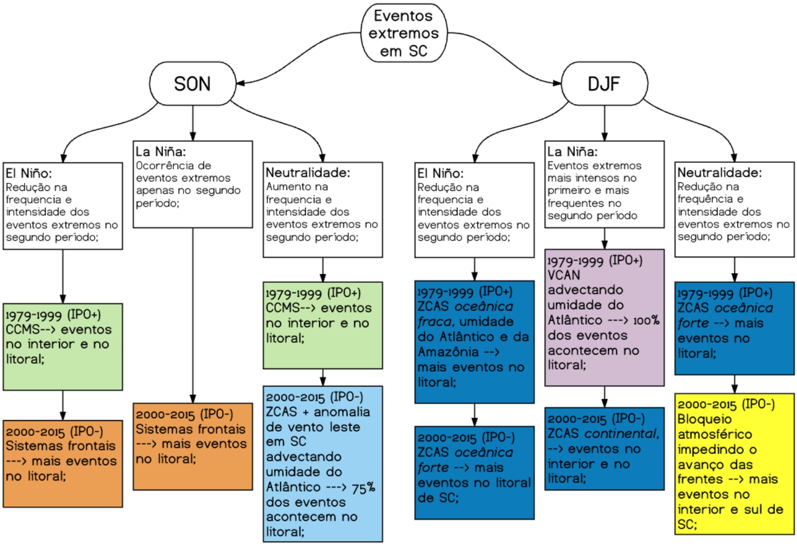
3 CONCLUSÕES E CONSIDERAÇÕES FINAIS

As mudanças na intensidade e frequência dos eventos extremos em SC, entre 1979-1999 e 2000-2015, estão relacionadas às diferentes fases da IPO. Na fase positiva (primeiro período), ocorreram fortes episódios de EN Leste. Na fase negativa (segundo período), os episódios de LN foram mais persistentes, com anomalias mais intensas na região central, apenas um episódio forte de EN Leste (2015/16) foi observado até o momento. Contudo, os eventos extremos no primeiro período estão relacionados aos episódios de EN central, mas esta compreensão só foi possível devido às análises de anomalia diária da TSM. Embora a média da anomalia mensal resulte em uma TSM mais intensa no Pacífico Leste, na data dos eventos, as anomalias são mais fortes no Pacífico central e desencadeiam um fluxo de onda de Rossby análogo à PSA2, com trem de ondas mais próximo da região equatorial.

Por outro lado, no segundo período, os eventos extremos acontecem em episódios de EN Leste, com padrão no trem de ondas típico da PSA1, percorrendo latitudes mais altas. Até mesmo o EN 2009/10, considerado central, apresentou anomalias de TSM mais intensas no Pacífico Leste, na data dos eventos extremos. Os episódios de LN relacionados aos eventos exibem um padrão de anomalias da TSM parecido nas análises diárias e mensais, e mais coerente com a relação entre o ENSO e a IPO: no primeiro período as anomalias de TSM são mais fracas e no segundo período mais intensas, sobretudo no Pacífico central. Estas diferenças nas anomalias de TSM do ENSO entre um período e outro desencadeiam padrões de teleconexões distintos (PSA1 e PSA2) que perturbam a atmosfera na América do Sul extratropical, favorecendo o desenvolvimento de sistemas atmosféricos diversos, associados aos eventos extremos em 1979-1999 e 2000-2015. A interpretação da relação entre os mecanismos atmosféricos atuantes nos eventos e as mudanças na frequência, intensidade e distribuição espacial dos mesmos, entre o primeiro e segundo períodos, é resumida na Figura 7.

Figura 7 - Resumo das mudanças na frequência, intensidade e distribuição espacial dos eventos extremos em SC, entre 1979-1999 e 2000-2015, associados a sistemas atmosféricos diversos, caracterizados por cores distintas nas caixas.



As diferenças entre os dois períodos não são consistentes em todos os casos analisados (SON e DJF, dentro de cada cenário de EN, LN e neutralidade), pois não são apenas alterações nos mecanismos da circulação atmosférica que explicam por si só as causas dos eventos extremos em SC, que está inserida em uma zona de transição com ampla complexidade climática. Apesar disso, é possível concluir que no primeiro período (1979-1999), durante a fase positiva da IPO, os eventos estão associados aos episódios de EN e alguns episódios de neutralidade, com forte influência do JBN no transporte da umidade da Amazônia para o Sul do Brasil, contribuindo para o desenvolvimento de CCMs na primavera. No entanto, no segundo período (2000-2015), quando a IPO alterou para a fase negativa, a frequência e intensidade dos eventos extremos aumentaram consideravelmente em episódios de LN e também de neutralidade, mas agora nestes casos, os eventos extremos não apresentam mais a mesma conexão com o JBN. Durante o ENSO, os eventos estão associados à ocorrência de sistemas frontais em SC e na neutralidade, ao estabelecimento da ZCAS ao norte de SC e à advecção de umidade do Atlântico subtropical, devido à persistência de ventos do quadrante leste na costa.

No verão, os eventos extremos se tornam menos frequentes e intensos no período de 2000-2015, pois os episódios de ZCAS com núcleos de convecção que alcançam áreas ao sul de sua posição climatológica não estão mais associados aos episódios de EN e neutralidade (1979-1999), mas aos episódios de LN, em 2000-2015, aumentando a incidência de eventos apenas dentro deste cenário. Nesta estação do ano, os eventos mais intensos aconteceram no litoral (em 1979-99), devido ao deslocamento de um VCAN sobre o Sul do Brasil, com intenso fluxo de umidade do Atlântico subtropical em direção à costa, durante episódios de LN. Os eventos menos frequentes e intensos no segundo período, estão relacionados à neutralidade, em períodos de bloqueio atmosférico no Sudeste e parte do Sul do Brasil. Deste modo, fica claro que SC pode apresentar registro de eventos tanto em episódios de ZCAS, que também originam extremos no Sudeste do Brasil, quanto em episódios de bloqueio com ausência da ZCAS, restringindo a ocorrência dos eventos nas regiões mais ao sul e no interior, padrão oposto ao observado em eventos com ZCAS, quando estes incidem em sua maioria na área litorânea mais ao norte.

Trabalhos posteriores devem ser realizados com o objetivo de averiguar quais seriam os possíveis modos de variabilidade climática relacionados aos eventos extremos durante a neutralidade do ENSO, como a Oscilação Madden-Julian ou ainda a Oscilação Antártica. A relação entre os eventos e a TSM no Atlântico subtropical também precisa ser investigada, pois anomalias positivas podem ter relação direta com o estabelecimento de episódios de ZCAS que abrangem parte do Sul do Brasil. Embora seja evidente que outros mecanismos de interação oceano-atmosfera devem ser analisados, as observações deste estudo fornecem informações adicionais importantes que podem ser utilizadas para monitorar com mais acurácia a ocorrência dos eventos extremos de precipitação em SC.

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