Positive Regional Sea Level Anomalies in Southern Brazil Due to Changes in Austral Atmospheric Circulation

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Positive regional sea level anomalies in southern Brazil due to changes in austral atmospheric circulation

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Abstract

Pressure gradients and winds play an important role in Southern Hemisphere (SH) sea levels, which are currently associated with the positive trend of the Southern Annular Mode (SAM). This study investigated regional sea level anomalies (SLAs) in the southern coast Brazil using altimeter data (1993–2019), post-processed by the X-TRACK (CTOH/LEGOS). We observed a negative SLA from 1993 to 2009 and a positive SLA from 2010 to 2019, with upward trends throughout the evaluation period. We analyzed wind stress curl, pressure, and wind fields at sea level (FNMOC and ERA 5, respectively) in addition to sea surface temperature and height anomalies (SSTA/SSHA-OISST) in the South Atlantic Ocean (SAO) for 1993–2009 and 2010–2019. In relation to the first period, the second shows the enhancement in Hadley and Walker cells and trade winds, in addition to greater SSTA and SSHA in SAO. The SAO subtropical gyre and zonal winds at 45°S contribute to the intensification of the western boundary current. A greater pressure gradient between the SAO surface and the southeast of South America is noteworthy. Regionally, the positive SAM brings an increase in sea level to the study area, caused by greater wind stress and variability in heat flows.

Keywords: Remote Sensing, Ocean, Teleconnections, Mid-Latitude, Brazil

Introduction

Coastal and oceanic sea levels vary in different ways both temporally and spatially. In coastal regions, where most of the global population lives, variability may occur across months or even days. This is why one of the greatest challenges for decision makers is to prepare for sea level rise (SLR) in coastal regions, as indicated by the Intergovernmental Panel on Climate Change¹. On a regional scale, sea level studies consider areas of dozens to hundreds of kilometers, resulting in variations among different factors². One of these factors is ocean–atmosphere coupling, which generates an interaction between wind and sea surface, near or far from the coast in this study¹. In the South Atlantic Ocean (SAO), regional variability of sea level, at interannual and multidecadal scales, is produced by surface wind and heat flow anomalies². Wind stress over oceanic surfaces causes undulation anomalies and variations in Ekman transport. These changes led to the coast by the rise in wave height and period, in addition to piles up water to the west. The hot water volume pumped from the tropics to higher latitudes will accelerate due to Ekman transport. This pumping causes a deepening in the tropical thermocline, raising local sea level and leading the cold water to superficial layers, which brings the thermocline to shallower levels and a decrease in sea level to the east. The friction generated on the oceanic surface by the wind produces oceanic Rossby waves to the west, followed by SLR throughout the propagation track³⁻⁶.

The Southern Annular Mode (SAM) is described as a pressure gradient between the middle and high latitudes in the Southern Hemisphere (SH). Zonally symmetrical SAM variations also affect the variability in SH oceans at large scales⁷⁻⁸. The positive SAM phase is associated with intensification of the west winds...
over the circumpolar ocean (approximately 60°S) and weakening in the north. This process induces Ekman transport to the north in all longitudes of the circumpolar ocean and to the south around 30°S. Due to mass conservation, Ekman transport generates anomalous resurgence along the Antarctic continent, and subsidence at approximately 45°S. Positive SAM tendency in the last decades, associated with a high interannual variability of wind force, effectively adds to oceanic circulation variability of subtropical and subpolar oceans. Many studies have identified changes in SH oceanic circulation in response to a positive SAM tendency.

In all SH oceans, positive SAM intensifies large gyres and increases the sea surface height, which, in turn, elevates sea surface temperature by isopycnal subsidence at 40°S. Oceanic gyres represent large oceanic current systems caused by winds on the surface, especially by the vorticity provoked by wind stress. Satellite images show consistent changes in the main subtropical gyres toward the pole in the last four decades. In addition, a propensity for warming in the west currents has been observed in the last century. The western boundary currents (WBCs) of subtropical gyres transport warm water from the tropics to the pole, thus contributing to increasingly humid and warmer climates on adjacent continents. Migration to the poles of extra tropical circulation agents, such as jet streams and west winds, show that all extra tropical circulation is moving to the south. Two other tendencies have been associated in the extratropical region: positive SAM and Hadley cell expansion. Climate models have shown that these tendencies are related to global atmospheric warming.

The troposphere temperature rise and tropopause height drive the Hadley circulation toward the pole on the SH. Oceanic gyres displacement, coupled with the change in direction of atmospheric extratropical circulation, widely affects ocean heat transport, regional SLR, and coastal ocean circulation. In the tropical Pacific, the SLR likelihood is three times higher than the global average, induced by trade winds intensification in the last decades. In the tropical Indian Ocean, there was a sea level rise in some regions, boosted by the strengthening of Walker and Hadley cells. Considering this global trend, this study discusses the possible causes of local sea variability in southern Brazil. For this purpose, we used three periods of altimetric monitoring of the sea level obtained from satellite sensors. We evaluated sea level variation in a WBC under the light of the strengthened atmospheric circulation (warmer), wind fields, wind stress curl (WSC), positive SAM tendency, and the tropic-pole teleconnections perspective over SAO.

Results

To obtain the SLA for the study area, 966 cycles were used for each of the two tracks covering it. By averaging the points and cycles, it was possible to obtain the annual SLA to the southern coast of Brazil between 1993 and 2019, where we can see the rise in the sea level from 2008 (Fig. 1). Between 1993 and 2001, figures were predominantly below average, showing an SLA increase between 2001 and 2003 and a subsequent decrease until 2008. From this period onward, we observed increasing SLA, reaching the highest point by the end of the 2010–2019 series.
Figure 1. Temporal evolution of regional sea level anomalies on the southern coast of Brazil

Description of atmospheric and oceanic fields with negative SLA

Between 1979 and 1992, no SLA satellite data exist. Nevertheless, when we compared atmospheric circulation over the SAO and Southern Ocean (SO) during this period, we noticed some important characteristics. In meridional wind fields at 850 hPa, the flow towards the equator prevailed in relation to the heat flow toward the pole. Over the SAO, we found the largest anomalies of cold air, arising from the Antarctic Peninsula region, although warm winds would blow to the Weddell Sea by the west. That is, the SAO in the study area was influenced by anomalies from the Antarctic Peninsula.

On the surface, between the equatorial region and medium latitudes, the pressure gradient resulted from the dominance of the SAO subtropical high; it is worth noting the presence of high pressure on the west coast. The subtropical high was fortified with a medium center of 1025 hPa (Fig. 2a, b).

Between the first and second periods (1993–2009), when the SLA survey by satellite was already available, the meridional anomalous wind field continued to prevail towards the tropic, even though heat flow was better organized from the equator to the pole. Over the SAO, the main atmospheric flow originated from cold air in the Weddell Sea east towards the region of study. Thus, colder air anomalies were present in the region of the study. The subtropical high presented intensification and expansion in its acting area (Fig. 3a, b).

The zonal flow over the extratropical SAO shows that its west component intensified around 45°S. The WBC, between 1979 and 2009, shows average meridional wind flow expanded on the northeast coast of Brazil, while it appeared weak in the south. The medium WSC, between 1981 (starting point of registered data) and 2009, showed few differences. Along with a stress rise over the SAO, downwelling occurred over the Weddell Sea and the Antarctic Peninsula. Over the Brazilian coast, including the area of research, there was a progressive reduction in WSC. This reduction also provides ocean water with lower volume aggregates on WBCs (Figs 4, 5).

In 1992, the first SLA surveys by Topex-Poseidon generated SLA data in coastal areas around the globe. For the study area, the SLA values in the scan tracks between 1992 and 2009 were negative, except
for 2003. In the same period, SSTA significantly changed all over the SAO, especially on WBC, along the subpolar front and tropical regions. In the study tangent area, warm current (Brazil Current) had a substantial rise in temperature, with anomalies of + 3.5 °C compared to the opening period in 1993 (OISST, not sho

Figure 2. Pressure and wind fields in Southern Hemisphere for the period of 1979–1992. In (a) wind fields (m s⁻¹) and medium and high latitudes pressure in surface (hPa) for the area of the study. In field wind anomaly (m s⁻¹) em 850 hPa in a polar projection

Figure 3. Pressure and wind fields in Southern Hemisphere for the period of 1993–2009. In (a) wind fields (m s⁻¹) and medium and high latitudes pressure in surface (hPa) for the area of the study. In field wind anomaly (m s⁻¹) with 850 hPa in a polar projection
The SSHA variable (OISST, not shown) also shows dipole dissolution between the Weddell Sea and SAO area, intensified in the first year of the series, 1993. During the 16 years, the SSHA on the Weddell Sea began to decrease while it rose over the SAO. During the same period, SSTA maps show clear warming for the entire SAO, especially in mid-latitudes, the same region as the rise of SSHA. In addition, when comparing WSC anomalies from the two periods, we can see a vorticity decrease of 60° to the south and SAO WBC and an intensification in the east boundary current, as well as in the mid-latitudes (Figs 4, 5).

Between 1981 and 1992, wind strength was predominantly downwelling in the SAO and upwelling in the SO. From 1993 onwards, the area to the south, which presented WSC upwelling, is intensified, especially on the Antarctic coast, with higher SSHA. Over the subtropical high, the convergent stress expands horizontally towards the WBC. Comparing the SSHA from the first and second series, the dipole dissolution between SO and SAO is clear, as the homogeneity of the deviation over the subtropical high disappears.

Figure 4. Wind stress curl in Southern Atlantic Ocean between 1981 and 1992. (a) anomaly results; (b) average results (1981–1992)

Figure 5. Wind stress curl in Southern Atlantic Ocean between 1993 and 2009. (a) anomaly results; (b) average results (1993–2009)
Description of atmospheric and oceanic fields with positive SLA

In the medium meridional wind field for 2010–2019, heat flows intensified, although there was a propensity for inversion when compared with the first period. This suggests a tropic-pole anomaly development. Over the SAO, we notice the inversion of meridional flow to the north by the Atlantic east and north to south anomaly by the west. This decade had, on average, north to south flow predominance in the area of study to the Antarctic Peninsula and Weddell Sea.

Meanwhile, at sea level, between the equatorial region and the mid-latitudes, the pressure gradient intensified throughout the study period, strengthening the characteristics of the subtropical high domain and positive SAM. The subtropical high remains fortified with an average center of 1021 hPa, which is more centralized over the ocean and away from the continents. This repositioning adds to the development of a low-pressure area from north to south over South America, from Bolivia to Patagonia, which was not observed in the previous decades (Fig. 6a, b). It is our understanding that this low-pressure area results not only from the subtropical high of the Atlantic and Pacific but also from Brazil’s current intensification and continental warming. At the same time, the Walker and Hadley cells weakened and expanded.

During this period, we observed the greatest shift and low-pressure belt change around the Antarctic. It began to organize three low centers dislodged to the north with the Amundsen-Bellingshausen Sea low and Lazarev and Dumont d'Urville-Davis Sea lows. We also observed the intensification of the pressure gradient between the high subtropical region toward the Lazarev Sea.

Figure 6. Pressure and wind fields in Southern Hemisphere for the period of 2010–2019. In (a) wind fields (m s^-1) and medium and high latitudes pressure in surface (hPa) for the area of the study. In (b) field wind anomaly (m s^-1) em 850 hPa with polar projection.
As of 2010, we observed a change in the SLA behavior in the study area. When using Mission Jason surveys, we noticed an anomaly increase until the end of the series in 2019. The SSTA elevates over the SAO and SO, except for a region below 40°S in WBCs. In conclusion, all extratropical SAO areas showed a gradual increase in SSTA (OISST, not shown). The warmer Brazil Current moves forward to the south, while the Malvinas Current progressively advances to the north with its lower temperatures (OISST - not show).

In this period, there was only one place where SSHA increase did not occur: east of the Antarctic Peninsula (OISST – not show). Between 2010 and 2019, the WSC anomaly related to the whole series shows a vorticity intensification over the SAO, highlighting the Weddell Sea and eastern Antarctic Peninsula, areas where torque was lower in the previous series. On average, during the 9 years, WSC kept with downwelling on SAO, with increasing capacity on the Brazilian and African coasts and upwelling of the SO, though comparably, more diluted on the Antarctic coast. Compared with the WSC from the previous series (1993–2009), the increase is clear between 30°S and 40°S latitudes (Fig. 7).

Figure 7. Wind stress curl on the Southern Atlantic Ocean between 2010 and 2019. (a) anomaly results; (b) average results (2010–2019)

Discussion and conclusion

Variations in ocean heat transport and regional sea level rise on the SAO were detected. The authors attributed these variations to the combination of extratropical atmospheric circulation and oceanic gyres toward the pole. From the coupled displacement of these two systems, it was possible to discuss regional sea level variations on the southern coast of Brazil.

This study identified an SLA inversion from negative to positive in 2010. Sea level rise in SAO has previously been identified through satellite data. The authors attributed this elevation to the steric height (halosteric and thermo steric) and changes in the oceanic mass. This elevation is coupled with movements to the subtropical, subantarctic, and polar fronts to the south, associated with the strengthening of the west winds to the west. The southernmost continental shelf of Brazil is considered by scholars to be an area with
long term high SLR propensity. Previously, southern Brazil and Uruguay coasts presented higher sea level values in summer and autumn, partially due to seasonal wind variability and solar radiation cycles\textsuperscript{37}.

The oceanic front displacement is simultaneous to the extratropical atmospheric circulation migration, resulting in two main reasons: positive annular mode tendencies\textsuperscript{19,20} and tropic expansion\textsuperscript{21}. As we observed in the period studied, between the first 30 years and the last 10 years, the Hadley cell expanded and weakened, although the zonal pressure gradient increased with less pressure over the South American continental border. Progressive deceleration of the zonal flow at the equator and baroclinic reduction at mid-latitudes over the South Atlantic prove the deceleration of Walker and Hadley circulations over the ocean\textsuperscript{38}. This affirmation allows us to claim that this process has been in progress for more than 15 years; however, the zonal barocliny over the SAO changed its behavior, with the presence of lower mean central pressure in the subtropical high after 2010, as well as a new lower pressure level along the Brazilian coast. Border Hadley cell location is intrinsic to oceanic factors, as eddy activities occur at mid-latitudes\textsuperscript{39–42}. Regression of meridional zonal mass medium flow, tropopause height, and static stability associated with positive SAM imply fostering Hadley circulation expansion toward the pole. Therefore, the southern extension of the Hadley circulation is susceptible to changes in forcing, such as rising greenhouse effect gases\textsuperscript{43–44}, sea surface temperature\textsuperscript{45} and stratospheric ozone depletion\textsuperscript{46–47}. A decrease in the meridional temperature gradient at mid-latitudes leads to the weakening of baroclinic wave activity, which allows Hadley cells to extend further toward the pole through tropopause height rise and conservation in tropical and subtropical latitudes of the SH\textsuperscript{33,40}. Its response to future global warming will be important weakening and expansion\textsuperscript{44–45,48–53}.

Wind anomalies on the surface also have an effect on sea surface temperature in middle latitudes. The SSTA of the SAO (1993–2019) presents growing values. The sea-level pressure fluctuation between mid and high latitudes associated with SAM causes oscillations in north-south subtropical jet streams\textsuperscript{7,54–58}. In the SAM-positive phase (negative), the SSTA tends to be negative (positive) at high latitudes and positive (negative) at medium latitudes\textsuperscript{59}. From 2014 onwards, the increase in SSTA at the WBC was even more pronounced. Throughout the period of the study, anomalies increased around 3.5 °C in the warm current (Brazil Current). It is also noteworthy that in the map series, the gradual advance of the Brazil Current toward the pole, while the Malvinas Current (cold) progresses less and less to the north. Similar results was reported, claiming strong regional and seasonal dependence of heat flows on SAO. The greatest increase in the heat flow is found in the limited region to the west and to the south by the Brazil Current front. The propensity to increase the SSTA is the main factor related to the heat flows along the Brazil Current front. The expansion and intensification of the subtropical high and gyre of the South Atlantic causes an increase in wind speed that intensifies the Brazil Current, leading to intensification of the heat flow in WBCs\textsuperscript{60}.

Comparing the first 30 years and the last 10 years, it is possible to see an inversion of the predominance of these streams. Initially, the meridional wind medium field at 850 hPa presents a stimulated flow towards the equator and cold over the SAO, originating from the Antarctic Peninsula. The zonal flow over the extratropical SAO presents its west component intensified around 45°S. During the period 1979–2009, the WBC on the northeastern Brazilian coast showed a strong medium meridional wind flow, while in the south, it appeared weak. This reduction also provides a lower volume of ocean water that pills up on WBCs.
From 2009, the heat flows intensified in both ways, although with an inversion in relation to the first period, suggesting anomalous growth between the tropic and the pole (vice versa). Over the SAO, there is also a south-to-north inversion of the eastern Atlantic fluxes and anomalous north-south from the west, originating from the study area to the Antarctic Peninsula and Weddell Sea, which is also responsible for the Hadley cell anomalies with anomalous heat and humidity transport to the south\textsuperscript{61–63}.

In relation to the Coriolis force in this process, it induces oceanic streams and sea surface high differences enforced by geostrophic balance and the pressure gradient. Our SSHA and SSTA records in SAO WBC between 1993 and 2019 show variations compatible with those of previous studies. The Brazil Current front, observed through SSTA and SSHA, presents 6° of latitude variation (1993-2008)\textsuperscript{64}. Regional sea surface height development is observed in mid latitudes in both hemispheres, while in high latitudes, the tendency is below the global average. Anticyclones and cyclone centers over subtropical and subpolar gyres are characterized by the regional sea surface height, which is used to detect oceanic gyre localization by ridges and valleys. These ridges and valleys are generated by downwelling and upwelling processes. Observing them between mid and subpolar latitudes, we noticed an increase in the sea level, together with the migration of subtropical and subpolar fronts towards the pole\textsuperscript{64}.

These fronts are the confluence and limit the subtropical, subpolar, and polar gyres. The subtropical fronts and gyres have been migrating decennially, 0.07° towards the poles\textsuperscript{18}. According to ocean circulation theory, oceanic gyres are propelled by wind on the surface, more specifically the WSC\textsuperscript{16}. The WSC sets up the wind capacity for transporting ocean water, as its speed does not clearly indicate its activity. Thus, we study wind stress as the horizontal force exerted on the oceanic surface, which is a vertical transfer of horizontal movement. Our study, in the period of 1981–1992, showed that force exerted by wind stress over SAO was predominantly downwelling. Between 1993 and 2009, WBC increase between 30°S and 40°S latitudes is clear, especially in SAO WBC. At the end of the series, the climatology presents vorticity intensification over the SAO. It is important to highlight WSC development on the Weddell Sea and eastern Antarctic Peninsula, where there was a decrease in torque. On average, during the 9 years, WSC kept with downwelling on SAO, with torque increase on the Brazilian and African coasts and upwelling on the SO, though comparably, more diluted on the Antarctic coast. WSC development on SAO WBCs collaborates with water piles in the study region, which, in turn, is associated with the subtropical gyre displacement, and SSTA and SSHA increase.

Comparing zonal wind climatology between 1993 and 2018, the pattern implies wind migration on the surface during the last four decades, from the extra tropical zone to higher latitudes. Consequently, the WSC has also changed\textsuperscript{18}. SAM positive tendency, through Ekman transport, shows maximum zonal wind stress at approximately 60°S, and maximum WSC at approximately 48°S\textsuperscript{16}. The SAM positive trends generates rotation of all ocean circulation at mid-latitudes and together, intensifies subtropical gyres towards the pole. This process causes the WSC vary implying changes in sea level (Fig. 8)\textsuperscript{10}. Modeling has demonstrated that extratropical atmospheric circulation undergoes systematic changes over gases, forcing the greenhouse effect, implying, consequently, in oceanic gyres\textsuperscript{11,13,14,18,19,65}. Shifting in gyres promotes a pronounced rise band at sea level over medium latitudes. This pattern overlaps with the global sea level average rise, causing an extra threat to the islands and coastal regions at medium latitudes\textsuperscript{66}. As part of
global circulation, the large-scale change in the oceanic gyre has the potential to reshape the circulation of the ocean over the tropics, close to coastal regions, and also to change meridional overturning circulation\textsuperscript{18, 67}.

![Figure 8. Comparison between sea level anomalies (left axis) from 1993 to 2019 in the study area and Southern Annular Mode index from Nan and Li (right axis)](image)

The consistent changes between 1993 and 2009 and between 2010 and 2019 in the SLA, SSTA, and SSHA were accompanied and influenced by significant variations in the pressure fields on the surface, winds, and temperature flows between high and medium latitudes. Regional sea level internal variability is one of the contributing factors for its increase, although recent studies have shown that anthropogenic forcing is an accelerating factor\textsuperscript{68}. Climate models that use increased greenhouse gas effects as a variable suggest that the change observed in oceanic gyres is a consequence of global warming, as the displacement of atmospheric circulation leads to changes in gyres and subtropical fronts\textsuperscript{18}. All rising global average temperatures cause changes in the coupling between atmospheric and oceanic circulations. Our results add to the understanding of the consequences of greenhouse gas increases in the atmosphere. This increase is correlated with the positive trend of the SAM and suggests effects on regional temperature and sea level in the middle latitudes of the SAO. Consequently, the continued expansion and weakening of the Hadley cell, associated with the displacement of oceanic gyres and fronts, drives regional SLAs in the SAO WBC. On the southern coast of Brazil, these anomalies have become positive. The risk to which the population of this area is subjected justifies the continuous monitoring of the causes and effects of global warming on the oceanic and atmospheric circulations of the SAO.

**Material and method**

Satellite sea level altimetric measures in coastal areas provide lower quality data because of the interference of obstacles that these surveys find (radar interaction with the solid surface of the ground and geophysical corrections–suspended particles in the atmosphere, reversed barometer, wind and tide effects, sea level variations among others). The software X-TRACK, designed by the Laboratoire d'Etudes en
Géophysique et Óceanographie Spatiale (LEGOS59–70), uses a post-processing algorithm that reexamines altimetry data from the seashore. Sea level anomalies (SLAs) were projected onto reference tracks with an interval of approximately 6–7 km between each point (1 s). Each processing step was performed on a regional basis with a low-pass filter (with a 40 km cutoff frequency). X-TRACK applies major corrections to SLA values obtained by Topex-Poseidon missions, Jasons 1, 2, and 3. This study used the product obtained from X-TRACK application over the SLA data (1993–2019) on the southern coast of Brazil (28°S, 35°S, 48°W, 54°W) from the Atlantic South American region obtained from https://www.aviso.altimetry.fr/. For the annual chart comparing the SLA and SAM series, we used the Nam and Li index71 (available at http://lip.gcess.cn/dct/page/65609).

Wind fields at 850 hPa and sea level pressure were obtained with reanalysis data ERA52,73 and Climate Reanalyzer (https://climatereanalyzer.org/ - Climate Change Institute, University of Maine)74, which uses data from ERA Interim. From monthly data, average and anomaly fields were generated for 1979–2019 in three periods: 1979–1992, 1993–2009, and 2010–2019. The choice of these three periods was determined by the results found in the SLA anomalies (positive from 2009, Fig 1). Thus, we observed and compared the wind field before the era of spatial altimetry and within satellite coverage time from Topex-Poseidon and Jason.

Wind stress curl (WSC) data were taken from the U.S. Navy Fleet Numerical Meteorology and Oceanography Center (FNMOC Wind and Ekman Transport Data, 360 × 180, monthly, from 6 h pressure, Lon+/-180; accessed via https://coastwatch.pfeg.noaa.gov/erddap/griddap/erdlasfnwpr_lonpm180.html; vectors "curl" from 1981 to 2019)76. Data were subjected to the same process we employed to calculate average and anomaly for the three periods mentioned above.

For observation and comparison, annual and monthly anomaly maps of sea surface temperature (SSTA)75 and sea surface height (SSHA)77 were obtained with Optimum Interpolation Sea Surface Temperature tool (OISST - accessed in https: //www.nmvl.noaa.gov/view/globaldata.html#SSTA https://www.nmvl.noaa.gov/view/globaldata.html#SSHA).

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Author contributions

V.S. analyzed the data, prepared the material, interpreted the results and wrote the manuscript; F.E.A. interpreted and revised the results; J.C.S. supervised the research and revised the manuscript ; P.A.R. prepared the data and maps and D.R.V. prepared de data and maps.

Competing interests

The authors declare no competing interests.
References

1. Church, J. A., Clark, P. U., Cazenave, A. & Gregory, J. M. Sea Level Change. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (eds Stocker, T. F. et al.) 1137–1216 (Cambridge University Press, 2013).

2. Gregory, J. M. et al. Concepts and Terminology for Sea Level: Mean, Variability and Change, Both Local and Global. Surv Geophys. 40, 1251–1289; 10.1007/s10712-019-09525-z (2019).

3. Ponte, R. M. et al. Towards Comprehensive Observing and Modeling Systems for Monitoring and Predicting Regional to Coastal Sea Level. Front Mar Sci. 6, 437; 10.3389/fmars.2019.00437 (2019).

4. Han, W. et al. Spatial Patterns of Sea Level Variability Associated with Natural Internal Climate Modes. Surv Geophys. 38, 217–250; 10.1007/s10712-016-9386-y (2017).

5. Fu, L. Wind-Forced Intraseasonal Sea Level Variability of the Extratropical Oceans. J Phys Oceanogr. 33, 436–449; 10.1175/1520-0485(2003)033<0436:WFISLV>2.0.CO;2 (2003).

6. Timmermann, A., McGregor, S. & Jin, F. F. Wind effects on past and future regional sea level trends in the southern Indo-Pacific. J Clim. 23, 4429–4437; 10.1175/2010JCLI3519.1 (2010).

7. Thompson, D. W. J. & Wallace, J. M. Annular modes in the extratropical circulation. Part I: Month-to-month variability. J Clim. 13, 1000–1016; 10.1175/15200442(2000)013%3C1000:AMITEC%3E2.0.CO;2 (2000).

8. Hall, A. & Visbeck, M. Synchronous Variability in the Southern Hemisphere Atmosphere, Sea Ice, and Ocean Resulting from the Annular Mode. J Clim. 15, 3043–3057; 10.1175/1520-0442(2002)015%3C3043:SVITSH%3E2.0.CO;2 (2002).

9. Roemmich, D. et al. Decadal spinup of the South Pacific subtropical gyre. J Phys Oceanogr. 37, 162–173; 10.1175/JPO3004.1 (2007).

10. Cai, W., Shi, G., Cowan, T., Bi, D. & Ribbe, J. The response of the Southern Annular Mode, the East Australian Current, and the Southern mid-latitude ocean circulation to global warming. Geophys Res Lett. 32(23); 10.1029/2005GL024701 (2005).

11. Cai, W. (2006) Antarctic ozone depletion causes na intensification of the Southern Ocean super-gyre circulation. Geophys Res Lett. 33(3); http://10.1029/2005GL024911 (2006).

12. Sen Gupta, A. & England, M. H. Coupled ocean–atmosphere–ice response to variations in the Southern Annular Mode. J Clim. 19, 4457–4486; 10.1175/JCLI3843.1 (2006).

13. Fyfe, J. C. & Saenko, O. A. Simulated changes in the extratropical Southern Hemisphere winds and currents. Geophys Res Lett. 33(6); 10.1029/2005GL025332 (2006).

14. Sen Gupta, A. et al. Projected changes to the Southern Hemisphere ocean and sea ice in the IPCC AR4 climate models. J Clim. 22, 3047–3078; 10.1175/2008JCLI2827.1 (2009).

15. Willis, J. K., Roemmich, D. & Cornuelle, B. Interannual variability in upper ocean heat content, temperature, and thermosteric expansion on global scales. J. Geophys. Res. 109(C120360); 10.1029/2003JC002260 (2004).

16. Munk, W. H. On the wind-driven ocean circulation. J Atmos Sci. 7, 80–93; 10.1175/1520-0469(1950)007%3C0080:OTWDOD%3E2.0.CO;2 (1950).

17. Wu, L. et al. Enhanced warming over the global subtropical western boundary currents. Nat Clim Chang. 2, 161–166; 10.1038/nclimate1353 (2012).
18. Yang, H. et al. Poleward shift of the major ocean gyres detected in a warming climate. *Geophys Res Lett.* **47**(5); 10.1029/2019GL085868 (2020).

19. Fyfe, J. C., Boer, G. J., Flato, G. M. The Arctic and Antarctic oscillations and their projected changes under global warming. *Geophys Res Lett.* **26**, 1601–1604; 10.1029/1999GL900317 (1999).

20. Thompson, D. W. J. & Solomon, S. Interpretation of recent Southern Hemisphere climate change. *Science.* **296**, 895–899; 10.1126/science.1069270 (2002).

21. Seidel, D. J., Randel, R. J. Recent widening of the tropical belt: Evidence from tropopause observations. *J Geophys Res.* **112**(D20); 10.1029/2007JD008861 (2007).

22. Hu, Y. & Fu, Q. Observed poleward expansion of the Hadley circulation since 1979. *Atmos Chem Phys.* **7**, 5229–5236; 10.5194/acp-7-5229-2007 (2007).

23. Seidel, D., et al. Widening of the tropical belt in a changing climate. *Nature Geosci.* **1**, 21–24; 10.1038/ngeo.2007.38 (2008).

24. Stachnik, J. P. & Schumacher, C. A comparison of the Hadley circulation in modern reanalyses. *J Geophys Res.* **116**(D22); 10.1029/2011JD016677 (2011).

25. Davis, S. M. & Rosenlof, K. H. A multidiagnostic intercomparison of tropical-width time series using reanalyses and satellite observations. *J Clim.* **25**, 1061–1078; 10.1175/JCLI-D-11-00127.1 (2012).

26. Liu, J., Song, M., Hu, Y. & Ren, W. Changes in the strength and width of the Hadley circulation since 1871. *Clim Past.* **8**, 1169–1175; 10.5194/cp-8-1169-2012 (2012).

27. Nguyen, H., Evans, A., Lucas, C., Smith, I. & Timbal, B. The Hadley circulation in reanalyses: climatology, variability, and change. *J Clim.* **26**, 3357–3376; 10.1175/JCLI-D-12-00224 (2013).

28. Adam, O., Schneider, T. & Harnik, N. Role of changes in mean temperatures versus temperature gradients in the recent widening of the Hadley circulation. *J Clim.* **27**, 7450–7461; 10.1175/JCLI-D-14-00140.1 (2014).

29. Solman, S. A. & Orlanski, I. Poleward shift and change of frontal activity in the Southern Hemisphere over the last 40 years. *J Atmos Sci.* **71**, 539–552; 10.1175/JAS-D-13-0105 (2014).

30. D’Agostino, R. & Lionello, P. Evidence of global warming impact on the evolution of the Hadley circulation in ECMWF centennial reanalyses. *Clim Dyn.* **48**, 3047–3060; 10.1007/s00382-016-3250-0 (2017).

31. Davis, N. A. & Davis, S. M. Reconciling Hadley cell expansion trend estimated in reanalysis. *Geophys Res Lett.* **28**, 439–446; 10.1029/2018GL079593 (2018).

32. Previdi, M. & Liepert, B. G. Annular modes and Hadley cell expansion under global warming. *Geophys Res Lett.* **34**(22); 10.1029/2007GL031243 (2007).

33. Mann, H. & Ha, K. Distinguishing changes in the Hadley circulation edge. *Theor Appl Climatol.* **139**, 1007–1017; 10.1007/s00704-019-03017-1 (2019).

34. Merrifield, M. A. & Maltrud, M. E. Regional sea level trends due to a Pacific trade wind intensification. *Geophys Res Lett.* **38**(21); 10.1029/2011GL049576 (2011).

35. Han, W. et al. Patterns of Indian Ocean sea level change in a warming climate. *Nat Geosci.* **3**, 546–550; 10.1038/ngeo901 (2010).

36. Ruiz-Etcheverry, L. A. & Saraceno, M. Sea Level Trend and Fronts in the South Atlantic Ocean. *Geosciences,* **10**(6); 10.3390/geosciences10060218 (2020).
37. Saraceno, M., Simionato, G. C. & Ruiz-Echeverry, L. A. Sea surface high trend at seasonal and interannual time scales in the Southeastern South American continental shelf between 27° S and 40° S. *Cont Shelf Res.* **91**, 82–94; [10.1016/j.csr.2014.09.002](https://doi.org/10.1016/j.csr.2014.09.002) (2014).

38. O'Neil, L. W., Chelton, D. B., & Esbensen, S. K. Observations of SST-Induced Perturbations of the Wind Stress Field over the Southern Ocean on Seasonal Timescales. *J Clim.* **16**, 2340–2354; [10.1175/2780.1](https://doi.org/10.1175/2780.1) (2003).

39. Grotjahn, R. Global atmosphere circulations-observations and theories. *Oxford University Press* (1993).

40. Held, I. M. The general circulation of the atmosphere, Geophysical Fluid Dynamics Program. *Woods Hole Oceanographic Institute.* [https://www.gfdl.noaa.gov/wpdb/downloads/files/user_files/ih/lectures/woods_hole.pdf](https://www.gfdl.noaa.gov/wpdb/downloads/files/user_files/ih/lectures/woods_hole.pdf) (2000).

41. Hu, Y. & Fu, Q. Observed poleward expansion of the Hadley circulation since 1979. *Atmos Chem Phys.* **7**, 5229–5236; [10.5194/acp-7-5229-2007](https://doi.org/10.5194/acp-7-5229-2007) (2007).

42. Korty, R. L. & Schneider, T. Extent of Hadley circulations in dry atmospheres. *Geophys Res Lett.* **35**(L23803); [10.1029/2008GL03584](https://doi.org/10.1029/2008GL03584) (2008).

43. Frierson, D. M. W., Lu, J. & Chen, G. Width of the Hadley cell in simple and comprehensive general circulation models. *Geophys Res Lett.* **34**(18); [10.1029/2007GL031115](https://doi.org/10.1029/2007GL031115) (2007).

44. Lu, J., Vecchi, G. & Reichler, T. Expansion of the Hadley cell under global warming. *Geophys Res Lett.* **34**(6); [10.1029/2006GL028443](https://doi.org/10.1029/2006GL028443) (2007).

45. Lu, J., Chen, G. & Frierson, D. M. W. Response of the zonal mean atmospheric circulation to El Niño versus global warming. *J Clim.* **21**, 5835–5851; [10.1175/2008JCLI2200.1](https://doi.org/10.1175/2008JCLI2200.1) (2008).

46. Son, S. W. *et al.* Impact of stratospheric ozone on Southern Hemisphere circulation change: a multimodel assessment. *J Geophys Res.* **115**(D3); [10.1029/2010JD014271](https://doi.org/10.1029/2010JD014271) (2010).

47. Kang, S. M., Polvani, L. M., Fyfe, J. C. & Sigmond, M. Impact of polar ozone depletion on subtropical precipitation. *Science.* **332**, 951–954; [10.1126/science.1202131](https://doi.org/10.1126/science.1202131) (2011).

48. Johanson, C. M. & Fu, Q. Hadley cell widening: model simulations versus observations. *J Clim.* **22**, 2713–2725; [10.1175/2008JCLI2620.1](https://doi.org/10.1175/2008JCLI2620.1) (2006).

49. Kang, S. M. & Lu, J. Expansion of the Hadley cell under global warming: winter versus summer. *J Clim.* **25**, 8387–8393; [10.1175/JCLI-D-12-00323.1](https://doi.org/10.1175/JCLI-D-12-00323.1) (2012).

50. Ceppi, P. & Hartmann, D. L. On the speed of the eddy-driven jet and the width of the Hadley cell in the Southern Hemisphere. *J Clim.* **26**, 3450–3465; [10.1175/JCLI-D-12-00414.1](https://doi.org/10.1175/JCLI-D-12-00414.1) (2013).

51. Seo, K. H., Frierson, D. M. F. & Son, J. H. A mechanism for future changes in Hadley circulation strength in CMIP5 climate change simulations. *Geophys Res Lett.* **41**, 5251-5258; [10.1002/2014GL060868](https://doi.org/10.1002/2014GL060868) (2014).

52. Tao, L., Hu, Y. & Liu, J. Anthropogenic forcing on the Hadley circulation in CMIP5 simulations. *Clim Dyn.* **46**, 3337–3350; [10.1007/s00382-015-2772-1](https://doi.org/10.1007/s00382-015-2772-1) (2016).

53. D'Agostino, R., Lionello, P., Adam, O. & Schneider, T. Factors controlling Hadley circulation changes from the Last Glacial Maximum to the end of the 21st century. *Geophys Res Lett.* **44**, 8585-8591; [10.1002/2017GL074533](https://doi.org/10.1002/2017GL074533) (2017).

54. Hartmann, D. L. & Lo, F. Wave-Driven Zonal Flow Vacillation in the Southern Hemisphere. *J Atmos Sci.* **55**, 1303–1315; [https://doi.org/10.1175/1520-0469(1998)055%3C1303:WDZFSI%3E2.0.CO;2](https://doi.org/10.1175/1520-0469(1998)055%3C1303:WDZFSI%3E2.0.CO;2) (1998).

55. Gong, D. & Wang, S. Definition of Antarctic Oscillation Index. *Geophys Res Lett.* **26**, 459–462; [10.1029/1999GL900003](https://doi.org/10.1029/1999GL900003) (1999).
56. Kidson, J. W. & Watterson, I. G. The structure and predictability of the “high-latitude mode” in the CSIRO9
general circulation model. J Atmos Sci. 56, 3859–3873; 10.1175/15200469(1999)056%3C3859:TSAPOT%3E2.0.CO;2 (1999).

57. Lorenz, D. J. & Hartmann, D. L. Eddy-zonal flow feedback in the Southern Hemisphere. J Atmos Sci. 58,
3312–3327; 10.1175/1520-0469(2001)058%3C3312:EZFFIT%3E2.0.CO;2 (2001).

58. Li, J. P. & Wang, J. X. L. A modified zonal index and its physical sense. Geophys Res Lett. 30 (12);
10.1029/2003GL017441 (2003).

59. Ciasto, L. M. & Thompson, D. W. J. Observations of large-scale ocean-atmosphere interaction in the
Southern Hemisphere. J Clim. 21, 1244–1259; 10.1175/2007JCLI1809.1 (2008).

60. Leyba, I. M., Solman, S. A. & Saraceno, M. Trends in sea surface temperature and air-sea heat fluxes
over the South Atlantic Ocean. Clim Dyn. 53, 4141–4153; 10.1007/s00382-019-04777-2 (2019).

61. Chiang, J. C. H. & Bitz, C. M. Influence of high latitude ice cover on the marine Intertropical
Convergence Zone. Clim Dyn. 25, 477–496; 10.1007/s00382-005-0040-5 (2005).

62. Yamazaki, K. & Watanabe, M. Effects of extratropical warming on ENSO amplitudes in an ensemble of
a coupled GCM. Clim Dyn. 44, 679–693; 10.1007/s00382-014-2145-1 (2015).

63. Zheng, F., Li, J. P., Kucharski, F., Ding, R. Q. & Liu, T. Dominant SST mode in the Southern Hemisphere
extratropics and its influence on atmospheric circulation. Adv. Atmos. Sci. 35, 881–895; 10.1007/s00376-
017-7162-7 (2018).

64. Goni, G. J., Bringas, F. & DiNezio, P. N. Observed low frequency variability of the Brazil Current front. J
Geophys Res. 116 (C10); 10.1029/2011JC007198 (2011).

65. Kushner, P. J., Held, I. M. & Delworth, T. L. Southern Hemisphere Atmospheric Circulation Response to
Global Warming. J Clim. 14(10), 2238–2249; 10.1175/1520-0442(2001)014%3C0001:SHACRT%3E2.0.CO;2 (2001).

66. Yin, J. & Goddard, P. B. Oceanic control of sea level rise patterns along the East Coast of the United States.
Geophys Res Lett. 40, 5514–5520; 10.1002/2013GL057992 (2013).

67. Lique, C. & Thomas, M. D. Latitudinal shift of the Atlantic Meridional Overturning Circulation source
regions under a warming climate. Nat Clim Chang. 8, 1013–1020; 10.1038/s41558-018-0316-5 (2018).

68. Hamlington, B. D. et al. Investigating the acceleration of regional sea level rise during the satellite
altimeter era. Geophys Res Lett. 47 (5); 10.1029/2019GL086528 (2020).

69. LEGOS. X-TRACK: Along track Sea Level Anomalies, date of access. http://doi.org/10.6096/CTOH_X-
TRACK_2017_02 (2020).

70. Birol, F. et al. Coastal applications from nadir altimetry: example of the X-TRACK regional products. Adv
Space Res. 59, 936–953; 10.1016/j.asr.2016.11.005 (2017).

71. Nan, S. L. & Li, J. P. The relationship between the summer precipitation in the Yangtze River valley and
the boreal spring Southern Hemisphere annular mode. Geophys Res Lett. 30 (24); 10.1029/2003GL018381
(2003).

72. Hersbach, H. et al. The ERA5 global reanalysis. Q J R Meteorol Soc. 146, 1999–2049; 10.1002/qj.3803
(2020).

73. Copernicus Climate Change Service (C3S); ERA5: Fifth generation of ECMWF atmospheric reanalyses
of the global climate. Copernicus Climate Change Service Climate Data Store (CDS), date of access. https:
://cds.climate.copernicus.eu/cdsapp#!/home (2017).
74. Climate Reanalyzer (Data/Image) from Climate Reanalyzer, Climate Change Institute, University of Maine, USA. date of access. https://ClimateReanalyzer.org (2020).

75. FNMOC. Fleet Numerical Meteorology and Oceanography Center: FNMOC Wind and Ekman Transport Data, 360x180, Monthly, from 6-hr Pressure. date of acess. https://coastwatch.pfeg.noaa.gov/erddap/griddap/index.html?page=1&itemsPerPage=1000 (2020).

76. OISST. Optimum Interpolation Sea Surface Temperature: Ocean temperature departure from average (Monthly Sea Surface Temperature Anomaly – SSTA), date of acess. http://www.ncdc.noaa.gov/oa/climate/research/sst/oi-daily-information.php (2020).

77. OISST. Optimum Interpolation Sea Surface Temperature: Sea surface height departure from the historical average (Monthly Sea Surface High Anomaly – SSHA). date of acess. http://ibis.grdl.noaa.gov/SAT/SeaLevelRise (2020).