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GEOSCIENCES

Glacial meltwater input to the ocean around the Antarctic Peninsula: forcings and consequences

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Abstract: The Antarctic region has experienced recent climate and environmental variations due to climate change, such as ice sheets and ice shelves loss, and changes in the production, extension, and thickness of sea-ice. These processes mainly affect the freshwater supply to the Southern Ocean and its water masses formation and export, being crucial to changes in the global climate. Here, we review the influence of the glacial freshwater input on the Antarctic Peninsula adjacent ocean. We highlight each climate process' relevance on freshwater contribution to the sea and present a current overview of how these processes are being addressed and studied. The increase of freshwater input into the ocean carries several implications on climate, regionally and globally. Due to glacier melting, the intrusion of colder and lighter water into the ocean increases the stratification of the water column, influencing the sea-ice increase and reducing ocean-atmosphere exchanges, affecting the global water cycle. This study shows the role of each hydrological cycle processes and their contributions to the regional oceanography and potentially to climate.

Key words: water cycle, climate change, Southern Ocean, ice-ocean-atmosphere interactions.

INTRODUCTION

The Southern Ocean (SO) has an important role in Earth's global climate. It is a significant sink for heat and CO_2 and is the world's most biologically productive ocean (Liu & Curry 2010). In the last decades, studies indicate that the SO is changing rapidly, presenting significant warming of the Antarctic Circumpolar Current (ACC) (Gille 2002, 2008, Auger et al. 2021), freshening (Antonov et al. 2002, Boyer et al. 2005, Durack & Wijffels 2010, Swart et al. 2018), decreasing in oxygen (Shepherd et al. 2017), and acidification (McNeil & Matear 2008, Henley et al. 2020, Figuerola et al. 2021).

The Antarctic Peninsula (AP) is the northernmost region of Antarctica and is located at the west side of the Antarctic Continent (Figure 1). The AP has increased its contribution of meltwater into the ocean during the last few decades (Adusumilli et al. 2018). Some of the most significant changes have been detected in that area, with the retreating of nearly 87% of the glaciers, not counting the countless collapses of ice shelves (Cook et al. 2016). Part of the increased melting is related to the warmer atmosphere associated with the intensification of the Southern Annular Mode (SAM) positive phase (Dickens et al. 2019). This climate mode influences the strengthening of warmer westerly winds and consequent surface melting on the AP's eastern side (Wachter et al. 2020).

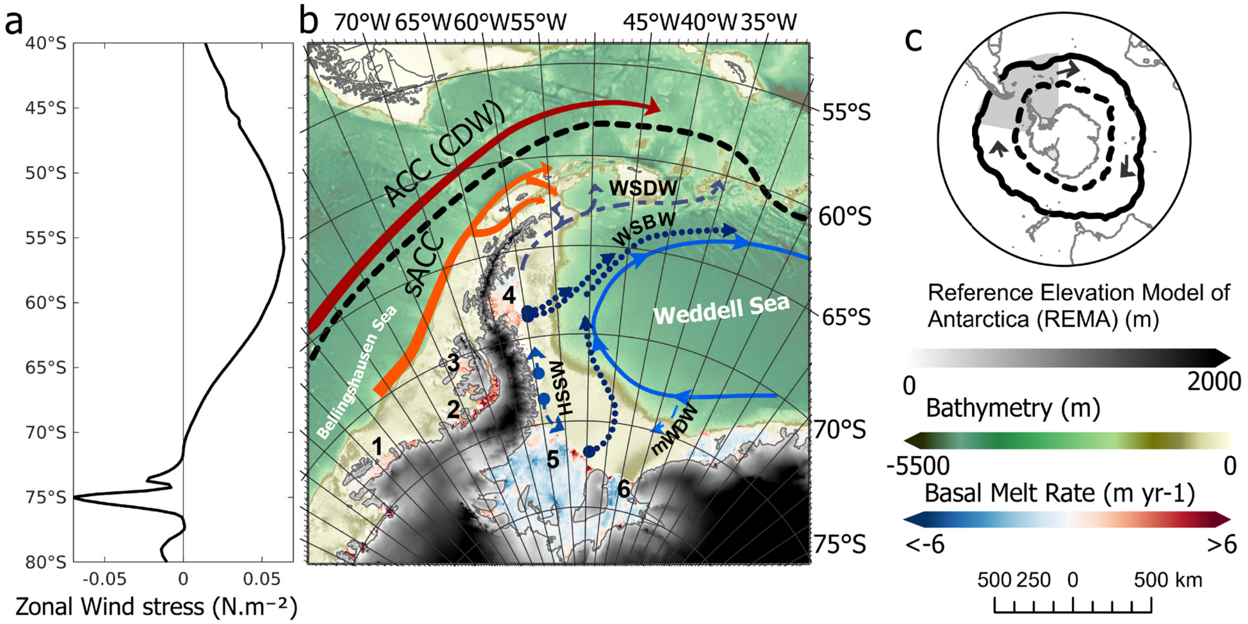

Figure 1. **Map of the Antarctic Peninsula with schematically ocean currents and water masses of the region. Antarctic Circumpolar Current (ACC); southern branch of the ACC (sACC); Circumpolar Deep Water (CDW); Weddell Sea Bottom Water (WSBW); Weddell Sea Deep Water (WSDW); Highly Saline Shelf Water (HSSW); modified Warm Deep Water (mWDW). Ice-shelves: 1. Abbott; 2. George VI; 3. Wilkins; 4. Larsen-C; 5. Ronne; 6. Filchner. (a) Mean zonal wind stress from ERA5 dataset (1998-2017). (b) The red tones (blue tones) continuous lines represent Bellinghshausen Sea (Weddell Sea) currents. The dashed lines represent the water masses. Black dashed line (continuous) represents the position of the Subtropical Front (STF) in the positive phase (negative phase) of SAM. The black arrows in (c) indicate the westerly winds and STF migrations in the SAM phases. The bathymetry data is from ETOPO1 (Amante & Eakins 2009), for elevation in the Antarctica continent Reference Elevation Model of Antarctica (REMA) (Howat et al. 2019), and basal melt rates (2010-2018) from Adusumilli (2020).**

The declining height and extension of AP ice shelves stem from a complex set of processes on the atmosphere, ocean, glaciers, and sea-ice. Changes in the freshwater balance resulting from variations in precipitation rate, sea-ice and the ocean-ice interactions can affect regional and thermohaline circulation strength (Lago & England 2019, Park & Latif 2019). Decreases in the extension of sea-ice further drive warming through the ice-albedo relationship due to the significant albedo reduction as the ice masses break and melt (Vizcaíno et al. 2010). The increasing high-latitude precipitation as the atmosphere warms (Durack 2015) or increasing glacial melt (Bintanja et al. 2015, Pellichero et al. 2018) can also modify buoyancy forcing and water masses formation in the SO, with implications for the overturning circulation. The glacial freshwater fluxes primarily come from melting icebergs and ice shelves. The increase of glacial meltwater into the SO alters the freshwater cycle and contributes to increased sea-ice cover (Zhang 2007, Bintanja et al. 2013).

The input of glacial meltwater into the ocean adds to multiple SO trends perceived in observations (particularly in sea temperature, salinity, sea-ice extent (SIE), and sea surface height (SSH)). Here, we review the freshwater input into the ocean around the AP. This region has contrasts between each side, on the Bellingshausen Sea (west) and the Weddell Sea (east) and is considered a climate hotspot (where climate change are more pronounced and well documented) (Rignot 2004, Meredith

& King 2005, Kerr et al. 2018b). This study shows the relevance of each process in freshwater contribution to the ocean and discusses the perspective about freshwater processes and their changes over high latitudes, focusing on the AP. Moreover, this presents a general overview of techniques to quantify the hydrological cycle in the AP (Figure 2).

The contribution of this review summarizing each climate process related to freshwater dynamics in the AP is timely as it presents a contrasting climate states and ocean dynamics of each coast side. For instance, the Bellingshausen Sea presents high melt rates consistent with a warmer ocean on the western side. In contrast, the Weddell Sea presents massive ice shelves collapse associated with surface melting and intensified atmospheric changes on the eastern side. In this sense, this review aims to contrast the principal processes that occur in each side of the AP, related to glacial freshwater and how it contributes to each climate component and its effects, regionally and globally.

THE ANTARCTIC ICE SHEET MASS BALANCE (CONTEXT)

Ice sheet mass balance results from variations of mass of ice over a stated time (Robin 1972, Hanna et al. 2013). It is expressed through the negative (loss or ablation) and positive (gain or accumulation) signals (Cogley et al. 2011). And when the accumulation and ablation are in balance over a long time, we have the balanced

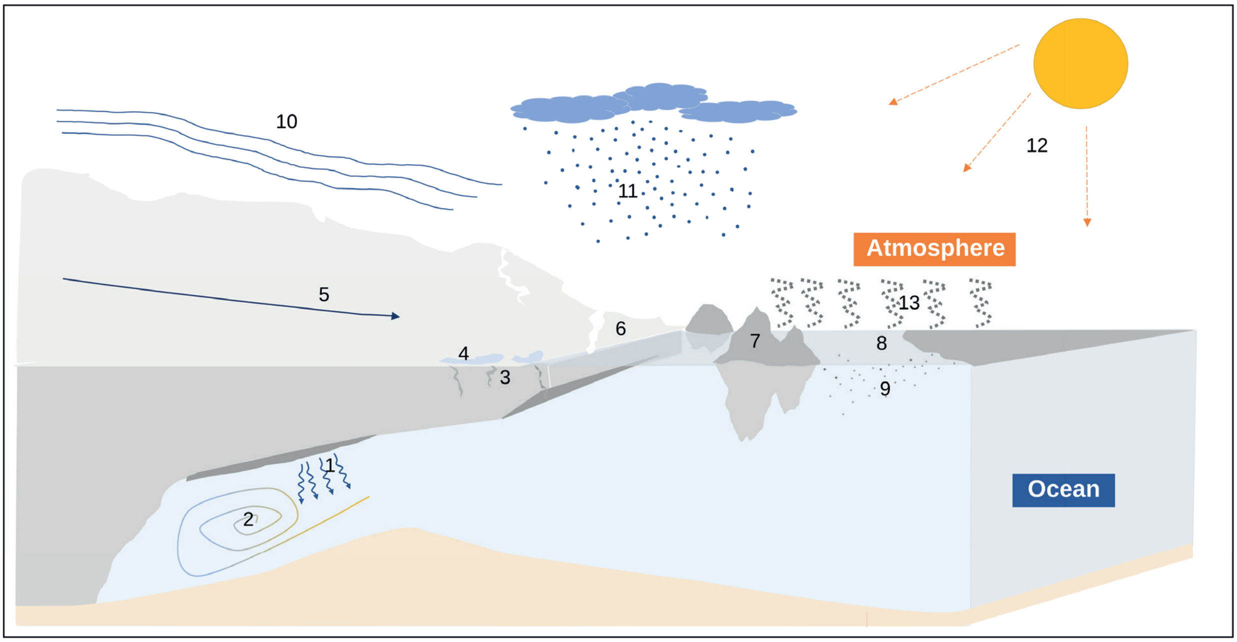

Figure 2. Water cycle over ice-shelves. 1. Basal melting – melting under ice shelf; 2. Water that upwells close to Antarctica is converted to denser bottom water by cooling and brine released during sea-ice formation; 3. Ice shelf crevasses – points of instability in ice-shelves where potentially can collapse; 4. Melting ponds – surface melting above ice-shelves; 5. Ice-velocity – ice movement from the continent into the ocean through ice-shelves; 6. Ice-shelves disintegration – formation of icebergs; 7. Icebergs – ice portions floating in the ocean; 8. Sea-ice – ice formatted by the cooling of the ocean as heat lost into the atmosphere, it causes brine rejection, increasing salinity in the ocean near these regions; 9. Salt rejection from sea-ice formation due brine rejection;10. Westerly and katabatic winds – contributing in the evaporation and heat transfer from continent, ocean and atmosphere; 11. Snow and precipitation; 12. Solar radiation; 13. Evaporation and sublimation.

or “steady state” situation (Robin 1972). It is determined by the surface mass fluxes (surface mass balance, SMB) and the ice flux across the grounding line (ice discharge, D). Also, there is the basal mass balance (BMB), determined by the balance between accretion and ablation at the ice shelf base (Depoorter et al. 2013). During condensation, precipitation and deposition, mass accumulates at the surface. The mass is lost when meltwater is not retained in the firn by freezing and capillary forces and leaves the ice sheet as runoff. Also, the wind can act redistributing the snow, causing erosion and deposition, and sublimation, either from the surface or from drifting snow particles (10, 11, 13, in Figure 2). Once accumulated, snow crystals are slowly deformed into ice, changing their structure and densifying. The firn layer can be between 0 and more than 100 m thickness, depending on the local climate (Ligtenberg et al. 2011). The glacier ice movement, from the interior ice sheet to the margins, can also influence the ablation, driven by basal sliding and internal deformation, followed by solid ice discharge when the ice crosses the grounding line and starts to float on the ocean.

The mass budget provides information which concerns physical processes that control the ice mass loss, i.e., the SMB, representing the difference between accumulation, runoff and other forms of ablation, and glacier dynamics (the ice mass fluxes into the ocean). Moreover, the surface meltwater in ice sheets and the adjacent floating ice shelves can significantly impact ice-sheet mass balance due to albedo changes and instability crevasses over the ice.

Given the difficulty of access and high cost of expeditions to the Antarctic continent and the surrounding areas, remote sensing has proved to be fundamental for investigating these processes. Among the Antarctic region’s balance, we have the accumulation of snow and ice process (input) and the loss of water by runoff (liquid form or ice movement) or evaporation (output) (Loewe 1967). Runoff is due to melting, which can occur on the ice sheet surface, on ice shelves, and in glaciers. The measure of water distribution can be done by observing ice and snow dynamics (Rignot 2004, Rignot et al. 2008, 2019, Mouginot et al. 2012). The new generation of satellites, as Surface Water Ocean Topography (SWOT) (Durand et al. 2010), promise synoptic observations of water balance aspects, including snow and ice thickness, which cannot be measured on a large spatial and temporal scale using conventional methods. Also, there are CryoSat-2, Jason-3 and Sentinel-4 acquisitions, as well Jason-CS/Sentinel-6, and ICESat-2 data collection.

ATMOSPHERIC INTERACTIONS

The last five decades have shown a rapid increase in air temperatures over the AP (Figure 3a), accompanied by increased precipitation (Figure 3c), and regionally opposing trends in sea-ice cover, with a decrease in Bellingshausen side, and increase in Weddell side (Kumar et al. 2021). In general, the SO has presented a small but significant increase in sea-ice cover associated by near-surface cooling (Armour et al. 2016). The ocean surrounding AP has presented significant freshening and lightening trends, with impacts on the water volume (Azaneu et al. 2013, Hellmer et al. 2011, Schmidtko et al. 2014, Ruiz Barlett et al. 2018, Dotto et al. 2021). Freshwater input into the ocean from the continent influences SSH, affects the formation of water masses and, consequently, global circulation. The melting of ice shelves and glaciers contributes to a positive signal in freshening along the AP coast. Due to the nonlinearity in the equation of state for seawater, at cold temperatures (high latitudes), salinity changes are more efficient at altering

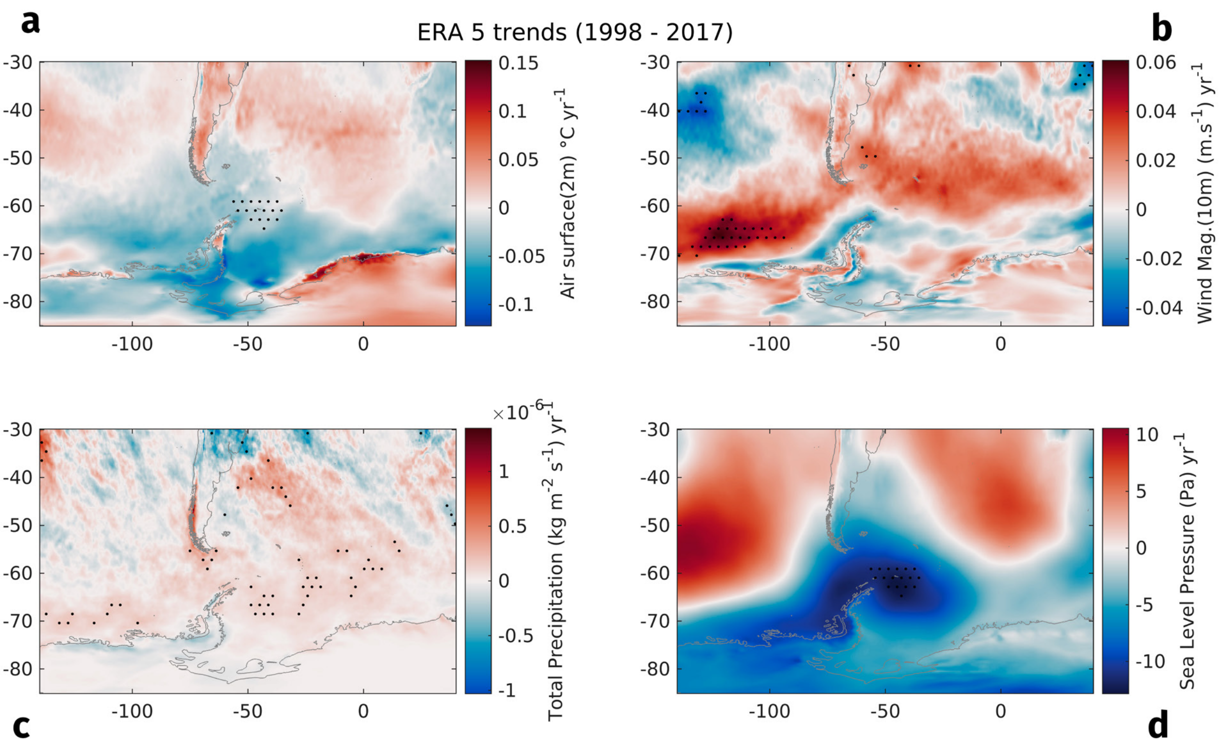

Figure 3. Yearly trends over Antarctic Peninsula through results of ERA5 Reanalysis data between 1998 and 2017), variables: (a) Air temperature at 2m (°C); (b) Wind Magnitude at 10m (m s^{-1}); (c) Total Precipitation (kg m^{2} s^{-1}); (d) Sea level pressure (Pa). Black dots represent the areas with significance of 0.05. Created with Climate Data Toolbox for Matlab (Greene et al. 2019).

the density of the seawater than changes in temperature (Sathiyamoorthy & Moore 2002).

The most significant warming trends have been in the western and northern parts of the AP (Figure 3a and Figure 4a). Air surface temperature trends show a significant increase across the AP and, to a lesser extent, to most of the western portion of the Antarctic continent since the early 1950s. Moreover, only slight changes have been observed across the rest of the continent (Turner et al. 2005, Carrasco 2013). The western Antarctic Peninsula (WAP) has shown the highest average in air temperatures over the past five decades, pronounced during winter (King et al. 2003, Vaughan et al. 2003, Carrasco 2013). The ocean water, in surface and bottom over large parts of the WAP, has warmed and has suffered salinity changes (Figure 4c), freshening the water masses due to increasing melting (Martinson et al. 2008, Meredith et al. 2018) and has declined in sea-ice extent and thickness (Parkinson 2019) (Figure 4d).

The westerly winds that overlie the SO have intensified over recent decades (Figure 3b). This is associated with enhanced warm advection due to changes in SO atmospheric circulation, resulting in increased air temperature over the AP and influencing its climate. More frequent positive phases of the SAM and the deepening of Amundsen Sea Low (ASL) influence the regional meridional wind field, which controls the moisture advection and heat into the continent. The main impacts on AP due to location and intensity of ASL, are the potential impacts in air temperature, wind, and pressure over the region, which can often lead to anomalies of opposite signs in sea temperature, sea ice, and precipitation in the coast and shelf region (Raphael et al. 2016). SAM is characterized by westerly circumpolar circulation variability related to the strong

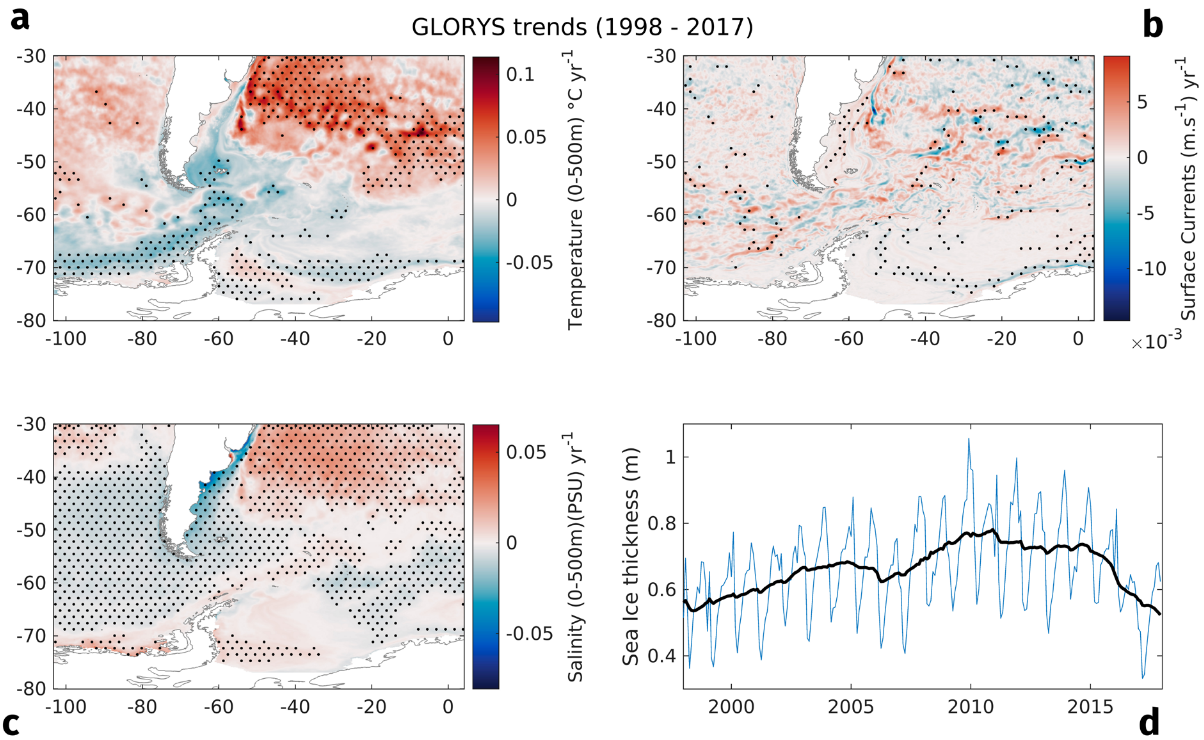

Figure 4. Yearly trends over Antarctic Peninsula through results of GLORYS Reanalysis data between 1998 and 2017, variables: (a) mean water temperature in °C for the first 500 meters; (b) Currents magnitude at the surface (m s^{-1}); (c) mean water salinity for the first 500 meters; (d) Mean sea-ice thickness (m), blue line is monthly mean, and dark line represents the yearly mean. Black dots represent the areas with significance of 0.05. Created with Climate Data Toolbox for Matlab (Greene et al. 2019).

meridional pressure gradient between the high and mid-latitudes of the Southern Hemisphere (SH), which significantly influences synoptic-scale activity over the SO (sea level pressure trends presented Figure 3d). The positive SAM causes poleward displacement of the cyclone tracks and reinforces the ASL, promoting surface warming over the AP (Marshall 2003, Parise et al. 2015). The SAM can also affect the distribution of sea-ice as a sign of the response, depending on the time scale considered (Ferreira et al. 2015).

The instantaneous response to increasing westerly winds is the intensification of Ekman's cold-water transport to the north and the sea-ice expansion. Although the SAM expands the ice to the north, it reduces its average thickness (Lefebvre & Goosse 2005). However, a strong upwelling eventually brings deeper warmer water to the surface, boosting sea-ice melting and retreating (Purich et al. 2016). The winds intensification can increase the inflow of warmer waters into the WAP continental shelf but not necessarily cause the increase of ice shelf basal melting (except for the shallower ice-shelves) (Dotto et al. 2021). SAM can also interfere over wind-driven Weddell Sea Gyre on the eastern AP, influencing inter-annual variations in bottom-water properties (Dickens et al. 2019).

The estimative of evaporation over the ocean requires the derivation of three surface variables obtained by satellites: air temperature, wind and specific humidity (Schlüssel 1996). The sea-ice and snow cover modulate the interaction between the ocean surface and the atmosphere just above. These structures strongly reflect solar radiation resulting in efficient insulators, prohibiting the exchange of heat and humidity. Boisvert et al. (2020) proposed a specific algorithm (turbulent flux algorithm) to estimate evaporation, combining derived data from satellite and numerical model reanalysis. They used air temperature and surface humidity data from Atmosphere Infrared Sounder (AIRS) onboard NASA's Aqua satellite and wind at 10 meters from NASA's MERRA-2 reanalysis and sea-ice concentration from SMMI. They estimated the daily evaporation between 2003 and 2016 and contributed to increased detail and reduced evaporation estimation errors over SO, an important variable in the water cycle and energy budget.

GLACIER DYNAMICS

Glaciers are large amounts of ice that slowly move downslope under the pull of gravity. The surplus ice mass forces the ice movement from years of accumulation in the higher altitudes (accumulation area) needs to be compensated by the outflow of ice in the ablation areas, where the ice is lost through melting and calving (e.g., Sharp & Tranter 2017). These formations appear static, but they slowly move like rivers of ice. The force of ice movement carries rocks, sediments, and debris from the surface. They also influence local and regional climate, driving cold and conserving low air temperatures and katabatic drainage winds, including nutrient delivery dynamics and influence of ecosystem structure over multiple trophic levels in coastal and fjord environments (DeBeer et al. 2020).

Nearly 80% of the world freshwater is locked up in glaciers and ice sheets (Vaughan et al. 2013). The Antarctic and Greenland ice-sheets has approximately 33 million km^3 of ice, holding the capacity of raise global sea level by 70 m (sea level equivalent, SLE) (Rignot & Thomas 2002). It is estimated that the Antarctic Ice Sheet has more than 55 SLE m (Morlighem et al. 2017, Sun et al. 2020), and Greenland Ice Sheet, 7.42 SLE m (Morlighem et al. 2017). Glacier melting also has a significant role in sea-level rise contribution, Farinotti et al. (2019) estimates of 0.32 ± 0.08 SLE m from global glacier volume. The quantification of glacier mass loss at regional and global scales is a challenge due to the sparsity of direct measurements and the limitations of remote sensing data (relatively short time and coarse resolution of gravity-based measurements, e.g. NASA Gravity Recovery and Climate Experiment - GRACE), and other problems in deriving digital elevation models from optical and altimetric data (Hugonnet et al. 2021).

Basal melting contributes to decreasing glacier mass. The meltwater from the glacier bed supplies the slow and gradual ablation of the glaciers. This process also contributes to ice sliding and increasing the ice velocity. Also, the subglacial conduits caused by melt form instability regions where glaciers stay more fragile (How et al. 2017). In the land/ocean interface, the cold fresh water from basal melt enters the ocean above warm salty water, driving diffusive convection that influences the ocean's vertical structure (Rosevear et al. 2021). Consequently, with the basal melting increase, we can expect effects over sea-ice and ocean mixed layer depth in the near ice-shelves areas (Parise et al. 2015).

THE ROLE OF ICE SHELVES AND ICEBERGS

Ice-shelves are in the interface between the ocean and the continent (1 to 6 in Figure 2). They represent the floating extensions of grounded ice sheets and modulate the release of grounded ice and water discharge to the ocean. They are responsible for the stability and play an important role in the mass balance of ice sheets (Stark et al. 2019). The gain of mass is due to snow accumulation and freezing of marine ice undersides the shelves and loss through iceberg calving and basal melting (Rignot et al. 2013). Icebergs and ice-shelves introduce freshwater in different depths in the water column. Hence, it is a potential cause of vertical instability. The major collapse events coincide with southward migration of the mean-annual -9ºC and -5ºC isotherms driven by regional atmospheric warming in the last years (Morris & Vaughan 2003). These isotherms are the proxy of summer surface melting that can lead to hydrofracturing (6 in Figure 2), which is instability points over ice shelves where they can collapse (Scambos 2004, Scambos et al. 2013).

The disintegration of ice shelves is the source of icebergs (7 in Figure 2). They can float away from their calving region and provide heat and freshwater fluxes further away from their origin (Merino et al. 2016). They concentrate mainly on offshore flowing branches of Antarctic subpolar gyres, with a large fraction found in the South Atlantic section of the SO. Melting icebergs can increase sea-ice concentration and thickness over most SO due to the convective overturning reduction capacity, limiting the heat supply from the deep ocean to the surface. However, in the Bellingshausen Sea, the iceberg melt results in thinner sea-ice due to the warmer waters advection flowing along with the ACC (Paolo et al. 2015, Merino et al. 2016).

Studies concerning atmospheric changes, including anthropogenic and stratospheric ozone influence over Antarctica and its effects, are still recent (Turner et al. 2016). The atmosphere can influence ice shelves SMB and near ocean height due to air pressure (Kuipers Munneke et al. 2017). Air temperature and winds are highly correlated, which has a consequent influence on surface waters (Turner et al. 2019). The wind has an important role in the ocean-atmosphere energy exchange. Both winds and meltwater imply changes over ocean ventilation south of the ACC, where surface and bottom waters interact through deep convection. Poleward intensifying winds increase mixing, causing the strengthening of deep water ventilation and mode water formation, while meltwater reduces the vertical mixing increasing the stratification, freshening the surface (Abernathey et al. 2011, Bronselaer et al. 2020). Also, the wind influences coastal polynyas formation and its consequent deep-water production, which can further influence the ocean heat flux under ice shelves. The energy exchange from the water phase affects directly over atmospheric heating, mainly through precipitation (P) and evaporation (E) (Gutenstein et al. 2021). The difference between E and P rates (E-P) is the freshwater flux across the surface to the atmosphere, which is positive (negative) where E (P) dominates (11 to 13 in Figure 2).

Icebergs have complex characteristics, with high variability in shapes, sizes, and high disintegration dynamics. These aspects result in difficulties face by numerical modelling of these processes (Rackow et al. 2017). Therefore, the use of remote sensing is fundamental for detecting icebergs. The high spatial and temporal resolution makes possible to estimate a variety of parameters and measurements such as drift speed and tracking of icebergs and meltwater injected into the ocean. Furthermore, iceberg tracking is also a powerful tool to detect ocean circulation patterns in remote areas with sparse data (Collares et al. 2018, Barbat et al. 2019, 2021). Iceberg's monitoring is essential not only for their contribution to the entry of freshwater into the ocean but also for the safe navigation of vessels. The Synthetic Aperture Radars Interferometry (InSAR) and SAR technology sensors are the most used to detect icebergs in the ocean (Tournadre et al. 2016, Barbat et al. 2019). The use of artificial intelligence to identify and monitor the space-time evolution of these ice features and their variation in size and distribution can contribute to understanding the role and impact of melting icebergs and the formulation of more accurate numerical models.

THE ROLE OF THE OCEAN

The SO has, on average, warmed (Gille 2002, Auger et al. 2021) and freshened (Durack et al. 2012) over the past several decades. At mid-depths and within the latitudes of the ACC, the warming has proceeded at nearly twice the rate of global upper ocean warming (Gille 2002). The ACC northern branch has presented a significant reduction of 0.01 in salinity per decade since the 1980s (Böning et al. 2008, Giglio & Johnson 2016). These changes can impact the deep ventilation and global thermohaline circulation. Another effect observed is the westerlies intensification due to increased greenhouse gas forcing. These results in enhanced cyclonic wind forcing, inducing westward flow closer to the Antarctic Continent, displaces the ACC southerly, affecting the Weddell Gyre and its strength (Vernet et al. 2019).

The Antarctic Bottom Water (AABW) exported from the Weddell Sea is freshening at decadal time scales (Jullion et al. 2013, Purkey & Johnson 2013, Holland et al. 2015, Kerr et al. 2018a). The AABW is formed through surface buoyancy losses via cooling and brine rejection from winter sea-ice formation on the Antarctic continental shelf (High Salinity Shelf Water – HSSW). The shelf water interacts and mixes with the Circumpolar Deep Water (CDW) that flow onto the shelf, characteristically warmer and saltier, and mixes too with the cold meltwater from the base of marine shelves, called Ice Shelf Water (ISW) (Jacobs et al. 1992, Snow et al. 2016).

Larsen ice shelves collapse at Weddell Sea, and accelerated glacier flow are most responsible for the shelf waters freshening of the AP's eastern side (Hellmer et al. 2012). The collapse of Larsen A and B ice shelves and glacial runoff acceleration (mainly Larsen C) is associated with the summertime intensification of the circumpolar westerly winds over SO, which are attributed in part to anthropogenic processes (Scambos et al. 2013, Jullion et al. 2013), including ozone depletion (Swart et al. 2018).

The declining extent and heigh of ice shelves from AP is attributed to a complex set of processes and interactions of the ocean, atmosphere, and sea-ice dynamics (Pritchard et al. 2012, Paolo et al. 2018, Adusumilli et al. 2018). The major collapses events were associated with the southward migration of mean-annual -9° C isotherm of surface air temperature (Morris & Vaughan 2003). Changes in atmospheric conditions are highly correlated with the sea-ice concentration and thickness, which causes changes in wind stress effects over ocean circulation (Kim et al. 2017). It also affects the ocean-atmosphere heat exchange and ocean mixing (Dinniman et al. 2012). The deep-water production in coastal polynyas, impacting overheat fluxes under ice shelves, affects the basal melt rates and freshwater exportation (Adusumilli et al. 2018, Holland et al. 2020).

THE ROLE OF SEA-ICE

The increase of meltwater input into the ocean can have a significant influence on sea-ice formation. Fresher waters present a higher freezing point, and consequently, less energy is required to produce sea-ice (Dierssen et al. 2002). Also, the stratification in the upper water column caused by the cold and less dense freshwater input can influence the heating and cooling rates of the sea surface, influencing the onset of sea-ice formation. The sea-ice-ocean interactions occur more intensely sea-ice limits (mainly through sea-ice lateral melting) and converge to reduce the oceanic vertical mixing caused by the enhanced buoyancy (Parise et al. 2015).

The sea-ice melt contributes to the cold and freshwater entrance into the ocean mixed layer, principally on the edge, through the sea-ice lateral melting. These waters stored in the upper ocean layers have a climate memory of approximately eight years, which can affect heat loss for the atmosphere (Parise et al. 2015). The surface freshening due to melting water input can also explain besides the sea-ice expansion, the SST cooling, and its influence over the mixed layer (Schultz et al. 2020).

The seasonal sea-ice cover has the potential to duplicate along the year (figure 4d), with a slowly autumn advance (March to early September) and a rapid spring retreat (November to early February)(Gordon 1981). This variation has a potentially effect in the climate system, affecting and interplaying with the planetary albedo, atmospheric circulation, ocean productivity, and thermohaline circulation (Eayrs et al. 2019).

EASTERN (COLD) VS WESTERN (WARM) ANTARCTIC PENINSULA

The AP is one of the most rapidly warming regions of the world registered in the twentieth century, where approximately 75% of the ice shelves have already reduced and retreated over the past decades (Rignot et al. 2013). This reduction of ice shelves affects the glaciers stability and the ice sheet mass balance, contributing to increased sea-level rise due to increased freshwater input into the ocean (Rignot et al. 2019). The AP presents different ocean dynamics on each side. The Bellingshausen Sea on the western side presents warmer waters and higher glacial and sea-ice melting rates, typically with a cold oceanic climate. On the eastern side of AP, the semi-closed geography of the Weddell Sea sustains much colder conditions, characteristically under a cold polar-continental regime.

The AP glaciers dynamics are changing and mainly becoming wet-based, influenced mainly due to climate factors, which contribute to high erosion and melting (Golledge 2014). The glacial thermal regime determines the subglacial processes based on the ice temperature and pressure. The wet-based glaciers have meltwater at the glacier's base, increasing the basal sliding and inducing rapid ice velocities (Kleman & Glasser 2007). On the surface, meanwhile, the melt ponds are the primary source of meltwater and critically affect the ice-shelves stability, implying hydro fractures and later collapses (Siegert et al. 2019).

The cumulative mass loss is dominated by the WAP (Pritchard et al. 2012), from George VI, West Graham Land, Wordie, Stange, and Bach (Rignot et al. 2019). Also, Wilkins Ice Shelf presented break-up events in 2008 and 2009 (Cook & Vaughan 2010). Muller, Wordie, and Jones ice shelves have collapsed or retreated, increasing the freshening on the Bellingshausen Sea (Adusumilli et al. 2020). Stange ice shelf, situated to the west of George VI Ice Shelf, displays relative stability in an area that may be subject to atmospheric and oceanic forcing. Bach Ice Shelf, located between Wilkins Ice Shelf and George VI Ice Shelf southern ice front, has increased glaciological changes in the last years. It has presented significant areas of passive ice that have already or will be removed, resulting in enhanced recession within the next decade (Holt & Glasser 2021).

On the eastern side of AP, the changes on water masses sourced in the Weddell Sea continental shelf may have directed the freshening signal (Caspel et al. 2015, 2018).

Besides, the significant break-up ice shelves collapse occurred since 1995, e.g., Larsen-A followed by Larsen-B in 2002, has been through abrupt contributions of great amounts of freshwater into the Weddell Sea. The collapse of Larsen-B caused the loss of approximately 3250 km^2 by calving huge icebergs to the ocean (Cook & Vaughan 2010). Before Larsen-A and Larsen-B collapse, the most northerly eastern ice shelf, Prince Gustav ice shelf, collapsed in 1995. There is evidence to suggest that this ice shelf became separated from Larsen Ice Shelf in the late 1940s (Cooper 1997), retreating to Cape Longing. Since then, there was a rapid retreat from 1957 to 1961, followed by a steadier retreat until the collapse in 1995 (Cook & Vaughan 2010).

The Larsen-C is the largest ice shelf of the AP. Situated on the northern part of the peninsula, it has retreated from the last years. In 2017, a large section had collapsed, leading to the calving off A68 iceberg (Larour et al. 2021), which represents a ~10% from the Larsen-C size (Hogg & Gudmundsson 2017). The warm ocean waters are pointed as a main responsible for driving melting at the ice-shelf base and conducting to ice-shelf instability.

NATURAL VARIABILITY

In contrast to Arctic sea-ice decreasing due to increased surface air temperature, observations show an expansion of SO sea-ice extent during the satellite era (1979-nowadays) (Pauling et al. 2017, Merino et al. 2018, Parkinson 2019). It is correlated to the observed SO cooling trend. Although, the sea surface temperature (SST) and sea-ice concentration (SIC) trends are not homogeneous in space (Simpkins et al. 2013, Swart et al. 2018), with opposing signs in the Amundsen-Bellingshausen seas versus the Ross and Weddell seas (Stammerjohn et al. 2008). Several explanations were proposed to explain these trends, including an increase of poleward-intensified westerly winds stress changes. The intensified winds are correlated by the positive trend of SAM, in reply to stratospheric ozone depletion, and a deepened ASL driven by tropical Pacific or North Atlantic SST anomalies (Zhang et al. 2019).

The SAM is the principal mode of climate variability over the extratropical Southern Hemisphere (SH) (Marshall 2003). It corresponds to the main answer of Antarctic climate to southern mid-latitudes climate and tropical variability (Fogt & Marshall 2020). The SAM positive trend in the last decades can cause the weakening of the SO carbon sink (Keppler & Landschützer 2019). Additionally, modelling studies indicate that the stronger zonal winds caused by the positive SAM can decrease sea-ice extent due to warm circumpolar deep water upwelling close to the Antarctic coast through enhanced surface easterly flow. The increased warming of coastal Antarctic waters through changes in upwelling of CDW has been linked to the melting of outlet glaciers, with influence over global sea-level rise (Purkey & Johnson 2013).

CLIMATE CHANGE AND FUTURE

Surface waters in the northern part of SO have warmed, freshened, and cooled in the southern part since the 1980s. The AABW has become less voluminous in SO and globally, and the eddy field has intensified since the early 1990s (IPCC 2019). Projections of future trends in the SO indicate the potential of continued strengthening westerly winds (Cheon & Kug 2020) and the warming and increasing of freshwater input from both increased net precipitation (Fyke et al. 2017) and changes in sea-ice and meltwater export (Bronselaer et al. 2018, 2020).

The westerly winds increasing trend will continue intensifying the eddy field (Munday et al. 2013), with potential effect over upper-ocean overturning circulation, including heat, carbon-oxygen and nutrients (Swart et al. 2019). Another effect of westerly winds intensification is the sea-ice increase in extension and decreases in thickness due to sea-ice movement caused by the strong winds (Holland & Kwok 2012).

Models have shown that meltwater from Antarctic ice sheets and shelves can affect the slowing increase of global temperatures and warming subsurface ocean temperatures principally near Antarctica and permit positive feedback more further ice melt and sea-level rise (Bronselaer et al. 2018).

CONCLUSIONS

The freshwater dynamics over AP has changed drastically over the past decades. AP is a critical region which is under climate change influences, but its effects are still poorly understood. The increase of ozone depletion caused by anthropogenic gases is associated as the cause of Antarctica's westerly winds intensification. This intensification can result in changes on water balance, increasing evaporation and hence precipitation. The wind changes also directly interfere on the currents magnitude (Figure 4b), modifying sea waters transport below ice shelves. The introduction of warmer water under ice shelves can contribute to the basal melting increasing. The surface melt can also weaken these ice masses' stability, contributing to their instability and high potential of collapse.

Regarding the effects on a global scale due to Antarctica changes, it is essential to consider and forecast the possible situations and their climate impacts. The positive and high entrance of meltwater on the ocean trend will affect the freshwater balance critically on a regional scale, principally near the AP, where occurs essential seawater masses formation, carrying on global consequences due to thermohaline circulation. Even, the freshwater from sea-ice melting has a potentially effect over the ocean mixed layer, as described by Parise et al. (2015) and Schultz et al. (2020).

In this context, it is necessary to discretize freshwater contributions to ocean dynamics near AP. Here, we highlighted the main tools to quantify and describe the known water processes. However, the knowledge of the variability and acceleration of the hydrological cycle and its consequences of regional and pursues global climate are still incipient. Therefore, it is necessary to improve and carry out specific studies on each variable of this complex climate region. The role of melting from different sources and the process which affect the increase or decrease of freshwater ocean input is still misunderstood. Studies leading each process separately, and sensitivity studies leading the direct effect of each freshwater source, can also bring an explanation and the relevance of each contribution. This review brings together a description of likely processes those contribute to variations of freshwater inputs into the ocean, as well as the contrasts that we have on each side of the Antarctic Peninsula.

This study is a part of the activities and planning developed by the Antarctic Modelling Observation System (ATMOS) project, which is a response to the Brazilian Antarctic Program (PROANTAR). This project aims to improve our understanding of sea-ice–ocean-atmosphere–waves interactions and turbulent fluxes exchanges in their interface, at micro and mesoscales in the Atlantic sector of the Southern Ocean.

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