The influence of Arctic sea ice extent on northern South American precipitation

By

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Abstract:

The arctic sea ice is presenting unprecedent retreat and some research state that the arctic region is warming three to four times faster than the rest of the world. At the same time, middle latitudes have experienced extreme events such as extreme snow fall and episodes of extreme low temperatures which some literature suggest that are connected to the arctic warming. In this thesis we explore teleconnections between the arctic and the tropics, most specifically northern South America (nSA). For this analysis we have two objectives: exploring how the arctic sea ice decline could influence the precipitation over nSA, and second, using two PAMIP models scenarios to explore future impacts of the arctic sea ice loss over the precipitation in nSA. Firstly, using sea ice data provided by NSIDC and precipitation monthly means reanalysis data for the same period provided by NCEP/NCAR, we correlate precipitation anomalies in equatorial South America with Arctic sea ice extent anomaly series. A precipitation center with the highest correlation with Arctic sea ice extent anomalies was identified in the eastern part of equatorial South America (in the Amazon rainforest). This region's time series was then compared to the sea ice extent anomaly using a linear regression dependence analysis. An rsquare of 15% was found; in other words, the sea ice variability might influence 15 percent of the precipitation volume anomaly in some parts of Brazil's northern and northeastern regions. Secondly, we used five models from the PAMIP to quantify the precipitation changes over nSA using two different scenarios, one employing present-day SST and sea ice concentration (SIC) and other consisting in projections of the SIC in the Arctic considering 2°C atmospheric warming relative to pre-industrial conditions. The model average projections for the DJF season show drier conditions in the northern part of the Amazon and wetter conditions in the southern part in the >2 °C scenario. At the same time, the JJA season shows wetter conditions in the western part of the Amazon region, and drier conditions in the eastern part. These precipitation changes are related to changes in the atmospheric circulation in the tropical Atlantic.

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Chapter 1 – Introduction

This thesis explores teleconnections between high latitudes and the tropics. Teleconnections in atmospheric sciences are described as a climate phenomenon that occurs in one region of the Globe and can be reflected in other regions (Nigam, 2003). El Niño, the anomalous warming of the Pacific Equatorial Ocean that causes precipitation anomalies around the globe, is probably the best example of teleconnections (Trenberth, 1997). We are particularly interested in whether Arctic warming can affect precipitation changes in northern South America, the region where the Amazon rainforest is located.

Among all regions of the Earth, there is a consensus in the literature that the Arctic region has shown the highest warming rate. Some papers show that the Arctic region has warmed twice (Cohen et al., 2014), three times (Bintanja, 2018), or nearly four times (Rantanen et al., 2022) as fast as the rest of the world. Due to such changes in the Arctic, the investigation of high latitudes – tropics teleconnections have gained momentum, especially using models (Deser, Tomas & Sun 2015; Sun, Alexander & Deser 2018; Wang et al., 2018). Atmosphere-only models show that the ITCZ (Intertropical Convergence Zone) could move northwards in response to Arctic sea ice loss, while ocean-atmosphere models show that the ITCZ could move southward. Changes in the ITCZ's position will reflect changes in the precipitation regime of northern South America. An anomalous change northward will lead to a long dry season in the Amazon, possibly driving droughts. In contrast, a southward change could increase the precipitation in the region.

1.1 Rationale and Context

The most pronounced of the many environmental changes experienced by the Arctic region in the early 21st Century is the retreating extent of sea ice cover (SIC), which has important consequences for the coupled atmospheric-oceanic system (e.g., by affecting the formation of the oceanic deep water) and the global climate. However, the implications of the rapid reduction transcend physical environmental changes. For example, retreating sea ice reduces the breeding areas available for seals and polar bears. Indigenous communities are forced to cope with extended periods of open water, hindering their ability to hunt. Additionally, the opening of the Northwest Passage is changing Arctic geopolitics by attracting new players (e.g., China) and modifying the military strategy for the Northern Hemisphere (ACIA, 2004; U.S. Navy, 2014; IPCC 2019).

Arctic sea ice formation and extent are driven by internal (e.g., feedback) and external forces, such as the tropical sea surface temperatures (SSTs) over the Pacific and Atlantic oceans (Flournoy et al., 2016; McCrystall et al., 2020). The focus of current literature is whether Arctic sea ice loss could influence mid-latitude weather and climate. Some studies indicate that sea ice loss has caused colder winters in mid-latitudes in the last decade (Cohen, Pfeiffer & Francis 2017), while some other researchers suggest that sea ice loss has minimal influence over midlatitude winters (Screen & Simmonds 2013). These findings have generated a new question regarding the possible impact of Arctic sea ice loss on low-latitude weather and climate. Results from atmosphere-only models suggest that the Intertropical Convergence Zone (ITCZ) could be displaced northwards, producing longer dry seasons over southern Amazonia and longer wet seasons in India (Broecker & Putnam, 2013). These changes in climate may result in social and economic impacts in the tropics (e.g., droughts in some regions of the Amazon (Nobre et al., 2018). However, ocean-atmosphere coupled models suggest that the weakening of the Atlantic meridional overturning circulation (AMOC) could dampen the shift of the ITCZ and move it southwards. Understanding future changes requires an analysis of past trends. Paleoclimate proxies show that the ITCZ shifted southward during colder periods in the Northern Hemisphere.

1.2 Relevance

Teleconnections between high latitudes and the tropics are poorly understood. Paleoclimate research shows that changes in high latitudes (viz., the expansion and contraction of polar ice cover) are linked to and affect low latitudes (i.e., by moving the thermal equator towards the warmest continent) (Broccoli, Dahl & Stouffer, 2006). As the Arctic has warmed up faster than any other region (Walsh, 2014), scientists have explored whether extreme events in the Northern Hemisphere mid-latitudes could be triggered by the Arctic Amplification (hereafter referred to as AA) (Vihma 2014; Cohen et al., 2018). Another question regarding the possible connection of Arctic warming to climate variability in distant regions such as the tropics is through the influence of the trade wind patterns or the ITCZ position. Sea ice loss could drive the North Atlantic Oscillation to its negative phase, which slows down the trade winds in the

Atlantic sector (Pedersen et al., 2016). On a larger scale, sea ice loss and the weakening of the AMOC could influence the position of the ITCZ (Liu & Fedorov, 2019), thus linking the high latitudes and the tropics.

Changes in the tropics can potentially affect the lives of millions of people worldwide through changes in precipitation patterns. We focus on possible impacts in northern South America, which is home to the Amazon rainforest, one of the most biodiverse places in the World. The tropical North Atlantic Ocean is the primary source of moisture in the Amazon rainforest. Variations in the velocity of the trade winds could influence the amount of humidity transported from the ocean toward the continent. The most important regional source of precipitation is from ITCZ-induced air mass movement. Thus, changes in the position of the ITCZ could affect the precipitation regime, especially at the borders of the ITCZ seasonal movement (Reboita et al., 2010). The Amazon region is also the primary source of moisture in the Midwest, Southeast, and South Brazil. The low-level jets (850 hPa) blowing from the tropical North Atlantic Ocean are deflected to the south-southeast by the Andean Cordillera, distributing the moisture to central and south-eastern South America (Vera et al., 2006) (Figure 1.1). Therefore, changes in the trade wind velocity or the ITCZ position could directly affect the precipitation regime throughout South America.

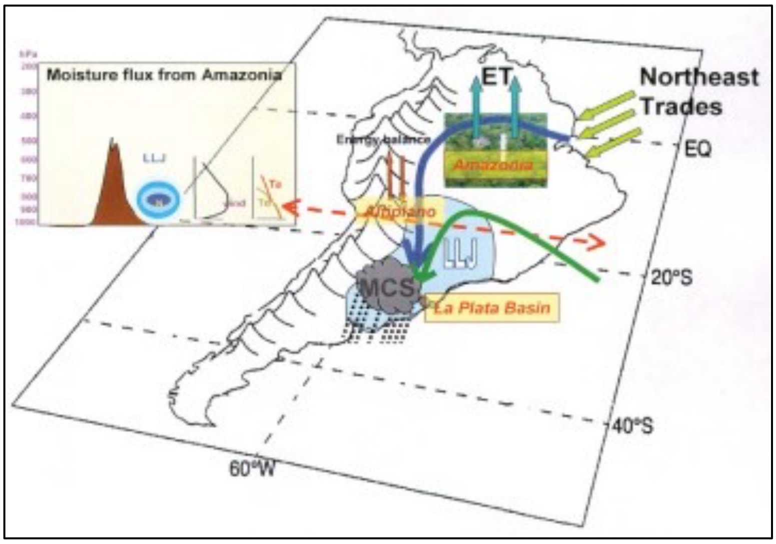

Figure 1.1 Schematic diagram of poleward moisture transport over South America. Source: Vera et al. (2006). Used with permission, American Meteorological Society.

According to Shi et al. (2000), that elaborates on 1960 – 1997 South America precipitation, the wettest region in South America is situated over northwest of Brazil, that includes that biggest part of the Amazon basin. In this region, the average precipitation is near 2450 mm/year. At the same time, northeastern Brazil has an average of 700mm/year. The precipitation over South America is not well distributed through the year, with the highest precipitation volumes during the southern hemisphere summer (December-January-February) (Reboita et al., 2010). Cai et al., (2020) pointed out that the El Niño–Southern Oscillation (ENSO) affects the precipitation over South America. El Niño is frequently associated with droughts in the Amazon region due to the change of the position of the Walker cell eastward.

1.3 Problem Statement and Objectives

The influence of teleconnections between the Arctic and northern South America is poorly understood. As a result of climate change in the Arctic, the position and width of the ITCZ may be affected, potentially resulting in drought and other impacts to the Amazon and the agricultural region of Brazil. The overarching goal of this master's thesis is to explore possible linkages between Arctic sea ice extent variability and the climate of the western hemisphere tropics. Two specific research questions are used to address the goal.

1.3.1 Is the precipitation in low latitudes affected by the variability of Arctic sea ice?

1.3.2 Could future changes in the Arctic sea ice extent affect the northern South American precipitation?

1.4 Methods

1.4.1 Methods Chapter 3

The National Snow and Ice Data Center (NSIDC) provides a robust and widely used global suite of sea ice products obtained by satellite microwave sensors with a 25 × 25 km resolution starting from January 1979. Many studies have used these products to obtain SIE monthly means from January 1979–the present (Fetterer, Knowles, Meier & Savoie, 2017).

Reanalysis products are widely used in climate and forecast research and commonly used to investigate teleconnections (i.e., Cohen 2016; Francis, Vavrus and Cohen, 2017). This product uses data assimilation to combine observations, such as buoys, aircraft, weather stations, and models, to provide a gridded dataset (Parker, 2016). Several reanalysis products are available that cover the globe or regional areas. The National Center for Environmental Prediction (NCEP) provides a particular global reanalysis with a spatial resolution of 2.5-degree latitude x 2.5-degree longitude, totalizing a grid of 144 x 73, from 90 degrees North to 90 degrees South and from 0 degrees to 357.5 East.

We used the above datasets to calculate SIE monthly anomalies between January 1979 – December 2019 and precipitation monthly anomalies and associated pressure fields over the same period. The study area was: 0° and 100° W, 88.5° N, and 20° S.

To validate the precipitation in northern Brazil, we selected weather stations (Fig. 1.2). We then performed the Kolmogorov-Smirnov test (KS test) between the weather stations and the nearest reanalysis grid point.

$$D_{max} = |F(X) - S_N(X)|$$

Where D_{max} is the maximum vertical distance between the F(X) (standard normal Cumulative Distribution Function - CDF) and $S_N(X)$ (empirical CDF) (Pes et al., 2017).

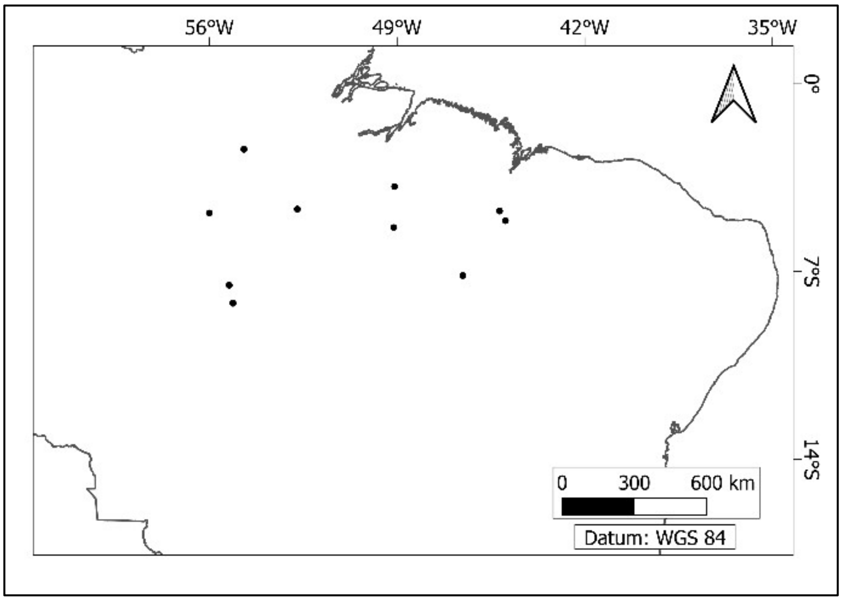

Figure 1.2 Location of weather stations used to validate precipitation reanalysis of NCEP

After validating the precipitation data, we produced correlation maps, a visual expression of correlation coefficients. Every grid point of the reanalysis products was correlated with Arctic sea ice extent anomalies, and these correlation coefficients interpolated (Nearest neighbor), forming a map.

$$P(\alpha_i, \alpha_j) = \frac{cov(\alpha_i, \alpha_j)}{\sqrt{var(\alpha_i) \times var(\alpha_j)}},$$

where cov(αi,αj) is the covariance, var(αi) is the variance of αi, and var(αj) is the variance of αj (Mu, Liu & Wang, 2018).

We then compared it with the SIE anomaly using a linear regression dependence analysis composed of a dispersion diagram. The cross-correlation analysis showed a one-month lag between the SIE and the precipitation.

Both time series were divided into three different periods, based on the SIE anomaly variability, first January 1979 – December 1996, second January 1997 – December 2006 & third January 2007 – December 2015. Linear regression was then calculated for each period, as the second period showed a moderate correlation, a *t*-test was performed, and the confidence exceeded 95%.

An article was submitted to the Brazilian Journal of Climatology (Souza Junior, Enoil, Eder Maier, Jefferson Simoes, Satwant Kaur, and David Barber. On the relationship between Arctic Sea Ice and Precipitation over the Brazilian Northeast and Amazon rainforest), based on Chapter 3 of this thesis.

1.4.2 Methods Chapter 4

To address the second research question, we used two SST and Sea Ice Concentration (SIC) scenarios provided by PAMIP (Polar Amplification Model Intercomparison Project). Which are: present SST - present SIC (pdSST-pdSIC), present SST - future Arctic SIC (pdSSTfutArcSIC) (Smith et al., 2019).

Present conditions are referent to the climatological mean from January 1979 to December 2008 and considering the global mean temperature of 14.24 °C). A 2 °C warmer (15.67 °C), above pre-industrial levels (13.67 °C), is considered for future conditions.

For pdSST-pdSIC and pdSST-futArcSIC there are five models available: canESM5, CESM2, FGOALS, MIROC6, and norESM2. Latitudinal and longitudinal resolution and the number of members is found in Table 1.1. We plotted the present scenario models alongside the NCEP Reanalysis (mean January 1979 – December 2008, the same period considered for present conditions in the models) to compare the reanalysis and models' datasets.

The first step is calculating the average of members for each model, for norESM2 only the first 100 ensemble were considerate. Then, the difference between pdSST-futArcSIC and pdSSTpdSIC will show any influence of the sea ice loss over northern South America.

Table 1.1 PAMIP models, resolutions, and a number of members

Model	Lat resolution	Lon resolution	Grid	Members
canESM5	2.76	2.81	64 x 128	100
CESM2	0.94	1.25	192 x 288	100
FGOALS	1	1.25	180 x 288	100
MIROC6	1.38	1.4	128 x 256	100
norESM2	1.89	2.5	96 x 144	200

To explore the mechanisms behind the precipitation changes, we performed the same experiments using different variables, such as zonal and meridional wind components.

An article will be submitted to Journal of Climate (or another climate-related journal) based on Chapter 4 of this thesis.

1.5 Thesis Outline

This thesis is composed of five chapters. Chapter two consists of a literature review describing the role of Arctic sea ice in the climate system. In addition, it explains how climate change has affected Arctic sea ice cover and its possible linkages with the weather and climate of middle latitudes. This chapter also details the relationship between the Arctic and low-latitude climate, mentioning paleoclimate research and forecasting models.

Chapter three explores the relationship between the Arctic sea ice extent anomalies and the precipitation anomalies over northern South America using NCEP reanalysis from January 1979 to December 2019.

Chapter four investigates how future changes in the Arctic sea ice concentration (SIC) could influence northern South American precipitation using the five Polar amplification Model Intercomparison Project (PAMIP). The methodology of both chapters is discussed in more detail in the next section. Chapter five is reserved for conclusions and final considerations.

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Chapter 2 - Background and literature review

2.1 Introduction

The most pronounced of the many environmental changes experienced by the Arctic region in the early 21st Century is the reduction of sea ice cover, which has important consequences for the coupled atmospheric-oceanic system (e.g., by affecting the formation of the oceanic deep water) and the global climate. However, the consequences of the rapid reduction transcend physical environmental changes. For example, retreating sea ice reduces the breeding areas available for seals and polar bears. Indigenous communities are forced to cope with more extended periods of open water, hindering their ability to hunt. Additionally, the opening of the Northeast Passage is changing Arctic geopolitics by attracting new players (e.g., China) and modifying the military strategy for the Northern Hemisphere (ACIA, 2004; U.S. Navy, 2014 & IPCC 2019).

Arctic sea ice formation and extent are driven by internal (e.g., feedback) and external forces, such as the tropical SSTs over the Pacific and Atlantic oceans (Flournoy et al., 2016; McCrystall et al., 2020). Recent studies have focused on whether Arctic sea ice loss could influence midlatitude weather and climate. These investigations indicate that sea ice loss has caused colder winters in mid-latitudes in the last decade (Cohen, Pfeiffer & Francis, 2017), however other models suggest that sea ice loss has minimal influence over mid-latitude winters (Screen and Simmonds, 2013;). Some research has been done regarding the possible impact of Arctic sea ice loss on low-latitude weather and climate. Results from atmosphere-only models suggest that the Intertropical Convergence Zone (ITCZ) could be displaced northwards, producing longer dry seasons over southern Amazonia and longer wet seasons in India (Broecker & Putnam, 2013). These changes in climate may result in social and economic impacts in the tropics (e.g., droughts in some regions of the Amazon (Nobre et al., 2018). However, ocean-atmosphere coupled models suggest that the weakening of the Atlantic meridional overturning circulation (AMOC) could dampen the shift of the ITCZ and move it southwards. Understanding future changes requires an analysis of past trends. Paleoclimate proxies show that the ITCZ shifted southward during colder periods in the Northern Hemisphere.

2.2 Arctic sea ice cover

2.2.1 Sea ice formation

A significant difference between the northern and southern polar regions is Antarctica, which is surrounded by an ocean, whereas the Arctic is an ocean surrounded by continental landmasses. The Antarctic ice sheet is more than 4,000-m thick and is surrounded by a sea ice cover ranging from 2.46 - 3.75 × 10^6 km^2 in summer to 17.5 - 18.9 × 10^6 km^2 in winter (Cavalieri & Parkinson, 2008). In the northern polar region, the ocean basin is almost entirely covered by sea ice during the winter, reaching 15.43 × 10^6 km^2 and shrinking to 6.41 × 10^6 km^2 in September (climatological mean values for 1981–2010) (NSIDC, 2020).

The Arctic Ocean begins freezing at approximately -1.8 °C (depending on the salinity), forming small ice crystals called frazil ice. The frazil ice aggregates, forming grease ice (in calm conditions) or pancake ice (in rough conditions). Grease ice evolves into a thin ice layer called nilas; the wind and currents push against each other in a process called rafting. Eventually, the ice continues to grow to form congelation ice. Under rough conditions, pancakes collide with each other during rafting, and if the ice is thick enough, ridging occurs (i.e., when piles of sea ice form ridges (Lüpkes et al., 2008).

The Arctic Ocean's primary sea ice circulation regimes are the Beaufort Gyre (BG) and the transpolar drift (TPD). The Beaufort Gyre, an anticyclonic circulation regime in the Beaufort Sea region, contributes to the recirculation and accumulation of sea ice in the Canadian archipelago (Lüpkes et al., 2008). The BG presents clockwise and counter-clockwise circulation patterns in the Beaufort Sea under the dominant influences of the Beaufort High and the Icelandic Low, respectively. The two atmospheric pressure systems alternate on time scales of 5–7 years and are driven by poorly understood mechanisms (Proshutinsky et al., 2015). The TPD moves the ice all the way from the Laptev Sea to the Fram strait (Dukhovskoy, 2004; Kaur, Ehn & Barber, 2018). The intensities of the Beaufort High and Icelandic Low-pressure systems are associated with the strength and orientation of the TPD. An intensified Beaufort High and weakened Icelandic Low led to a more direct path from the Laptev Sea to the Fram

Strait. A weakened Beaufort High and intensified Icelandic Low cause sea ice to drift counterclockwise in the Eurasian Basin, flowing from the Laptev Sea towards the Canadian Basin and the Fram Strait (Kwok, Spreen & Pang, 2013), where it melts (Figure 2.1).

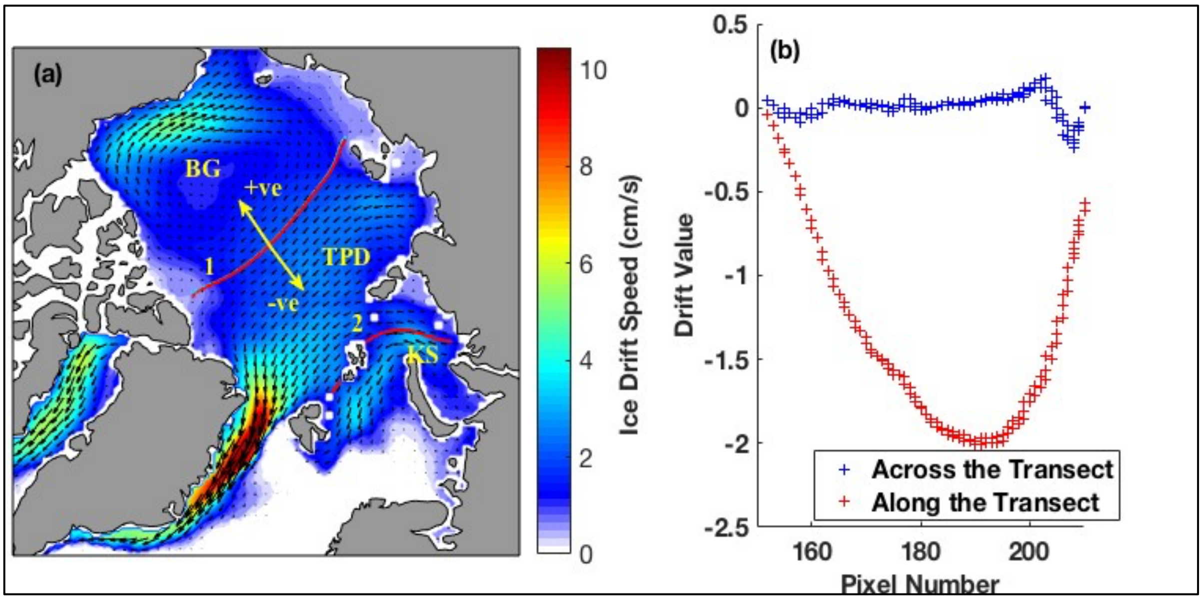

Figure 2.1 (a) Beaufort Gyre and Transpolar Drift. The latter drags a significant part of the sea ice south along the east coast of Greenland, plotted here with mean winter sea ice drift speed (cm/s) from October 1979 to April 2015. (b) Relative values across and along the transect. Source: Kaur, Ehn & Barber (2019).

The North Atlantic and the North Pacific winter sea ice cover extents are very different. During the maximum sea ice extent (March), open water is found as far north as 75°N to the west of Svalbard due to heat transport by the North Atlantic Drift (the continuation of the Gulf Stream) that flows through the Fram Strait and the Norwegian sea. In the North Pacific, sea ice extends farther south, covering one-third to one-half of the Bering Sea (Barry & Hall-McKim, 2018).

2.2.2 The role of sea ice cover in the climatic system

The polar regions are crucial to the climate system and act as planetary radiators (heat sinks). The atmosphere and the oceans transport heat toward the poles. The poles are cold during the polar night because of the lack of solar radiation and the highly reflective surfaces created by the snow and ice, which reflect approximately 60%–95% of the received solar radiation. In contrast, the ocean reflects 4%–10% of the energy received from the Sun (Serreze & Barry, 2011). Specifically, sea ice acts as an insulator between the ocean and the atmosphere. The low thermal conductivity of sea ice (further decreased with a snow cover) reduces ocean-atmosphere heat exchange, moisture transfer from the ocean to the atmosphere, and momentum from the atmosphere to the ocean (Shokr & Sinha, 2015; Barry & Hall-McKim, 2018; Zheng et al., 2019).

The energy released to the atmosphere when seawater freezes is approximately 80 cal g^{-1}; energy is absorbed as sea ice melts to produce water at the same temperature. The heat exchange between the ocean and the atmosphere can influence local weather and the regional climate (Shokr & Sinha, 2015). Since the sea ice is in constant motion, openings can occur in the sea ice pack. The winter heat flux from the openings can release large amounts of energy into the atmosphere; however, the openings tend to refreeze quickly (Maykut, 1982). The opening and re-freezing could account for approximately half of the turbulent heat transfer to the atmosphere in winter (Maykut, 1982). Nonetheless, even a small percentage of open water or refrozen thin ice in the middle of the sea ice pack could release enough energy to increase the overlying atmosphere by several degrees (Lüpkes et al., 2008). Barry (1997) observed up to 200–300-m wide openings in the Arctic.

Polynyas (a Russian term), another type of opening in the ice pack, are important for heat transfer from the ocean to the atmosphere. A polynya is an area of open water surrounded by sea ice formed by upwelling or katabatic winds. Barber & Massom (2007) mapped the principal arctic polynyas, the largest of which are off the coast of Siberia; many smaller polynyas are close to the Canadian Arctic Archipelago.

Sea ice formation is also connected to the formation of deep ocean currents. Freezing seawater slowly expels salt into the surrounding water, increasing salinity and density, and sinks into the deep ocean. This process originates from the thermohaline circulation (the global conveyor belt), which then flows southward (Rahmstorf, 2013). A similar process occurs in the Southern Ocean and the subglacial meeting of the Antarctic ice shelves that force thermohaline circulation.

2.2.3 Forcing factors affecting sea ice extent

Internal and external forces can induce sea-ice variability. Internal forces include climatic components, such as the atmosphere (winds and sea level pressure), ocean SSTs and ocean currents), and thermodynamic processes, such as albedo (IPCC, 2014). External forces include orbit cycles, massive volcanic eruptions, oceanic multidecadal cycles, and climate teleconnections (Halloran et al., 2020). The latter is explained in more detail in Section 2.6.3, and the role of ocean circulation is described in more detail in Sections 2.4 and 2.5. Internal processes include several feedbacks in the regional environment, such as permafrost thawing, bio-optical feedback, and albedo. The permafrost stores abundant greenhouse gases which are released into the atmosphere when it thaws. This increases the greenhouse effect and leads to the further melting of sea ice (Goosse et al., 2018). The bio-optical feedback occurs when sea ice retreat leads to phytoplankton blooms, which absorb solar radiation, resulting in warmer SST (Goosse et al., 2018). The albedo feedback occurs with the reduction of sea ice cover; the ocean absorbs the radiation reflected by the snow cover on the top of the sea ice and warms the SST, which releases more energy to the overlying atmosphere, contributing to higher sea ice loss (Serreze & Barry, 2011; Bhatt et al., 2014). These internal positive feedbacks lead to disproportionate warming between the Arctic and the mid-latitudes known as the Arctic Amplification (AA) (Serreze & Barry, 2011; Bhatt et al., 2014).

Suborbital scale forcing also influences the Arctic SIE on millennial to decadal scales in the form of solar activity, volcanic eruptions, and oceanic and atmospheric circulation (Polyak et al., 2010). Bond (2001) attributes a 1,500-year cycle in thermohaline circulation to solar cycles. In the late Holocene (4,000 BP), temperature variations caused cooling and warming intervals that produced greater sea ice cover variation than the last millennium (Jennings & Weiner, 1996; Bond et al., 1997; Moros et al., 2006).

2.3 Late 20th and early 21st Century warming and reduction of Arctic sea ice extent

According to Richter-Menge et al. (2016), the Arctic region recorded a total average surface temperature increase of 3.5 °C from 1900–2016. In 2019, surface air temperatures above 60°N registered the second warmest year since 1900, only behind 2016 (Thoman et al., 2020). This rapid warming is attributed to the intensification of the greenhouse effect due to the increase in greenhouse gas concentrations in the atmosphere (Stroeve & Notz, 2018) and to internal feedbacks. A combination of various climate proxies from around the Arctic region shows that temperatures from the mid-19th to mid-20th Century reached the highest levels in 400 years (Overpeck et al., 1997). According to Overpeck et al. (1997), warming is related to solar activity and decreased volcanic eruptions. Kaufman et al. (2009) indicated that the Arctic region is now warmer than at any time in the past two thousand years, reverting the cooling trend that initiated the Little Ice Age. Meier et al. (2012) used pre-satellite data to reconstruct the Arctic SIE starting in the 1950s. The September SIE decreased by 6.8% and 12.9% per decade^{-1} from 1953–2011 and 1979–2011, respectively.

The Arctic is anomalously warmer in the fall and winter than in the spring and summer because the ocean radiates summer energy back into the atmosphere due to sea ice loss (Serreze & Barry, 2011; Zheng et al., 2019). Sea ice has been continuously monitored with satellites and their passive microwave sensors since 1978, providing data on sea ice concentration and extent every other day until July 1987 and daily from 1987 to the present (Stroeve & Notz, 2018). The Arctic is changing rapidly; the sea ice extent in September 2012 was 55% smaller than in September 1980 (Jeffries, Overland & Perovich, 2013). The decrease in the extent and thickness of Arctic sea ice is accelerating (ACIA 2004; Meredith et al., 2019). Sea ice decline has been more pronounced in summer than in winter (Comiso, 2012). In addition, the proportion of multiannual sea ice (MYI) in relation to the first-year ice (FYI) has declined rapidly in recent decades. Multiyear sea ice is thicker and has more ridges and hummocks than FYI, slowing the ocean-to-atmosphere heat transfer (Comiso, 2012).

Sea ice loss differs by region, with the most significant decline in the western Arctic (Barents & Kara seas) (Ding et al., 2017). The mechanisms that lead to the accelerated decline in the west of the Arctic are not yet fully understood (Liu et al., 2021). According to Liu et al. (2021), the recent positive Pacific North Atlantic (PNA) pattern may have contributed to sea ice decline in the region through heat and moisture fluxes into the western Arctic that increased lower tropospheric temperatures and downwelling long-wave radiation. Spreen, Kwok & Menemenlis (2011) found that the drift speed of sea ice increased by 10.6% from 1992–2009. The increased mobility of sea ice causes openings and closings that affect the heat exchange and momentum between the ocean and the atmosphere (Kwok et al., 2013). Lindsay and Schweiger (2015) found that the annual mean Arctic sea ice thickness decreased by 65% from 3.59 m in 1979 to 1.25 m in 2012. Kwok (2018) analyzed the sea ice cover from 1999–2017 and found that MYI shrank by 2×10^6 km^2, which corresponds to 50% of the total area and represents an ~85% variance in the sea ice volume.

SIE shows a significant negative linear correlation with increasing global temperatures (Mahlstein & Knutti, 2012). The trend accelerated after a positive anomaly in September 1996, as SIE decreased by 18% per decade from 1996–2010 (Ogi & Rigor, 2013). Additionally, Ogi and Rigor (2013) found that the increasing trend is associated with a change in the mean wind circulation at 925-hPa from 1979–1996 and 1996–2010. Winter winds blew from the Norwegian Sea towards the Barents Sea from 1979–1996 and the Barents Sea towards the Fram Strait from 1996–2010. A low-pressure cell centered in northern Russia resulted in air flow towards north Alaska during the summer. However, anticyclonic circulation over the Arctic throughout the year may have favoured sea ice runoff through the Fram Strait, leading to negative SIE anomalies (Ogi & Rigor, 2013) (Figure 2.2).

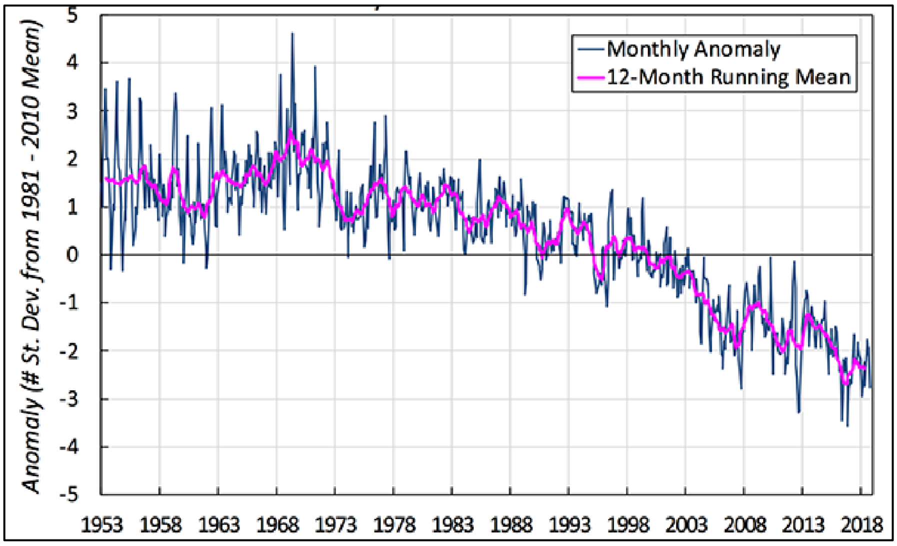

Figure 2.2 Mean sea ice anomalies, 1953–2018: Sea ice extent departures from monthly means for the Northern Hemisphere. Data from the UK Hadley Centre from January 1953 to December 1979 are based on operational ice charts and other sources. Data from January 1979 are derived from passive microwave satellite sensors. Image by Walt Meier and Julienne Stroeve, National Snow and Ice Data Center, University of Colorado, Boulder.

September 2007 marked a record low SIE (4.16 million km^2), 24% lower than the previous record in September 2005. The reasons for the record low value are attributed to positive temperature anomalies and southwards winds pushing more sea ice out of the Arctic (Comiso et al., 2008). Another record low was set in September 2012 (3.4 million km^2) due to storms penetrating the central Arctic a month earlier (Parkinson and Comiso, 2013). In 2016, SIE reached virtually the same extent as in 2007 (4.17 million km^2). In the last 13 years, the Arctic SIE has recorded its 13 lowest extents during the satellite observational era (NSIDC, 2019), with the second-lowest satellite record extent (3.92 million km^2) in September 2020 (Figure

2.3) (NSIDC, 2020). This sharp reduction in sea ice coverage is projected to cause a summer sea ice-free Arctic (Stroeve et al., 2012; Meredith et al., 2019).

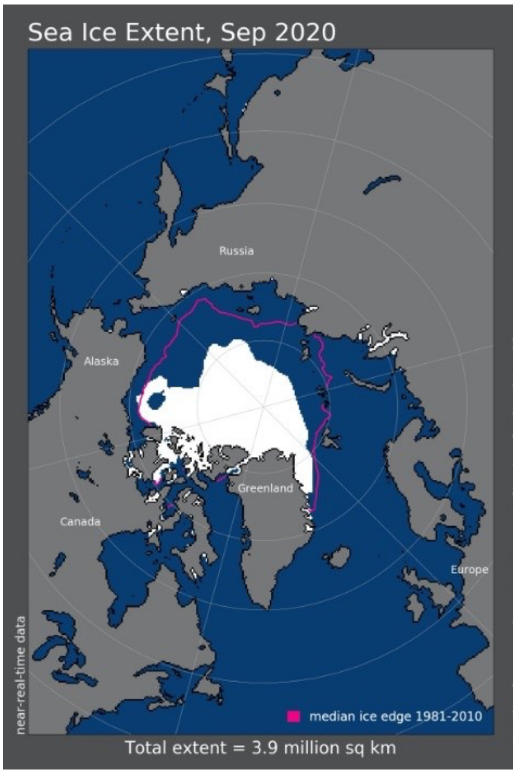

Figure 2.3 Monthly sea ice extent in September 2020, the second lowest since 1978. Source: National Snow and Ice Data Center, University of Colorado.

The observed SIE decreased faster than the model predictions, leading modelers to update their estimates for a summer ice-free Arctic Ocean, previously estimated to occur in approximately 2100 CE (Boé et al., 2009). Newer models predict a seasonally sea ice-free Arctic by 2030/40 (Overland & Wang, 2013) or mid-century (Screen & Deser, 2019). The observed changes in September have been unprecedented over the last 1000 years (Meredith et al., 2019).

2.4 The Arctic and the mid-latitudes

Although the Arctic has warmed twice as fast as the rest of the world (Serreze & Barry, 2011), the mid-latitudes have behaved differently. The mid-latitudes (30–60º) have recently experienced extreme events during the winter, such as the 2010 Snowmaggedon (a storm over North-eastern US with a high snow volume), the 2012 hurricane Sandy, and cold outbreaks in January 2014 and February 2015 (Cohen, Pfeiffer & Francis, 2018). The cause of this phenomenon remains a matter of debate; however, many researchers have associated the colder winters with a warmer Arctic (Francis and Vavrus 2012). The multiple research reports and reviews published provide contradictory conclusions regarding the effect of the Arctic Amplification on mid-latitude winters (e.g., Walsh, 2014; Cohen et al., 2014; Vihma, 2014; Barnes & Screen, 2015; Overland et al., 2015; Gao et al., 2015; Cohen et al., 2018).

Francis and Vavrus (2012) first approached the link between Arctic warming and changes in the mid-latitudes. They suggested that the lowest part of the atmosphere (1000–500 hPa) thickens at high latitudes, decreasing the meridional pressure gradient. The pressure gradient between high and mid-latitudes determines the upper-level zonal wind velocity; a reduced temperature gradient produces a slower, more meridional jet stream that brings extreme conditions to mid-latitudes. These conditions can last for long periods, given the waviness of the jet (Francis et al., 2009; Francis & Vavrus, 2012, 2015).

Changes in the Arctic climate have occurred most rapidly in the last 10–20 years, a period too short to find statistical significance for the linkages (Francis and Skific 2015; Overland et al., 2015); however, based on self-organizing maps, Francis and Skific (2015) found that the jetstream has become wavier, especially in fall and winter. According to Screen (2014), the temperature variability between high and middle latitudes during the sub-seasonal cold season has decreased in recent decades; northerly winds and cold days are warming faster at high latitudes than southerly winds and warm days in middle latitudes.

The heating of the Barents-Kara seas plays a vital role in the links between high/mid-latitudes. In summer, the energy absorbed in this oceanic region is released into the atmosphere in early winter, creating a positive height anomaly in the mid-troposphere and weakening the polar vortex (Petoukhov & Semenov, 2010; Kim et al., 2014). Moreover, cold winters in North America could be connected to the warming of the East Siberian–Chukchi Sea region. In contrast, warming over the Barents-Kara seas would be responsible for cooling over East Asia (Kug et al., 2015), and according to Kug et al. (2015), warming over these two regions of the Arctic Ocean generates an anomalous anticyclone and the downstream development of a midlatitude trough.

The stratospheric polar vortex is a large-scale cyclone that forms in the fall in the middle atmosphere (14–50 km above the surface) and lasts until spring (Lawrence and Manney, 2018).

The tropospheric polar vortex is larger than the stratospheric vortex and occurs year-round, and both vortices could be related to mid-latitude events (Waugh et al., 2017). The relationship between the stratospheric polar vortex variability and changes in surface conditions is stable. The troposphere is dynamically coupled to changes in wind speeds that form the stratospheric polar vortex, and the weakening of stratospheric westerlies shifts the storm track equatorward (Mitchell et al., 2013). The slower jet stream could also affect tropospheric weather and contribute to intense low temperatures during mid-latitude winters (Kidston et al., 2015).

The stratospheric polar vortex restricts freezing air to high latitudes because of its strong circumpolar flow. Kretschmer et al. (2018) investigated the period from 1979–2015. They showed that weak stratospheric polar vortex episodes in mid-late winter (January/February) have been more frequent since 1990 and caused extreme mid-latitude weather. There is no consensus among the scientific community on Arctic changes and the observed modifications in mid-latitude weather (Tollefson, 2014). Still, many researchers suggest that Arctic warming is responsible for extreme weather in the mid-latitudes. Barnes (2013) used three different reanalyses and affirmed that the planetary-scale wave is not significantly slower, nor has it shown more meridional behavior. On the other hand, Screen and Simmonds (2013) argue that the planetary wave amplitude has indeed increased but is not related exclusively to Arctic warming.

Screen, Deser & Sun (2015) suggest that freezing temperatures over Central and Eastern North America have become less frequent since 1980 and argue that the mid-latitudes are warming; thus, larger-magnitude cold anomalies would be required to cause extreme cold temperatures at mid-latitudes. Moreover, high latitudes warm faster than mid-latitudes, decreasing the thermal gradient. Thus, an air mass traveling southward from high latitudes will have a smaller temperature anomaly than an air mass traveling poleward from the mid-latitudes. Some scientists relate extremely cold weather in Europe and Siberia to Arctic sea ice loss, generating the term "warm Arctic, cold continents." Nevertheless, Sun, Perlwitz & Hoerling (2016) uphold that sea ice reduction presents no linkages with lower latitudes; however, they agree that sea ice loss causes atmospheric warmth in high latitudes and that the mid-latitude cooling could be related to internal atmospheric variability. These conclusions are based on models that highlight ambiguous results present in some models and absent in others.

Cohen et al. (2014) stated that AA is the best hypothesis for explaining the recent colder midlatitude winters. Changes in storm tracks, jet streams, and planetary waves may explain the link between the high and mid-latitudes. Arctic warming modifies storm tracks. AA, combined with the North Atlantic Oscillation/Arctic Oscillation (NAO/AO), affects precipitation variability and surface temperature, especially over the North Atlantic (Bader et al., 2011). The NAO index is obtained from the surface sea-level pressure difference between the Azores subtropical high and Icelandic subpolar low-pressure systems (Thompson & Wallace, 2000). The positive phase of the NAO/AO increases the pressure gradient between the Azores High and the Icelandic Low.

During this period, storm tracks are deflected northward; northern Europe, Asia, and the eastern United States experience mild winters, while the Arctic is cold. Conversely, when the NAO/AO enters the negative phase, the storm tracks are deflected southwards; northern Europe and Asia and the eastern United States experience colder winters, and the Arctic is mild (Overland, Wood & Wang 2011) (Figure 2.4). Thus, changes in sea ice cover could affect the phase and amplitude of the NAO/AO (Cohen et al., 2014).

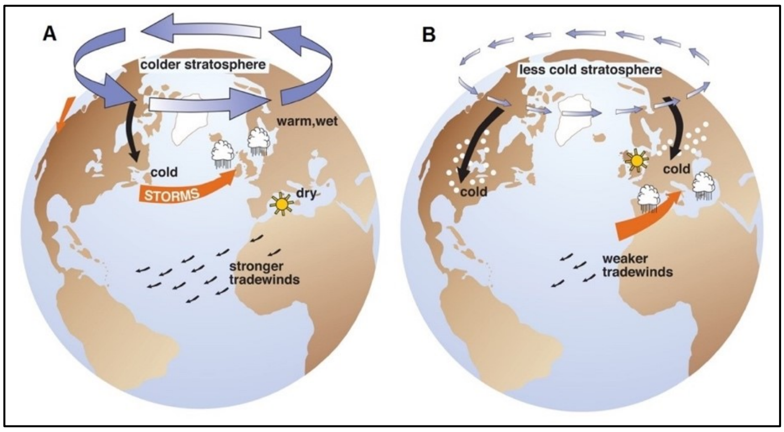

Figure 2.4 (A) A more zonal circulation signifies a greater sea ice extent. Trade winds are stronger in the Arctic Oscillation (AO) positive phase. (B) The negative phase of the AO is characterized by a smaller sea ice extent and weaker trade winds. Source: NSIDC. Credit: J. Wallace, University of Washington

The second mechanism is jet stream shifting. However, more studies are needed to prove the relationship between Arctic warming and jet stream amplitude (Tang et al., 2013; Cohen et al., 2014). The third mechanism that could link high latitudes to severe winters in mid-latitudes is the shifting of large-scale Rossby waves. Sea ice loss over the Barents-Kara seas could induce local atmospheric perturbation by heat fluxes that may affect large-scale planetary waves

(Cohen et al., 2013). The energy released in the Barents-Kara seas affects the vertical structure of the atmosphere, forcing the ascension of planetary waves into the stratosphere, which weakens the stratospheric polar vortex and favors a persistent negative NAO/AO phase (Jaiser, Dethloff & Handorf, 2013).

Walsh (2014) suggested different mechanisms that could link a warmer Arctic with mid-latitude cooling, including changes in the geopotential height and increased continental snow cover. Sea ice loss in the Arctic Ocean creates vast areas of open water that serve as a source of vapor to the atmosphere (Walsh, 2014; Yeo, Kim & Kim, 2017). Liu et al. (2012) suggested that autumn sea ice loss correlates with recent anomalous snowfalls over North America, Europe, and East Asia. The observational analysis demonstrated that the reduction of 1 million km^2 of autumn sea ice increased winter snow cover by 3%–12% over the northern continents. The mechanism behind these changes in the atmospheric circulation pattern is related to the AO-negative phase, which leads to a more meridional circulation that results in persistent blocks and cooling over the mid-latitudes (Liu et al., 2012). A higher volume or greater extent of surface snow drives the development of an anomalous high-pressure system over Europe and Asia, increasing vertical Rossby wave propagation. This scenario perturbs the stratospheric polar vortex and results in an AO-negative phase (Cohen et al., 2007).

Scientists have looked at specific time windows to understand the causes of the exceptionally recent cold winters in the Northern Hemisphere. Ogi et al. (2016) concluded that the frigid winter of 2013/14 in North America was caused by the warming of the SST in the Barents Sea, as proposed by Van Oldenborgh et al. (2015). Cohen et al. (2020) advocated that observational experiments show a connection between AA and extreme events in the mid-latitudes. However, model experiments show different results; the resulting discrepancy has hindered a better understanding of the physical mechanisms behind these teleconnections.

2.5 The North Atlantic Oscillation/Arctic Oscillation and sea ice extent

The AO, also known as the Northern Hemisphere annular mode, is a seesaw pressure anomaly over the Arctic and is a statistical feature found using Empirical Orthogonal Functions (EOFs) (Thompson & Wallace, 2000). The stratospheric polar vortex potentially drives AO, but the AO index is calculated at the surface (Kennedy & Lindsey, 2014). The NAO and AO are highly correlated during the winter (Ambaum, Hoskins & Stephenson, 2001) and thus are usually referred together.

The NAO plays an essential role in the Northern Hemisphere (especially over the North Atlantic), affecting biology, SSTs, and sea ice extent. Furthermore, the NAO is vital for influencing the path of extratropical storms and jet streams (Bader et al., 2011). Colder winters at mid-latitudes are correlated with the NAO-negative phase (Bader et al., 2011). Blackport & Screen (2019) indicated that sea ice loss could induce the NAO to its negative phase during winter.

Orsolini et al. (2016) found that the severe and snowy winter of 2009/10 was related to a noteworthy NAO-negative phase. The negative anomaly in mid-latitudes favored vertical planetary wave propagation into the stratosphere that slowed the polar stratospheric jet; thus, snow depth may contribute to maintaining the NAO-negative phase (Orsolini et al., 2016). Fereday et al. (2012) also mentioned that the utmost NAO-negative phase favored a colder winter in 2009/10 in North America, Europe, and Asia.

Sea ice extent could influence the NAO/AO phases. Nakamura et al. (2015) used reanalysis to propose that sea ice loss in November was responsible for a NAO/AO negative phase. The SIE positive anomaly in the same month was responsible for a positive phase in early and late winter. Nakamura et al. (2015) used simulations to suggest that decreased SIE generates colder winters over North America and Eurasia that change the atmospheric circulation pattern and lead to the NAO/AO negative phase. Similar results were reported by Crasemann et al. (2017). They also used reanalysis data to investigate the circulation pattern when the Arctic presented reduced sea ice extent in a NAO-negative phase observed in February and March.

Screen (2017) argues that Northern European winter temperatures are only weakly correlated with shrinking Arctic sea ice but are correlated with intensified NAO-negative phases. Screen (2017) showed that the NAO-negative phase was not related to cooling over Northern Europe. In fact, the number of snowy days could be decreasing in the region because of the compensation for thermodynamic warming.

An important NAO characteristic is its influence on the trade winds in the North Atlantic. A negative NAO phase (weakened sub-tropical high) induces slower trade winds, decreases evaporation, and warms the sea surface (Hastenrath and Greischar, 2001; George and Saunders, 2001). Tokinaga & Xie (2011) found that the recent increase in the Atlantic SST is connected to weakening trade winds. A warmer sea surface may reinforce atmospheric convection, creating storms over the tropical Atlantic. Fraza et al. (2016) found similar results while investigating hurricane intensification in the North Atlantic basin and showed that the negative NAO phase might intensify hurricane rates; the hypothesis is that trade winds become weaker in the negative NAO phase, decreasing vertical wind shear.

The NAO also influences precipitation in South America. Polzin & Hastenrath (2014) pointed out that the Nordeste semi-arid region (north-eastern Brazil) may experience drought or wet years depending on the North Atlantic Ocean temperature and the trade wind velocity. During drought periods, the North Atlantic Ocean is warmer, and trade winds are weaker (-NAO). The North Atlantic Ocean is cooler in wet years, and the trade winds are faster (+NAO).

2.6 The Arctic and the Tropics

2.6.1 Characterization of northern South America precipitation

The northern South America region presents significant spatial heterogeneity in precipitation, having the average precipitation amount observed in the western sector of this region exceeding 2450mm/year (Shi et al., 2000). The northwest sector of the Amazon region may present extreme rainfalls reaching up to 3000 mm/year, the central part of the Amazon region around 5°S presents precipitation amounts of 2500 mm/year, while the southern part of the Amazon region shows precipitation above 1750 mm/year (Shi et al., 2000).

The precipitation in the northwest and central regions of the Amazon are associated with the moisture transported by the trade winds from the Atlantic Ocean (Reboita et al., 2010). Also, the rainfall in northern South America is also associated with the seasonal migration of the ITCZ Marengo e Hastenrath, 1993). The ITCZ corresponds to the region of the confluence of the trade winds from southern and northern hemisphere and it is characterized by intense convective rainfall (Reboita et al., 2010). The ITCZ reaches its southernmost position during the months of February to April, around ~4S in the Atlantic and its northernmost position during the months of August to October (~10°N Atlantic and 13°N in the Pacific Ocean) (Hastenrath, 1991), period that shows the smallest precipitation values in the region.

2.6.2 Tropical influence over the Arctic

The tropics play a vital role in the global climate system (Seager, Chiang & Shaman, 2015) and some research suggests that tropical forcing could influence the Arctic warming. Therefore, this section explores the influence of the tropics at high latitudes. Lee et al. (2011) showed that the Arctic ice-covered regions experienced increased temperatures because of horizontal temperature advection and adiabatic warming from 1958–1977 and 1982–2001. Ice-free regions became warmer due to infrared downward flux; thus, an increase in poleward heat transportation could be responsible for the AA.

Ding et al. (2014) used models and reanalysis and found that tropical forcing is responsible for increasing surface and tropospheric temperatures over northeastern Canada and Greenland. Ding et al. (2014) also reported that Rossby waves developed in the tropical Pacific are related to the expansion of the 200 hPa geopotential height over north-eastern Canada and Greenland. Reanalysis showed that SSTs over the tropical Pacific drive the extra-tropical wave train, forming an arc shape from the central Pacific poleward and returning to the tropical Atlantic. This condition is more likely to occur during a negative NAO phase.

McCrystall et al. (2020) examined geopotential height anomalies over Northern Canada and Greenland using models and reanalysis data. They found that tropical Pacific and Atlantic SSTs can contribute to the expansion of geopotential height in those regions. Meehl et al. (2018) showed that the tropical Atlantic influenced circulation anomalies over the Arctic and consequently decreased SIE from 2000–2014. Tokinaga, Xie & Mukougawa (2017) used models and observational data to argue that interdecadal Pacific–Atlantic variability leads to a warmer Arctic by intensifying the Aleutian low and westerly circulation over northern Europe and Asia and exporting warmer winds toward that region.

Flournoy et al. (2016) used reanalysis and data from the Baseline Surface Radiation Network

(BSRN) to affirm that the Tropically Excited Arctic WarMing (TEAM) mechanism promotes poleward propagation of Rossby waves and influences Arctic warming by transporting water vapor and heat toward the Arctic region. Flournoy et al. (2016) believe that the TEAM mechanism induces warm advection, latent heat release, and increased cloud cover, which may increase downward infrared radiation and cause Arctic warming. Similar results were proposed by Park et al. (2015) and Park, Lee & Feldstein (2015). They found that moisture flux into the Arctic caused by tropical convection over the Indian and western Pacific oceans increased the downward infrared radiation by 30–40 W m^{-2} over 1–2 weeks.

Goss, Feldstein & Lee (2016) argue that Arctic warming is not triggered by warm pool convection but enhances Arctic warming. After establishment, warm pool convection affects the Arctic, increasing surface air temperature and reducing the sea ice cover in the Barents and Kara seas. In addition, warm pool convection weakens the stratospheric polar vortex and leads to a negative phase of AO. Feldstein & Lee (2014) noted that positive convection anomalies precede variability in the jet stream over the warm pool. Moreover, tropical convection over the warm pool amplifies planetary-scale waves. Rossby waves are forced by tropical convection and initiate Rossby wave trains over the North Pacific, thus intensifying the December-March climatological stationary waves. This process transports latent and sensible heat into the Arctic and takes moisture from mid-latitudes poleward when connected with synoptic-scale waves, (Baggett, Lee & Feldstein, 2016; Baggett & Lee, 2017).

Other large-scale climate modes may influence the Northern Hemisphere high latitudes; Schwartz and Garfinkel (2017) indicate that the NAO negative phase is connected to the Madden-Julian Oscillation (MJO) (phases 6/7 – West Pacific) and sudden stratospheric warming (SSW). They reported that most SSW was preceded by Madden-Julian Oscillation phases 6/7. SSW originates from the upward propagation of tropospheric planetary waves into the stratosphere during winter; in SSW events, the stratospheric polar vortex may be split into two parts or present a waiver behavior (Andrews, Holton & Leovy, 1987).

Yoo et al. (2012) investigated the influence of the MJO on Arctic surface air temperature. They used models to find that the MJO phases 1 and 5 are related to cooler and warmer Arctic surfaces, respectively. MJO phase 5 induces more vigorous wave activity toward high latitudes, increasing the SAT. On the other hand, less convection over the western Pacific during phase 1 excites fewer waves that propagate to the Arctic, thus decreasing the Arctic SAT.

The El Niño Southern Oscillation (ENSO) is another large-scale phenomenon that may influence the Arctic. Hu et al. (2016) demonstrated that the Central Pacific El Niño might inhibit summer Arctic warming by intensifying circumpolar westerly winds and reinforcing the tropospheric polar vortex, thereby preventing sea ice melting. Hu et al. (2016) also indicated that without Central Pacific El Niño events, the Arctic sea ice would probably retreat faster in the summer. Takemura & Maeda (2016) claim that El Niño events are related to negative AO phases. They found that El Niño and the Pacific-North Atlantic patterns strengthen planetary waves that propagate vertically and northward into the lower stratosphere from the mid-latitude troposphere and lead to the negative AO phase. The simultaneous occurrence of El Niño and SSW in winter coincides with a warmer polar stratosphere that propagates to the surface, elevating sea level pressure over the Arctic. During El Niño events without SSW, the upper troposphere and stratosphere (but not the surface) are colder. Thus, ENSO may be connected to the stratospheric variability (Richter et al., 2015). Butler and Polvani (2011) observed a warmer winter stratosphere and a weaker polar vortex during El Niño events than during the neutral phase. These findings reinforce the idea that ENSO is coupled with stratospheric conditions; La Niña, the negative phase of ENSO, has a smaller impact. Butler & Polvani (2011) observed that winter SSW is more likely to occur during La Niña events than during the neutral phase.

Yang et al. (2017) demonstrated that La Niña and the Pacific North Atlantic teleconnection pattern (PNA) suppressed the propagation of planetary waves into the stratosphere from the mid-latitude troposphere from 1951–1978, thus intensifying the stratospheric polar vortex during the Northern Hemisphere. However, this characteristic was not observed from 1979–2015, when the La Niña event was dislocated eastward. Thus, the teleconnection had a small influence on the planetary waves and presented minor interference in the stratospheric polar vortex. Iza, Calvo & Manzini (2016) found that upward planetary waves into the stratosphere were weakened during La Niña winters from 1958–2012 because stratospheric winds strengthened due to destructive interference between the climatological and anomalous La Niña tropospheric stationary eddies over the Pacific–North America. However, during extreme La Niña events, the stratospheric polar vortex in the Northern Hemisphere was cooler and stronger. Shi & Fu (2012) examined the extreme cold polar vortex of the 2010–2011 winter, which occurred during an intense La Niña period. They found that the Wave 1 eddies were reduced in this event, while the Wave 2 eddies propagated from the troposphere into the stratosphere. Shi and Fu (2012) also pointed out that generally stronger and weaker polar vortexes are observed during La Niña and El Niño events, respectively, notwithstanding those neutral phases of the polar vortex also occur during El Niño and La Niña events. Therefore, they suggested that other factors, such as solar cycles and surface conditions, may influence polar vortex behavior. Furthermore, Matsumura & Kosaka (2019) suggested that weather in Eurasia is connected by a combination of ENSO and Arctic sea ice. El Niño warms the tropical Atlantic Ocean. A warmer tropical Atlantic could force anomalous Rossby wave trains into Eurasia, increasing sea ice and warming the landmass. On the other hand, La Niña could decrease the SIE and cool Eurasia.

2.6.3 The Arctic and the low latitudes

Low-pressure surface systems at the Equator are generated by constant solar radiation. The north-eastern and south-eastern trade winds converge in the equatorial region, transferring heat and moisture from the lower levels of the tropics to the upper atmosphere for poleward movement. The upward movement of the winds causes cooling at higher levels, leading to precipitation. The largest part of the air sinks in the subtropics, and the air in the mid-latitudes flows toward the tropics, forming the Hadley cell. The ascending part of the Hadley cell is called the intertropical convergence zone (ITCZ) (Figure 2.5). Although the Arctic has shown increased warming, studies have begun to focus on the influence of the climate warming on the future position of the ITCZ. Atmosphere-only models predict the northward displacement of the ITCZ, whereas ocean models (ocean-atmosphere coupled models) show a narrowing of the ITCZ and equatorward movement.

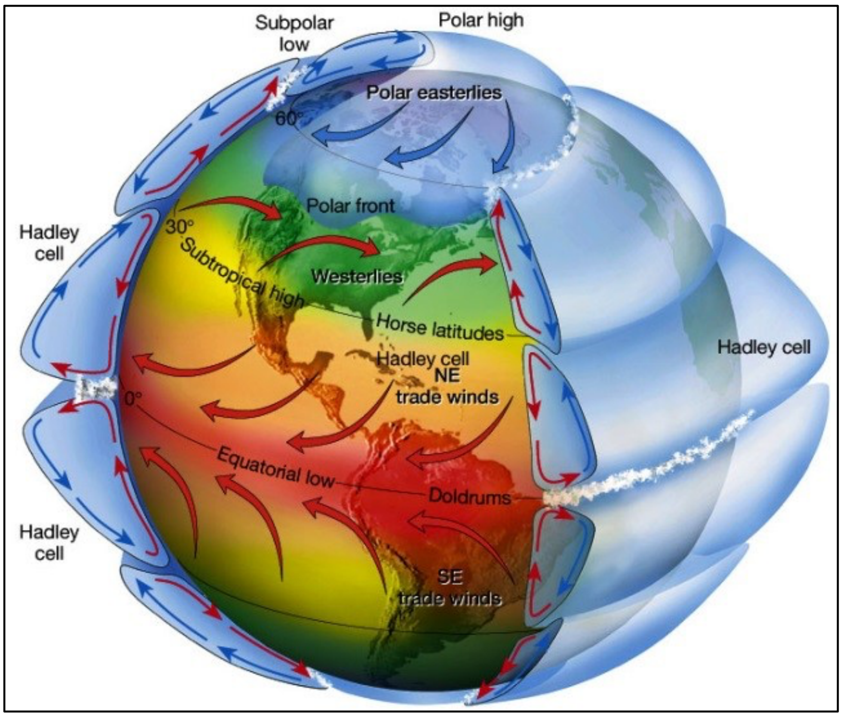

Figure 2.5 Global circulation. Idealized model, three-cell atmospheric convection on a rotating Earth. Source: Lutgens and Tarbuck (2007) used with permission, Pearson.

The ITCZ is responsible for 32% of the global precipitation (Kang et al., 2018). The mean position of the ITCZ is 5°N (Gruber, 1972). The belt reaches its northernmost and southernmost positions in August–September (at approximately 14° N) and March–April (at approximately 2°S), respectively (Carvalho & Oyama, 2013). This anomalous position occurs because of the interhemispheric temperature difference (Broccoli et al., 2006). Wodzicki & Rapp (2016) examined the ITCZ position over the Pacific Ocean using observed data and did not find significant changes. However, the ITCZ narrowed, and convection intensified. Bellomo & Clement (2015) indicated that the Walker cell has weakened and moved eastwards in the last century, according to Atmospheric Model Intercomparison Project (AMIP) models. External forcings, such as SST, partly caused these changes. In addition, some Coupled Model Intercomparison project (CMIP5) projections demonstrated a narrowing and deepening of the ITCZ, reducing precipitation in north-eastern Brazil (Lau & Kim, 2015). ITCZ Narrowing is also projected in response to global warming in both models and observations (Byrne & Schneider, 2016). Tomas, Deser & Sun (2016) used thermodynamic and dynamic oceanatmosphere models to find different responses to the Arctic influence at low latitudes; thermodynamic models presented warmer SST at high latitudes and northwards displacement of the ITCZ. However, thermodynamic and ocean-atmosphere dynamics coupling showed symmetry in SSTs in both hemispheres and no changes in the ITCZ position.

Green and Marshall (2017) found no significant position anomaly using a coupled atmosphereocean general circulation model. They argued that in contrast to a warmer/colder Northern Hemisphere, surface wind stress over the subtropical ocean would compensate for the ITCZ displacement. Chemke, Polvani & Deser (2019) used different models and found that thermodynamic coupling weakens the Hadley cell and its northward displacement. However, dynamic coupling cools the Northern Hemisphere and slows ITCZ movement. Similar results were found by Voigt et al. (2014) using clear-sky albedo aquaplanet simulations, where the atmosphere was adjusted to compensate for changes in the ITCZ position.

Wang et al. (2018) investigated the future impacts of Arctic sea ice loss using two different configurations: a Full Ocean Model (FOM) and a Slab-Ocean Model (SOM). The SOM feedback shows an anomalously warmer North Hemisphere, slight differences in the Southern Hemisphere, and a northward displacement of the ITCZ and the Hadley circulation. Conversely, the FOM showed an equatorward intensification of the ITCZ and Hadley circulation, as a slowed thermohaline circulation inhibits heat transfer from the tropics toward the poles and slows the ITCZ displacement.

Sun, Alexander & Deser (2018) investigated the global impacts of sea ice loss in the 21st Century using the Geophysical Fluid Dynamics Laboratory Coupled Model version 3. They argued that sea ice loss contributes to increased warming over the Northern Hemisphere extratropics and leads to a small equatorward displacement of the ITCZ in the Pacific. Moreover, Deser, Tomas & Sun (2015) used the Community Climate System Model version 4 (CCSM4)—which includes an ocean general circulation model—and found different ITCZ responses to sea ice loss. In full-depth models, the ITCZ moves equatorward, whereas the Pacific ITCZ undergoes northward displacement in the slab-ocean model.

Liu & Fedorov (2019) examined the impacts of sea ice decline on decadal, interdecadal, and centennial timescales. On a short scale (decadal), atmospheric processes predominantly lead to a pronounced temperature difference between the Northern and Southern Hemispheres that displaces the ITCZ northwards. At longer timescales (e.g., decades or centuries), the weakening of the AMOC could warm the Southern Hemisphere, decrease Antarctic sea ice, and move the ITCZ southward.

Cvijanovic et al. (2017) considered how recent Arctic changes could affect precipitation in California and suggested a two-step teleconnection. First, the sea ice shrinkage would cause the Rossby waves to propagate southward, changing the tropical atmospheric circulation and convection. Second, in response to this mechanism, convection and upper-level divergence would be reduced in the tropical Pacific, forcing the northward propagation of the Rossby wave with an anticyclonic flow in the North Pacific. This two-step mechanism could deflect humid air masses away from California. Cvijanovic et al. (2017) explained that this mechanism is not the only driver but is a factor that decreases precipitation in California.

Recent research suggests that sea ice loss can initiate Central Pacific El Niño events. Kim et al. (2020) indicated that diminishing sea ice concentration could affect tropical Pacific SST and that sea ice reduction could influence the positive phase of the North Pacific Oscillation to warm the central tropical Pacific Ocean. Similarly, Kennel & Yulaeva (2020) argued that shrinking sea ice in the Siberian Arctic could perturb the upper troposphere, which transports momentum and heat southwards in the upper atmosphere. This could lead to a teleconnection between the region north of the Siberian Arctic coast and the ITCZ, which could reverse the trade winds over the central Pacific, triggering El Niño events. England et al. (2020) also mentioned that sea ice loss could warm eastern equatorial Pacific waters through zonal asymmetries in the tropical SST linked to ocean dynamics, resulting in increased rainfall over the equatorial Pacific.

2.6.4 The Arctic paleoclimate and its influence over low latitudes

For the last 30 years, climate change has been a popular topic in scientific and political agendas. The climate is now undeniably changing faster than can be attributed to natural variability (Stroeve & Notz, 2018; Overland et al., 2019). Some changes are enhanced by anthropogenic greenhouse gas emissions (IPCC, 2014). This section discusses observed Northern Hemispheric historical climate changes and their interactions with low-latitude regions.

Paleo-records show that the ITCZ is displaced toward the warmest hemisphere (McGee et al., 2014). For example, Schneider, Bischoff & Haug (2014) analyzed Cariaco basin sediments (northern coast of Venezuela) and showed that the ITCZ is displaced southward as the Northern

Hemisphere cools. Greenland ice cores show temperature variations during the last glacial period, known as the Heinrich and Dansgaard-Oeschger stadial (Dansgaard et al., 1993). Zhang et al. (2017) found a weakening of the AMOC and a southwards ITCZ shift during the Dansgaard-Oeschger stadials. The near shutdown of the AMOC further contributed to the southward displacement of the ITCZ during Heinrich stadials.

McGee et al. (2018) used trade wind proxies (e.g., dust from the Atlantic basin). They showed a weakening and strengthening of the Hadley cell and trade winds in the warmer and colder hemispheres, respectively, and a southward displacement of the ITCZ during the Heinrich stadials. The temperature increased at the end of the last glacial maximum (14,500 years BP) but suddenly dropped again (at approximately 12,500 years BP) in the Northern Hemisphere in a period called the Younger Dryas (Alley, 2000). Large discharges of freshwater into the North Atlantic changed the temperature and salinity of the North Atlantic Ocean; the consequent weakening of the AMOC is thought to have caused the cooling (Alley, 2000). Paleoceanographic proxies show a weakening of the AMOC during the Younger Dryas and a consequent southward shift of the ITCZ (Venancio et al., 2020; Renssen et al., 2018).

Even during shorter cooling periods such as the Little Ice Age (LIA, AD 1200–1850), lake sediments show that the ITCZ over the Pacific was 500 km south of its modern-day position (Sachs et al., 2009). Lozano-García et al. (2007) indicated the expansion of tropical vegetation in Central and South America during the LIA due to an increase in precipitation due to the southerly position of the ITCZ. Lechleitner et al. (2017) used paleoclimate proxies to argue that the ITCZ shifted southward during the LIA.

2.7 Approaches to understanding the interconnections between Arctic sea ice and lower latitude weather and climate

The above-presented literature contains two sources of information for climate studies: reanalysis and climate models. Reanalysis assimilates various atmospheric and oceanic observations and produces a data grid of climate information with the help of models, such as air temperature, pressure, wind speed, precipitation, and SST (Laloyaux et al., 2016). Climate models use mathematical equations to simulate climate systems, such as the atmosphere, ocean, and sea ice (NOAA, 2020). Climate models allow us to assess multiple climate scenarios and to obtain a greater understanding of the climate by isolating different elements to understand it better. However, each model has different dynamical cores, physics, and parameterizations that produce a wide range of variability among models.

Reanalysis is the closest approach to observational data and provides conveniently detailed, gridded estimates of atmospheric conditions at regular intervals for interdecadal periods. Therefore, reanalysis is helpful in evaluating climate models, climate change detection and attribution, and various other applications (Parker, 2016). Additionally, reanalysis encompasses internal atmospheric variability to represent one interpretation of how the atmosphere works.

A limitation of reanalysis products is different observational systems, which have changed significantly in recent decades. Surface observations before the 1940s are very different from the present space-based system. Thus, reconstructing long-term climate trends is difficult (Bengtsson, Hagemann & Hodges, 2004). Another limitation of reanalysis products are the determination of energy and water fluxes, especially between the atmosphere and the surface. The fluxes cannot be determined directly from observations and must be calculated using models (Bengtsson et al., 2007).

Multiple reanalysis products are used to account for varied sources of raw input data that sometimes generate different results due to constant changes in the observational network. Current products assimilate 7–9 million observations each time step (Dee et al., 2014). Models are considered an extension of weather forecasting over longer time scales that focus not on meteorological events but on the evolution and statistics of events and features (e.g., ice sheets and oceans) (Bader et al., 2008). Climate models are essential for studying the climate system's response to different forcings and predicting climate on seasonal, decadal, century, and millennial scales (Flato et al., 2013).

In recent decades, climate modeling has gradually improved; however, some aspects of the climate system (e.g., precipitation) are challenging to simulate. The correlation between models and observations for seasonal means at scales of a few hundred kilometers is 50%–60%. Most regions show similar magnitudes when comparing models and observed precipitation maps; however, the most significant differences are found in the tropics due to the presence of the ITCZ (Bader et al., 2008). Bader et al. (2008) argued that storms and the jet streams in the

Northern Hemisphere mid-latitudes are well-represented in the models. Nonetheless, Cohen et al. (2020) showed that the models and observations showed different AA interaction results with the middle latitude jet stream. Bader et al. (2008) note that circulation changes in the Northern Hemisphere have proven difficult to capture with models.

Different approaches are often taken in climate investigations. Scientific debates on the possible influence of the AA on mid-latitude weather are divisive and inconclusive. Researchers work with reanalysis, models, or both. Most results based on reanalysis support the hypothesis that AA could make mid-latitude weather more extreme. However, some models do not capture these teleconnections. According to the models, the AA has little or no influence over midlatitude weather, and recent extreme events are connected to mid-latitude internal variability. The difficulty of representing the complexity of the climate system with the models is considered a limitation of this approach.

Cohen et al. (2020) argued that multiple observational and select model studies support the AA mid-latitude teleconnection theory. In contrast, most model studies show little or no influence of the AA over mid-latitude weather. As the Arctic continues to warm faster than any other region, possible effects on low latitudes have become more prevalent. The connection between the Arctic and mid-latitude extreme events has recently gained considerable attention. The potential influence of Arctic sea ice loss over tropical climate patterns has been discreet in the last decade but is gaining momentum.

The literature above shows that the interaction between high and low latitudes is a two-way process. On the one hand, increased tropical Pacific SSTs could influence Arctic warming (Ding et al., 2014) and anomalies in the geopotential height in some Arctic regions (McCrystall et al., 2020). On the other hand, Kennel & Yulaeva (2020) proposed that Arctic sea ice loss could influence Pacific trade winds, potentially reversing their direction and triggering El Niño events. However, the scientific community has not fully understood the mechanisms that trigger El Niño events.

The teleconnections between the Arctic and mid-latitudes are still under debate. However, research suggests that the sea ice decline could influence the NAO to its negative phase. The

NAO can act as a link between the sea ice loss and the tropical Atlantic. Therefore, it is relevant to investigate how the arctic sea ice could influence the NAO and, consequently the trade winds.

The negative NAO phase is marked by the weakening of the Azores High, which leads to slower trade winds. Slower trade winds are connected to droughts in north-eastern Brazil (Polzin & Hastenrath 2014). The paleoclimate research shows that the anomalous displacement of the ITCZ can be driven by changes (warming/cooling) in the polar regions. The mechanism is the weakening of the Hadley cell in the warmest hemisphere. Tokinaga & Xie (2011) showed that the north-eastern trade winds speed is anomalously negative. Liu and Fedorov (2019) show that the ITCZ is projected to be displaced northward after the Arctic sea ice disappears in the summer.

Based on the literature presented above, this thesis proposes to investigate two mechanisms: changes in the trade winds speeds and the ITCZ position, between sea ice loss from Arctic warming and the low latitudes, specifically in the Atlantic, and its connections to climate variability in northern South America; the weakening of the trade winds and changes in the ITCZ position. Teleconnections between high and low latitudes in the Northern Hemisphere are beginning to receive attention (Kennel & Yulaeva, 2020; England et al., 2020), but the Atlantic sector is only briefly mentioned. After identifying this gap in the literature, we investigated if Arctic sea ice loss could influence the tropical Atlantic.

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Chapter 3 - Article 1

This paper has been submitted to the Brazilian Journal of Climatology. This work represents a core chapter of my thesis that was conceived, analyzed, and reported by me as the primary author.

On the relationship between Arctic sea ice extent and precipitation over the Brazilian Northeast and Amazon rainforest

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3.1 Introduction

The Arctic region has warmed more than twice as fast as the rest of the planet (Cohen et al., 2014). Consequently, the Arctic sea ice extent has declined rapidly over the last three to four decades (Stroeve et al., 2007; Ding et al., 2017). In a scenario with business-as-usual CO_2 emissions, climate models forecast a seasonally ice-free Arctic Ocean by the mid-to-late twenty-first century (Overland & Wang, 2013; Stroeve & Notz, 2018).

Arctic sea ice loss can potentially impact climate regionally and globally (Liu & Fedorov 2019). As sea ice vanishes, Arctic Ocean open waters release heat and moisture into the atmosphere aloft, warming the lower troposphere (Screen & Simmonds, 2013). Such changes in the Arctic have raised a debate about whether extreme events in mid-latitudes are connected to the Arctic Amplification or its own variability of the mid-latitudes (Francis &Vavrus, 2012; Barnes, 2013; Barnes & Screen, 2015; Francis & Skific, 2015).

The potential hemispheric-scale teleconnections between high northern latitudes and the Tropics are gaining interest within the climate change research community. Previous studies

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have shown that the Arctic sea ice loss could decrease the convection (Cvijanovic et al., 2017) and even reverse the direction of the trade winds in the Central Pacific (Kennel & Yulaeva, 2020). Atmosphere-only models predict a northward displacement of the ITCZ (Deser, Tomas & Sun, 2015; Tomas, Deser & Sun, 2016); however, when the ocean dynamics are added, the models show a different response, the ITCZ intensifies equatorward (Deser, Tomas & Sun, 2015; Tomas, Deser & Sun, 2016; Sun, Alexander & Deser, 2018).

Changes in the position or intensification of the ITCZ may affect the precipitation regime in northern South America, home to the Amazon rainforest. Climate and vegetation depend on each other, and one could be altered by another (Nobre, Sellers & Shukla, 1991). The rainforest evapotranspiration allied to low-level jets blowing from the North Atlantic Ocean is responsible for distributing moisture through almost all South American continent (Vera et al., 2006). The evapotranspiration has an important role in recycling the water in the rainforest and is a contributor for the spatial distribution of precipitation in the Amazon, however, there are many uncertainties in its measurements (Baker, 2021).

3.2 Background

Here we summarize the key surface and atmospheric states that provide a physical basis for the hypothesized Arctic-equatorial South American teleconnections.

A warmer Arctic would lead to a decrease in the pressure gradient between high and midlatitudes. This pressure gradient determines the velocity of upper-level zonal winds, and these winds, when slower, are responsible for elongating troughs and ridges, making the eastward wave propagation slower. This leads to longer events and increases the frequency of extreme events in the mid-latitudes (Francis et al., 2009; Francis & Vavrus, 2012, 2015).

The heating of the Barents-Kara Seas also plays a crucial role in the linkages between high/midlatitudes. During the summer, the energy absorbed in this region is released to the atmosphere in early winter, creating a positive height anomaly in the mid-troposphere, and weakening the polar vortex (Petoukhov & Semenov, 2010; Kim et al., 2014). The energy released by the Barents-Kara Seas affects the vertical structure of the atmosphere. It forces the ascension of planetary waves into the stratosphere, which can weaken the stratospheric polar vortex and favor a persistent negative phase of the North Atlantic Oscillation (NAO)/Arctic Oscillation (AO) (Jaiser, Dethloff & Handorf, 2013).

Changes in the stratospheric polar vortex during the winter alter tropospheric conditions. For example, a faster jet stream circulation generates a poleward shift in the storm tracks, while a slower jet stream induces an equatorward shift in the storm tracks. A slower jet stream affects tropospheric weather, contributing to much lower than normal temperatures in the mid-latitudes during winter (Kidston et al., 2015). Colder winters in mid-latitudes correlate with the NAO field's negative phase (Bader et al., 2011). For example, in 2009/10, a severe and snowy winter was related to a strongly negative NAO (Orsolini et al., 2016).

Numerical analysis and modeling have demonstrated that sea ice conditions force a remote atmospheric response at the end of winter, favoring colder-than-normal temperatures in the mid-latitudes (Peings & Magnusdottir, 2014). Anomalies in sea ice extent affect Rossby wave penetration in the stratosphere, weakening the polar vortex and resulting in negative anomalies in the Arctic Oscillation (AO). The opposite happens when the NAO/AO is in its negative phase. Storm tracks are deflected southwards, and the northern parts of Europe and Asia and the eastern part of the United States experience a colder winter, while the Arctic is milder than normal (Overland, Wood & Wang, 2011). Changes in sea ice can possibly affect the phase and amplitude of the NAO/AO (Cohen et al., 2014). Similar results have also shown that a warmer Arctic decreases the meridional temperature gradient, causing atmospheric circulation in the Northern Hemisphere to be more meridional (Francis & Skific, 2015).

The NAO also influences the trade winds in the tropical North Atlantic sector. A negative NAO (i.e., weakened subtropical high) causes the trade winds to slow, and this decreases wind shear over the ocean and can lead to warmer sea surface temperatures (SST) (Hastenrath & Greischar, 2001; George & Saunders, 2001). Northern Atlantic SSTs have been increasing, which is connected to the weakening of the trade winds. Warmer SSTs can enhance atmospheric convection and increase storminess in the tropical Atlantic (Tokinaga & Xie, 2011). Similar results were also found while investigating hurricane intensification in the North Atlantic Basin

(Fraza, Elsner & Jagger, 2016). According to Fraza, Elsner & Jagger (2016), a negative NAO is associated with stronger hurricanes because the trade winds are weaker, decreasing vertical wind shear.

Previous studies have also investigated the potential connections between the high and low latitudes, including the potential reciprocal interactions between sea ice and tropical responses.

Lee et al. (2011) proposed that Arctic surface warming is triggered by tropical convection. Ding et al. (2014) suggested that tropical forcing may be connected to rising temperatures over northeastern Canada and Greenland. Additionally, Chiang & Bitz (2005) proposed that, during the Last Glacial Maximum, the marine intertropical convergence zone (ITCZ) was driven southwards due to increases in the sea ice extent (SIE).

The Intertropical Convergence Zone (ITCZ) plays an important role in the precipitation variability in the Brazilian North and Northeast. The ITCZ migrates seasonally between 14° N (August-September) and 15° S (March-April) (Barry, 2009). This oscillation depends on the intensity of the southeast and northeast trade winds. If the ITCZ stalls out in a location, this will increase precipitation in that location and decrease precipitation in other areas (Melo, Cavalcanti & Souza, 2009). Paleoclimate investigations suggest that atmospheric changes in the polar regions influence the ITCZ position (Broccoli, Dahl & Stouffer, 2006). As the Arctic continues to warm and sea ice extent (SIE) decreases, the ITCZ position could shift northwards, potentially impacting the Amazon rainforest environment in South America. Modifications in the ITCZ may change the precipitation regime over South America and impact its biodiversity (Nobre et al., 2007; Nobre, Sampaio & Salazar, 2008).

Cold fronts from the southern high latitudes and ENSO also influence regional precipitation patterns (Cavalcanti et al., 2009). Another mechanism that influences the precipitation in this region is the Atlantic Niño and Niña, the warmer (colder) period causes precipitation to increase (decrease) in northeast Brazil (Lübbecke et al., 2018). The NAO also affects South American precipitation. NAO is strongly correlated with North Tropical Atlantic SST after the early1990s (Chen, Wu & Chen 2015). The Nordeste semiarid region (Brazilian Northeastern) may experience drought or wet years depending on the North Atlantic Ocean's temperature and the trade winds' velocity. The North Atlantic Ocean is typically warmer during drought periods, and trade winds are weaker (-NAO). While in wet years, the North Atlantic Ocean generally is cooler, and trade winds are faster (+NAO) (Polzin & Hastenrath, 2014). Reboita et al. (2010) found similar results.

The interest in potential linkages between polar and lower latitude teleconnections has started to gain momentum (Ding et al., 2014; Walsh, 2014; Cohen, Pfeiffer & Francis, 2017; McCrystall et al., 2020; Kennel & Yulaeva, 2020). The climate system is complex, and there is considerable uncertainty regarding how mid and low-latitudes will respond to Arctic warming. Meredith et al. (2019) concluded that there is currently only low to medium confidence in understanding the linkages between the Arctic and mid-latitudes. Thus, it is necessary to explore possible connections between high and low latitudes.

3.3 Materials and Methods

This study uses Arctic SIE monthly mean data from Jan 1979 to Dec 2019 provided by the National Snow and Ice Data Center (NSIDC) and precipitation and pressure fields monthly means reanalysis data for the same period provided by NCEP/NCAR (Kalnay et al., 1996). The reanalysis data grid has a spatial resolution of 2.5° x 2.5° latitude and longitude. Monthly anomalies of precipitation, winds, and Arctic SIE were calculated in MATLAB R2012b software.

Correlations between precipitation and Arctic SIE anomalies were calculated for Jan 1979 - Dec 2019. We selected a point called P1 from an area of positive correlation between the Amazon rainforest and Northeast Brazil and extracted a time series of precipitation. We then performed a cross-correlation analysis and examined the relationship between precipitation and SIE, the highest correlation coefficient was detected in a one-month lag . After that, we calculated the seasonal linear regression between the precipitation and the SIE and between the zonal wind and the SIE, considering no lags.

3.4 Results

3.4.1 Correlation between the anomalies of sea ice extent and precipitation volume

An area with a moderate positive correlation (i.e., correlation coefficients reaching 0.45) between precipitation and Arctic SIE was found between the Amazon rainforest and northeastern Brazil (P1, Figure 3.1).

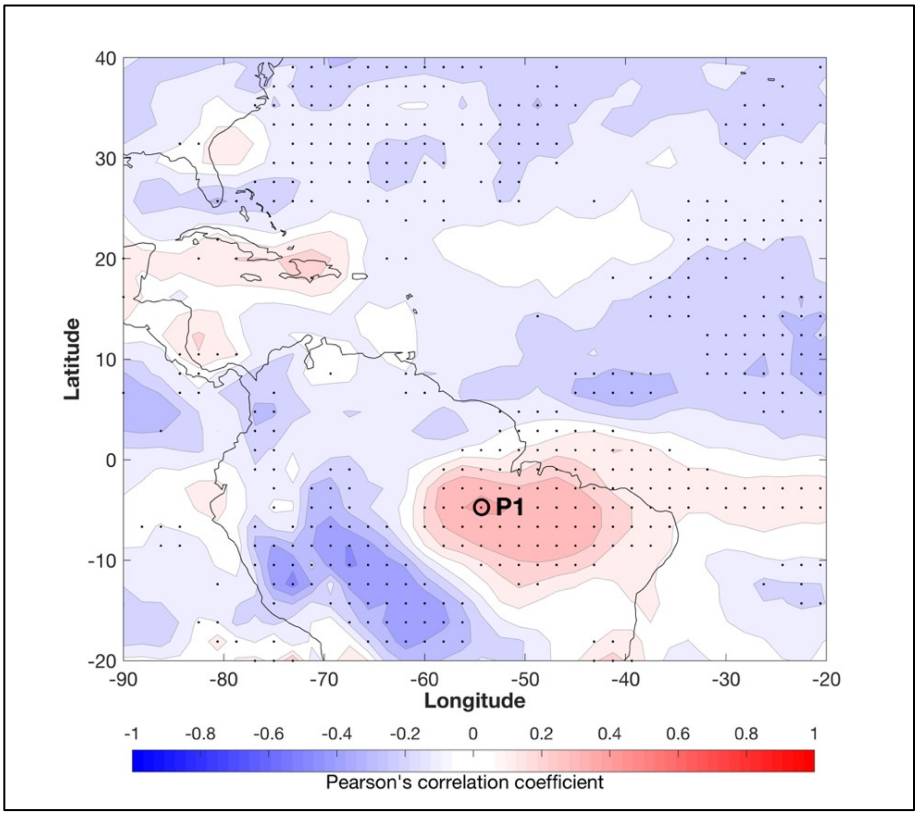

Figure 3.1 Correlation between monthly precipitation and Arctic SIE anomalies for the period January 1979 - December 2019. Note the moderate positive correlation of the precipitation in the Brazilian northern and northeastern regions with SIE anomalies. Black dots represent locations where the correlation is statistically significant based on the 95% confidence interval

The spatial distribution of correlations shows that the relationships between Arctic SIE and precipitation may be associated with the intensity and anomalous location of the atmospheric circulation mechanisms over the North Atlantic Ocean and South America's low latitudes. Figure 3.1 shows a center of negative correlation over the Tropical North Atlantic, approximately at 10° N latitude, and another positive correlation center over South America at approximately 5° S exists both with an east-west elongated shape.

In the next step, we divided both time series precipitation anomalies and SIE anomalies into seasons: December-January-February (DJF), March-April-May (MAM), June-July-August (JJA), and, September-October-November (SON). Then the seasonal averages were determined, and the linear regressions were calculated (Figure 3.2).

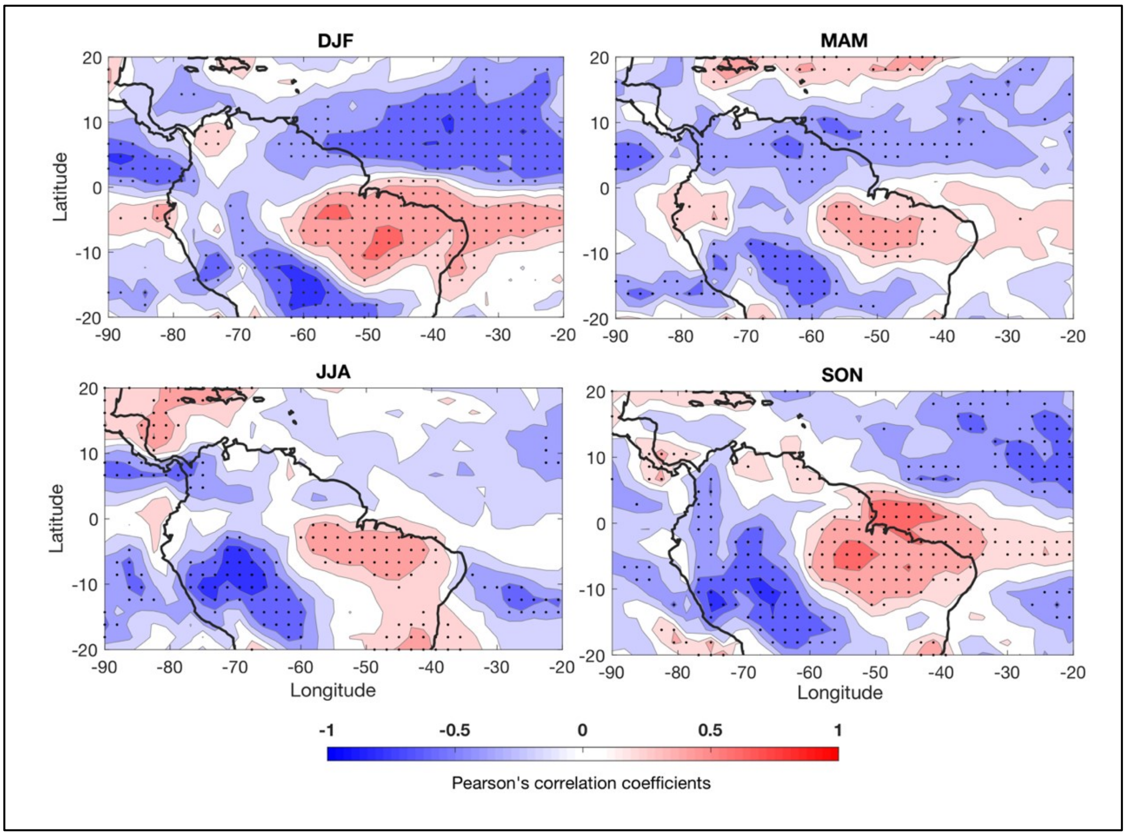

Figure 3.2 Seasonal correlation between precipitation and Arctic SIE anomalies for the period January 1979 - December 2019. Black dots represent locations where the correlation is statistically significant based on the 95% confidence interval

The spatial distributions of the seasonal correlation coefficients resemble the one found in Figure 3.1, with higher values, especially DJF and SON. In the DJF the ITCZ reaches its southernmost position, and in SON the Arctic SIE reaches its minimum extent. The highest correlation coefficients are found in Brazil's Northern and Northeastern regions, reaching 0.65 in DJF and 0.70 in SON.

DJF and MAM show a west-east strip of negative correlation coefficients around 0.5 to 0.55 in the North Atlantic approximately at 10° N. All seasons show a dipole between the positive correlation in the northern and northeastern Brazilian regions and a negative correlation coefficient in western South America.

3.5 Discussion

The spatial patterns of correlation found in this study may be associated with the increase/decrease of the North Atlantic high-pressure center and the ITCZ position. The variation of sea ice and its teleconnection with the NAO increases or decreases the North Atlantic pressure (Hastenrath & Greischar, 2001; Alexander et al., 2004; Deser, Tomas & Peng, 2007; Peings & Magnusdottir, 2014; Sun, Deser & Tomas, 2015). This variation also implies precipitation variations in the negative correlation center area approximately 10° N because an increase in atmospheric pressure favors a precipitation decrease in this region and vice versa.

The intensity of the northeast trade winds in this region also affects the ITCZ's latitudinal position (Melo, Cavalcanti & Souza, 2009). For example, when the northeast trade winds intensify, the ITCZ shifts anomalously to the south, increasing precipitation in the region where the ITCZ is located and reducing it in other locations. This atmospheric circulation spatial pattern is associated with the positive correlation center pattern found at ~5° S.

Recent literature has found that the Arctic sea ice loss could impact the ITCZ position. Atmosphere-only models predict the northward displacement of the ITCZ, whereas ocean models (ocean-atmosphere coupled models) show a narrowing of the ITCZ and equatorward movement. Tomas, Deser & Sun (2016) used thermodynamic and dynamic ocean-atmosphere models to find different responses to the Arctic influence at low latitudes; thermodynamic models presented warmer SST at high latitudes and northwards displacement of the ITCZ. However, thermodynamic and ocean-atmosphere dynamics coupling showed symmetry in SSTs in both hemispheres and no changes in the ITCZ position.

Wang et al. (2018) investigated the future impacts of Arctic sea ice loss using two different configurations: a full ocean model (FOM) and a slab-ocean model (SOM). The SOM feedback shows an anomalously warmer North Hemisphere, minor differences in the Southern Hemisphere, and a northward displacement of the ITCZ and the Hadley circulation. Conversely, the FOM showed an equatorward intensification of the ITCZ and Hadley circulation as slowed thermohaline circulation inhibits heat transfer from the tropics toward the poles and slows ITCZ displacement.

Liu & Fedorov (2019) examined the impacts of sea ice decline on decadal, interdecadal, and centennial timescales. On a short scale (decadal), atmospheric processes predominantly lead to a pronounced temperature difference between the Northern and Southern Hemispheres that displaces the ITCZ northwards. At longer timescales (e.g., decades or centuries), weakening the Atlantic Meridional Overturning Circulation (AMOC) could warm the Southern Hemisphere, decrease Antarctic sea ice, and move the ITCZ southward.

As the SIE continues to decline and the northern polar region warms proportionately to midlatitudes, the ITCZ is expected to be displaced northward after the Arctic reaches a sea-ice-free summer. The first step of this mechanism is weakening the trade winds and consequently the Hadley cell. Figure 3.3 shows that the northeastern trade winds are positively correlated with the Arctic sea ice, which means that as the sea ice declines, the trade winds are also losing intensity. Slower trade winds in the North Atlantic region can reflect less moisture transported from the Atlantic Ocean toward north South America, which can impact the amount of precipitation in the Amazon rainforest and the Brazilian northeast semiarid region.

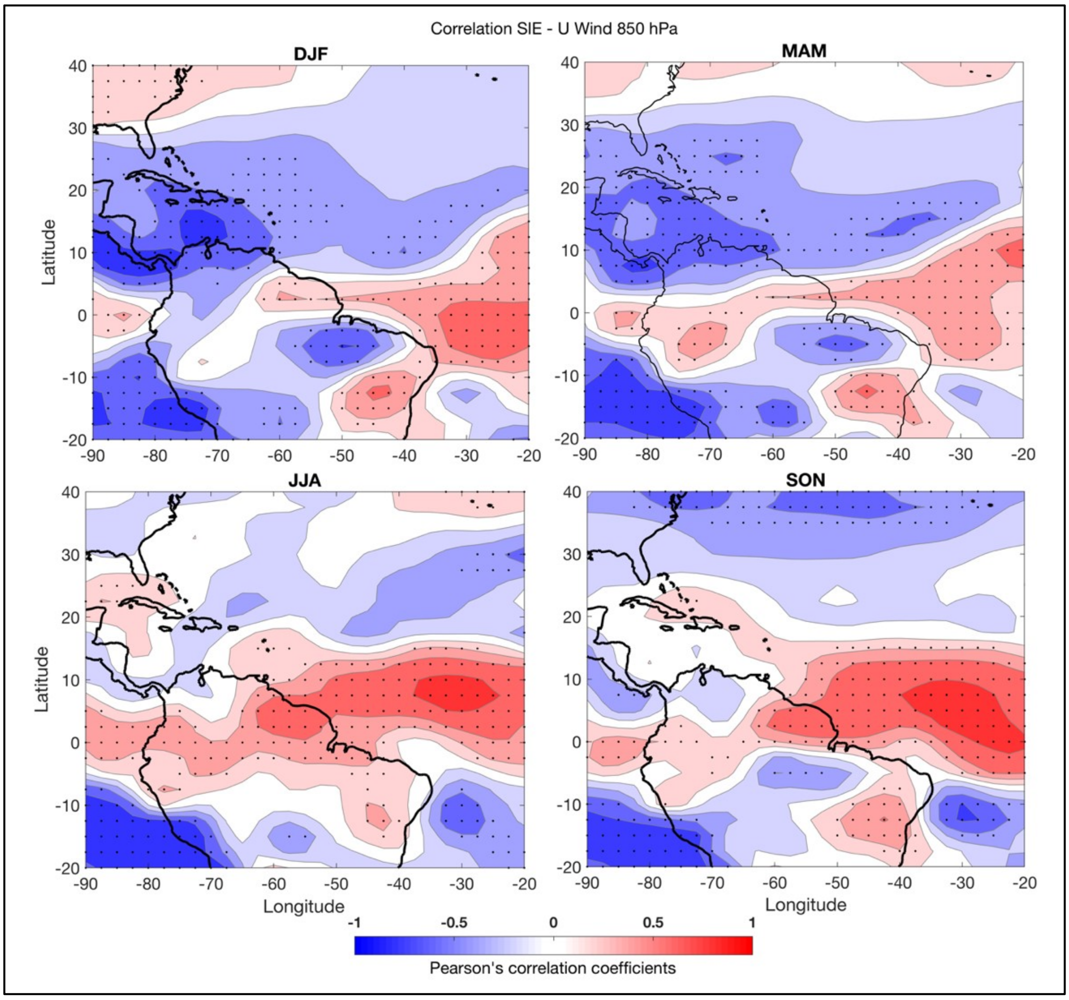

Figure 3.3 Seasonal correlation between zonal winds and Arctic SIE anomalies for the period January 1979 - December 2019. Black dots represent locations where the correlation is statistically significant based on the 95% confidence interval

The 850 hPa was chosen to investigate the trade winds to avoid surface interference. All four seasons show positive correlation coefficients between the zonal wind and SIE anomalies, with the highest values during JJA (0.80), when the ITCZ reaches its northernmost position and SON (0.85). Also, all seasons show negative correlation coefficients in the Pacific Ocean on the coast of Peru.

3.6 Limitations

Limitations of this work are that only the SIE anomalies were investigated with the Brazilian northern and northeastern regions' precipitation variability. However, the literature shows that ENSO significantly influences the region (Cavalcanti et al., 2009), and it is the primary source of precipitation variability in those regions. Other teleconnections must be considered, such as Pacific Decadal Oscillation, Atlantic Multi-decadal Oscillation, and South Atlantic Oscillation.

Additionally, the NAO mechanism may explain only part of the precipitation anomalies in this region. Following this investigation, it is necessary to explore the global and regional phenomena that may influence the relationship between precipitation in the equatorial region of South America and the Arctic sea ice extent, especially since both regions have suffered rapid climatic and environmental alterations for the last decades.

3.7 Conclusions

We have found a correlation between precipitation anomalies over the Brazilian northern and northeastern regions and the Arctic SIE anomaly, with an r-square of 15% ($\alpha = 0.05$) for the entire period. Higher correlation coefficients were found when analyzing the four seasons, reaching values of 0.65 and 0.70 during DJF and SON, respectively. SON marks the transition of the ITCZ to its southernmost position in the months of DJF, so any changes in the precipitation in the Amazon during this period could reflect in changes in the precipitation regime in other parts of South America. This has important societal and economic impacts in agriculture, cattle raising and water supplies, especially in the central parts of South America.

The literature shows that the decline of the Arctic SIE could drive the NAO to its negative phase (Nakamura et al., 2015), causing changes in the pressure gradient over the North Atlantic midlatitudes, and influencing the trade winds. A higher/lower pressure gradient in the mid-latitudes over the North Atlantic Ocean intensifies/weakens the northeast trade winds, which intensify or shift the ITCZ to the south/north hemisphere, generating positive/negative precipitation anomalies in the eastern part of the South American equatorial region.

Additionally, the NAO mechanism may explain only part of the precipitation anomalies in this region. Following this investigation, the ITCZ is projected to be displaced northward after the Arctic becomes seasonally ice-free, looking for the new thermal Equator. This mechanism could affect the precipitation in low latitudes (Chemke, Polvani & Deser, 2019; Liu & Fedorov, 2019).

Other authors also explored the relationship between high and low latitudes, such as Broccoli, Dahl & Stouffer (2006) that showed that in the Last Glacial Maximum, when the Arctic had a larger ice cap, the ITCZ was displaced Southwards. Kennel & Yulaeva (2020) showed a possible influence of the SIE loss in September over the Central and Eastern Pacific Ocean, which could even revert the trade winds direction in that region.

Teleconnections between high and low latitudes are receiving more attention lately, and two mechanisms could link the precipitation over South America and the Arctic sea ice decline. One is the relationship between the Arctic sea ice and the phases of NAO, and another is the relationship between the Arctic sea ice cover and the ITCZ position. Both mechanisms are related to the weakening of the trade winds in the tropics. McGee et al. (2014) showed that the Hadley cell circulation weakened in the warmest hemisphere, so the ITCZ is displayed towards the warmest hemisphere.

For future work, we will use PAMIP climate models to contrast a future scenario for the precipitation over northern South America, considering a 2°C warmer Arctic when compared to the 1979–2008 climatology. Using these models, we can isolate the Arctic influence in the tropics, which will help better understand the polar-tropics teleconnections.

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Author contribution

The authors confirm contribution to the paper as follows: study conception and design: De Souza Junior; Maier; data collection: De Souza Junior, E; analysis and interpretation of results: De Souza Junior, E; Maier, E; Kaur, S; draft manuscript preparation: De Souza Junior, E; supervised the findings of this work: Simoes, J; Hanesiak, J. All authors reviewed the results and approved the final version of the manuscript.

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Chapter 4 - Article 2

This article will be submitted to Journal of Climate, or another climate-related journal.

The potential impact of Arctic sea ice reduction on precipitation in northern South America using the Polar Amplification Model Intercomparison Project (PAMIP) experiments

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4.1 Introduction

The Arctic region has a warming rate two to three times higher than the global mean (Bintanja 2018). This rate difference between the polar region and the mid-latitudes is called Arctic Amplification (AA). It is caused by positive feedback such as sea ice retreat and increased albedo (Serreze & Barry, 2011). The Arctic sea ice has declined sharply in the twenty-first century; the 15 lowest extents since 1979 occurred in the last 15 years (Moon, Druckenmiller & Thoman 2021). The sea ice shrinking has the potential to weaken deep water formation, known as the Atlantic Meridional Overturning Circulation (AMOC) (Sévellec, Fedorov & Liu 2017; Suo et al., 2017). The slowdown of the AMOC could lead to enhancing the temperature difference between the Northern and Southern Hemispheres (Chiang & Bitz, 2005), affecting the precipitation over the Sahel and tropical storms (Smith et al., 2019). The disappearance of the Arctic sea ice might potentially lead to changes in global circulation which may also intensify tropical storms (Francis, 2021).

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While the Arctic has shown increased air temperatures (Overland et al., 2019), mid-latitude extreme events have increased in frequency (Cohen et al., 2014; Francis, Skific & Vavrus, 2020). This phenomenon triggered an intense scientific debate about the influence of the AA on mid-latitude weather and climate. Some researchers argue that the Arctic warming can lead the jet stream to become more meridional and propagate eastward slower or that the sea ice decline could lead to changes in Stratospheric Polar Vortex, causing colder winters in the midlatitudes (Cohen, Pfeiffer & Francis, 2018; Francis & Vavrus, 2012, 2015). On the other hand, other researchers state that the mid-latitudes variability causes such extreme weather and that Arctic warming has little influence on lower latitudes (Barnes, 2013; Screen, 2017).

The potential impacts of Arctic warming in low latitudes has received more attention recently. Model simulations show possible displacement of the Intertropical Convergence Zone (ITCZ) northward, while others result in a slightly southward displacement (Tomas, Deser & Sun, 2016; Sun, Alexander & Deser, 2018). Paleo records show that abrupt changes in the Arctic have driven changes in low latitudes. For example, Woods et al. (2020) suggested that Dansgaard-Oeschger's (DO) interstadials, abrupt climate fluctuations in the late stages of the last glacial period (Dansgaard et al., 1993), could weaken the South American Monsoon during that time, which led to an extensive retreat of Peruvian glaciers above 4,700 m of altitude, and possibly driving drier conditions in the Amazon basin. Also, according to Haug et al. (2001), Cariaco Basin sediments (northern Venezuela) are correlated with climate records of the highlatitude Northern Hemisphere, showing that changes in the North Hemisphere climate might reflect in low latitudes precipitation.

Paleo records show that the ITCZ does not stay in a stationary zonal-mean position but can be displaced northward or southward following the warmest hemisphere. Sachs et al. (2009) stated that during the Little Ice Age (LIA) (*ca.* AD 1400–1850), the ITCZ was displaced 500 km south of its current position; also, Lozano-García et al. (2007) pointed out that during this period tropical vegetation expanded, due to the southward position of the ITCZ. Schneider et al. (2014) argued that during the LIA, the northern Hemisphere cooled after the Holocene thermal maximum, which may have driven the ITCZ to be displaced southward.

Broecker & Putnam (2013) pointed out that the Northern Hemisphere is likely to warm faster than the Southern Hemisphere, leading to a northward displacement of the ITCZ; consequently, the southern Amazon may potentially become drier and Venezuela wetter. Field Lee and Wang (2014) also identified the hemispherical temperature difference as a driver for the ITCZ northward displacement followed by the intensification of the Hadley Cell. However, Byrne et al. (2018) indicated that the ITCZ has presented no changes in its zonal-mean position in recent decades. The models analyzed show no robust projected changes in the twenty-first century. Half of these models show the ITCZ will slightly shift northward, while the other part shows a slight shift southward.

Liu & Fedorov (2019) analyzed the impacts of the sea ice decline on different scales, reaching up to 200 years in the future. Their simulations show a northward displacement of the ITCZ within ~25 years after the seasonal arctic ice-free period occurs; Liu & Fedorov (2019) argued that changes in the atmospheric dynamics drive this change. However, the ITCZ is projected to shift southward after this period due to the Atlantic Meridional Overturning Circulation (AMOC) slowing down.

Future projections for the zonal-mean position of the ITCZ present different results depending on the model's configuration; atmosphere-only models present a northward migration, while ocean-atmosphere models present an equatorward intensification of the ITCZ or even a southward displacement (Wang et al., 2018; Sun, Alexander & Deser, 2018).

The polar influence over the tropics has been poorly explored; nonetheless, Cvijanovic et al. (2017) suggested that recent changes in the Arctic have the potential to affect the tropical convection over the Pacific Ocean and force the northward propagation of the Rossby wave with an anticyclonic flow in the North Pacific. For example, this mechanism could force drier conditions over California, contributing to droughts (*ibidem*). Therefore, changes in the Arctic might be reflected in the tropical regions.

Recent research suggests that sea ice loss can initiate Central Pacific El Niño events. Kim et al. (2020) indicated that diminishing sea ice concentration (SIC) might affect tropical Pacific sea surface temperature (SST) and that sea ice reduction could influence the positive phase of the North Pacific Oscillation to warm the central tropical Pacific Ocean. Similarly, Kennel and

Yulaeva (2020) argued that shrinking sea ice in the Siberian Arctic might perturb the upper troposphere, which transports momentum and heat southwards in the upper atmosphere. This could lead to a teleconnection between the region north of the Siberian Arctic coast and the ITCZ, which has the potential to reverse the trade winds over the central Pacific, triggering El Niño events. England et al. (2020) also mentioned that sea ice loss could warm eastern equatorial Pacific waters through zonal asymmetries in the tropical SST linked to ocean dynamics, resulting in increased rainfall over the equatorial Pacific.

The tropical North Atlantic Ocean is the primary source of moisture in the Amazon rainforest. Variations in the trade winds' velocity have been shown to influence the amount of humidity transported from the ocean toward the continent. The most important regional source of precipitation is from the ITCZ-induced air mass movement. Thus, changes in the position of the ITCZ affect the precipitation regime, especially at the borders of ITCZ seasonal movement (Reboita et al., 2010).

Considering this past research on uncertainties of the impact of sea ice variability on the low and mid-latitudes climate, this paper investigates how future changes in the Arctic sea ice extent may affect low-latitude precipitation. Specifically, the focus is on northern South America because changes in this region can impact the hydrologic regime of the Amazon rainforest, using models from the Polar Amplification Model Intercomparison Project (PAMIP) (Smith et al., 2019).

4.2 Methodology

4.2.1 Atmosphere General Circulation Model (AGCM) Description

Five atmospheric general circulation models - AGCM (canESM5, CESM2, FGOALS, MIROC6, norESM2; Table 1) (Tatebe et al., 2018; Zhou et al., 2018; Swart et al., 2019; Danabasoglu et al., 2020; Seland et al., 2020) from the PAMIP (Smith et al., 2019), which are part of the Coupled Model Intercomparison Project – CMIP6 (Eyring et al., 2016) of the World Climate Research Programme (WCRP), were used to quantify the precipitation changes over northern South America using two different scenarios. We chose the PAMIP models because they were specially designed to investigate how changes in the Arctic affect other regions of the world.

The first scenario employs present-day SST and SIC data (1.1 pdSST-pdSIC) hereafter "Present" and represents the global mean temperatures between 1979–2008. The second scenario uses present-day SST and future SIC (1.6 pdSST-futArcSIC) hereafter "Future", consisting of forecasting the SIC in the Arctic considering 2°C global warming (15.67°C) relative to pre-industrial conditions (13.67°C) (Smith et al., 2019). According to Niederdrenk & Notz (2018), an increase of 2°C in the pre-industrial temperature could represent the ice-free Arctic in September. The main objective of the PAMIP is to understand how the global climate responds to changes in the Polar Regions. Both experiments, Present and Future, are tier 1 atmospheric time slices; their only difference is the sea ice concentration. The processes used to force the models are found in the appendix of Streffing et al. (2021). All data are available at https://esgf-node.llnl.gov/search/cmip6/.

Table 4.1 PAMIP models resolution used in this investigation and main characteristics

Model	Lat resolution	Lon resolution	Grid	Characteristics
CanESM5	2.76	2.81	64 x 128	Set for seasonal and decadal predictions; it consists of the three-dimensional atmosphere (T63 spectral resolution / 2.8°) and ocean (nominally 1°) general circulation models
CESM2	0.94	1.25	192 x 288	More realistic representation of Greenland's ice sheet dynamics; improved detail of how crops interact with the Earth system, better representation of clouds and rain, addition of wind-driven waves over the ocean surface
FGOALS	1	1.25	180 x 288	Refined performance of cloud-radiation processes, including Asian monsoon, ENSO, Atlantic Meridional Overturning Circulation (AMOC), and sea ice
MIROC6	1.38	1.4	128 x 256	Improved tropical climate systems (e.g., summertime precipitation in the western Pacific and the eastward-propagating Madden–Julian oscillation) and also midlatitudes atmospheric circulation (e.g., the westerlies, the polar night jet, and troposphere–stratosphere interactions)
norESM2	1.89	2.5	96 x 144	Improved atmosphere components such as aerosol and chemistry, including interactions with clouds and radiation; improvements in the formulation of local dry and moist energy conservation, local and global angular momentum conservation, and computations for deep convection and air-sea fluxes.

First, we calculated the ensemble average for both scenarios for each model. The models (canESM5, CESM2, FGOALS, MIROC6) consist of 100 ensembles and norESM2 200 ensembles, so we opted to use the first 100. After having the ensemble mean for each scenario, we calculated the difference between the present and future. To calculate the difference's statistical significance, we used each scenario's ensembles, selecting the seasonal means DecJan-Feb (DJF) and Jun-Jul-Aug (JJA) for each ensemble and performing the Mann-Whitney U test. We opted for using these two seasons because, in this period, the ITCZ is in its southernmost and northernmost position, respectively.

The next step was to calculate the models' precipitation mean. Since they present different resolutions, we interpolated them to the lowest model resolution (canESM5) in a grid of 2.78 x 2.81 latitude by longitude. We calculated the ensemble mean difference and model mean using the same models' zonal and meridional wind components to understand the dynamic changes.

To improve our understanding of the precipitation changes, we applied the same method to plot the surface winds, so changes in the atmospheric circulation will give further insights, such as changes in speed and position of the trade winds, into the precipitation changes under a 2°C global warming. Three of the five models used in this paper do not have wind data over the continents, so we did not calculate the inter-model mean.

4.2.2 AGCM Validation

In order to validate the PAMIP models with the NCEP reanalysis, we selected the period of January 1979 to December 2008, period that comprises the Present scenario for the models, we plotted the five models plus the NCEP for the season DJF (Figure A1 supplemental material), then we calculated the difference between the models and the NCEP (Figure A2). We did the same for JJA (Figures A4 and A5).

For DJF the models canESM5, CESM2, MIROC6 and norESM2 do a good job representing the precipitation over the northern South America, FGOALS is the most biased, underestimating the precipitation over the continent. For JJA all the five models represent well the precipitation when comparing the reanalysis, FGOALS also underestimates the precipitation over the Atlantic Ocean in the equatorial region.

4.3 Results

4.3.1 Precipitation

The precipitation difference between the Present (1979-2008 model climatology) and the Future scenario for December-January-February (DJF) is presented in Figure 4.1. The five models used in this comparison show varying results: canESM5, CESM2, FGOALS, MIROC6, and norESM2. CanESM5, CESM2, and norESM2 show a decrease in the precipitation around the Equator in the northernmost part of South America. CanESM5 also shows reduced precipitation over central South America, while CESM2 and norESM2 show increased precipitation in the same region.

In contrast, FGOALS results in an increase in precipitation in almost all northern parts of the continent, with a marked increase in the Atlantic Ocean coast at the Equator. MIROC6 shows increased precipitation in an area centred at 5° S and 60° W and decreased precipitation over the Brazilian northeast and Bolivia.

The model average (Fig. 4.1) shows two distinctive regions of precipitation changes (in millimetres per day) during DJF, almost divided by the Equator: the region north of the Equator shows a decrease in precipitation; in the one to the south, the precipitation increases during DJF.

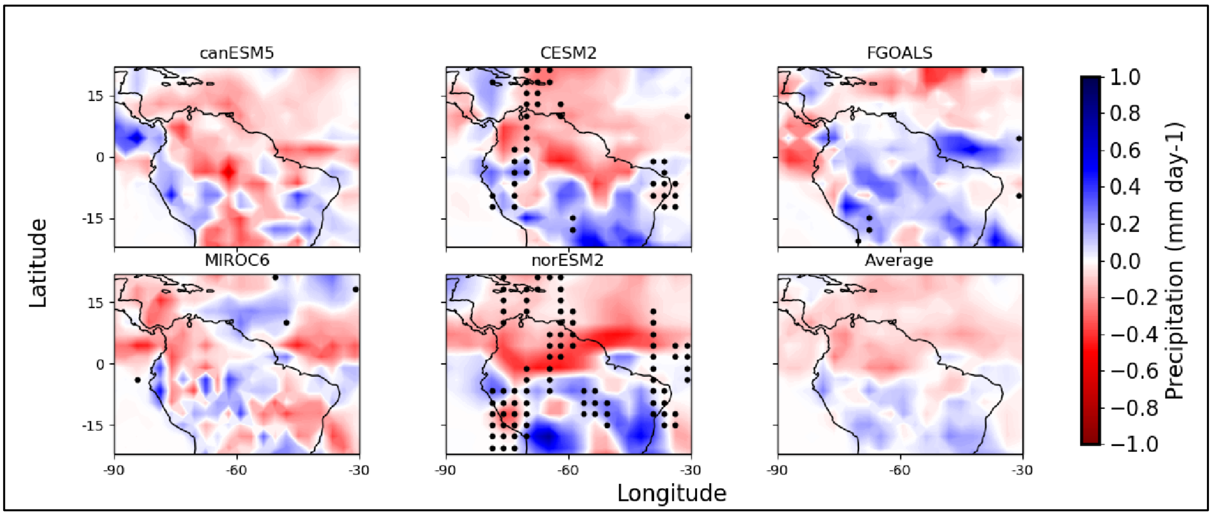

Figure 4.1 Precipitation difference between modelled Present and Future seasonal mean for December-January-February (DJF), black dots represent 95% confidence interval.

(supplementary materials figure A1, show the precipitation seasonal mean ensemble average, for each model for DJF present and, and also the NCEP reanalysis for the same period. Figure A2 shows DJF for future. Figure 4.5 shows the inter-model precipitation average for DJF for present and future).

Figure 4.2 shows the comparison between the present and future for JJA. Here, it is also possible to notice the spread in results among the models. CanESM5 shows a latitudinal increase in precipitation around 10° N and 30°–65° W, and a region of reduced precipitation at the Equator latitude in the area corresponding to Peru/Bolivia and 30°–60° W. The norESM2 shows a similar result; however, the latitudinal area with the most enhanced precipitation is located at the Equator crossing the South American continent. There are two areas of increased precipitation, one over the Caribbean Sea and North Atlantic Ocean, and the second at 5° S and 30°–60° W.

CESM2 and MIROC6 show similar results; however, MIROC6 has a greater magnitude in predicted differences. An increased precipitation region is projected in the western part of the Amazon, with reduced precipitation over the northern coast of South America around the area of the Amazon River mouth. These models also predict a reduced precipitation region over the Pacific coast around Central America. FGOALS shows spread results with two areas of increased precipitation, one over the Brazilian northeast and another around the western Amazon and Central America. This model also predicts an area of decreased precipitation over central and central northern parts of South America.

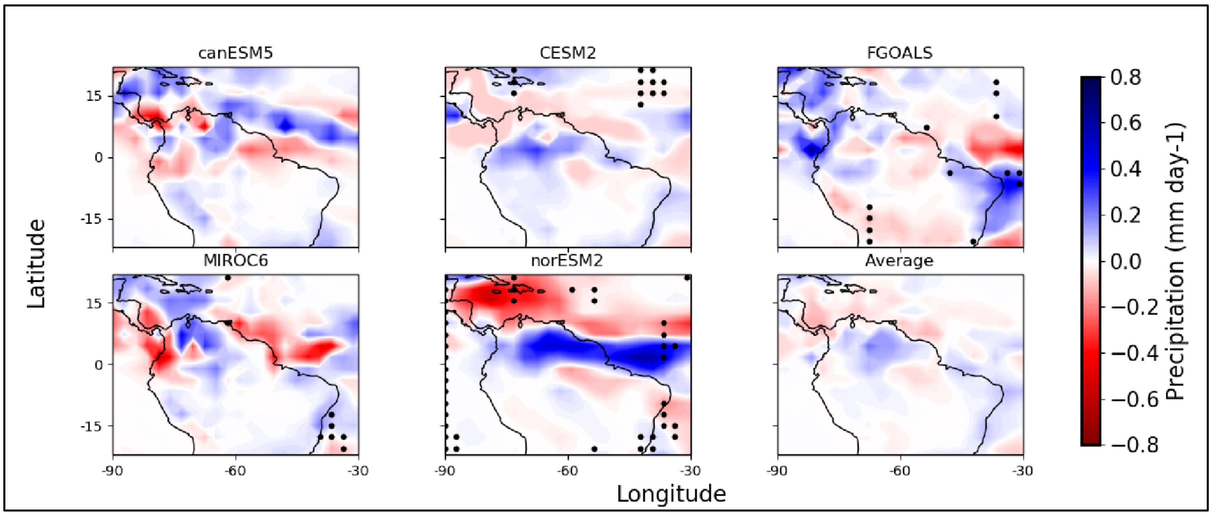

Figure 4.2 Precipitation difference between modelled Present and Future seasonal mean for June-July-August (JJA), black dots represent 95% confidence interval. (supplementary materials figure A4, show the precipitation seasonal mean ensemble average, for each model

for JJA present and, and also the NCEP reanalysis for the same period. Figure A6 shows JJA for future)

The models' average shows a slight difference in the precipitation with increased precipitation over the central Amazon (2°N, 65°W) and the northeast Brazilian coast. Also, two reduced precipitation areas, one over the Caribbean Sea and another over the central east Amazon (2°S, 50°W).

The DJF and JJA show different results. The model average for DJF shows drier conditions in the northern part of South America and wetter conditions in southern Amazonia. While in JJA, the average shows wetter conditions in the western part of the Amazon region while drier conditions in the eastern part. There is more inter-model variability in the JJA season, this may affect the inter-model average result. The IPCC projections for northern South America show an increase in the extreme precipitation and flooding (IPCC, 2021), however their results are not divided into seasons.

4.3.2 Winds

For DJF, the canESM2 model predicts a decrease in the northeastern trade winds over the Atlantic and a decrease in wind speed of larger magnitude on the Pacific coast of northern South America, which rare responsible for the predicted decrease the precipitation in the north part of South America and increased precipitation in the southern part of Central America (Figure 4.3).

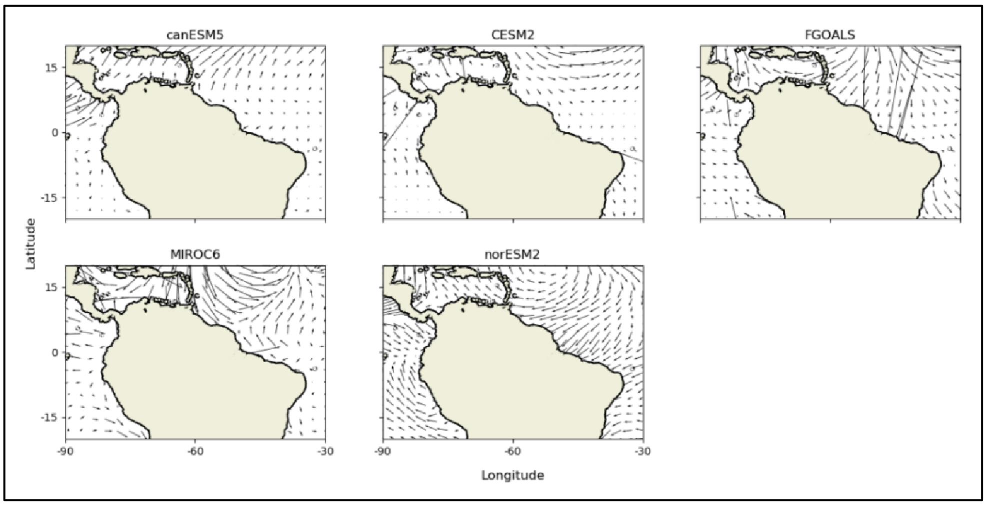

Figure 4.3 Surface wind speed difference between present and future seasonal mean for DJF. (supplementary materials figure A7, show the surface wind seasonal mean ensemble average,

for each model for DJF present and, and also the NCEP reanalysis for the same period. Figure A8 shows DJF for future)

The CESM2 model deflected the northeastern trade winds towards Central America, which decreased the moisture transport from the North Atlantic towards South America. FGOALS shows an increased wind speed and intensity from the North Atlantic towards South America, leading to increased precipitation. On the Pacific side, however, the trade winds slowed down, and there was a decrease in precipitation in the southern part of Central America and the coast of Ecuador and Peru.

The MIROC6 model also shows a deflection of the trade winds on the northeastern coast of Brazil towards the northern portion of South America and slower trade winds over 15° N and 60° W, which lead to prediction of wetter conditions in this region. The norESM2 model shows an area in northeastern Brazil where the trade winds are faster, coinciding with increased precipitation. The North Atlantic trade winds are deflected northward, leading to drier conditions over the northern South and Central America.

During JJA, the inter-model mean shows wetter conditions in the northernmost part of South America and the northeastern Brazilian coast while showing drier conditions in the eastern part of the Amazon. CanESM5 shows a slight displacement of the trade winds over the North Atlantic in the JJA period, associated with the ITCZ moving northward, while the northeastern part of South America becomes drier (Figure 4.4).

The CESM2 model shows the trade winds changing such that the ITCZ shifts southward, which leads to the area around equatorial South America being wetter and the region around 10° N drier. The FGOALS model shows weaker northeastern trade winds, but at the same time, stronger southeastern trade winds contribute to increasing the precipitation over the Brazilian northeast.

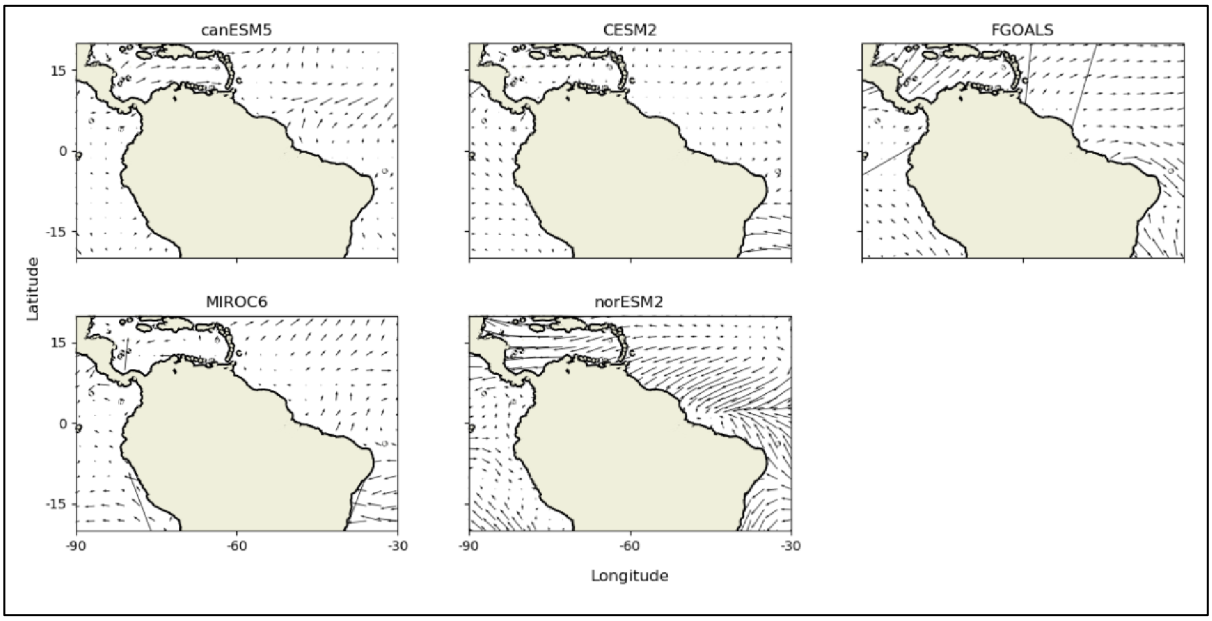

Figure 4.4 Wind speed difference between present and future seasonal mean for JJA. (supplementary materials figure A9, show the surface wind seasonal mean ensemble average, for each model for JJA present and, and also the NCEP reanalysis for the same period. Figure A10 shows JJA for future)

The MIROC6 model presents slower northeastern trade winds that may possibly have decreased the convection in the northeast part of South America. The norESM2 model shows stronger trade winds over the North Atlantic with a southward shift of the ITCZ, leading the north part of South America to become wetter while the Caribbean region becomes drier.

4.4 Discussion

The precipitation inter-model average for DFJ and JJA, considering the difference between present and future, show that during the months of DJF, the South American regions below the Equator become wetter while the parts in the northern hemisphere become drier. The findings also show that the months of JJA present wetter conditions in the north part of South America. The results show that changes in the SIC possibly will influence precipitation anomalies in the north of South America regions. These findings are similar to Tomas et al. (2016) & Sun et al. (2018), where atmosphere only models show a northward migration of the ITCZ while leading to wetter conditions in that region during JJA.

Marengo (2004) studied the interdecadal variability of Amazon's precipitation in the period 1929–98, finding negative rainfall trends in the entire Amazon basin in the period 1950–98.

The regional analyses revealed two distinct regions; the northern Amazon region presented a negative trend, while the southern region presented a positive trend. The PAMIP results show that during DJF, the north Amazon basin is expected to become drier while the southern region will be wetter; however, during JJA, western regions are expected to become slightly wetter.

A drier DJF in the Amazon region results in a shorter wet season; as the ITCZ reaches its southernmost position during this time of the year, this region receives its precipitation peak. Marengo & Souza (2018) point out that longer dry seasons in the Amazon region might be combined with more frequent droughts, which must be considered in climate change scenarios for the Amazon region. So, changes in the precipitation in DJF are more significant than JJA because it could result in negative impacts for the South America, possibly resulting in drier conditions in central parts of the continent in the following months due to decreases in moisture transported southward by the low-level jets.

Recent research, mainly focusing on the tropical Pacific, shows a teleconnection between the Arctic and the tropics. Kim et al. (2020) showed that the Central Pacific has potential to become warmer due to sea ice loss. Kennel & Yulaeva (2020) showed that the Arctic sea ice loss could weaken the trade winds in the central Pacific, and also England et al. (2020) showed that SST in the eastern equatorial Pacific would also increase due to changes in the SIE. These results agree with future changes presented in the PAMIP model averages discussed in this paper.

Even though the northern hemisphere is becoming warmer than the southern hemisphere, the ITCZ does not move northwards as has happened in the past (Broecker & Putnam 2013), which would lead to a longer dry sea in the Amazon basin; paleoclimate research using sediments of the Cariaco basin (Venezuela) shows that the thermal Equator migrates in the direction of the warmest hemisphere (McGee et al., 2014). This may actually be due to human-induced climate change's complexity. Also, according to Liu and Fedorov (2019), the atmosphere would have a predominant role in the first decades after the Arctic sea ice's disappearance in summer, which would lead the ITCZ to move northwards. However, the PAMIP models show that with the future reduction of the SIC, the atmospheric dynamics will possibly drive the ITCZ southwards, especially during JJA.

During the process of validation of the models, when we calculated the NCEP reanalysis using the same time frame as the climatological mean used for the model’s present scenario (Jan 1979 to Dec 2008), we ranked the models that are more similar to the reanalysis-based on the magnitude of the differences. As shown in Figure A2 (supplemental material), in DJF the norESM2 presents results more similar to the reanalysis while the FGOALS presents higher values which means that FGOALS differ more than the reanalysis; that is, norESM2 is the more reliable model. The same approach was used for JJA, in this case canESM5 presented smaller values for the difference reanalysis minus models and again FGOALS showed higher values for the difference; canESM5 is the most reliable model for JJA.

Limitations of this work are related to the present scenarios that are not based on reanalysis but use the models' internal variability climates, which may not represent the 1979-2008 period with fidelity. Another limitation is the number of models available in the PAMIP project; we used these five models because they were the only ones with the climatological mean and future SIC with precipitation data. Besides, in future scenarios, SST are expected to increase, potentially affecting the results presented here.

4.5 Conclusion

We investigated how future Arctic sea ice conditions, considering a 2°C warming above the pre-industrial level, could impact the precipitation over northern South America, particularly in the Amazon region, using the PAMIP models.

We focused our analysis on two seasons: DJF when the ITCZ reaches its southernmost position and JJA when it reaches its northernmost position. The precipitation inter-model mean for DJF shows that the northern Amazon becomes drier compared to the present conditions, while the southern region becomes wetter. For the JJA, the precipitation inter-model mean shows the northern Amazon to become wetter.

Our results show that during DJF, the trade winds weaken in the Atlantic sector, affecting the moisture transport from the Atlantic Ocean towards the South American continent. At the same time, during JJA, the ITCZ could be displaced southward, increasing precipitation on the southern border of the ITCZ seasonal mean position. However more research is necessary to determine the root cause of such precipitation and trade wind changes. Considering the role of the seasonal variability of the ITCZ in controlling the precipitation in the tropics our findings result from changes in the atmospheric circulation related to the weakening of the trade winds in the Atlantic sector and southward migration of the ITCZ in both seasons.

When calculating the differences between the models and the NCEP reanalysis for the DJF, we can rank the models that are more similar to the reanalysis, to provide some indication of confidence in model projections; they are as follows in order of most confidence: norESM5, canESM5, CESM2, MIROC6, and last FGOALS. For the JJA season, the best fit is canESM5, followed by norESM2, CESM2, MIROC6, and lastly FGOALS.

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Author contribution

The authors confirm contribution to the paper as follows: study conception and design: De Souza Junior, E; McCrystall, M; data collection: De Souza Junior, E; analysis and interpretation of results: De Souza Junior, E; Marchetto Silva, P; draft manuscript preparation: De Souza Junior, E; supervised the findings of this work: Simoes, J; Hanesiak, J. All authors reviewed the results and approved the final version of the manuscript.

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Chapter 5- Summary and conclusion

5.1 Summary of major findings

The research work presented in this thesis is designed to improve our understanding of sea ice loss and its teleconnections to low latitudes, over northern South America. The research work is based on both reanalysis and climate models.

Major Finding 1

Using sea ice data provided by NSIDC and precipitation monthly means reanalysis data for the same period provided by NCEP/NCAR, we correlate precipitation anomalies in equatorial South America with Arctic sea ice extent anomaly series. A precipitation centre with the highest correlation with Arctic sea ice extent anomalies was identified in the eastern part of equatorial South America (in the Amazon rainforest). This region's time series was then compared to the sea ice extent anomaly using a linear regression dependence analysis. An r-square of 15% ($\alpha = 0.05$) was found; in other words, the sea ice variability might influence 15 percent of the precipitation volume anomaly in some parts of Brazil's northern and northeastern regions. The Arctic sea ice decline could drive the NAO to its negative phase, causing changes in the pressure gradient over the North Atlantic mid-latitudes, influencing the trade winds. This suggests that a higher/lower pressure gradient in the mid-latitudes over the North Atlantic Ocean intensifies/weakens the northeast trade winds. This then intensifies or shifts the ITCZ to the south/north hemisphere, generating positive/negative precipitation anomalies in the eastern part of the South American equatorial region.

Major Finding 2

We used five atmospheric general circulation models from the Polar Amplification Model Intercomparison Project (PAMIP) to quantify the precipitation changes over northern South America using two different scenarios, one employing present-day SST and sea ice concentration (SIC) and other consisting in projections of the SIC in the Arctic considering 2°C atmospheric warming relative to pre-industrial conditions. The model average projections for the December-January-February (DJF) season show drier conditions in the northern part of the

Amazon and wetter conditions in the southern part in the > 2 °C scenario. We found that norESM5 is the model that better represents the precipitation when comparing the NCEP reanalysis and FGOALS is the model that showed most pronounced differences from the reanalysis. At the same time, the June-July-August (JJA) season shows wetter conditions in the western part of the Amazon region, and drier conditions in the eastern part. These precipitation changes are related to changes in the atmospheric circulation in the tropical Atlantic. For the JJA, the best fitting model for the NCEP precipitation is canESM5 and worst is FGOALS. Our results show that during DJF, trade winds weakened in the Atlantic sector, affecting the moisture transport from the Atlantic Ocean towards the South American continent. During JJA, the Intertropical Convergence Zone (ITCZ) shows a slight displacement southward, increasing precipitation on the southern border of the ITCZ seasonal mean position. It is noted that these results represent the model average, and there is a large spread in the intermodel variability. Our DJF results agree with the ones shown in the IPCC 2021, with respect to future precipitation over northern South America projecting a negative trend of the precipitation, however IPCC also projects more extreme events of high rate of precipitation over this region.

5.2 Limitations of work

The thesis consists of the study of the Arctic sea ice loss and atmospheric teleconnections to the tropics. For this study, we used NCEP reanalysis and the PAMIP models. Only the parameters focused on are wind and precipitation. Other factors such as geopotential height, atmospheric pressure, and temperature have not been considered. Also, the use of only one reanalysis dataset can be seen as a limitation; other datasets could provide different insights into this research.

5.3 Future steps and recommendations

The high-low latitudes teleconnections can be better explored. We have seen that atmosphereonly and full ocean models have shown different results for the Arctic sea ice loss and its influence on the ITCZ. This field of study tends to improve significantly with use of different reanalysis products.

I recommend investigating the period of the Arctic sea ice in positive anomalies (January 1979 – December 2019) and negative anomalies (January 2000 – present) using reanalyses products to U-component winds, sea level pressure and geopotential height in NCEP-DOE, ERA5, JRA55, and MERRA. After that, plot a figure with four boxes (for each reanalysis), period A, period B, and the difference between periods A and B. This will show if the Arctic SIE changes have influenced the tropical Atlantic trade winds.

APPENDIX A: Supplemental material for Chapter 4

In order to compare the PAMIP models with a reanalysis product, we plotted the present scenarios' seasonal average 1979-2008 with the same period as the NCEP reanalysis (Figure A1) and also calculate the difference from the NCEP reanalysis to models (Figure A2). We selected the same period used in the present scenarios and calculated the average for the NCEP reanalysis. From the five models, FGOALS underestimates the precipitation over the South American continent, while the other models perform similarly to the reanalysis.

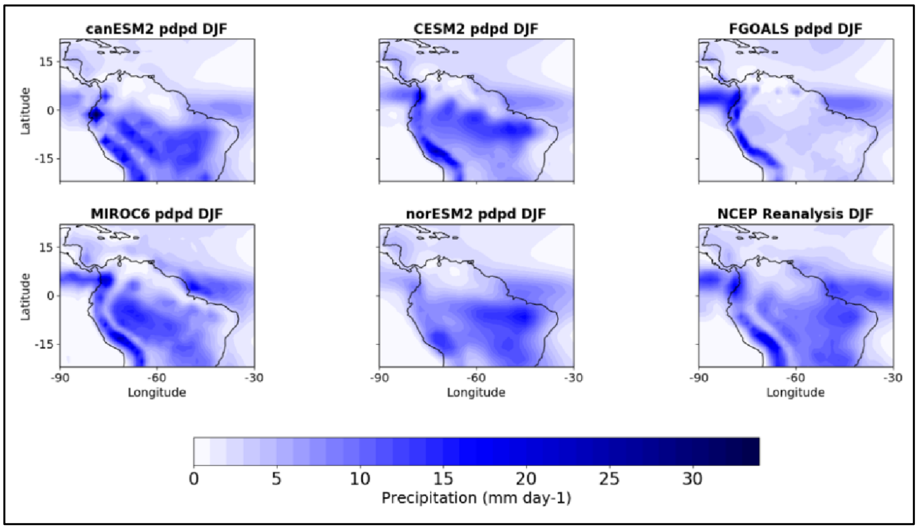

Figure A1 Seasonal average for the pdSST-pdSIC (present) for the PAMIP models and NCEP Reanalysis for the months of December-January-February (DJF)

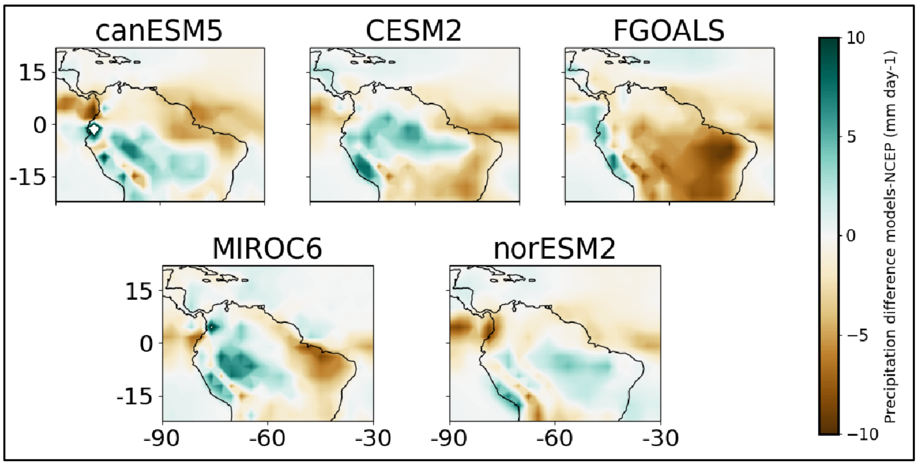

Figure A2 Seasonal difference NCEP reanalysis minus each model for the months of December-January-February (DJF)

We also plotted the model's precipitation for the future scenario (Figure A3) and comparing with the other models FGOALS shows lower precipitation over the South American continent for DJF season.

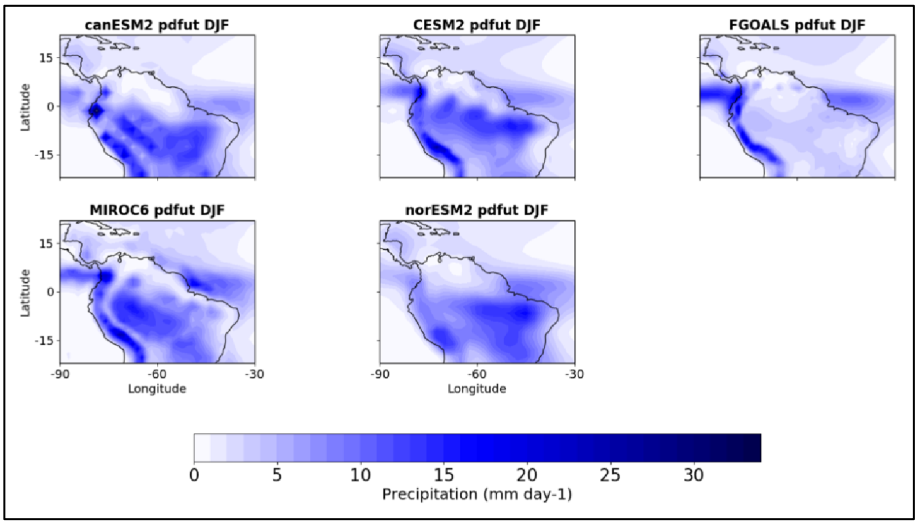

Figure A3 Seasonal average for the pdSST-futArcSIC (present) for the PAMIP models over the DJF period

We also compared the present scenario the June-July-August (JJA) seasonal average with the NCEP reanalysis (Figure A4), and calculated the difference from NCEP reanalysis to the models (Figure A5). Here once again, all of the models perform similarly with the reanalysis except for FGOALS that shows small amounts of precipitation in the ITCZ location, and also showing the ITCZ over the Atlantic located 5 degrees further south than the reanalysis.

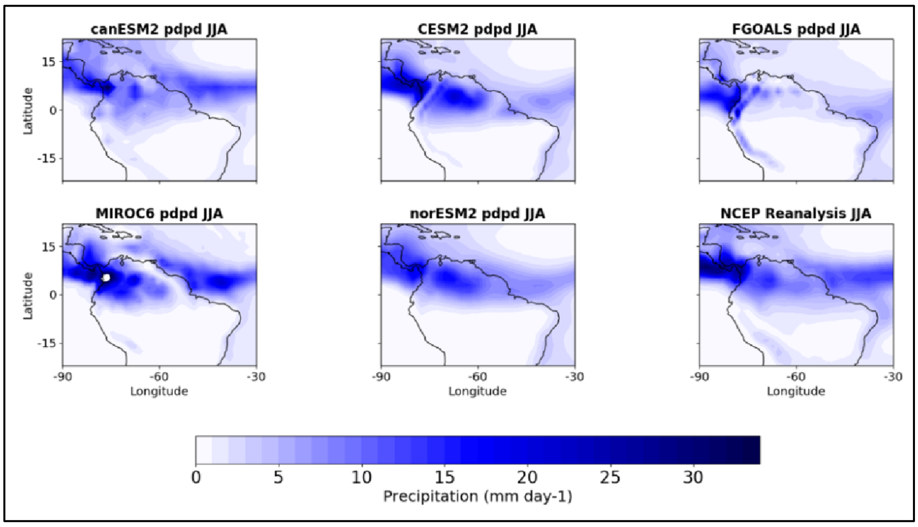

Figure A4 Seasonal average for the pdSST-pdSIC (present) for the PAMIP for the months of June-July-August (JJA).

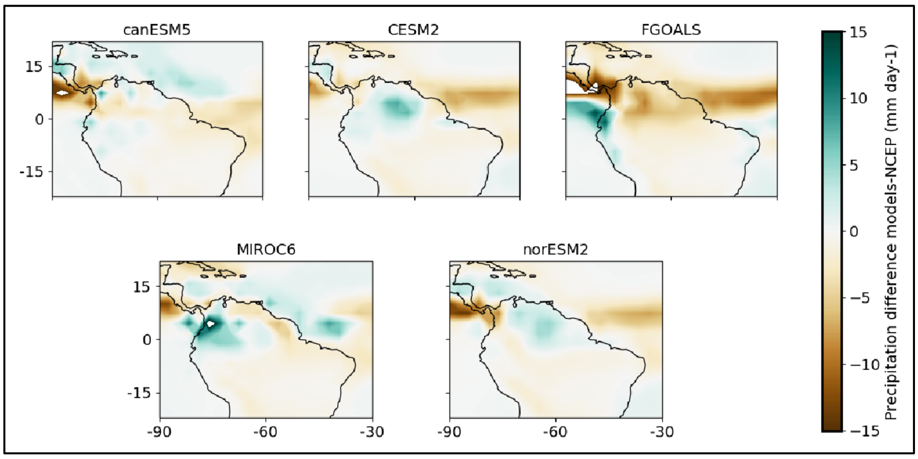

Figure A5 Seasonal difference from PAMIP models to NCEP reanalysis for the months of June-July-August (JJA)

Here, we plotted the future precipitation scenario for JJA for the models (Figure A6) and again the models perform similarly except for FGOALS that shows smaller amounts of precipitation in the Equator, location of the ITCZ.

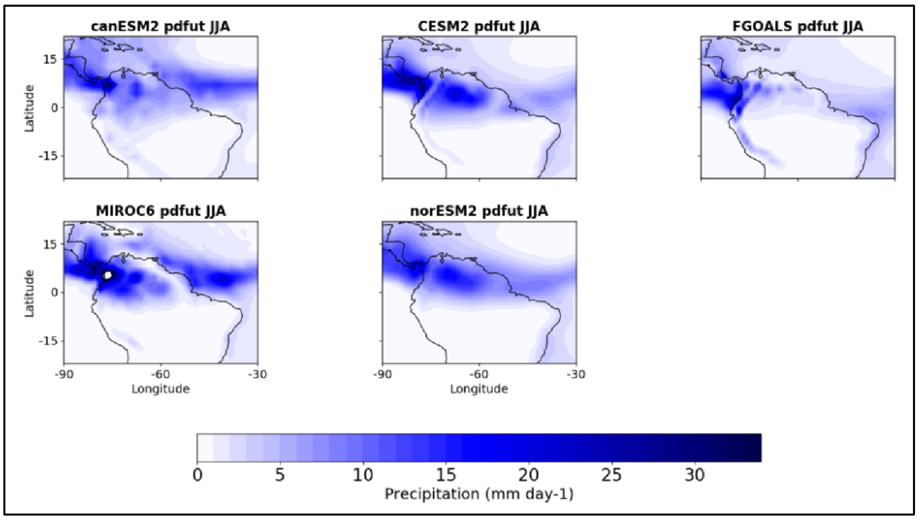

Figure A6 Seasonal average for the pdSST-futArcSIC (future) for the PAMIP models over the JJA period

A comparison between surface winds from the PAMIP models and NCEP reanalysis in DJF, shows that all models appear to simulate realistic surface wind patterns in the domain of interest (Figure A7). For example, the ITCZ location (convergence region) is similarly located off the east coast of S. America, however, it does appear that the norESM2 may overestimate wind speed magnitudes; differences between NCEP reanalysis and the models was not calculated due to model resolution variations and no winds over terrestrial regions.

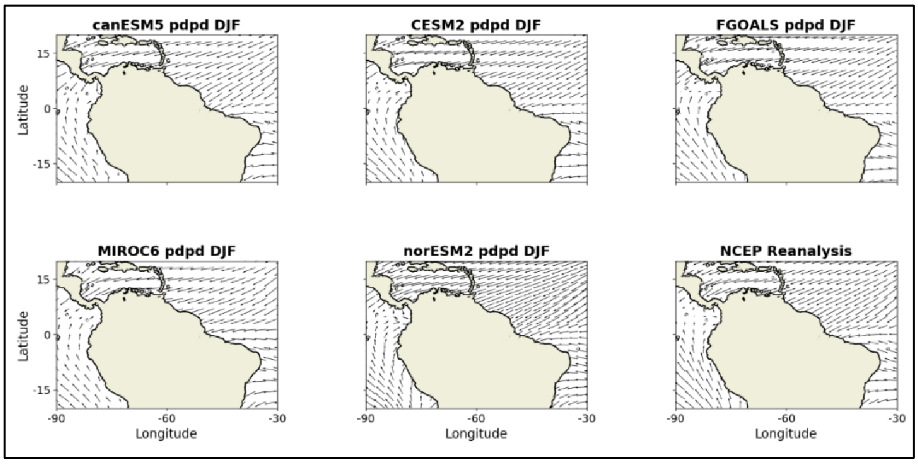

Figure A7 Seasonal average of surface winds of the pdSST-pdSIC for the PAMIP models and NCEP reanalysis over the DJF period.

We also plotted the surface wind circulation for the future scenario for the JJA season (Figure A8). They show similar results to present scenario with changes only perceptible when calculating the difference of both scenarios (Figures 4.3 and 4.4).

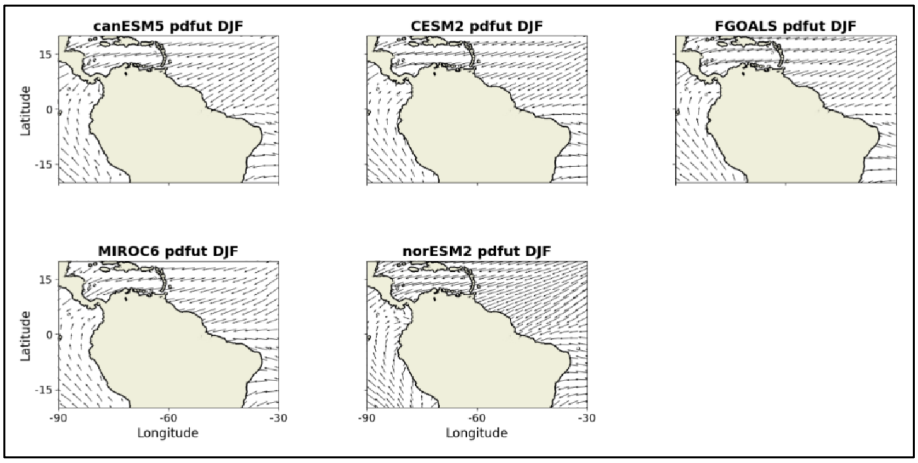

Figure A8 Seasonal average of surface winds of the pdSST-futArcSIC for the PAMIP models over the DJF period.

For the JJA season comparing the present scenario with the NCEP reanalysis, canESM5, MIROC6, and norESM2 are similar to the reanalysis, however, CESM2 and FGOALS show slower northeastern trade winds over the Atlantic (Figure A9). However, all models appear to position the ITCZ in a similar location compared to NCEP reanalysis.

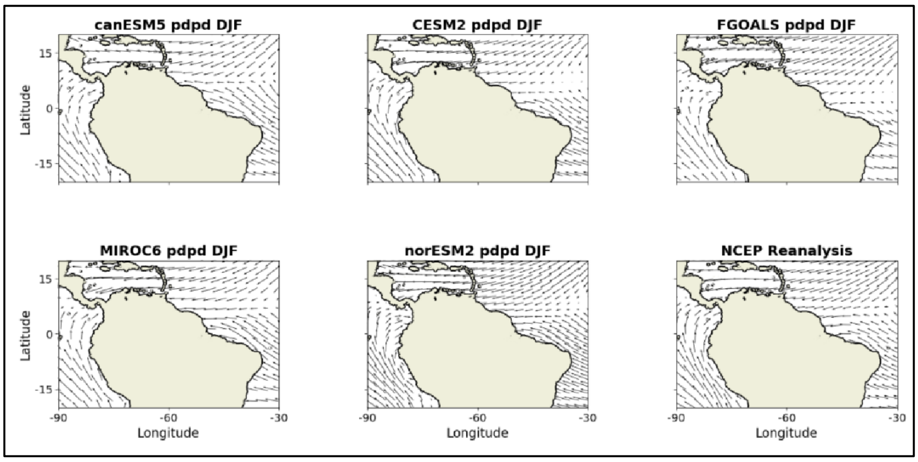

Figure A9 Seasonal average of surface winds of the pdSST-pdSIC for the PAMIP models over the JJA period.

In the future scenario for the JJA season the models present corresponding results with the present scenario (Figure A10).

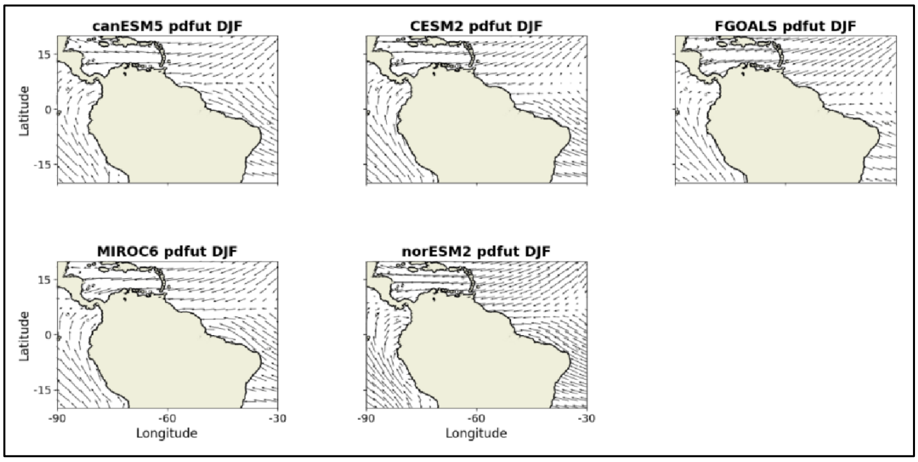

Figure A10 Seasonal average of surface winds of the pdSST-futArcSIC for the PAMIP models over the JJA period.