

**Faculté des sciences**

# The atmospheric hydrological cycle in Antarctica – past and future

Mémoire présenté en vue de l'obtention du grade académique de  
Master [120] en sciences physiques, finalité approfondie.

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Academic year 2021-2022



# Abstract

The hydrological cycle sets the climate of polar regions through changes in surface albedo, ice sheet surface mass balance, sea surface temperature and salinity, in particular in Antarctica. Global warming is known to cause an intensification of the global hydrological cycle. A serious obstacle to a quantitative understanding of the Antarctic hydrological cycle is the lack of reliable observations. Recently, a new atmospheric reanalysis (ERA5) has been released by the European Centre for Medium-range Weather Forecasts. In parallel, a large database of historical and climate change projection simulations has become available through the Coupled Model Intercomparison Project, phase 6. Few specific studies exist in the field but no global study. Here, we document for the first time the seasonal state, year-to-year variability and long-term trends of the Antarctic atmospheric hydrological cycle by process and regions. We find that seasonal thermodynamic (temperature and sea ice) and dynamic (surface pressure) drivers explain the seasonal variability of the cycle. Our analysis indicates an intensification of the atmospheric hydrological cycle over the last four decades, largely driven by precipitation and moisture convergence changes (with little role for evaporation). Changes in temperature, sea ice, and surface pressure (SAM) explain this multi-year evolution of the processes. By analyzing the ACCESS-ESM1.5 data, we show that the atmospheric hydrological cycle is projected to intensify by the end of the century, with a leading role from moisture convergence (increasing by +22.1% compared to present-day levels), followed by precipitation (+18.5%) and evaporation (+10.4%). Our study could be a starting point for the study of the global freshwater cycle in Antarctica.

# Acknowledgments

This master's thesis results from months of work and would not be what it is today without the support of people I would like to personally thank.

First, I would like to express my gratitude to my supervisor. I want to thank Professor François Massonnet for his availability and good advice throughout the realization of this Master's Thesis. I also want to thank Professor Thierry Fichet for his advice and the way he's been pushing me to go further since the end-of-baccalaureate project. Thank you both too, for sharing your passion for Climate Physics during your lectures which definitely got me interested in the field.

I would also like to warmly thank Xia and Katy. Thank you Xia for your experience, your answers to my questions and the time you spent advising me. Thank you Katy for your kindness, good advice and all the time you dedicated to helping me with this thesis, with a special and huge thank you for proofreading this thesis.

Finally, I would also like to thank some family and friends for their support during my studies.

Words cannot express my gratitude to my parents, who always supported me. They offered me the best conditions to study, whereas it was good homemade meals and endless encouragement. But also for instilling in me a sense of curiosity and optimism. I also want to thank my little sister for his support and my in-laws for all the good times I shared. And for all the discussions with Maxence about science.

These years at UCLouvain also gave me the chance to meet amazing people. Thank you to the MERCATOR Team for being the best classmates I could have hoped for. I would also like to thank all my other friends for all those shared moments to take my mind off things.

To conclude, thank you Adèle to be always there at my side, encouraging me and advising me. I look forward to sharing new adventures with you!

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## List of abbreviations

|              |                                                    |
|--------------|----------------------------------------------------|
| <b>ABS</b>   | Amundsen-Bellingshausen Seas                       |
| <b>AIS</b>   | Antarctic Ice Sheet                                |
| <b>DJF</b>   | December, January, February                        |
| <b>ECMWF</b> | European Center for Medium-Range Weather Forecasts |
| <b>EKE</b>   | Eddy Kinetic Energy                                |
| <b>EOF</b>   | Empirical Orthogonal Function                      |
| <b>IO</b>    | Indian Ocean                                       |
| <b>JJA</b>   | June, July, August                                 |
| <b>MAM</b>   | March, April, May                                  |
| <b>PO</b>    | Pacific Ocean                                      |
| <b>RCP</b>   | Representative Concentration Pathway               |
| <b>RS</b>    | Ross Sea                                           |
| <b>SAM</b>   | Southern Annular Mode                              |
| <b>SAO</b>   | Semi Annual Oscillation                            |
| <b>SH</b>    | Southern Hemisphere                                |
| <b>SMB</b>   | Surface Mass Balance                               |
| <b>SON</b>   | September, October, November                       |
| <b>SSP</b>   | Shared Socioeconomic Pathways                      |
| <b>WS</b>    | Weddell Sea                                        |

# Introduction

## Context

According to the latest report of the Intergovernmental Panel on Climate Change (IPCC-AR6) [IPCC, 2021], each of the last four decades has been successively warmer than any decade that has preceded it since the pre-industrial period. In particular, the global mean surface temperature was  $1.09^{\circ}\text{C}$  higher over the last decade (2011-2020) than over 1850-1900. This increase is due to human activities' greenhouse gases (GHGs). Although climate change is global, the polar regions are the scene of major changes (e.g. surface mass balance of the ice sheet, surface albedo, sea surface temperature and salinity) that strongly affect the climate in turn [Stuecker et al., 2018].

While global surface warming is well known, many spatial and temporal changes induced by temperature change are often less well understood. One of the challenges is the changes that are taking place in the global hydrological cycle. Bengtsson et al. [2011] stated that the hydrological cycle in Antarctica is intensifying. This hydrological intensification is global, which means it takes place in the atmosphere by changes in evaporation, water vapour transport and precipitation, in the ocean by changes in freshwater transport and sea ice formation and on the ice sheet by changes in runoff and ice-shelf calving. In the atmosphere, rising temperatures enhance causes the water holding capacity of air - a fundamental thermodynamical relationship known as the Clausius-Clapeyron law. In the Antarctic Ice Sheet (AIS), the increase in temperature causes the surface mass balance (SMB) to change. And in the ocean, the rise in sea surface temperature induces changes such as the melting rate of ice and iceberg calving and change in the upward heat transport [Liu and Curry, 2010]. In Antarctica, the three states of the water (solid, liquid and gas) participate in the hydrological cycle, further complicating understanding.

Models can help perform future climate projections and thus guide policymakers in designing appropriate climate adaptation strategies. But different processes involved in the hydrological cycle of the polar climate are not well understood, and therefore models cannot account for them correctly yet. Consequently, it is essential to improve the simulation of the processes in Antarctica, given the importance of this place in the climate system via its contribution to rising sea levels and changes in oceanic circulation. Therefore, improving our qualitative and quantitative understanding of these processes involved in the global hydrological cycle, such as precipitation, evaporation, moisture transport, ocean freshwater transport, runoff, ice-shelf calving, and sea ice formation is needed.

A serious obstacle to a quantitative understanding of the Antarctic hydrological cycle is the lack of reliable observations over long periods with a good spatial distribution [Jung et al., 2016]. Figure 1 shows Antarctica’s low number of observations compared to the adjacent continents. In the absence of proper observational records for the entire studied region over long periods, climate reanalysis provides spatio-temporally climatological records and fills the gap. Recently, the European Centre for Medium-Range Weather Forecasts (ECMWF) release an atmospheric reanalysis, ERA5, which mainly accounts for atmospheric phenomena. Therefore it allows the study of the atmospheric hydrological cycle. In addition, the study of the global hydrological cycle requires other data that are sometimes still poorly estimated and for which there is no new reanalysis such as melt rate at the bottom of ice shelves and iceberg discharge. These two main reasons are why this thesis will focus on the atmospheric part of the hydrological cycle.

In the field of the atmospheric hydrological budget over the Antarctic, Tietavainen et Vihma [2008] are the precursors of the study of the atmospheric hydrological cycle by processes (i.e. evaporation, moisture convergence and precipitation). Based on the ERA-40 reanalysis of the ECMWF (1979-2001), they show a spatial analysis of the atmospheric hydrological cycle by processes at a seasonal time scale and spatio-temporal analysis of the annual mean-state of the cycle. Afterwards, Bengtsson et al. [2011] and Oshima et al. [2017] used ERA-Interim reanalysis data to study atmospheric hydrological cycle evolution in polar regions. Therefore, with the new data from the ERA5 reanalysis and the recent model ACCESS-ESM1.5 data, this thesis documents for the first time the seasonal state, the year-to-year variability and long-term trends of the Antarctic atmospheric hydrological cycle by process and regions, with a spatio-temporal analysis.

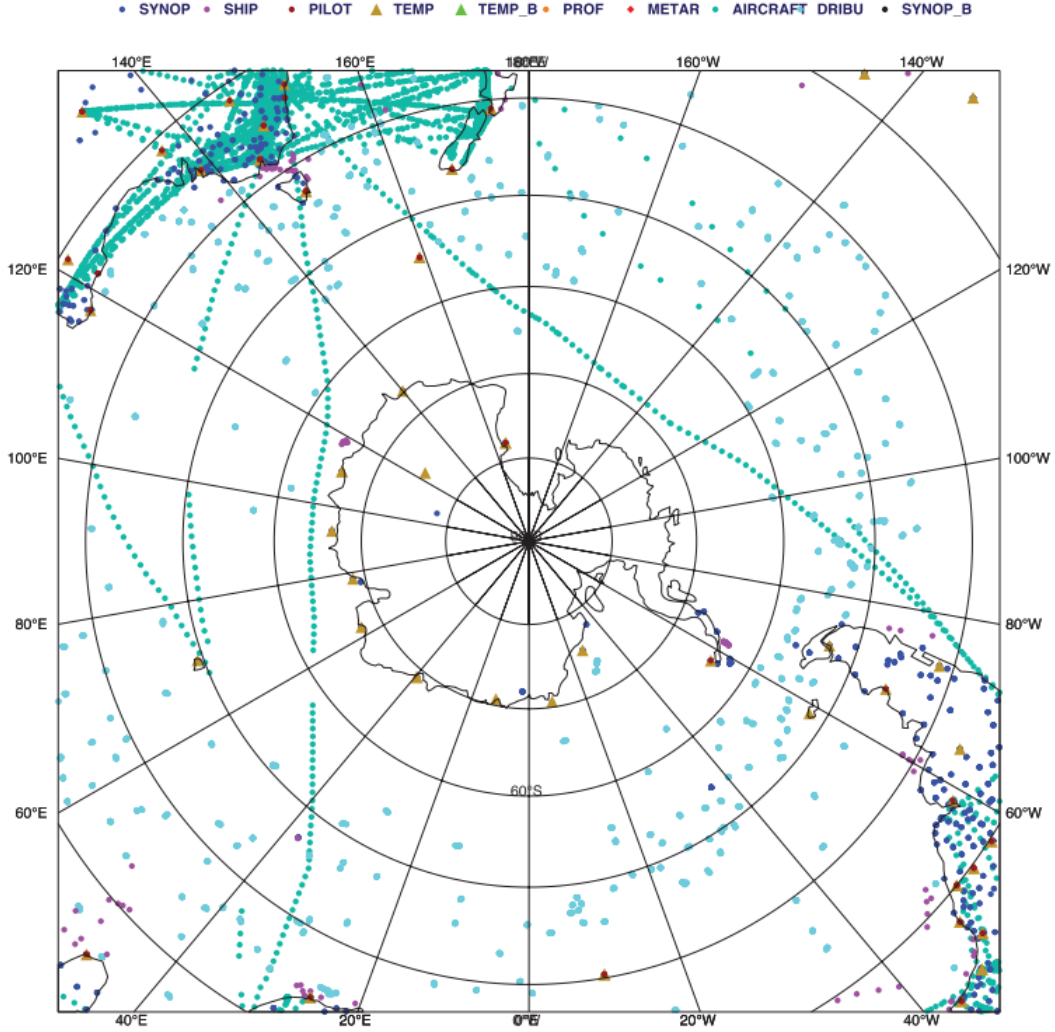


Figure 1: *Conventional observations that were assimilated by the operational forecasting system at ECMWF on 15 Apr 2015. Different colors are used for different observation types (see legend) [Jung et al., 2016]. This figure shows the poor number of observations made in Antarctica.*

## Research questions

In this work, the seasonal cycle and the patterns of change over time of the processes involved in the atmospheric hydrological cycle (precipitation, evaporation and moisture transport) are introduced by using ERA5 reanalysis data. These processes' future evolution is evaluated using CMIP6 model (ACCESS ESM 1.5). To study the atmospheric hydrological cycle in Antarctica in past and future, the three following questions are addressed:

- What is the seasonal cycle of the processes involved in the Antarctic atmospheric hydrological cycle and what explains its variability ?
- How have these processes evolved over the past four decades and why ?
- How will these processes change in the future, according to climate model projections?

To answer these questions, this thesis includes five chapters. The first chapter introduces the background knowledge of the environment and climate physics helpful in understanding the processes involved in studying the atmospheric hydrological cycle. The second chapter includes the data (ERA5 and ACCESS-ESM1.5) and methodology. The seasonal cycle of evaporation, moisture convergence and precipitation and explanations for their variability is introduced in chapter 3. The trend analysis discusses the evolution of these processes over the last four decades in chapter 4. In chapter 5, the evolution of these processes in the future is investigated based on the CMIP6 model outputs. Finally, a conclusion is provided at the end of the thesis.

## Background knowledge

The first chapter presents work to help understand the atmospheric hydrological cycle in Antarctica. The Antarctic environment will be shown in the first instance (section 1.1). This section will be followed by a description of the atmospheric hydrological cycle (section 1.2). Then, because atmospheric dynamics are crucial for the water cycle, the atmospheric circulation (section 1.3) and the internal modes of variability (section 1.4) are presented.

### 1.1 The Antarctic environment

The Antarctic continent is composed of steep slopes on its edge, with altitude increasing rapidly to thousands of meters (see Fig. 2). Therefore, by gravity, the wind is generally directed towards the edges of the continent, following the slope. These winds are called katabatic winds and play a significant role in the atmospheric circulation of the continent and the coastal region. Due to its considerable elevation, with a plateau at over 4000m above sea level, the coldest temperatures on Earth were recorded in Antarctica, particularly at Vostok station, where the surface temperature was  $-89.2^{\circ}\text{C}$  on the 21 July 1983 [Turner et al., 2009]. A mountain range (the Transantarctic Mountains) divides the Antarctic into two parts, West and East Antarctica. West Antarctica has an average elevation of fewer than 1000m, allowing air from the ocean into the continent to penetrate easily. East Antarctica, on the other hand, has an average elevation of over 2000m, making it much more difficult for air to penetrate this part of the continent. However, recently an event has revealed the existence of an extreme atmospheric river that transports water vapour to the continent's interior [Samennow and Patel, 2022]. This atmospheric river is believed to be caused by a storm that diffuses its moisture into the continent's interior. It is not yet clear whether this is a rare event or whether it will become a new trend. The consequences of an intense flow of moisture over the continent are an increase in temperature and hence melting in this region, which is unusual because the interior of Antarctica does not often experience melting.

There is also a peninsula separating the Bellingshausen and the Weddell Seas, located in the western part. Due to its elevation of about 1500m, the Antarctic Peninsula acts as a barrier to air flows. This substantial variation in altitude allows the Foehn effect to occur in this region [Van Wessem et al., 2016]. The Foehn effect occurs when moist air meets a mountain. The air undergoes an orographic ascent, and precipitation follows, emptying the air of its water content and the air mass passing the mountain is then dried out.

Antarctica is an ice-covered continent surrounded by water south of  $60^{\circ}S$ . The Antarctic Ice Sheet (AIS) is the largest ice sheet on Earth with an area of around  $14.1 \times 10^6 \text{ km}^2$ , which is larger than Europe. This ice sheet is a result of snow accumulation and compression over millions of years. The volume of the AIS is  $27 \times 10^6 \text{ km}^3$  and if all the ice melts, this would have a 58m sea-level rise contribution [Fretwell et al, 2013]. This makes it a central element in the Earth's energy and freshwater balance. There are two reasons for this: the large amount of latent heat required for ice melting and the large amount of energy reflected due to the albedo being close to 1. Around this continent is the Antarctic Ocean linking the Atlantic, Indian and Pacific Oceans. This ocean encircles several seas, such as the Amundsen Sea, Bellingshausen Sea, Weddell Sea, Ross Sea and others. The Antarctic Circumpolar Current is a marine current that flows from west to east around Antarctica. It plays a driving role in the global ocean circulation and carries about 150 Sverdrups ( $10^6 \text{ m}^3/\text{s}$ ).

Two types of ice structures float over the water around Antarctica: ice shelves and sea ice. Ice shelves form due to the Antarctic glacier flowing to the sea and are a marine extension of the Antarctic ice sheet. They can reach thicknesses of 100m to 1000m and are made up of freshwater, thus playing a key role in the Antarctic freshwater balance. In addition, the ice shelves act as a buttress and provide stability to the grounded ice sheet [Dupont and Alley, 2005]. The stability is maintained for as long as the stress of the ice-shelf that acts on the grounding line - the line that separates the grounded ice from the floating ice shelves, is compensated by the stress exerted by the grounded ice. Therefore, as the ice shelf thins or disintegrates, the ice-shelf stress is reduced, and the upstream flow of ice is less restricted and can increase, causing a loss in the ice volume. This effect is called the buttressing effect in reference to the buttressing role played by the ice shelf on the grounded ice sheet. All around Antarctica, there is also the formation of sea ice. The sea ice formation plays a crucial role in the deep convection around the Antarctic. In addition, the variability of the sea ice extent and concentration plays a significant role in the seasonal energy balance of this region. Over the past decades, the Antarctic sea ice cover has shown an increase that is most pronounced in the period of sea ice growth. This trend is dominated by increased sea ice coverage in the western Ross Sea and is mitigated by a strong decrease in the Bellingshausen and Amundsen seas [Hobbs et al., 2016].

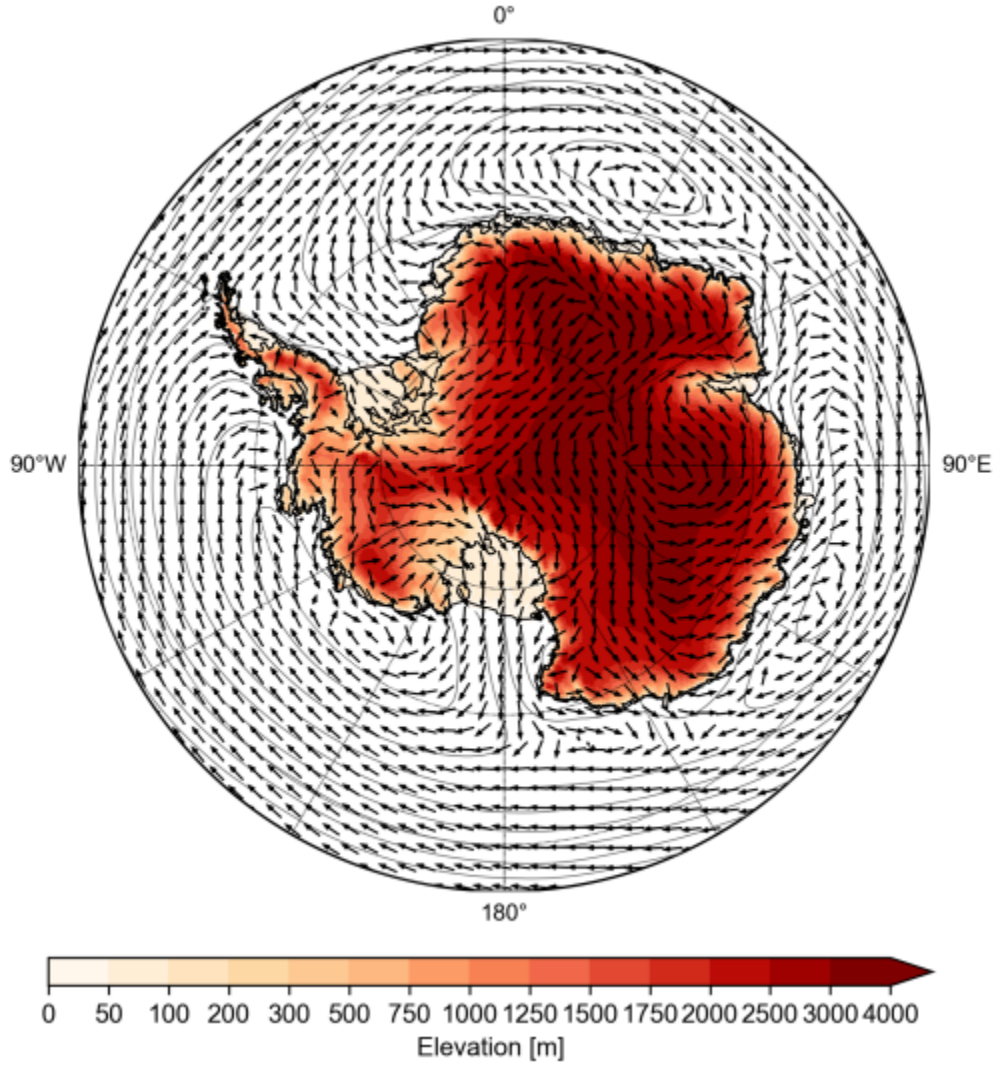


Figure 2: *Time mean of near-surface winds over 1979–2019 from the ERA5 reanalysis. The colored background represents the Antarctic elevation (in m) and the contours in the background represent the mean isobars. [Quentin Dalaiden (thesis), 2021]*

Antarctica is experiencing seasonal temperature variability. Because of the obliquity of the Earth, the seasons are opposite for the Southern and Northern Hemispheres. Indeed, when most of the Northern Hemisphere receives solar radiation (summer), most Southern Hemisphere does not (winter). Since Antarctica is located in the Southern Hemisphere, the Southern seasons are used in this study. It is always daylight during the summer and always dark during the winter, due to poles high latitudes locations. This has strong consequences on the seasonal temperature variability in these regions. Temperature also exhibits variability with altitude. Indeed, with altitude, the atmospheric pressure decreases and the air

masses can expand. However, to expand the air masses must expend energy, which causes the surrounding temperature to drop. A temperature change without heat exchange but through a change in pressure is an adiabatic change. Known as an adiabatic cooling in the case of a temperature decrease [Marshall and Plumb, 2008]. In general, a decrease in temperature of  $6.5^{\circ}\text{C}/\text{km}$  in the troposphere (0-10km) is an average. This temperature variation is greater if the air is dry, as in Antarctica. As the Antarctic continent has a high elevation, low temperatures are expected on the AIS. Another factor that influences the temperature in Antarctica is the albedo. Over Antarctica, up to 80% of the sun's radiation is reflected, which limits heat absorption at ground level [Marshall and Plumb, 2008].

## 1.2 Atmospheric water cycle

Since this thesis is interested in the atmospheric hydrological cycle, the different processes involved in the cycle are presented. Three processes contribute to the change in water content in an atmospheric column: evaporation, moisture transport and precipitation (see Figure 3). These three processes form a subset of the global hydrological cycle.

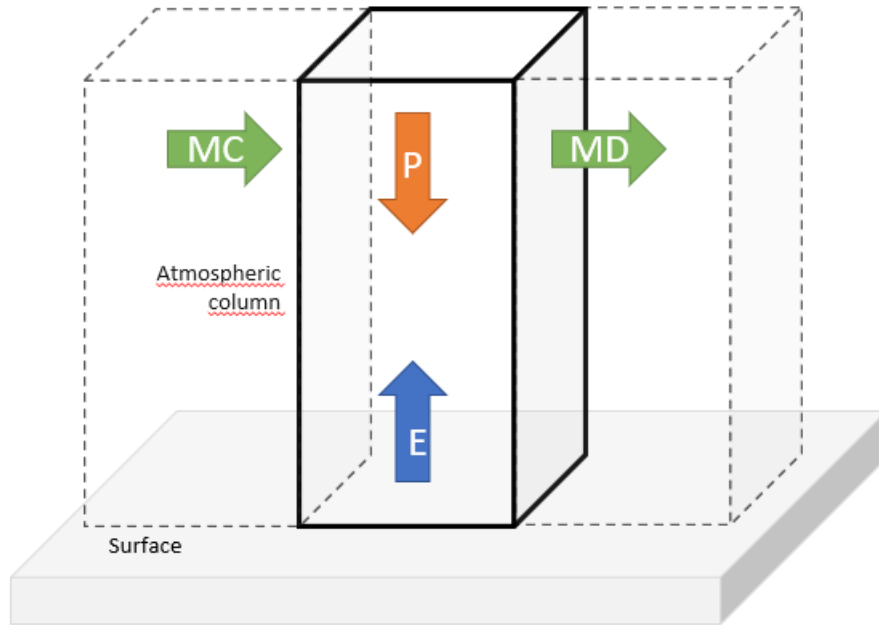


Figure 3: Diagram of the processes of the atmospheric hydrological cycle. Entry of water vapour into the air column through the evaporation process (blue arrow), transverse movement of water vapour characterised by moisture convergence/divergence (green arrows) and exit of water through the precipitation process (orange arrow).

The atmospheric hydrological cycle describes the continuous movement of water on, above and below the surface of the Earth, and the water passes through all its states (solid, liquid, gas). Water is evaporated from the oceans and land. During this process, water changes from liquid or solid to a gaseous state (by vaporisation or sublimation, respectively). This process depends on several factors: the energy to be supplied, the liquid surface available, the humidity in the air and the saturation vapour pressure.

The first factor that influences evaporation is the temperature, near air surface temperature and the water surface temperature. The temperature plays several roles. The first role is to provide enough energy for evaporation to take place. Indeed, evaporation being an endothermic process, energy supply is necessary so that the liquid water can undergo vaporisation, and this energy is known as latent heat of vaporisation. This latent heat is provided by the water that evaporates. There exist two possible cases,  $T_{air} > T_{water}$  or  $T_{air} < T_{water}$ . In the first case, evaporation occurs as long as the pressure  $e$  of the water vapour is lower than the saturation vapour pressure  $e(T_{water})$ . In the second case, evaporation occurs as long as  $e < e(T_{air})$ . The second role of temperature is to increase the saturation vapour pressure  $e(T)$  and thus increase the capacity of the air to contain water vapour. Kininmonth [2010] shows that a temperature increase of  $1^{\circ}C$  is associated with an overall increase in atmospheric humidity of about 7% in accordance with the Clausius-Clapeyron law, which regulates the amount of water in the atmosphere in relation to temperature.

Sea ice has an enormous impact on evaporation in Antarctica. Indeed, sea ice acts as a barrier to the evaporation of liquid water. The larger the concentration of ice, the smaller the contact area, and the less evaporation occurs. Moreover, to evaporate water in the form of ice, it is necessary to melt it first, which requires energy. Therefore, there is less vaporisation from ice than from the water for a fixed amount of energy.

The last factor that influences the evaporation is wind. Since evaporation depends on the saturation of the air. Indeed, saturated air with water vapour can not hold more moisture and therefore no evaporation takes place. Hence, the greater the air renewal, the more favourable the evaporation. As a result, the variation in air circulation has an impact on the evaporation process.

Then, atmospheric circulation can transport evaporated water from one place to another in the hydrological system. In the atmosphere, air masses move according to the atmospheric circulation, which is governed at a large scale by the pressure distribution and the Coriolis force. This results in moisture convergence and divergence regions. The moisture convergence represents a more significant moisture input than the moisture discharge in a fixed area. Conversely, the divergence expresses a more significant discharge of moisture than the moisture input of a region.

Finally, precipitation allows water to leave the atmospheric hydrological system. The water vapour can be transformed into liquid water in the form of drops or into solid water in the form of snow (condensation). Condensation of water vapour occurs when the moist air mass experiences a change in pressure and temperature. Such a change occurs when the air mass rises. There are several mechanisms of lifting, for example, orographic lifting or air mass convergence. Orographic lifting is the process that forces the air mass to rise due to the relief. There are two mechanisms of precipitation formation. The first is the coalescence effect, in which tiny condensation droplets merge to form large drops. The second is the Bergeron effect which occurs in clouds at temperatures below freezing. At this temperature, the three phases of the water molecule coexist in the air: water vapour, supercooled droplets and ice crystals. This effect consists of a continuous transfer of liquid water from the supercooled droplets to the solid water in the ice crystals within the cloud. In both cases, the crystals will eventually fall under their weight and form snowflakes by coalescence [Lutgens et Tarbuck, 2004].

## 1.3 Atmospheric dynamics

Because atmospheric dynamics are crucial for the water cycle, the atmospheric circulation and the underlying processes are essential to understanding the cycle.

As can be seen in Figures 4 and 2, there is a well-defined pressure structure with three low-pressure zones in the low-pressure belt around Antarctica, which is defined as Zonal Wave 3 (ZW3) pattern [Goyal et al., 2021; Raphael, 2004]. In the clockwise direction, the first of the low-pressure zone is off Dronning Maud Land, around  $25^{\circ}E$ . The second is off Queen Mary Land at around  $100^{\circ}E$ . The last low pressure is around  $130^{\circ}W$  in the Amundsen Sea. The ZW3, which generates seasonal slight longitudinal movements, is quasi-stationary. In addition, the ZW3 pattern also exhibits amplitude and phase variations on different time scales ranging from daily to interannual. These amplitude and phase variations play an essential role in several variables' meridional and zonal variability. Indeed, the ZW3 pattern impacts meridional energy transport and can be linked to sea ice concentration variability [Raphael, 2004] and moisture transport.

Cyclones and anticyclones form between the ground and the tropopause (see Fig. 5). First, let us define a cold air mass as an air mass surrounded by warm air and vice versa. This colder air mass is dense due to the low agitation of the particles that compose it and, therefore, is also heavier for the same volume. Therefore, under its weight, the heavy air mass will tend to move towards the ground and form a so-called high-pressure column at the surface. Depending on the hemisphere N/S, the air moves in a clockwise/counterclockwise direction. The Coriolis force dictates the direction of rotation of the different air masses

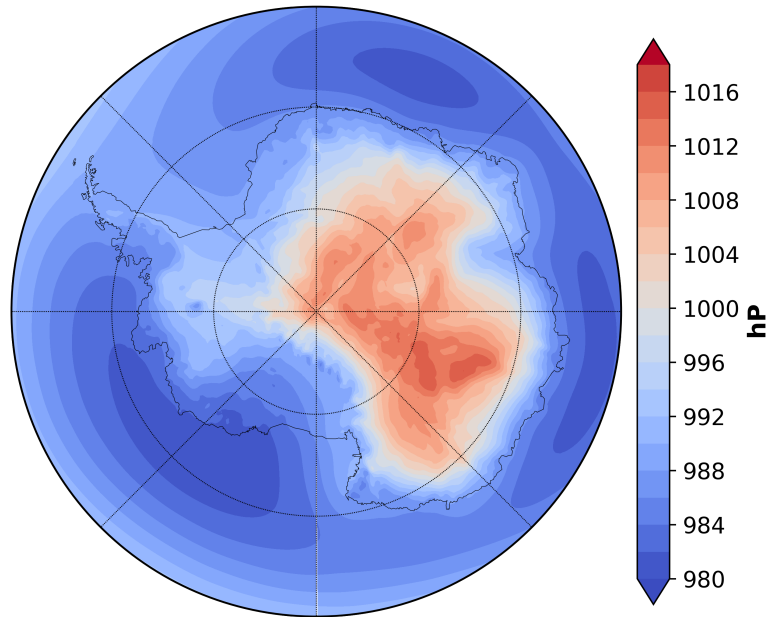
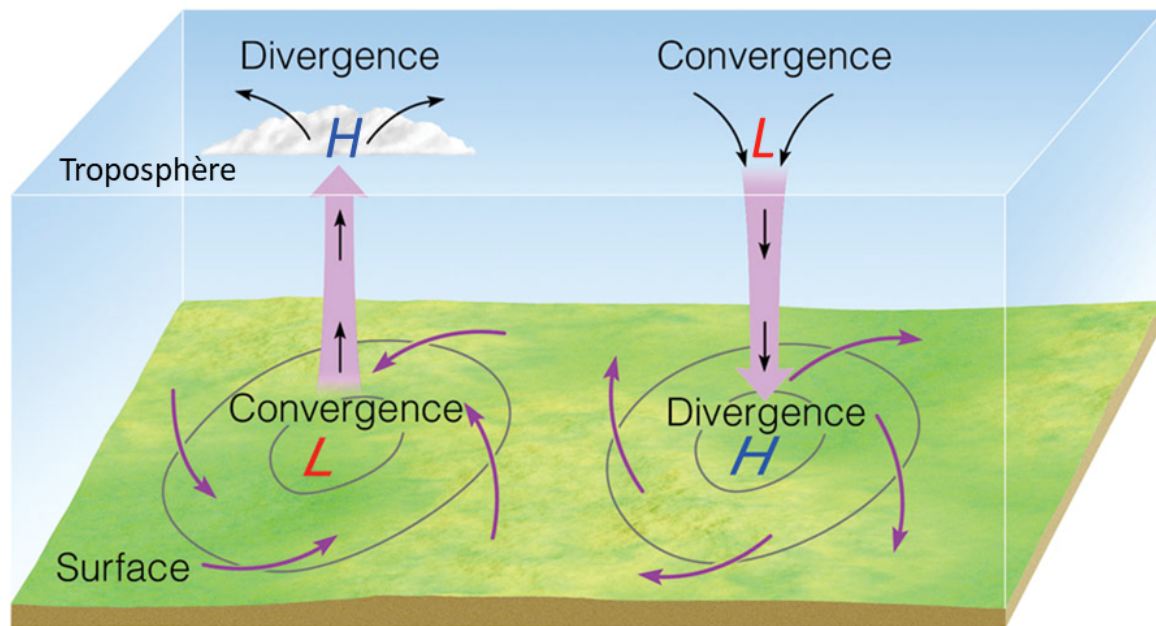


Figure 4: Annual mean 1979-2020 of sea level pressure with monthly averaged ERA5 data. This map show the pressure pattern with three lows.

during their journey. This explains why a difference in rotation between the Northern and Southern Hemispheres is observed. The air mass which descends by turning to ground level will diverge from the base of the high-pressure column. The divergence of these air masses from the centre of high pressure to a centre of low pressure is due to the force generated by the pressure difference applied to the air masses. As the air passes close to the surface, its temperature and water vapour content can increase. Because the air warms up and therefore becomes less dense, which is the opposite case of before, the air mass tends to rise, and the pressure at the surface is low. The direction of the air masses' rotation (counter-clockwise/clockwise) as they lift depends on which hemisphere is being considered (N/S). In addition to lifting, the air masses will be constrained by new pressure and temperature conditions. These warm and humid air masses hold a large volume of water vapour, which results in the condensation of water vapour into fine droplets to form clouds, and sometimes the clouds exceed saturation point, leading to precipitation. Generally, in meteorology, high pressure is called an anticyclone, synonymous with fair weather and conversely, low pressure is called a cyclone and is synonymous with bad weather. Finally, there is a pressure gradient since the pressure at the centre of the cyclone is greater than the pressure surrounding the centre in the upper troposphere. The air masses in the troposphere are directed along this pressure gradient which points towards the top of the anticyclones (high-pressure area). The air closes the loop by descending to the ground in the high. [Triplet and Roche, 1986]



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Figure 5: *Convergence and divergence of air masses around low and high pressure zones in North hemisphere. Original image available at <http://www.atmosedu.com/meteor/images/0833.jpg>*

From this description of cyclogenesis, it is clear that the pressure pattern (ZW3) plays a role in the variability of the Antarctic atmospheric circulation.

## 1.4 Internal modes of climate variability in the Southern Hemisphere (SAM, SAO, BAM, PSA)

In the field of climate prediction, weather changes are related to internal modes of climate variability, the persistence of anomalous climatic conditions and external forcings. In this section, some internal modes of climate variability are introduced. They refer to the recurrence or oscillatory nature of the variability of variables in time and space. The internal modes exist without the presence of external forcing variations. They are the result of feedbacks. The study of modes helps to understand variability on different time scales.

The Southern Annular Mode (SAM), also called Antarctic Oscillation (AO or AAO), is the first internal mode of variability to be discussed. This mode is dominant in the Southern Hemisphere (SH) [Marshall, 2007; Thompson and Wallace, 2000] and exhibits variability on time scales ranging from weeks to years. The SAM refers to the variability of the zonal pressure difference between  $65^{\circ}S$  and  $40^{\circ}S$  [Wachter et al., 2020]. Because of this difference in pressure and the Coriolis force in the SH, a strong westerly wind belt surrounding Antarctica is observed. This belt is directly associated with climate variables such as precipitation, temperature, and moisture convergence. Therefore, studying the SAM variability is essential to understanding the atmospheric circulation changes in Antarctica. The SAM has three phases, positive, neutral and negative. The positive phase of SAM exhibits a large pressure gradient between the mid and polar latitudes, which results in strong westerly winds. Conversely, a negative phase shows a slight pressure gradient between the mid and polar latitudes and thus a weakening of the westerly wind belt. Moreover, in positive phases, the westerly wind belt is displaced poleward of its climatological mean position [Thompson and Wallace, 2000], and conversely, in negative phases, it expands towards mid-latitudes.

Another internal mode of variability that affects the Antarctic climate is the Semi-Annual Oscillation (SAO). The SAO expresses the semi-annual contraction and intensification and the semi-annual expansion and weakening of the trough surrounding Antarctica [Van den Broeke, 1998; Meehl et al., 1998]. This process is due to the heat content difference between Antarctica and the surrounding oceans. As a result of an intensification of the temperature gradient ( $50^{\circ}S - 65^{\circ}S$ ) twice a year, the mean sea level pressure has a semi-annual cycle. Indeed, when taking the first two harmonics of the mean sea level pressure, the first harmonic shows a large interannual oscillation while the second harmonic shows a double oscillation. This second harmonic explains a large part of the annual variance of the sea-level mean pressure, up to 70 – 80% in some regions where there is a peak [Van Loon and Rogers, 1984]. When the circumpolar trough of low pressure surrounding Antarctica is at its most southerly location, there is an amplification of the ZW3 pattern [Tietavainen and Vihma, 2008]. This causes an increase in meridional air transport from low latitudes to the Antarctic continent [Van den Broeke, 1998]. There are maximum expansions during the extreme seasons in January and July and maximum contractions in March and September. As a result, cyclonic activity intensifies in autumn and spring. The SAM and the SAO are connected, and a weakening of the SAO in the late 1970s has been related to the increase in the SAM [Marshall, 2003].

The following internal mode of variability is called the Baroclinic Annular Mode (BAM). This mode is derived from the time series of the leading empirical orthogonal function (EOF) of the SH daily mean zonal mean Eddy Kinetic Energy (EKE). This mode represents the pulsing (the variation of the amplitude) of EKE rather than the shift in the SAM. Indeed, from a synoptic point of view, the SAM describes variations in the meridional propagation of wave activity, whereas the BAM describes variations in the amplitude of developing baroclinic

waves. Together, they explain much of the variance in energy cycling in the SH atmosphere at mid-high latitudes. The period of this mode is about 20 to 30 days [Thompson and Woodworth, 2013]. During a positive phase, the wave amplitude is larger than normal, and vice versa when the polarity is negative [Marshall et al., 2017].

Finally, the last mode is the Pacific South American (PSA). They are often analysed as a pair of the EOF of the geopotential height, called PSA1 and PSA2. Some scientists interpret these patterns as an eastward propagating wave [Irving and Simmonds, 2016]. The PSA mode strongly influences the Antarctic wind and wave height across the SH oceans [Lou et al., 2021]. A zonal asymmetry characterises them in the pressure anomaly around West Antarctica. These two PSA modes have their most considerable impact on surface air temperature in the West Antarctic region [Marshall et al., 2017].

## Data and methods

This chapter introduces the different datasets used in the study of the atmospheric hydrological cycle. Section 2.1 presents the ERA5 dataset used for past data. Section 2.2 introduces the atmospheric moisture budget with ERA5 data. The ACCESS-EMS1.5 data for the projection of the atmospheric hydrological cycle is presented in section 2.3. The last section (2.4) of this chapter is given to the comparison of the two datasets.

The different codes used to realize the figures presented in this thesis are available on a Github at this address: <https://github.com/NoePirlet/Master-s-thesis.git>

### 2.1 ERA5 dataset

Since observations are not evenly distributed around the globe and are limited when we go back in time, climate reanalysis is used. The principle of a reanalysis is to combine today's weather models with observations made in the past to deliver a complete and consistent picture of past weather. The first dataset used is the ERA5 monthly averaged data on single levels from 1979 to the present. These data come from the ERA5 reanalysis, a global climate and weather reanalysis for the last few decades. This reanalysis is the latest product of the European Center for Medium-Range Weather Forecasts (ECMWF). ERA5 is a global reanalysis, which means that data are available for the whole world. However, as our study focuses on Antarctica, only data south of  $60^{\circ}S$  is used. Although the native resolution of the dataset is vertically 137 pressure levels and horizontally 31km, data with a single pressure level and regridded data to a regular latitude-longitude grid of  $0.25^{\circ} \times 0.25^{\circ}$  degrees are chosen. The dataset has a temporal resolution of one month. ERA5 has a good performance in representing atmospheric variables such as precipitation and temperature [Tewari et al., 2022] and was therefore selected for the present study.

In the following paragraphs, the different data used are described:

**The mean total precipitation rate  $P$  [ $\text{kg m}^{-2} \text{s}^{-1}$ ]:** These data are the result of the sum of the rates due to large-scale precipitation and convective precipitation (rain and snow). Because  $1\text{kg}$  of water spread over  $1\text{m}^2$  of surface is  $1\text{mm}$  deep (neglecting the effects of temperature on the density of water), the units ( $[\text{kg m}^{-2} \text{s}^{-1}]$ ) can be converted to  $[\text{mm s}^{-1}]$ . This parameter is always positive and has the effect of reducing the water content in the atmospheric column.

**The mean evaporation rate  $E$  [ $\text{kg m}^{-2} \text{s}^{-1}$ ]:** These data represent the amount of water that has evaporated from the Earth's surface (ocean and land). This parameter considers the evaporation of water and sublimation of the snow. This parameter has the effect of increasing the water content in the atmospheric column.

**The mean vertically integrated moisture divergence  $\nabla \cdot \vec{Q}$  [ $\text{kg m}^{-2} \text{s}^{-1}$ ]:**  $\vec{Q}$  is the result of the vertical integration of the horizontal rate of flow of moisture, over a column of air extending from the surface of the Earth to the top of the atmosphere. It can be divided into northward (meridional) and eastward (zonal) components. Its horizontal divergence ( $\nabla \cdot \vec{Q}$ ) is the rate of moisture spreading out from the column per square meter. This parameter is positive for moisture spreading out (divergence), and it is negative for moisture converging in the column (convergence). This parameter characterises a reduction of the water vapour content when there is divergence and, conversely, an increase of the water vapour content when there is convergence in the atmospheric column.

**The total column water  $W$  [ $\text{kg m}^{-2}$ ]:** is the result of the sum of all sources of water in all their forms in the atmospheric column.

**The mean sea level pressure in  $[Pa]$ :** is the result of the pressure of the atmosphere adjusted to the height of the mean sea level. This parameter represents the weight of the air column.

**The sea-ice concentration,** is dimensionless. It represents the fraction of sea ice cover present in the grid cell. Since ERA5 is an atmospheric reanalysis, the sea ice concentration is not generated by the ERA5 modelling system. Data are generated elsewhere based on satellite observations: by EUMETSAT's Ocean and Sea Ice Satellite Application Facility (OSI SAF) (1979-2007) and by UK MetOffice Operational Sea Surface Temperature and Sea Ice Analysis (OSTIA) (2007-onward). Finally, these two sea ice products are used in ERA5.

**The 2m temperature  $[K]$ :** It represents the temperature of air near-surface of the Earth. Simple conversion to Celsius can be made by subtracting 273.15.

Data are available at: <https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels-monthly-means?tab=overview>.

## 2.2 Atmospheric moisture budget

It is helpful to perform a numerical study of the balance to verify that the data used correctly reflect the atmospheric moisture budget. To do this, Serreze et al. [2006] consider an atmospheric column extending from the surface to the top of the atmosphere. The atmospheric water budget of such a column is computed as:

$$\frac{\partial W}{\partial t} = -(P - E) - \nabla \cdot Q \quad (1)$$

where  $\partial W/\partial t$  represents the change of the precipitable water ( $W$ ) in the atmospheric column for an interval of time. On the right side of the equation, the first term is the difference between the total precipitation rate of the column ( $P$ ) and the evaporation rate ( $E$ ). ( $P - E$ ) is called the net precipitation. The second term of the right side of the equation is the divergence of the horizontal water vapour flux ( $Q$ ) integrated over the entire height of the column. This term is called the vertically integrated moisture divergence ( $\nabla \cdot Q$ ).

By inspecting equation 1, it could be assumed that the left side of the equation is equal to zero for a steady-state and for a sufficiently long time. This assumption can be checked by calculating the difference between precipitable water at the beginning and the month's end and then dividing it by the time between these two measurements. As expected, a value very close to zero is obtained. Thus, in this case, the net precipitation ( $P - E$ ) is equal to the vertically integrated moisture convergence ( $-\nabla \cdot Q$ ).

Because Serreze et al. [2006] work is only about the Arctic and since one of the major differences between the two poles is the presence or absence of a large ice sheet, the presence of the snow sublimation in the balance has been checked. In addition, the red curve in Figure 6 is always close to zero, as expected. This means that the hydrological cycle is in balance at the first order.

With the help of table (1), quantification of the contribution of the right-hand' terms in the equation 1 is done. It can be seen that the percentage of precipitation remains constant from February to September and shows a slight decrease with a minimum in December. Evaporation offer a large variation in the monthly contribution of water in the air column. Indeed, evaporation has a maximum contribution in April and then decreases to its minimum in September. And since the contribution of precipitation is almost constant, the convergence of humidity balances evaporation in contributing to the amount of water in the air column.

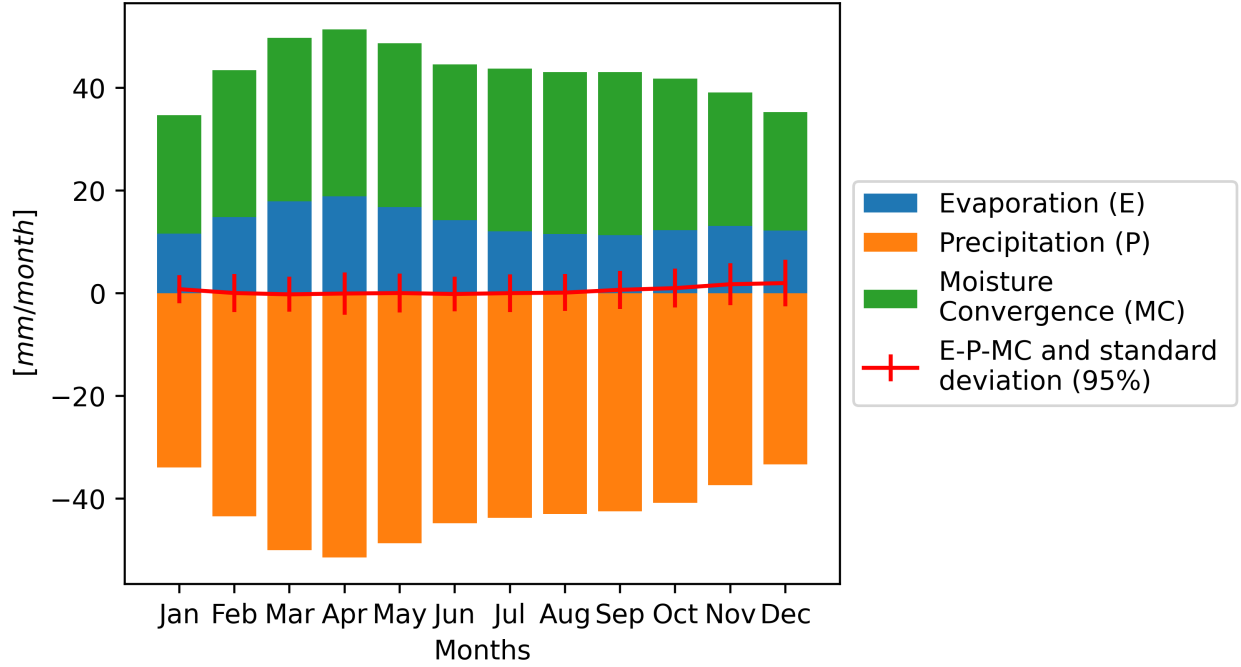


Figure 6: *The budget of the atmospheric hydrological cycle. Each colour bar represents one term in the budget equation, and this figure shows the relative role played by each term for each month. The values shown in this figure are time averaged during 1979-2020 for each variable.*

| Terms  | J    | F    | M  | A    | M    | J    | J    | A    | S    | O    | N    | D    |
|--------|------|------|----|------|------|------|------|------|------|------|------|------|
| E [%]  | 17   | 17.1 | 18 | 18.4 | 17.3 | 15.9 | 13.8 | 13.4 | 13.2 | 14.9 | 17.2 | 17.8 |
| P [%]  | 49.4 | 50   | 50 | 50   | 50   | 50   | 50   | 50   | 49.6 | 49.4 | 48.8 | 48.5 |
| MC [%] | 33.6 | 33   | 32 | 31.6 | 32.8 | 34   | 36.2 | 36.7 | 37.1 | 35.7 | 34   | 33.7 |

Table 1: Relative percentage associated with each of the right-hand terms in the equation 1.

## 2.3 ACCESS-ESM1.5 dataset

In order to study climate projections of the atmospheric hydrological cycle in Antarctica, it is no longer possible to use the ERA5 data as they are only available for the past. For this purpose, an Earth System Model (ESM) is used. This is a model that takes the equations of dynamics and thermodynamics to simulate both the global atmospheric circulation and the global ocean circulation, which is called a General Circulation Model (GCM), in which physical, biological and chemical processes (such as the carbon cycle) are included. Many

models meet these criteria; however, some models are better than others.

These datasets from the ACCESS-ESM1.5 were chosen because this model is one of the best-performing CMIP6 models for the Antarctic. Indeed, performance evaluation based on Pearson Correlation Coefficients (PCC) with ERA5 climatology, and Root Mean Squared Error (RMSE) with climatology in various consortia, show that ACCESS-ESM1.5 is one of the best performing models in CMIP6 [Tewari et al., 2022]. Therefore, it can produce the most accurate projections available for the Antarctic. In addition, ACCESS is an Australian model, a country that is relatively close to Antarctica and therefore possibly able to better represent this region’s climate.

The Australian Community Climate and Earth-System Simulator (ACCESS) has been extended to include land and ocean carbon cycle components to form an Earth System Model (ESM). This model was developed to participate in the Coupled Model Intercomparison Project Phase 6 (CMIP6). The final model produced by CSIRO (Commonwealth Scientific and Industrial Research Organisation) is the ACCESS-ESM1.5. This model provides tools to explore how climate change might impact the Antarctic [Ziehn et al., 2020]. The model has three main components, atmosphere, land and ocean. The atmospheric part is the one that is relevant to the study of the atmospheric hydrological cycle. The resolution of the atmospheric component is  $1.875^\circ$  longitude by  $1.25^\circ$  latitude with 38 vertical levels, extending from the surface to  $40km$ . Most forcing files have been adapted from the UK Met Office setup for CMIP6.

There are different experiments from this model. The historical experiment is appropriate to compare to the climate state observed in recent decades. Validation over the historical period against observations shows good agreement [Ziehn et al., 2020]. This historical dataset allows us to compare the previously used data (ERA5) and the ACCESS-ESM1.5 model to continue studying the atmospheric hydrological cycle. Section 2.4 is devoted to this comparison between the two datasets. A second experiment that is interesting in the study of Antarctica’s future atmospheric water cycle is the SSP-based RCP scenario with high radiative forcing by the end of the century. The selected data follow the trajectory of the RCP8.5 global forcing with the SSP5 socio-economic conditions, which means that the radiative forcing by the greenhouse gases, aerosols, and other emissions in the year 2100 totals to  $8.5Wm^{-2}$ . The initialisation is from the end of the historical experiment to provide continuity between simulations of the recent past and future scenario simulations.

The ACCESS-ESM1.5 data used in Chapter 5 are:

**The evaporation rate including sublimation and transpiration** in  $[kg\ m^{-2}\ s^{-1}]$ . Evaporation historical dataset for the period 1979-2014. The evaporation for the SSP-based RCP8.5 scenario dataset for 2074-2100. **The precipitation rate** in  $[kg\ m^{-2}\ s^{-1}]$ . Precipitation historical dataset for the period 1979-2014. The precipitation for the SSP-based RCP8.5 scenario dataset for 2074-2100.

tation historical dataset for the period 1979-2014. Precipitation for the SSP-based RPC8.5 scenario dataset for the period 2074-2100. The period chosen for the historical data is the period for which the ERA5 and ACCESS-ESM1.5 data overlap. The period chosen for the SSP data has the same length as the historical period to have an average over the same number of years. Therefore data for the last 36 years of the century are selected.

For moisture convergence, calculations had to be made because the "Mean Vertically Integrated Moisture Divergence" data was unavailable for ACCESS. To get the moisture convergence term, the data "**Vertically Integrated Eastward Moisture Transport**" and "**Vertically Integrated Northward Moisture Transport**" were used. The unit of these data is  $[\text{kg m}^{-1} \text{ s}^{-1}]$ . To obtain the desired term, the divergence in spherical coordinates of the two-dimensional vector is calculated for each cell. The divergence is calculated by discretising with the finite difference method. This calculation method is carried out for historical and SSP585 data.

To present the changes in surface air temperature, sea ice concentration, and pressure, we used 3 historical datasets and 3 SSP585 datasets. Variable names of the selected datasets are **Near-surface air temperature** in [K], **Sea ice area fraction** infraction of the cell and **Sea level pressure** in [Pa].

The variant-id of these data are r1i1p1f1 for realisation 1, initialisation method 1, physics 1 and forcing 1. As for the ERA5 datasets, the temporal resolution is one month.

Data are available at: <https://esgf-node.llnl.gov/search/cmip6/>.

## 2.4 Comparison between ERA5 and ACCESS ESM1.5

Before looking at the ACCESS projections, an evaluation with ERA5 is necessary. To do this, Figure 7 represents the difference between the two datasets. The difference is shown for each sector's atmospheric hydrological cycle component. Sectors are defined as in [Massonnet et al., 2013], so the study area ( $60^{\circ}S$  to the South Pole) is divided into five sectors. They are the Weddell Sea sector (WS,  $60^{\circ}W$ ,  $12^{\circ}E$ ), Indian Ocean sector (IO,  $12^{\circ}E$ ,  $84^{\circ}E$ ), Pacific Ocean sector (PO,  $84^{\circ}E$ ,  $156^{\circ}E$ ), Ross Sea sector (RS,  $156^{\circ}E$ ,  $132^{\circ}W$ ) and Amundsen-Bellinghausen Sea sector (ABS,  $132^{\circ}W$ ,  $60^{\circ}W$ ).

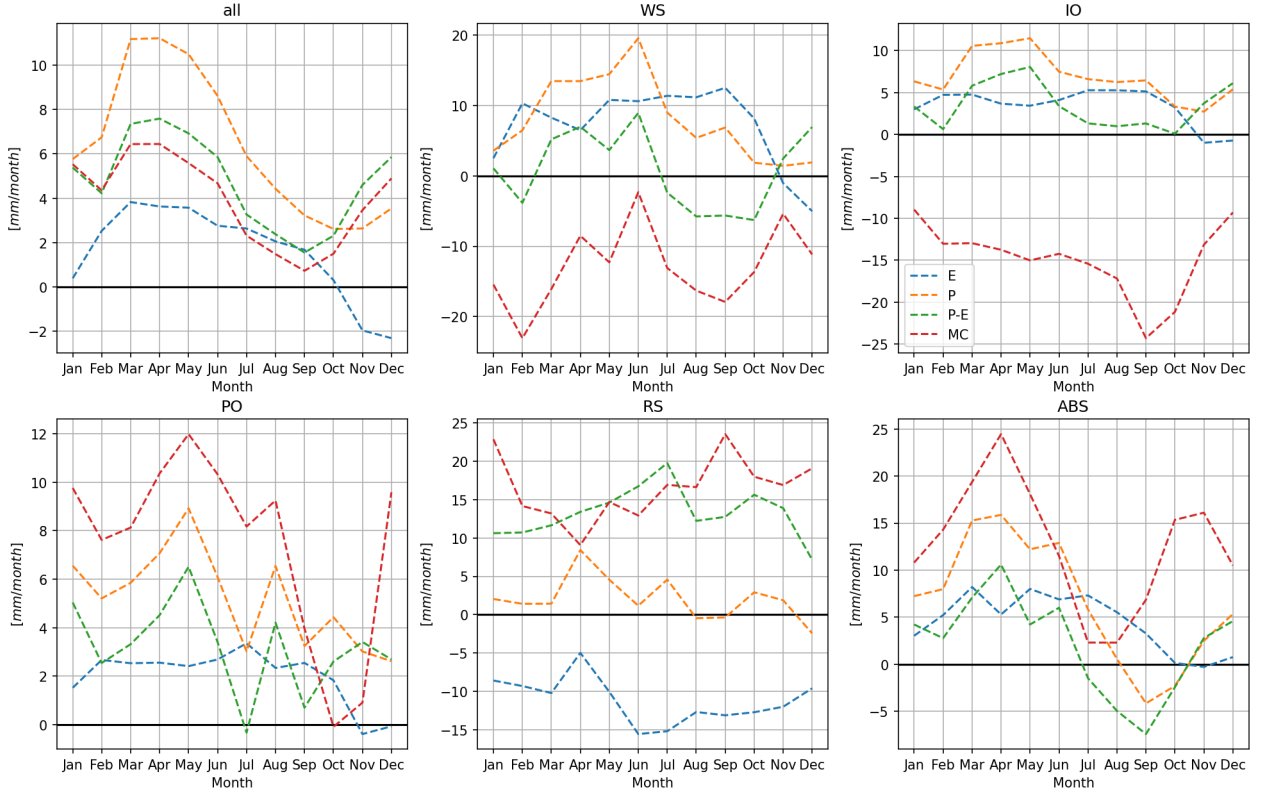


Figure 7: *The difference between ACCESS historical and ERA5 for the twelve months (1979-2014), each sector and each component of the atmospheric hydrological cycle (evaporation (E), precipitation (P), P-E and moisture convergence (MC)).*

Antarctica shows a positive difference between the two datasets, except for evaporation at the end of the year (November, December) and the moisture convergence from July to November. This means that the ACCESS dataset overestimates the data compared to the ERA5 dataset for precipitation and net precipitation. A significant increase in the difference is observed during the intensification of the atmospheric hydrological cycle in autumn. The smallest difference is observed in October (in Spring). Of the components of the atmospheric hydrological cycle, precipitation shows the largest difference (annual mean 6.42mm/month). Evaporation shows an overestimation of the ACCESS data compared to the ERA5 data except in November and December. The mean annual difference is 1.61mm/month. For the moisture convergence, values are always higher than zero. There is a maximum of overestimation in autumn and a minimum in September, while the mean annual difference is 3.95mm/month.

In Figure 7, large values for the difference in moisture convergence between the two datasets are observed. These large values are explained by a different share of moisture con-

vergence between the two datasets. Indeed, regions of divergence are present in the ACCESS data, whereas there are almost none in the ERA5 data. Due to the position of the moisture divergence zones, the ACCESS model seems to represent the katabatic winds better. Indeed, the divergence zones appear mainly in the WS (Coats Land coast), and IO (Amery Ice Shelf) sectors, which explains why an underestimation of the convergence is observed in these sectors.

The WS sector shows an overestimation of precipitation, especially in winter. An underestimation of  $P - E$  is observed in February as well as in July, August, September and October. In Table 2, the mean values are high for evaporation and precipitation, while  $P - E$  shows a value close to zero, which means the two datasets have similar  $P - E$  values in this sector. The moisture convergence shows a large underestimation in this sector, caused by divergence zones in ACCESS that does not appear in ERA5. In the IO sector, precipitation and  $P - E$  only show positive difference values. Evaporation shows a positive difference of around 4mm/month throughout the year except in November and December, where underestimation is shown. The moisture convergence shows a large underestimation all year, with the largest values in September, mainly caused by the simulation of a divergence zone from the Lambert Glacier to the Amery ice shelf created by katabatic winds. The annual mean difference for precipitation, evaporation and moisture convergence is closer to zero than in the WS sector (see Table 2). The PO sector shows low values for precipitation and evaporation while a large positive difference for moisture convergence is observed. Table 2 shows mean values close to zero, indicating a slight difference between the datasets for precipitation, evaporation and net precipitation. In this sector, the moisture convergence is overestimated by ACCESS compared to ERA5, except in spring, with values closer to zero. The RS sector shows the highest difference values for evaporation with an average underestimation of  $-11.12\text{mm/month}$  and the lowest values for precipitation with an average of  $2.17\text{mm/month}$ . The evaporation underestimation is due to large differences in sea ice extent and concentration that are lower in ACCESS data than in ERA5 data. The moisture convergence is overestimated as in the previous sector but exhibits higher values around  $16.49\text{mm/month}$  than in the PO sector. The ABS sector shows a semi-periodicity with an overestimation of  $P$  and  $P - E$  in the year's first half and an under-estimation in the second part. The evaporation difference shows positive values with an annual mean of  $4.47\text{mm/month}$ . For the moisture convergence, a peak of overestimation is observed in autumn and spring. In the last three sectors, overestimations are likely due to an enhancement of the atmospheric circulation intrinsic to ACCESS.

| Sectors                 | All  | WS     | IO     | PO   | RS     | ABS   |
|-------------------------|------|--------|--------|------|--------|-------|
| E [ <i>mm/month</i> ]   | 1.61 | 7.19   | 3.42   | 2.01 | -11.12 | 4.47  |
| P [ <i>mm/month</i> ]   | 6.42 | 8.16   | 6.94   | 5.26 | 2.17   | 6.67  |
| P-E [ <i>mm/month</i> ] | 4.8  | 0.97   | 3.52   | 3.25 | 13.29  | 2.2   |
| MC [ <i>mm/month</i> ]  | 3.95 | -12.94 | -14.87 | 7.5  | 16.49  | 12.66 |

Table 2: *Annual mean difference (ACCESS - ERA5) of evaporation, precipitation, P-E and moisture convergence for each sector*

## Atmospheric hydrological cycle at the seasonal time scale

This third chapter introduces the seasonal cycle of the different processes involved in the Antarctic atmospheric hydrological cycle. The aim is to answer the question: *What is the seasonal cycle of the processes involved in the Antarctic atmospheric hydrological cycle and what explains this variability?* In order to answer this question, the seasonal cycle of evaporation, precipitation and moisture convergence in the ERA5 reanalysis in different sectors of Antarctica is described in section 3.1. Then, using the spatial and temporal variability of atmospheric variables (e.g. temperature, pressure), the spatio-temporal variability of evaporation, moisture convergence and precipitation is interpreted in section 3.2. The last section summarises the discussion of the results (section 3.3).

### 3.1 Description of the seasonal cycle

In order to study the atmospheric water cycle at the seasonal time scale, as shown previously (section 2.4) the study area ( $60^{\circ}S$  to the South Pole) is divided into five sectors following Massonnet et al. [2013].

Figure 8 shows the seasonal variability of the atmospheric water cycle for each sector and the whole study area. Four curves are shown: evaporation in blue, precipitation in orange, moisture convergence in green, and net precipitation (precipitation - evaporation) in red. The values represented by these curves are the result of the integration of the value of each grid cell in the fixed sector. Its area weights values of each cell to consider the change in latitude. The units are [mm/month]. The vertical bars intersecting the different curves represent one standard deviation of the variability over the study period.

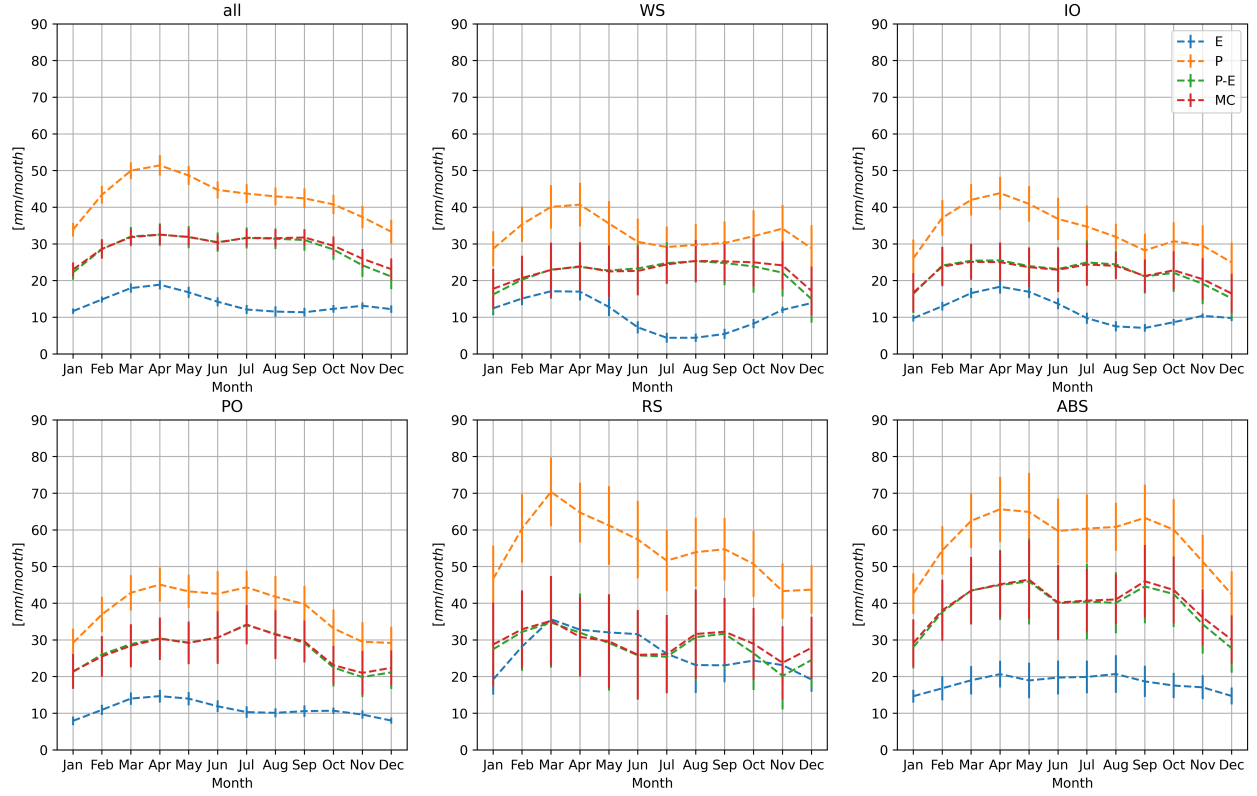


Figure 8: *The 1979-2020 monthly mean atmospheric terms from ERA5 monthly mean outputs. The atmospheric terms include precipitation (orange), evaporation (blue), moisture convergence (red) and (P-E) net precipitation (green). Monthly mean atmospheric terms are shown for the entire study area as well as for each sector (WS, IO, PO, RS, ABS). The error bars denote the standard deviation of the 1979-2020 monthly atmospheric terms. Compared to Figure 6 the convention has changed and the values of the different processes in this figure are all set positive.*

For the seasonal cycle of the entire study area (all), an increase in the different variables is noticed. This increase begins in the summer (DJF) and reaches its peak in autumn (MAM) and is followed by a decrease until the summer begins again. This is consistent with the results from Tang et al. [2018]. Indeed, Figure 8 and Table 3 show the same seasonal curve shape and similar values for the Antarctic precipitation cycle. Precipitation intensifies strongly during the summer to reach a maximum in April (4.38mm/month/month). Then there is a decrease until December but with a different rate of decrease. The decrease after April until June is about  $-2.23\text{mm/month/month}$ . During winter (JJA), the rate of decline weakens to  $-0.59\text{mm/month/month}$ . Finally, in spring (SON) the rate decrease again ( $-2.28\text{mm/month/month}$ ) until December. Evaporation shows a rapid increase during the summer (1.8mm/month/month) with a maximum in April. Then evaporation decreases at

the end of autumn and in winter with an opposite rate to that encountered during the increase. The minimum is reached in September, followed by a bump in spring and early summer. The moisture convergence increases in summer (2.93mm/month/month) as for the other variables, with a maximum in April (32.5mm/month). Then the values stabilize around 30mm/month until early spring. During the spring, there is a large decrease in the moisture convergence ( $-2.16\text{mm/month/month}$ ), with a minimum in January. Finally, a slight difference between P-E and the moisture convergence in November and December is noted.

In the WS sector, there is a large difference between the autumn and winter for precipitation and evaporation values. In addition, there is a second peak in late spring (November) for precipitation. The moisture convergence and net precipitation follow a rapid decrease in late spring and then a slow increase during the rest of the months. This expresses an increase in net precipitation values in late spring and early summer.

In the IO sector, the seasonal cycle is similar to that in the WS sector, despite a difference in precipitation and evaporation during spring. Indeed, the second peak of precipitation and evaporation is much less visible due to a slower rate of decline and a further, less pronounced increase. There is also a stabilization of the moisture convergence and net precipitation of around 24mm/month from the summer's end until the winter's end. P-E and moisture convergence values remain relatively close across the twelve months.

In the PO sector, the precipitation has a higher intensity (see Table 3) and the peak intensity lasts longer than in the other sectors discussed above. The peak starts in the autumn and ends at the end of the winter. For the evaporation, there is a peak in autumn followed by a slow decrease until the beginning of summer. Concerning the moisture convergence, the mean is higher than in the previous sectors, with a peak in winter (July). Moreover, the maximum moisture convergence is no longer reached in autumn but in the middle of winter (July). This particular cycle feature leads us to believe that this sector has something different in the atmospheric hydrological cycle in winter. As expected, P-E and moisture convergence remain relatively close.

In the RS sector, the different variables have higher mean values than in the previously discussed sectors. Indeed, the mean value for evaporation is more than twice as high in this sector as in WS, IO and PO and the mean value for precipitation is also higher (see in Table 3). Precipitation increases rapidly in summer to reach a maximum in March. Thereafter, the precipitation decreases and almost stabilizes from July to October at about 53mm/month. A significant peak in precipitation in autumn is noted. Precipitation decreases until November. For evaporation, a behaviour similar to that encountered for precipitation is shown, with a peak in autumn and a stabilization in late winter and early spring. The moisture convergence and net precipitation curves appear to have a half-year cycle, with minimums in June and November and maximums in March and September.

In the ABS sector, the amount of precipitation is large, and the net precipitation and moisture convergence are much higher than in the other sectors. In addition to the peak in autumn, it is important to note that there is a second peak in these values (precipitation and moisture convergence) during the spring. This semi-annual cycle comes out of the atmospheric hydrological cycle in ABS and RS sectors and would be interesting to understand. In addition, the evaporation does not exhibit a decrease in evaporation in winter. Indeed, there is a decrease in spring, followed by a minimum in summer, and then evaporation is almost constant during autumn and winter. The annual mean of the evaporation is lower than in RS ( $-8.3\text{mm/month}$  in comparison) but higher than in WS, IO and PO ( $+7.4\text{mm/month}$ ,  $+6.4\text{mm/month}$ ,  $+7.1\text{mm/month}$  in comparison).

Table 3 shows that the values of the first two sectors are very close. In the PO sector, slightly higher values except for evaporation are estimated. Then in RS and ABS sectors, values for processes are more significant than in other sectors. Therefore, the variability in the cycle of these two last sectors plays a leading role in the variability of the atmospheric hydrological cycle in Antarctica than in the three others.

| Sector | Evaporation<br>[mm/month] | Precipitation<br>[mm/month] | Moisture<br>convergence<br>[mm/month] | P-E<br>[mm/month] |
|--------|---------------------------|-----------------------------|---------------------------------------|-------------------|
| All    | 13.9                      | 42.7                        | 29.3                                  | 28.8              |
| WS     | 10.8                      | 32.9                        | 22.6                                  | 22.1              |
| IO     | 11.8                      | 33.9                        | 22.2                                  | 22.1              |
| PO     | 11.1                      | 38.1                        | 27.3                                  | 28.4              |
| RS     | 26.5                      | 54.9                        | 29.5                                  | 28.4              |
| ABS    | 18.2                      | 57.3                        | 40.0                                  | 39.1              |

Table 3: *Annual mean (1979-2020) for mean total precipitation rate (orange), mean evaporation rate (blue), mean vertically integrated moisture convergence (red) and net precipitation (green). This mean is provided first for the whole study area and then for each sector presented in the clockwise direction starting from the WS sector. The unit used is [mm/month].*

## 3.2 Spatio-temporal variability of atmospheric variables

Following the seasonal cycle of the atmospheric hydrological cycle, it is necessary to complete our understanding of the cycle by making seasonal maps. These maps highlight the spatio-temporal variability of these atmospheric variables. Since the temperature, pressure, and sea ice are three factors that influence the atmospheric hydrological cycle, the first three subsections explain the seasonal variability of these variables (subsections 3.2.1, 3.2.2 and 3.2.3). Afterwards, the seasonal variability of the hydrological cycle processes is introduced, starting with evaporation (subsection 3.2.4), followed by moisture convergence (subsection 3.2.5) and ending with precipitation (subsection 3.2.6).

### 3.2.1 Temperature

As described in section 1.2, surface temperature variations play a major role in the variability of evaporation and indirectly in the variability of precipitation. It makes the spatio-temporal study of this variable essential for understanding the seasonal variability of the hydrological cycle.

The temperature near the surface (2m) displays seasonal variability. The combination of obliquity and revolution creates a variation in sunlight, which explain this seasonal variation in surface air temperature (see section 1.1).

As can be seen in Figure 9, the surface temperature in Antarctica varies over the year. The mean temperature values for the whole study area are  $-9^{\circ}\text{C}$  for summer,  $-17.8^{\circ}\text{C}$  for autumn,  $-22.88^{\circ}\text{C}$  for winter and  $-17.98^{\circ}\text{C}$  for spring. The temporal cycle of the temperature is thus established with a maximum in summer and a minimum in winter. Such a seasonal temperature cycle can be found in Tang et al. [2018].

Surface temperatures also exhibit spatial variability. First, there is a variation according to the latitude (Fig. 9) with a temperature increase equatorward. This results in a high to low latitudes meridional temperature gradient, which evolves symmetrically around the pole. In addition to the latitudinal variability, the temperature varies with altitude and the reflective nature of the ice/snow, as explained in section 1.1. The high altitude and large albedo of the Antarctic plateau limit heating so much that the temperature is always well above zero Celsius in this region. Finally, the low temperatures recorded on the continent are explained by a combination of these factors.

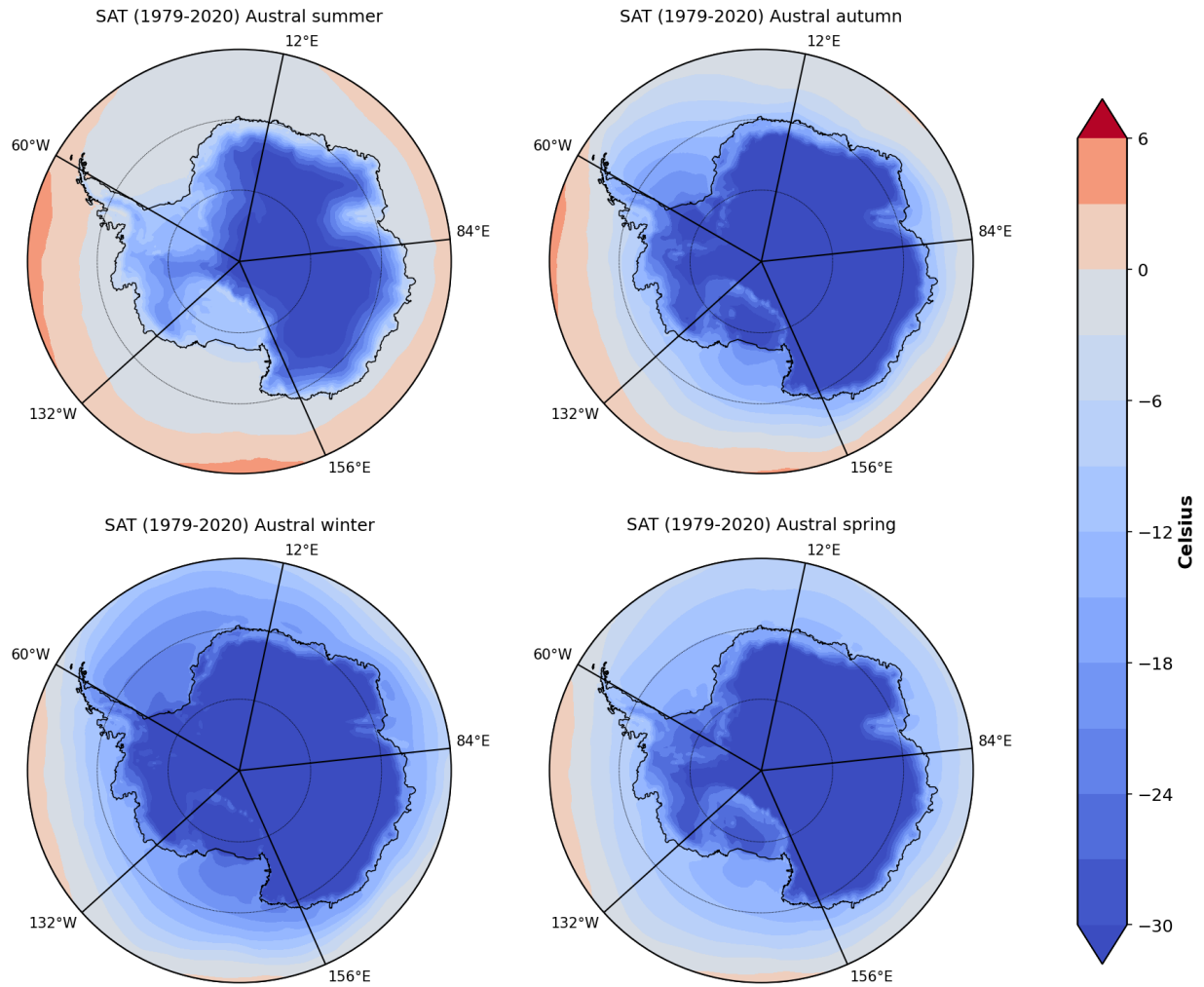


Figure 9: The 1979-2020 mean 2m temperature from the ERA5 monthly mean outputs. Each map represents a season: DJF for summer, MAM for autumn, JJA for winter and SON for spring.

### 3.2.2 Sea Level Pressure

Another factor that influences the atmospheric hydrological cycle is the atmospheric circulation, the variability of which depends on the pressure patterns (see sections 1.2 and 1.3). Therefore, spatio-temporal analysis of this variable is relevant in the study of this cycle.

As mentioned in section 1.3, there is a pressure pattern called the ZW3 pattern. In this pattern, three low pressures centres of action constitute the low-pressure belt around Antarctica. This pattern is said to be quasi-stationary because, on the one hand, it has a well-defined annual climatological mean. Still, on the other hand, it shows slight longitudinal and latitudinal seasonal variations. Raphael [2004] stated that the ZW3 pattern significantly impacts atmospheric circulation. Studying such a pattern with seasonal variation can help us understand the seasonal cycle of the hydrological cycle.

The seasonal temporal variation of the low pressure is marked by two minimum and two maximum pressures during the year. The first of these minimum pressures occurs in March and the second in October, while the two maxima occur in January and June, at  $65^{\circ}S$ . As seen in Figure 10, in autumn, there is a deepening of the pressure pattern as well as in spring. For example, the differences in the low pressure of the Amundsen Sea between summer and spring show the large pressure variability in this region. This can be described as a semi-annual pressure cycle around Antarctica. In section 1.4, a mode of variability, the SAO, is discussed, which is a semi-annual variation of the pressure in Antarctica. Van den Broeke [1998] and Meehl et al. [1998] state that this oscillation has sea level pressure minima in March and September and maxima in June and December, which seems to be consistent with what is observed in Figure 10.

In Figure 10, the low-pressure centres show a zonal shift from one season to another. Indeed, all low-pressures move a little from their average position. The most obvious example occurs in summer, with the low pressure of the Amundsen Sea shifting towards the Peninsula. In addition to the zonal shift, there is a meridional shift of the low pressure. It can be read in Meehl et al. [1998] and Van Loon [1967] and, as described in section 1.4, the SAO has phases of expansion and contraction. As a result, the trough is located further south in March and September and further north in June and December. The impact of such variations in amplitude and position plays a major role in the structure of the atmospheric circulation, as explained in section 1.3.

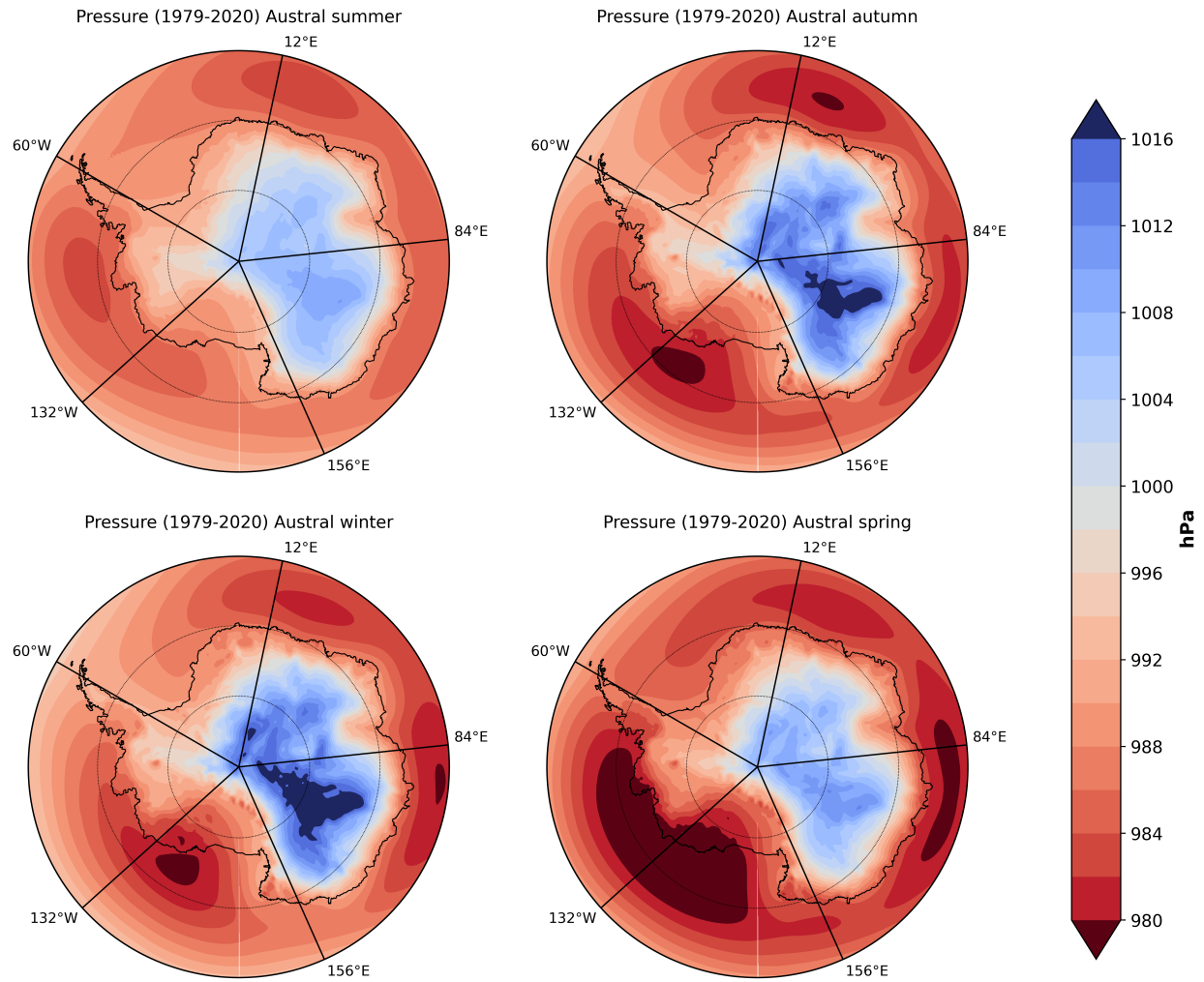


Figure 10: *The 1979-2020 annual mean sea level pressure from the ERA5 monthly mean outputs. Each map represents a season: DJF for summer, MAM for autumn, JJA for winter and SON for spring.*

### 3.2.3 Sea ice

After describing the spatial and temporal variability of surface temperature and sea level pressure, the variability of sea ice remains to be described before the tools to understand the variability of evaporation are complete (see section 1.2).

In Figure 11 (dashed lines), a temporal variation of the sea ice extent (surface covered by sea ice concentration exceeding 15%) for each of the seasons is observed. There is an increase in extent and concentration during the autumn and a decrease during the spring. The minimum is reached in summer and the maximum in winter. This sea ice cycle follows

the temperature cycle described earlier in section 3.2.1. During the year, some features of the sea ice extent are highlighted: in summer, there is an opening of the ice in the Ross Sea and in winter and spring, an almost complete sea ice cover of the WS and IO sectors.

### 3.2.4 Evaporation

Now that the toolbox is complete, the seasonal study of the atmospheric hydrological cycle can begin. The first component studied is the process of water entering the cycle. The input of water into the air is through the process of evaporation. As we have seen in the first part of this chapter (section 3.1), evaporation has a seasonal cycle that varies from area to area.

Firstly, Figure 11 shows a clear difference in evaporation between the oceanic and continental parts of Antarctica, and the evaporation from the AIS is negligible compared to oceanic evaporation.

Over the AIS, the temperatures are so low that little evaporation can occur, but there is still seasonal variability, with a peak in evaporation in summer. Only a few low-altitude regions show low evaporation values in autumn and winter — the extent of these areas increases in spring. According to the ERA-5 reanalysis, there are white areas on the maps (Fig. 11) that show negative evaporation values, expressing a water vapour deposition. Physically this would correspond to the condensation of water vapour into ice, the so-called hoarfrost. For example, regardless of the season, the high plateau ( $\geq 3000m$ ) always has negative values related to the hoarfrost. Tietavainen and Vihma [2008] and van de Berg et al. [2005] find the same region with negative evaporation values. In general, evaporation's spatial and temporal variability over the AIS depends mainly on the seasonal air temperature variation and altitude.

The oceanic part, which contributes to the main part of the variability of evaporation, exhibits a large spatio-temporal variability. This variability is explained by the variation in temperature, sea ice extent and wind intensity. The maximum evaporation is in autumn. During this season, atmospheric circulation is intensifying, related to the SAO combined with low sea ice cover and temperature close to the annual mean. In winter, a high sea ice concentration and low temperatures explain low evaporation in sea ice-covered regions. Over ice-free regions, the evaporation is the largest in winter. This significant evaporation in ice-free regions is due to air and sea temperature differences. When the sea surface temperature is higher than the air surface temperature, evaporation is accelerated. This is due to a larger difference between saturation vapour pressure and water vapour pressure, especially in winter when the temperature difference is larger. In spring, temperatures increase and the concentration of sea ice decreases, which explains the weak reactivation of evaporation in the

sea ice-covered region. In open ocean regions, the evaporation decreases compared to winter. Finally, in summer, the ice-covered region shows the largest evaporation rates in four seasons but also the lowest values for the ice-free region. The low sea ice concentration explains the high evaporation in the sea ice region. The weakening of the atmospheric circulation during summer is part of the explanation for a reduction in evaporation.

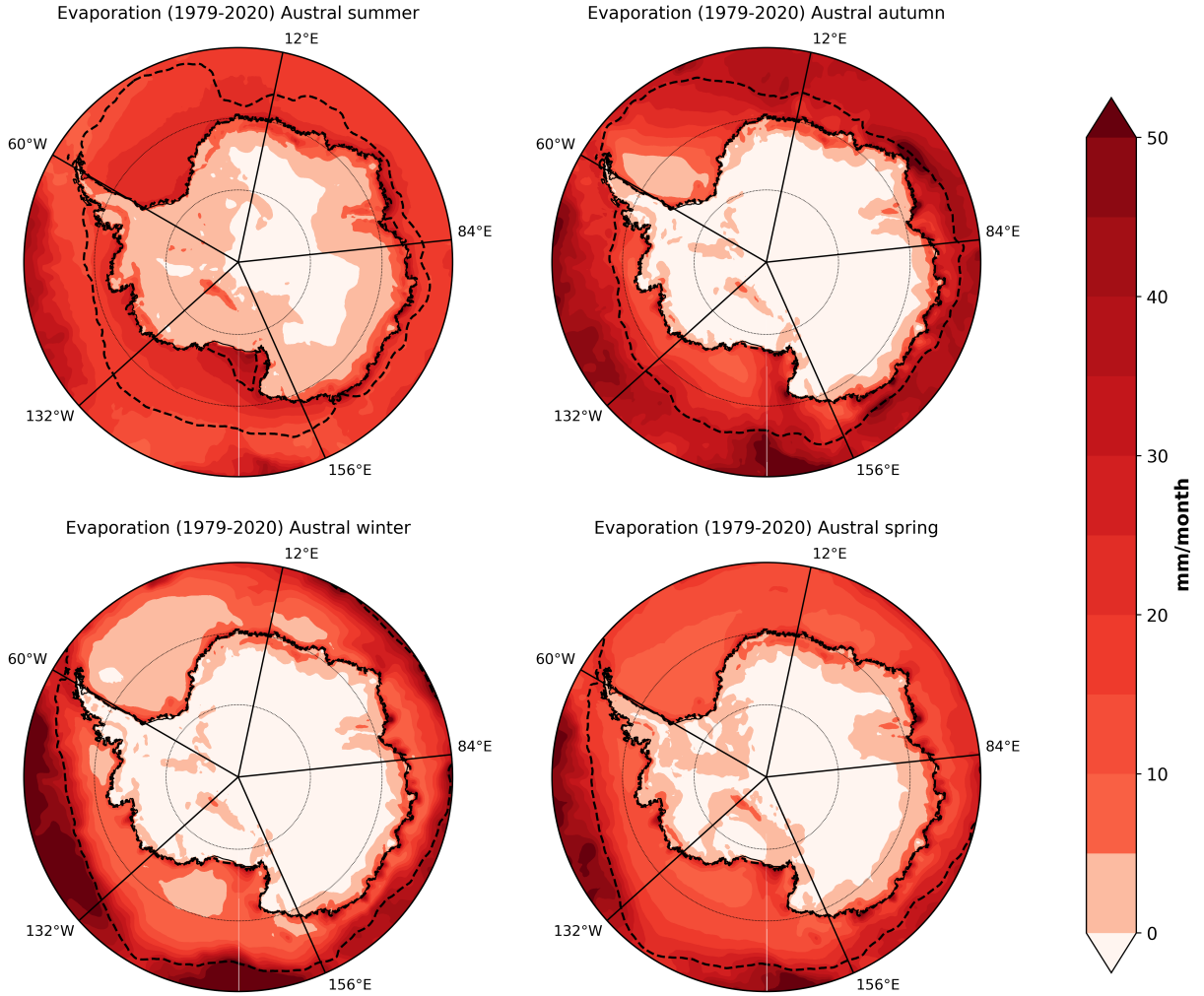


Figure 11: The 1979-2020 annual mean total evaporation rate from the ERA5 monthly mean outputs. Each map represents a season: DJF for summer, MAM for autumn, JJA for winter and SON for spring. The dashed lines represent sea ice edge (1979-2020) in the different seasons (concentration  $\geq 15\%$ ).

The evaporation also shows spatial variability (Fig. 11). Indeed, the evaporation curve was markedly different depending on the sector (see Fig. 8). The annual mean of sea ice concentration in the WS sector is the largest. In addition, during winter and spring, almost the entire oceanic part of the sector is sea ice-covered. This explains the low values of evaporation in this sector. In the IO sector, there is a similar sea ice variability of the sea ice cover to WS, with almost total cover in winter and spring. As a result, this sector's annual mean evaporation values are low. Nevertheless, compared to autumn WS sector evaporation, in IO, there is a well-defined region of high values for evaporation. This region occurs between the two lows ( $50^{\circ}E - 55^{\circ}E$ ). The meridional air transport generated by the deepening of low pressure around  $25^{\circ}E$  in autumn explains these larger evaporation values in this region. For the PO sector, there is little seasonal variability (see Fig. 8) with a slight increase in autumn. This increase in evaporation is due to the combination of low sea ice extent and intense atmosphere circulation in autumn. As in the previous sector, the region of maximum values ( $130^{\circ}E$ ) of evaporation is swept by the meridional flow of air generated by the low pressure ( $100^{\circ}E$ ). In the RS sector, the evaporation is the largest, with an annual mean of  $26.5mm/month$ . In summer, the region of highest evaporation is an ice opening in the Ross Sea. Bromwich [1989] states that this opening is due to the katabatic wind, which also explains why this region has high evaporation. Dry air from the continent is blown onto a surface where water is in its liquid state. In other seasons it is around  $180^{\circ}E$  in the open ocean that the maximum evaporation is observed. In the ice-free region, evaporation is greatest in the winter due to the more significant temperature difference between water and air. However, the concentration and the extent of sea ice are the largest in this same season, which explains why the maximum evaporation is not in winter. The maximum is in autumn when the values for evaporation are more homogeneous throughout the marine region. The proportion of sea ice and open ocean areas in the ABS sector is nearly equal. Therefore, the previously mentioned argument to explain the maximum evaporation in autumn and not in winter is no longer valid. This explains why evaporation is constant from the beginning of autumn to the end of winter. The minimum evaporation is observed in summer as in the RS sector. Around the coasts of all sectors, there is a thin band where evaporation is high. One explanation for these evaporation values is the presence of coastal polynyas [Stossel and Markus, 2004]. Indeed, polynyas are areas of open ice in the pack ice, so evaporation in these regions is facilitated.

### 3.2.5 Moisture convergence

After discussing the process of water input into the air column, the transverse movement of water vapour is considered. In order to analyse this dynamic component, the convergence and divergence of vertically integrated moisture in the air column are used.

The main factor influencing moisture transport is wind (see section 1.2). There are two main types of wind in Antarctica — offshore winds and onshore winds. The offshore winds are driven by cyclonic activity, as described in section 1.3 of Chapter 1. The AIS winds are katabatic, i.e., driven by gravity and flow along the glacier slope.

The temporal variability of the moisture convergence in the study area shows a stabilisation throughout the year and a minimum in summer (Fig. 8). In section 3.2.2 on pressure, the pressure pattern in summer was weakened, resulting in a decrease in the atmospheric circulation, which explains the smaller moisture convergence values. The moisture convergence variability of the WS and IO sectors seems similar to the general variability. In the PO sector, the maximum annual contribution is made in winter. In Figure 4, the moisture convergence region extends along the entire coast in winter and is larger than in other seasons. In RS and ABS sectors, moisture convergence is double peak. The two maxima are in autumn and spring, and the two minima in winter and summer. The winds in these two sectors are mainly dictated by the Amundsen Sea Low (ASL). Moreover, the variability of this low pressure (see Fig. 10) has a semi-annual oscillation with an intensification in autumn and spring, as predicted by the SAO [Tietavainen and Viham, 2008] and section 3.2.2. The SAO mainly explains the seasonal variability of the moisture convergence in these sectors.

Figure 12 shows a spatial distribution of moisture convergence in three main zones. There is a small region of convergence over the coastal region around  $50^{\circ}E$ , the second region of convergence over the coastal region around  $130^{\circ}E$  but which can extend almost all the way to the coastal region of the PO sector ( $100^{\circ}E - 135^{\circ}E$ ) and the third region of convergence over the Peninsula which can extend to the Ross Sea. These three regions of convergence are determined by the spatial distribution of the pressure systems. Indeed, the pressure patterns (shown in Fig. 10) associated with the dynamic atmospheric theory (section 1.3) explain the meridional flow towards the coasts which exists between each low-pressure area. And once the air reaches the coast, it meets the steep slope of the AIS, which blocks this moist air and forms a moisture convergence region. As mentioned, these convergence zones vary. Indeed, when there is an intensification of the atmospheric circulation, typically from autumn to spring, the convergence zone expands. In the ABS sector, the Peninsula acts as a barrier to the zonal wind and contributes to forming a convergence region on the west side. Whereas on the eastern side, the foehn effect induces a decrease in the humidity in the air, which explains the lower humidity concentration in the WS.

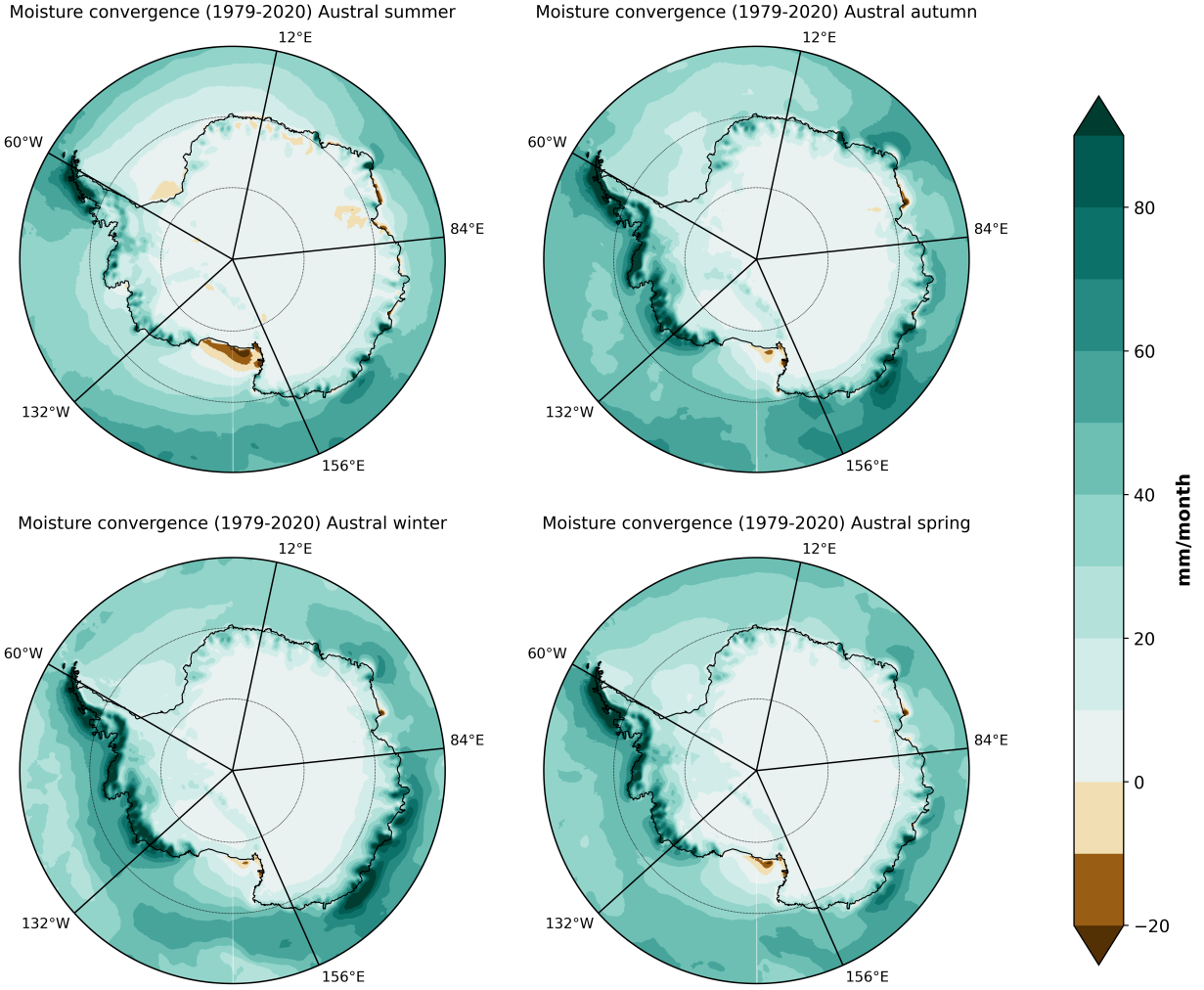


Figure 12: *The 1979-2020 annual mean vertically integrated moisture convergence from the ERA5 monthly mean outputs. Each map represents a season: DJF for summer, MAM for autumn, JJA for winter and SON for spring.*

There are also areas of divergence, in the Weddell Sea, near the Princess Astrid coast ( $0 - 30^{\circ}E$ ), around the Amery Ice Shelf ( $65 - 75^{\circ}E$ ) and in the Ross Sea. All these regions are known to be swept by katabatic winds. These winds explain these different regions of divergence because they provide dry air from the AIS and blow northward. The Ross sea divergence region is also due to topographic effects with Victoria Land that act as a moisture barrier. Tietavainen and Vihma [2008] provide a similar explanation. There is seasonal variability in these divergence zones, with more abundant and larger zones in summer and fewer and smaller ones in winter. However, the katabatic winds are stronger in winter than in summer. In order to have a better understanding of these regions and their variability, it

would be necessary to carry out a more detailed local study, e.g. the seasonal study of katabatic winds and their correlation with moisture transport. For this purpose, a model with a good representation of the katabatic winds is needed (i.e. ERA5 underestimates katabatic winds).

Finally, over the AIS, little convergence of moisture is observed (Fig. 12), except at low altitudes (the western part of Antarctica and the coast). This is because the steepness of the AIS prevents moist air from entering the continent.

### 3.2.6 Precipitation

This section introduces the spatio-temporal variability of precipitation. After some time, the water that has evaporated may condense and cause precipitation. During this process, water leaves the air column and returns to the surface, where the water can be evaporated again.

Precipitation is mainly found on the coasts of Antarctica and offshore around  $60^{\circ}S$  as can be seen in Figure 13. The comparison between the precipitation (Fig. 13) and the moisture convergence (Fig. 12) shows that the areas of high moisture convergence are identical to the areas of precipitation. Indeed, it is necessary to have humidity in the air to have precipitation; the more humidity, the more precipitation. As the moist air flow is directed towards the continent, it encounters the abrupt slope of the AIS in the coastal region. The air mass undergoes an orographic lift (see section 1.3), which leads to the saturation of the air and is followed by the condensation process that turns the water vapour into liquid or solid water. Given the temperatures in Antarctica, both the Bergeron effect and the coalescence effect are present (see section 1.2). This phenomenon of precipitation by orographic lift takes place all around Antarctica and mainly at the moisture convergence zones, as seen in Figure 13. The orographic lifting with adiabatic cooling is particularly important on the west coast of the Antarctic Peninsula [Van Lipzig et al., 2004]. The precipitation combines orography and atmospheric circulation [Marshall, 2017; Dalaiden et al., 2021]. Therefore, the variability of atmospheric circulation strongly influences precipitation.

On the Antarctic Peninsula, the Foehn effect occurs when moist air meets a mountain. The air undergoes an orographic ascent, and precipitation follows, emptying the air of its water content and the air mass passing the mountain is then dried out. This effect explains the low moisture content in the WS sector (see Fig. 12) and the low precipitation.

Precipitation close to  $60^{\circ}S$  is the result of large evaporation. The air becomes saturated, and then clouds can form and cause precipitation (section 1.2).

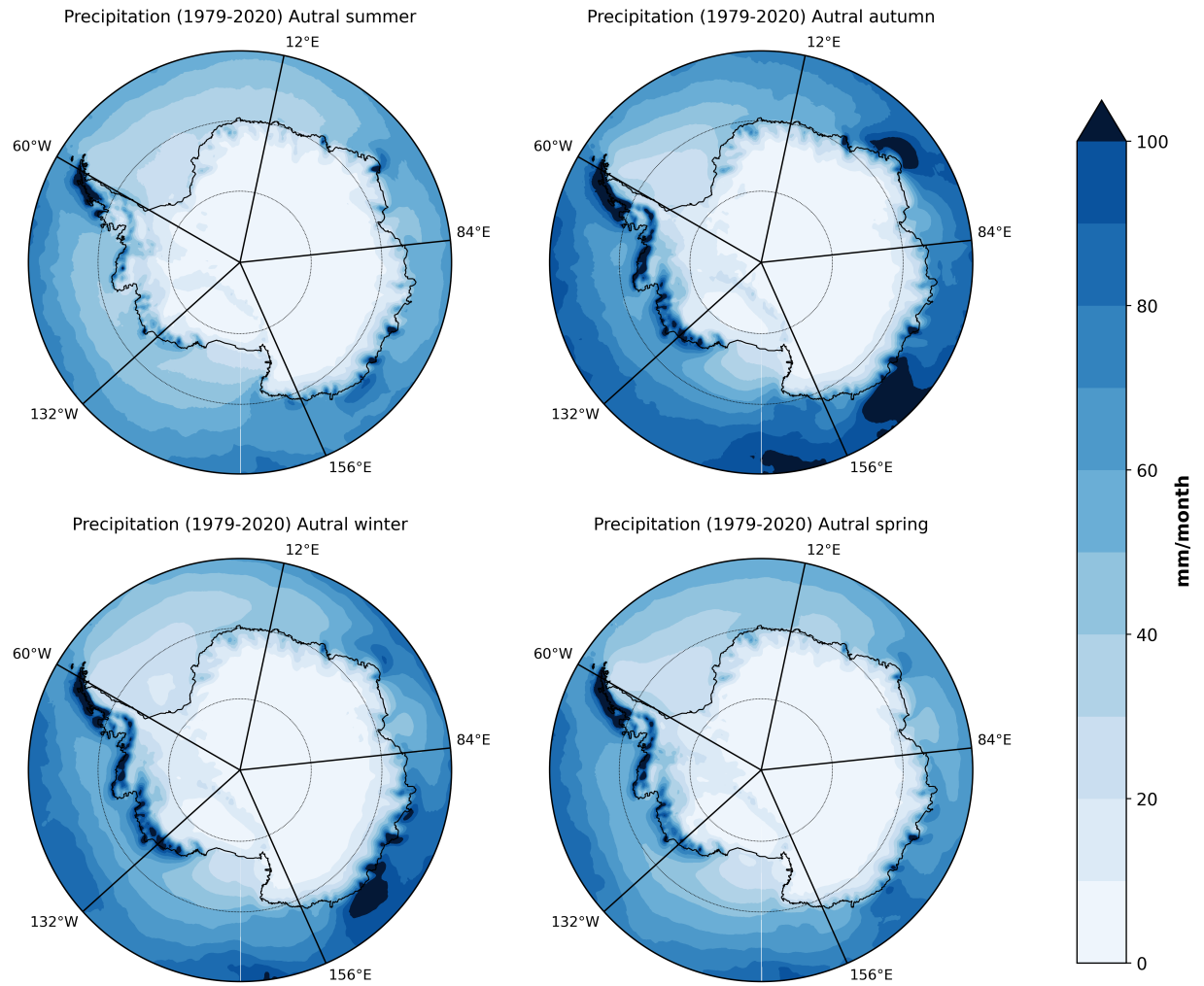


Figure 13: *The 1979-2020 annual mean total precipitation rate from the ERA5 monthly mean outputs. Each map represents a season: DJF for summer, MAM for autumn, JJA for winter and SON for spring.*

Over the Antarctic continent, the air is dry. Therefore, nearly no precipitation is observed over the higher altitude of the AIS. Low precipitation values are observed in the lower altitudes regions where the temperature and atmospheric circulation allow moisture.

The temporal variability of precipitation depends mainly on the variation of the atmospheric circulation and the variation of humidity in the air through the evaporation and moisture convergence process. The combination of these two factors explains the seasonal precipitation.

### 3.3 Summary

Evaporation is spatio-temporally dependent on thermodynamics (temperature and sea ice) and winds. Indeed, temperature for its thermodynamic effect on air and water, sea ice, and the atmospheric circulation intensity influence the evaporation. Due to these factors, global evaporation peaks in autumn decreases in winter, rises slightly in spring, decreases at the end of this season, and increases in summer. Due to the spatial variability of the different factors influencing evaporation, the WS, IO and PO sectors seem to follow the global cycle (all). In contrast, the RS and ABS sectors show different variability and higher values. The main explanations for high values in ABS and RS sectors are the wide variability of the ASL and the large difference in air and sea temperatures in winter. Spatial variability is also strongly affected by sea ice concentration and extent, which explain the low values of evaporation in WS and IO sectors during winter. On the AIS, evaporation depends mainly on air temperature and altitude. Evaporation is much lower than over the ocean.

The atmospheric dynamics explain the spatio-temporal variability of the moisture convergence. Indeed, the major contribution to the seasonal variability comes from the atmospheric circulation, more precisely from the SAO and the westerly winds around Antarctica. The seasonal evolution of the global moisture convergence shows a minimum in summer followed by a higher and almost constant moisture convergence during autumn and winter and then decreases in spring to the low values found in summer. As for evaporation, spatial variability is particularly noticeable, and a semi-annual cycle is observed in the RS and ABS sectors. For the PO sector, further study is needed to explain the peak of moisture convergence in winter. The WS and IO sectors follow the global variability, with low values due to moisture loss as the air passes through the Peninsula. Once again, the RS and ABS sectors show the highest values. Three main regions of convergence are observed and are explained by atmospheric dynamics. On the AIS, little moisture convergence is observed due to the pronounced topography that the air masses encounter.

Finally, the seasonal variability of precipitation depends on the combination of thermodynamics and the interaction between dynamics and orography. As a result, global precipitation is minimal in summer, followed by a sharp increase in autumn and a decrease in winter and spring. Like evaporation and moisture convergence, the RS and ABS sectors show large values and their own cycles. In the PO sector, precipitation increases in autumn, which continues into winter and then decreases in spring to reach its minimum in summer. Again the WS and IO sectors show the lowest values with a variability close to the global variability. The spatial variability of precipitation follows the pattern of the three main moisture convergence regions. On the AIS, as expected, little precipitation is found due to low moisture convergence in the region.

## The multi-year evolution of the atmospheric hydrological cycle

After studying the seasonal variability, the fourth chapter focuses on the inter-annual and multi-annual variability of the last four decades and aims to answer the question: *How have processes been involved in the Antarctic atmospheric hydrological cycle evolved over the past four decades and why?* In order to answer this question, the first section introduces the trends in the different processes for the past four decades (section 4.1). Then the spatial distribution of the trends is discussed in the second section (section 4.2). This chapter ends with a summary (section 4.3).

### 4.1 Change in the atmospheric hydrological cycle for the last four decades

This section begins with the temporal analysis of the evolution of the atmospheric cycle over the last four decades. For this purpose, Figure 14 shows the average annual evolution of evaporation, precipitation, moisture convergence and net precipitation. The study period is from the onset of the modern satellite era in 1979 to the present day (2020).

The first graph shows the evolution of evaporation over the period 1979-2020. The latter does not show any significant trends over the last four decades  $p = 0.08 > 0.05$ . This p-value means that potentially the simple variability explains the trend, here with a probability of 8%. In this case, no conclusions about a potential change in the evaporation process can be drawn. Nevertheless, three main deviations can be noted from the mean of 169.4mm/year. Two positive deviations in 1983 with a mean annual evaporation rate of 188.2mm/year and 2017 with an evaporation of 183.1mm/year, and one negative deviation in 2002 with an evaporation of 153.6mm/year. In 2017, a new minimum sea ice extent was observed [C. Eayrs et

al., 2021], which could be part of the explanation for the evaporation peak.

The second curve shows precipitation. The p-value of the regression line is well below 0.05, which means that it is statistically significant. This trend shows a significant increase in water vapour leaving the air column. This increase through decades is shown by a linear regression line with a slope of +0.48. Therefore, there is a strong probability that there is another explanation than variability alone for this positive trend in precipitation.

The second to last graph is the moisture convergence evolution. As with the precipitation graph, the moisture convergence has increased in the study area since 1979. Moreover, the p-value is lower than 5%, which means we also have statistical significance for moisture convergence. The trend shows an increase of 0.48mm/year per year, which is the same as that recorded for precipitation. The annual variations of moisture convergence are relatively similar to those of precipitation. These similarities make sense since precipitation comes from condensing water vapour in the air.

Net precipitation exhibits a positive trend as for precipitation and moisture convergence. This trend is statistically significant since it registers a p-value well below 0.05. The slope of the linear regression line shows an increase of 0.63mm per year.

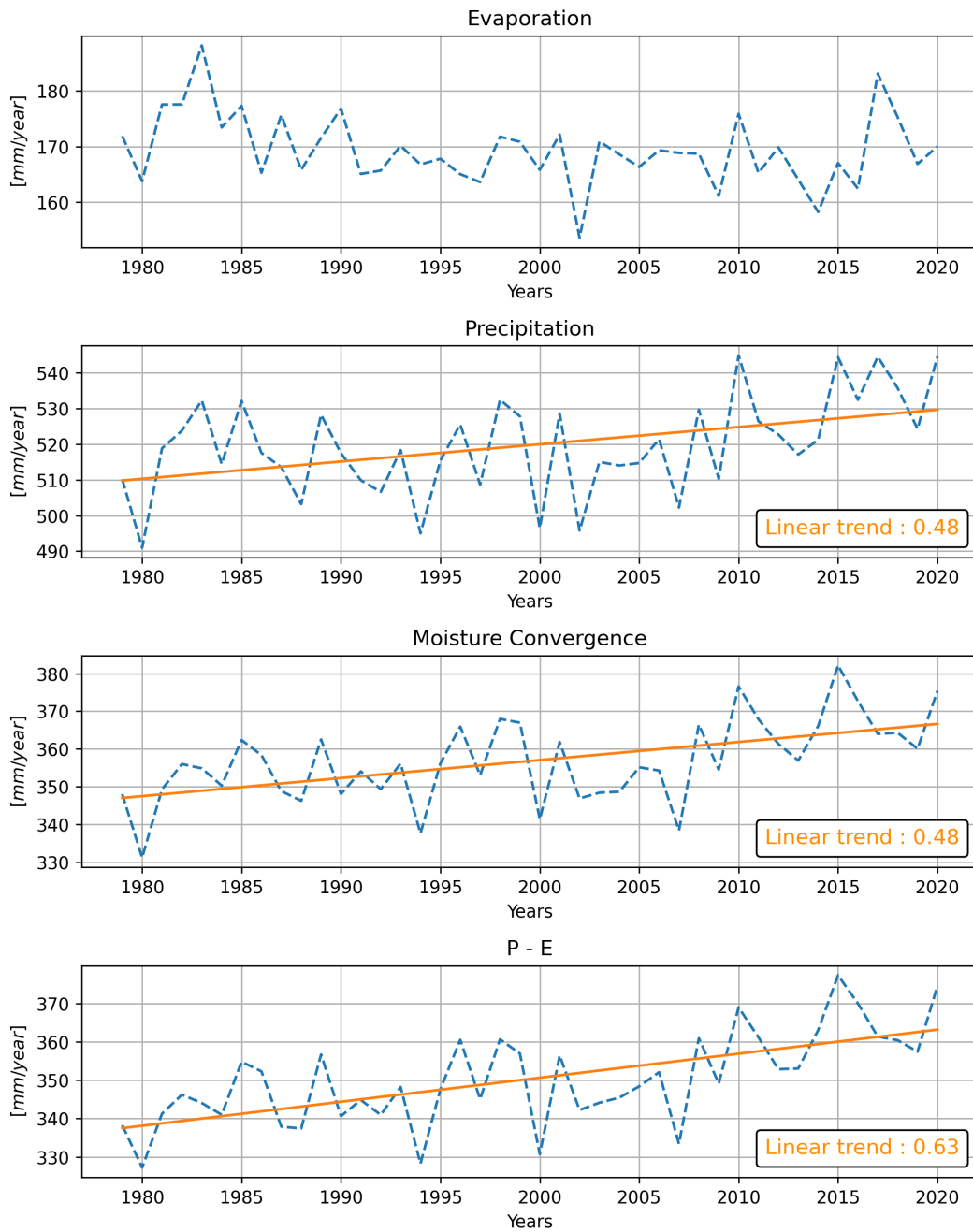


Figure 14: The 1979 -2020 time series of annual mean for evaporation, precipitation, moisture convergence and P-E (blue dashed lines) and statistically significant trends  $p < 0.05$  (orange line) in [mm/year/year]. The values shown are for the "all" study region, i.e. the region below  $60^{\circ}\text{S}$  latitude.

## 4.2 Spatial variability of atmospheric variables

Having discussed the interannual change of different processes for the past four decades and because sectors show different trends (not shown), spatial variability is introduced to complete our understanding of the evolution of the cycle. For this purpose, trend maps are used and represent for each of the cells in the study area the slope of the linear regression of the value of that cell over the period 1979-2020. In addition to the values shown in colour on the maps, the statistical significance ( $p < 0.05$ ) areas are hatched. The study area is again divided into five parts, i.e. WS, IO, PO, RS and ABS, as in chapter 3.

The main factors influencing the atmospheric hydrological cycle are temperature, sea ice and atmospheric circulation. Therefore, first, the temperature changes (subsection 4.2.1), then the sea ice change (subsection 4.2.2) and finally, the change in atmospheric circulation (subsection 4.2.3) are introduced. Then, changes in the atmospheric hydrological cycle: evaporation (subsection 4.2.4), moisture convergence (subsection 4.2.5) and precipitation (subsection 4.2.6) are studied. This chapter ends with a summary of the previous sections (section 4.3).

### 4.2.1 Temperature change

Surface air temperature is one factor that influences evaporation and moisture convergence and, thus, indirectly, precipitation. Therefore, studying this factor's evolution is essential to understanding the evolution of the atmospheric hydrological cycle. With the help of Figure 15, the spatial distribution of surface temperature evolution during the last four decades is introduced. As in Chapter 3, the different atmospheric processes evolve differently in the continental and oceanic regions. For this reason, these two regions will be described separately.

First, the trends on the AIS are introduced. Mainly positive temperature trends are observed on the AIS. Still, some regions have negative values, such as over Adelie Land in the PO sector and south of the Lambert Glacier between the IO and PO sectors. However, neither of these negative regions show statistically significant trends. Conversely, most of the positive regions show statistically significant trends. These regions can be easily seen in Figure 15.

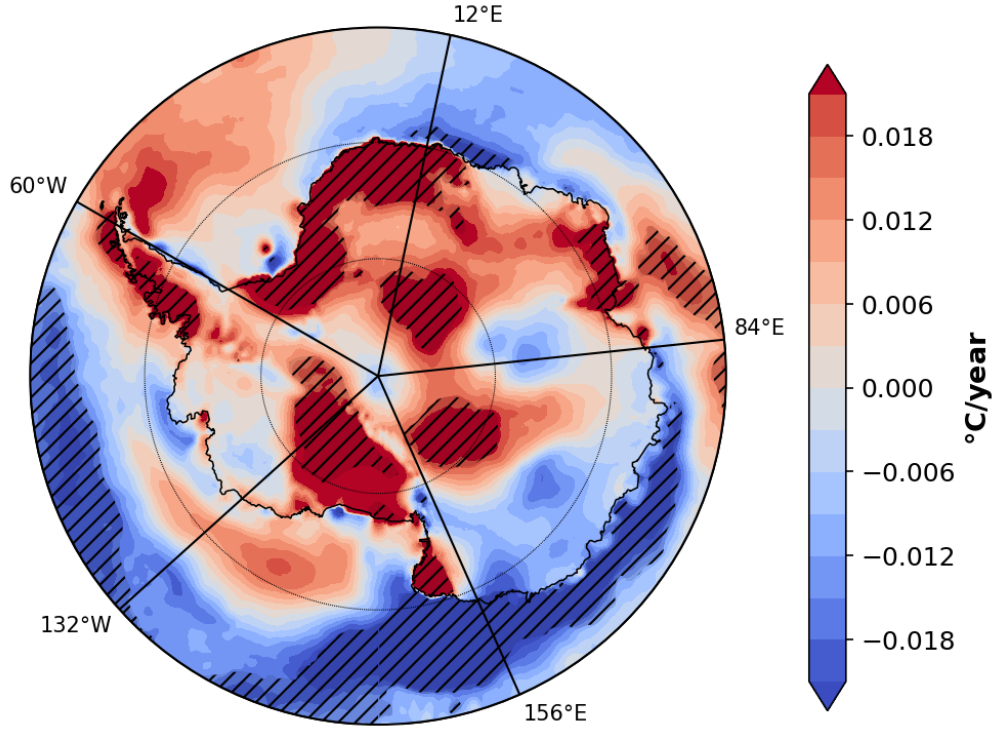


Figure 15: *The 1979-2020 trends map of the surface air temperature. Statistically significant trends ( $p < 0.05$ ) are represented by the hatched areas.*

In contrast to the continental region, most of the oceanic region exhibits negative trends. Indeed, there are three regions with positive values, but only one is statistically significant, located off the Amery ice shelf. There are only two areas where the trends are negative, but these are all statistically significant and larger than the positive one. The first and smaller of the two areas is around  $20^{\circ}E$ , with significant values only observed near the coast. The second region extends from the PO sector to the Peninsula. Significant trends are observed along the coastline of the PO sector, this region extends into the Ross Sea, and other significant trends are located in the ABS sector.

An explanation of this trend's spatial distribution is the variability of the SAM. A stronger circumpolar vortex (high SAM index) induces significant cooling over most of East Antarctica and significant warming over the Antarctic Peninsula [van den Broeke and van Lipzig, 2004; Fogt and Marshall, 2020]. Furthermore, Fogt and Marshall [2020] state that the SAM display a positive trend from 1957 to the present day. Therefore, the combination of the evolution and the impact of SAM partly explains the temperature evolution. This temperature change is also related to sea ice. Indeed, the strong warming over the western Antarctic Peninsula and the Weddell Sea is likely to be at least partly caused by a more significant northerly

wind component combined with decreased sea-ice cover in the Bellingshausen Sea [Marshall and King, 1998].

#### 4.2.2 Sea ice change

Sea ice is a second factor that influences evaporation and thus the amount of water in the atmospheric hydrological cycle (see section 1.2). Related to temperature, sea ice plays an essential role in the variability of evaporation in the ocean region. Therefore, this section introduces the evolution of sea ice concentration to explain better the spatial distribution of evaporation over the ocean over the last four decades. Figure 16, which is a map of trends in ice concentration, is used to account for this spatial distribution. Similarities between this map and the surface air temperature trend map are apparent. Indeed, since the formation of sea ice depends on air temperature, it is normal to find similarities.

In general, an increase in sea ice concentration is observed. The trend pattern of Zhang [2007], Massonnet et al. [2013] and Simmonds et al. [2021] resembles the one in Figure 16. As these studies used different data sets, confidence in the existence of such a model is increased. In Figure 16, a significant increase in coastal concentration is observed almost all around the AIS. The only regions that show a decrease in sea ice concentration are Marie Byrd Land’s coasts and Ellsworth Land’s coasts to the tip of the Peninsula. The non-coastal region that shows negative values is off the Amery ice shelf. This region corresponds to the statistically significant region of surface air temperature increase seen in the previous section. The rest of the ice-covered region shows positive values, consistent with the observed air temperature. Only the Weddell Sea region does not match this correlation and shows an increase in concentration.

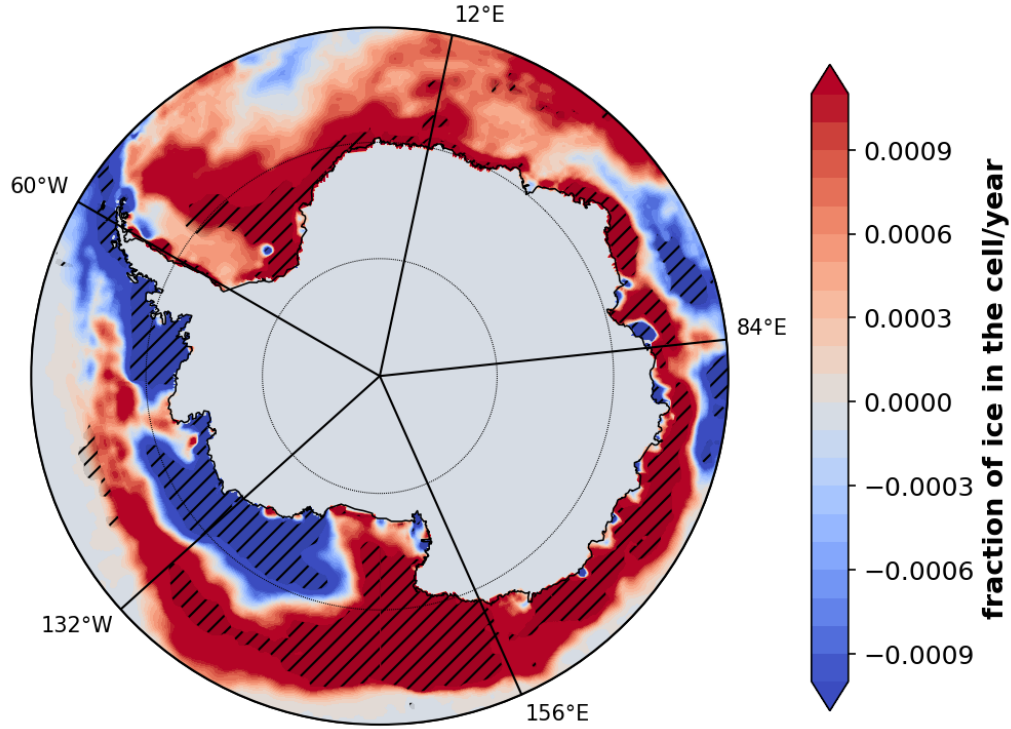


Figure 16: The 1979-2020 trends map of the sea ice concentration. Grey shade represent regions with no trend. Statistically significant trends ( $p < 0.05$ ) are represented by the hatched areas. The convention of positive trends in red and negative trends in blue is retained. We apologise for the confusion that this counter-intuitive colour coding may cause.

### 4.2.3 Atmospheric circulation change

Changes in atmospheric circulation are the route by which global warming forcing exerts a dynamic effect on water redistribution [Zhang et al., 2012]. Indeed, evaporation, moisture convergence and precipitation depend on the atmospheric circulation. The study of atmospheric circulation changes over the last four decades is, therefore, necessary to understand past changes in the atmospheric hydrological cycle. In order to study these changes, it is necessary to observe the evolution of the pressure. With the ERA5 data, a trend map of the mean sea level pressure is presented (Fig. 17). It may also be interesting to look at trends at other geopotential heights such as  $500hPa$  or  $850hPa$  as they do not contain the same information. Only the map of mean sea level pressure trends is shown. However, our analysis of the atmospheric circulation changes is complemented by the literature, including the impact of these other pressure levels.

The trend patterns of the mean sea level pressure are shown in Figure 17. The trends shown show some similarity to those found in Holland et Kwok [2012] and Simmonds and Li [2021], especially for the low-pressure region of the Amundsen and Bellingshausen Seas. First, only a few regions are statistically significant, suggesting that it is mainly inter-annual variability that explains the trends. The results of this figure should be taken with caution. On this map, a significant decrease of more than  $5Pa$  per year in the Amundsen Sea Low (ASL) region is observed, which will impact the circulation around West Antarctica. A decrease in pressure in the Weddell Sea is also observed. Over the eastern part of the continent, positive trend values showing a slight increase in pressure are shown. This increase is most pronounced over the Lambert Glacier and off Queen Mary Land ( $100^{\circ}E$ ), where there is a low-pressure centre. Around  $25^{\circ}E$ , there are negative values for the last low-pressure centre. A significant intensification of the atmospheric circulation in the ABS/RS sector, a slight increase around the WS/IO low-pressure and a slight decrease in the PO sector are expected.

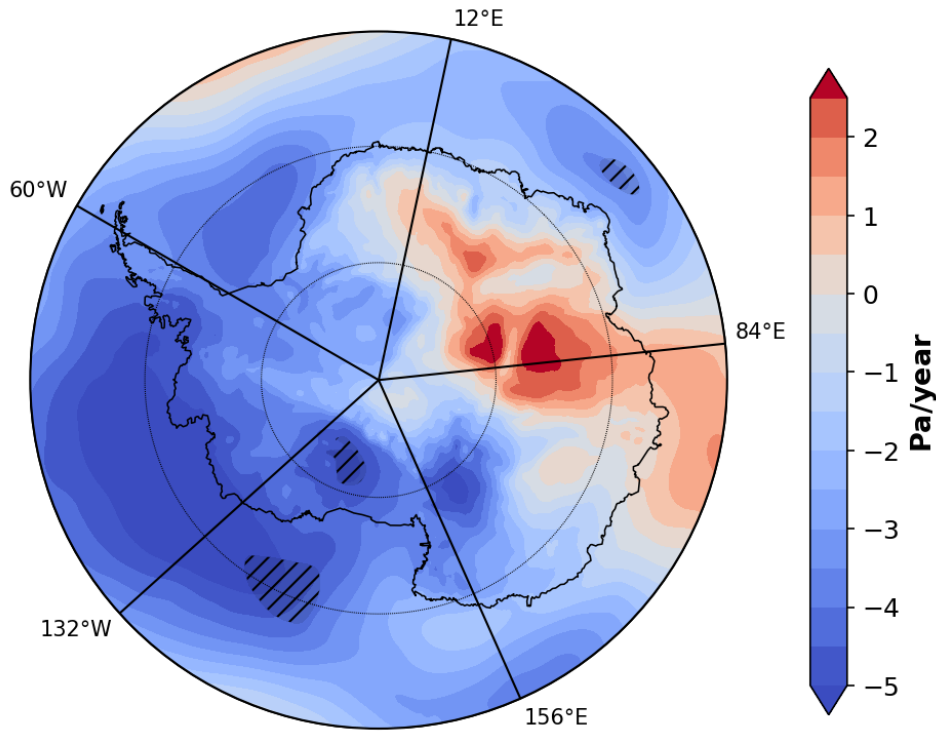


Figure 17: *The 1979-2020 trends map of the mean sea level pressure. Statistically significant trends ( $p < 0.05$ ) are represented by the hatched areas.*

According to the definition of SAM in Chapter 1, section 1.4, SAM is the dominant mode of internal variability in the Southern Hemisphere. The SAM index has a strong correlation with the zonal circulation and a weaker correlation with the meridional circulation [Marshall et al., 2017; Tietavainen and Vihma, 2008]. Furthermore, the area where SAM shows the most significant pressure response is off the west coast of Antarctica [Fogt and Marshall, 2020]. In several papers (e.g. Fogt and Marshall et al. 2016, 2020, Marshall 2003, Thompson et al., 2000), it is stated that the SAM index shows a statistically significant positive trend over recent decades. A higher recurrence and amplitude of the SAM index implies an intensification of the atmospheric circulation, especially zonal but also meridional, over the entire Antarctic maritime region with a pronounced influence on the western part. In addition to having a positive annual trend, SAM shows positive seasonal trends — the SAM index has exhibited an enhancement in summer and autumn since 1979 [Fogt and Marshall, 2020]. This will influence an intensification of the atmospheric circulation during these two seasons.

In addition to SAM, other modes of internal variability explain a change in atmospheric circulation. BAM is presented in section 1.4, which plays a role in the eddy amplitude variations but not in the zonal mean flow. Then, PSA1 is another mode which is centred in  $120^{\circ}W$  inducing strong meridional winds that bring moisture towards the continent from the Ross Sea (and away from it at the Peninsula), as well as PSA2, which is centred at  $150^{\circ}W$  and induces strong meridional winds but shifted by 30 degrees towards the west. PSA2 also shows an alternation between equatorward and poleward meridional flow bands for the eastern hemisphere. The poleward convergence regions are located between  $60^{\circ}W - 30^{\circ}W$ ,  $30^{\circ}E - 70^{\circ}E$  and around  $120^{\circ}E$  [Marshall et al., 2017]. As seen in the previous chapter, the SAO also plays an important role in the atmospheric circulation variability. Since 1979, there has been a reduction in the amplitude of the SAO [Meehl et al., 1998].

#### 4.2.4 Evaporation change

Now that the evolution of the thermodynamic and dynamic factors influencing the atmospheric hydrological cycle has been described, a discussion of the spatial distribution of evaporation trends may be presented. In order to perform that, a map of evaporation trends for the last four decades (Fig. 18) is introduced.

Over the continent, the trends for evaporation are positive except in the higher elevation region. West Antarctica shows an increase in evaporation related to the temperature increase observed in this region. The regions with the greatest temperature increase are the coastal region of the WS sector, the region between  $80^{\circ}S - 90^{\circ}S$  and  $60^{\circ}W - 180^{\circ}W$  and the western Peninsula. Furthermore, the trends for these regions are statistically significant. For East Antarctica, a surface temperature-evaporation correlation is no longer applicable. Indeed, the pattern seems to be reversed, with the high altitudes showing a decrease in evaporation and Adelie Land showing an increase in evaporation.

In the oceanic region, in addition to temperature, evaporation depends on the sea ice cover. For the coastal region of the WS, IO and PO sectors, there is an increase in sea ice concentration which leads to a decrease in evaporation. However, several small coastal regions show an increase in evaporation. These small regions are related to a decrease in ice concentration and, more specifically, to coastal polynyas. The significant temperature increase off Marie Byrd Land is reflected in the maps of ice concentration (region of decrease) and evaporation with a region of increase. The same can be said for the western Peninsula region. With an increase in evaporation especially marked over the tip of the Peninsula. The western Ross Sea shows a decrease in evaporation due to increased sea ice concentration. Oceanic evaporation in the WS and IO did not show a large change. In these same regions, the evolution of sea ice concentration and surface temperature is no longer weakly correlated. In the non-ice-covered regions, there is an air surface temperature-evaporation correlation. Air surface temperatures have decreased around  $60^{\circ}S$  in the ABS and RS sectors. Therefore the difference between saturation vapour pressure and water vapour pressure is reduced. This reduction leads to a speed decrease in the evaporation process, which explains the diminution in evaporation in these regions.

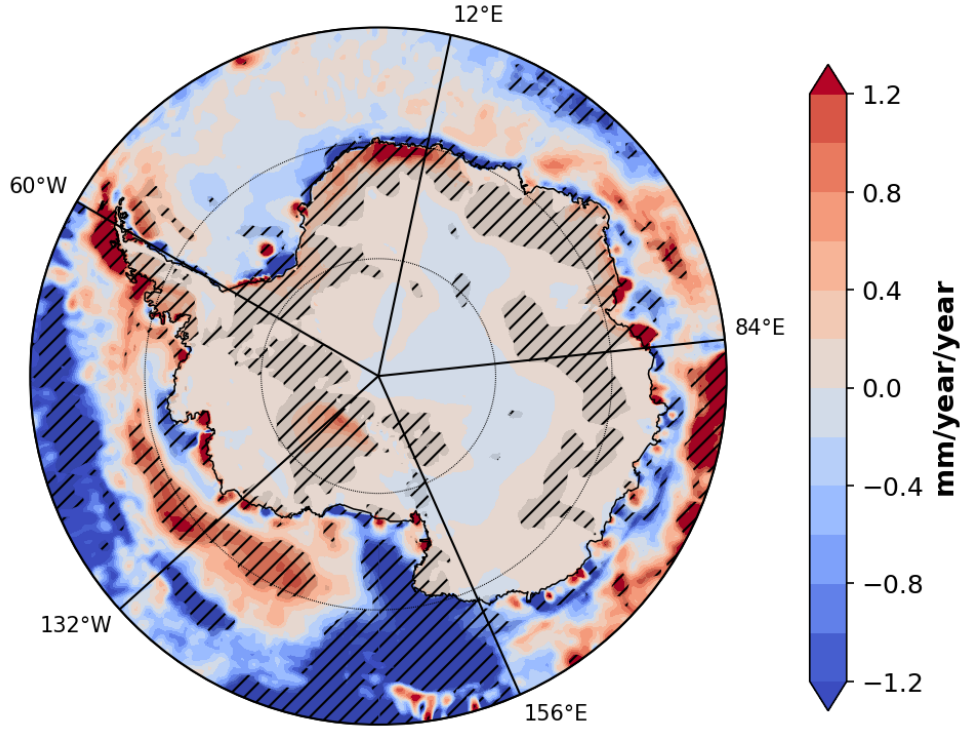


Figure 18: *The 1979-2020 trends map of the mean evaporation rate. Statistically significant trends ( $p < 0.05$ ) are represented by the hatched areas.*

#### 4.2.5 Moisture convergence change

Another component of the atmospheric hydrological cycle is moisture convergence. In this section, the evolution of moisture convergence is studied in order to establish the spatial distribution of the regions of increase and decrease of moisture convergence. For this purpose, the moisture convergence trend map (Fig. 19) is introduced.

An increase in moisture convergence is observed in the convergence region around  $50^{\circ}E$  (see section 3.2.5). The increase region extends beyond the Amery ice shelf ( $90^{\circ}E$ ). The increase in temperature and the intensification of the circulation in this region explains the increase in moisture convergence. The variability of the BAM mode generates a significant meridional transport difference in this region [Marshall et al. 2017]. Therefore, further study of the impact of this mode on the atmospheric circulation in the IO sector could explain the observed convergence increase.

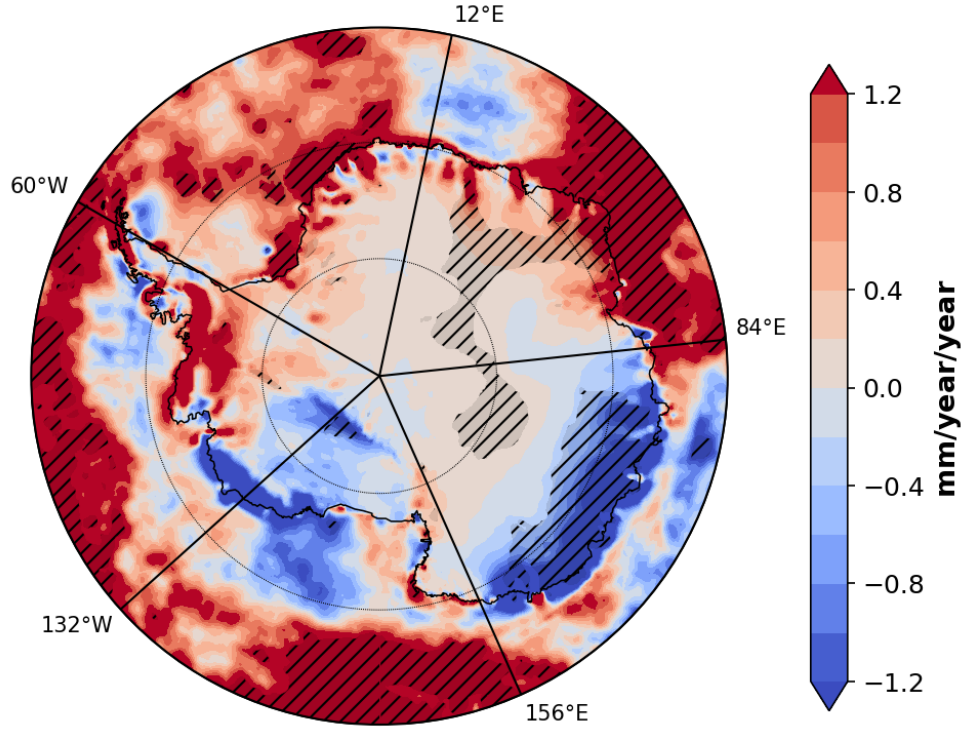


Figure 19: *The 1979-2020 trends map of the mean vertically integrated moisture convergence. Statistically significant trends ( $p < 0.05$ ) are represented by the hatched areas.*

In the convergence region on the coasts of the PO sector, a decrease in moisture convergence is observed. The increase in pressure observed in this region (see section 4.2.3) and the increase of SAM explains the decrease in the atmospheric circulation in this region. Moreover, the decrease in temperature observed in this region reduces the capacity of the air to hold water vapour. Therefore, the moisture convergence is decreased because the transport and quantity of moisture to this region are weakened.

The last convergence region, which includes the coastal region of the ABS sector and extends to the Ross Sea, does not show a homogeneous change. The coasts of Marie Byrd Land show a decrease in convergence also shown inland. In Ellsworth Land, an increase is observed. On the Peninsula, some regions show a decrease in moisture convergence and others, like the tip, an increase. However, for this third region of convergence, none of the trends is statistically significant. A study of the temporal evolution of the PSA1 mode could explain this decrease over Marie Byrd Land and the Ross Ice Shelf and the increase in convergence over the rest of West Antarctica. Indeed, the PSA1 mode creates an opposite meridional flow between the East and West of the ABS coasts [Marshall et al., 2017].

In addition to the three convergence regions, other regions such as at mid-latitudes ( $60^{\circ}S - 68^{\circ}S$ ) in the ABS and RS sectors and WS coast show an increase in moisture convergence. The interior of the continent undergoes only slight changes. This region's atmospheric circulation and topography change too little to induce a large change in convergence. A temperature change is the main factor explaining a change in convergence within the continent. A statistically significant increase in convergence on the plateau can be pointed out where a temperature increase is observed.

## 4.2.6 Precipitation change

The last component of the atmospheric hydrological cycle that remains to be analysed for the last four decades is precipitation. For this purpose, the precipitation trend map (Fig. 20) is introduced.

A decrease in precipitation is observed along the coast of the PO sector and up to Cape Adare ( $170^{\circ}E$ ). The statistically significant region of these trends is related to the significant region of negative trends in the moisture convergence. The explanation for the decrease in precipitation in this region comes from a decrease in surface temperature and the decrease in atmospheric circulation in this region. This leads to a decrease in the amount and transport of moisture and thus precipitation in this region.

On the coasts of Marie Byrd Land, a decrease in precipitation is observed, which is related to the decrease in moisture convergence described in the previous section. On Ellsworth Land, an increase in precipitation is observed. For the western side of the Peninsula, the trends are positive, while the lee side shows weak trends, synonymous with little change in precipitation. The discharge of water vapour during the Foehn effect that occurs in this region explains this [Van Lipzig, 2008]. As for the moisture convergence trends, they are not statistically significant in this region. As a result of the increase in the SAM index, an increase in precipitation of 30% is observed over the eastern part of the Peninsula. In contrast, a decrease of the same magnitude is observed over the Marie Byrd Land and the adjacent Ross ice shelf [Van den Broeke and Van Lipzig, 2004]. Furthermore, with a positive trend in the SAM index observed over the last decades [Fogt and Marshall, 2020], the observation of this opposite trend pattern over West Antarctica makes sense.

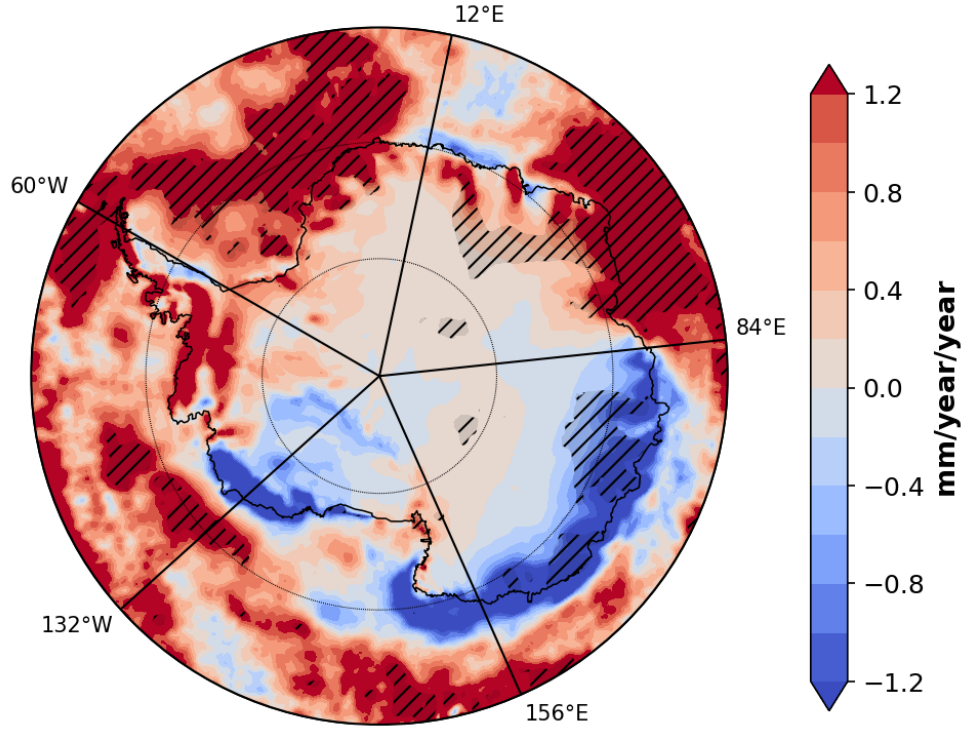


Figure 20: *The 1979-2020 trends map of the mean total precipitation rate. Statistically significant trends ( $p < 0.05$ ) are represented by the hatched areas.*

As for the moisture convergence trends off the tip of the Peninsula, positive trends are observed for precipitation. In the WS sector, a significant increase in precipitation is observed. Indeed, it is not only the coast of Coast Land that experiences an increase, but also the Weddell Sea. As a result of the increase in moisture convergence from  $40^{\circ}E$  to  $85^{\circ}E$  in the IO sector, precipitation increases in this region.

The oceanic regions of moisture convergence increase in the ABS and RS sectors are not as clearly marked in the precipitation trend map. Indeed, only certain small regions stand out as statistically significant; of these, the region around  $180^{\circ}E - 63^{\circ}S$  and the region around  $130^{\circ}W - 70^{\circ}S$  are the main ones.

The Antarctic plateau shows positive moisture convergence and temperature values. Continental regions with a positive (negative) surface air temperature trend are generally similar to regions with a positive (negative) precipitation trend [Van den Broeke and Van Lipzig, 2004; Tang et al., 2018]. This is because the warmer surface air temperature is able to retain more moisture according to the Clausius-Clapeyron law (see section 1.2). This argument works well for the continent, except for the Ross Ice Shelf region. In this region, the increase in SAM index during the last decades has led to less precipitation.

### 4.3 Summary

No particular trend in evaporation has emerged over the last four decades. The record melting of sea ice in 2017 impacted the amount of evaporation in that year. This showed the importance of sea ice in the atmospheric hydrological cycle. The trend distribution for evaporation showed an increase in evaporation over the continent except over the high-altitude region of the AIS. A positive trend band off Marie Byrd Land was observed in the oceanic region. This band is explained by decreasing sea ice concentration and increasing surface temperature in this region. Negative trends were observed mainly in the ABS and RS sectors. These regions were partly located in the  $60^{\circ}S$  where the sea ice concentration is less than 15%. The decrease in surface air temperature in these regions is the primary explanation for the existence of these negative trends. Indeed, due to the decrease in the surface air temperature, the speed of the evaporation process is reduced. The decrease in evaporation on the coasts of the WS, IO and PO sectors could be equated to an increase in coastal sea ice concentration. In this coastal band, the existence of polynyas allows the explanation of small areas of increased evaporation.

The moisture convergence trend map shows distinct regions of increase and decrease. The intensification of the atmospheric circulation and the increase in temperature explains the increase in moisture convergence in the IO sector. The convergence in the PO sector is weakened by a decrease in temperature and atmospheric circulation. Offshore of the RS and ABS sectors, an increase in moisture convergence is observed and contributes mainly to the increase noted in these sectors. The coasts of Marie Byrd Land show a decrease in convergence, while the coasts of Ellsworth Land show an increase. In the WS sector, an increase is observed, especially on the eastern coasts of this sector. All sectors except the PO sector show an increase in moisture convergence, which is related to the observed global increase (Fig. 14).

For precipitation, a majority of positive trends are found. However, two main regions show negative trends, located on the coasts of the PO sector and extending along Cape Adare and the other on the coasts of Marie Byrd Land and towards the interior. In the PO sector, the decrease in moisture convergence explains the decrease in precipitation. The decrease over Marie Byrd Land and the increase over Ellsworth Land and the western Peninsula is explained by an increase in the SAM index — which induces a contraction and poleward shift of the Westerlies over the Southern Ocean and leads to a change in the atmospheric circulation. Over the eastern Peninsula, the Foehn effect explains the small changes observed. In the IO sector, increasing precipitation is observed due to a significant increase in convergence in this sector. The same is true for the WS sector, which also experiences precipitation increases. Over the continent, the Clausius-Clapeyron relationship explains the observed precipitation

except for the Ross Ice Shelf region. A further study of the impact of the BAM and PSA modes on the change in the atmospheric hydrological cycle of the IO and ABS/RS sectors, respectively, would perhaps explain the trends observed in these sectors. Overall, an increase in precipitation is observed in Antarctica, which is related to the positive trend in Figure 14.

## Projections for the atmospheric hydrological cycle

To complete the study of the atmospheric hydrological cycle, Chapter 5 looks at the future evolution of the cycle and aims to answer the question: *How will these processes change in the future, according to climate model projections?* In order to answer the question, the difference between the processes at the end of the century (2074-2100) and the beginning of the century (1979-2014) is investigated. The data used for these projections is the ACCESS-ESM1.5 data described in Chapter 2 (section 2.3). To organize the analysis of this change this chapter consists of 3 sections. The first section compares the seasonal cycle at the beginning of the 21st century and the end of the century (section 5.1). Then the second section will discuss the spatial differences between the beginning and the end of the century for evaporation, moisture convergence, and precipitation (section 5.2). The chapter ends with a summary of the results (section 5.3).

### 5.1 Projection of the seasonal cycle

Figure 21 represents the difference between the mean 2074-2100 and the mean 1979-2014 for the various components involved in the atmospheric hydrological cycle and shows the changes by the end of the century. Therefore, positive values mean an increase and negative values mean a decrease in the processes during this time interval.

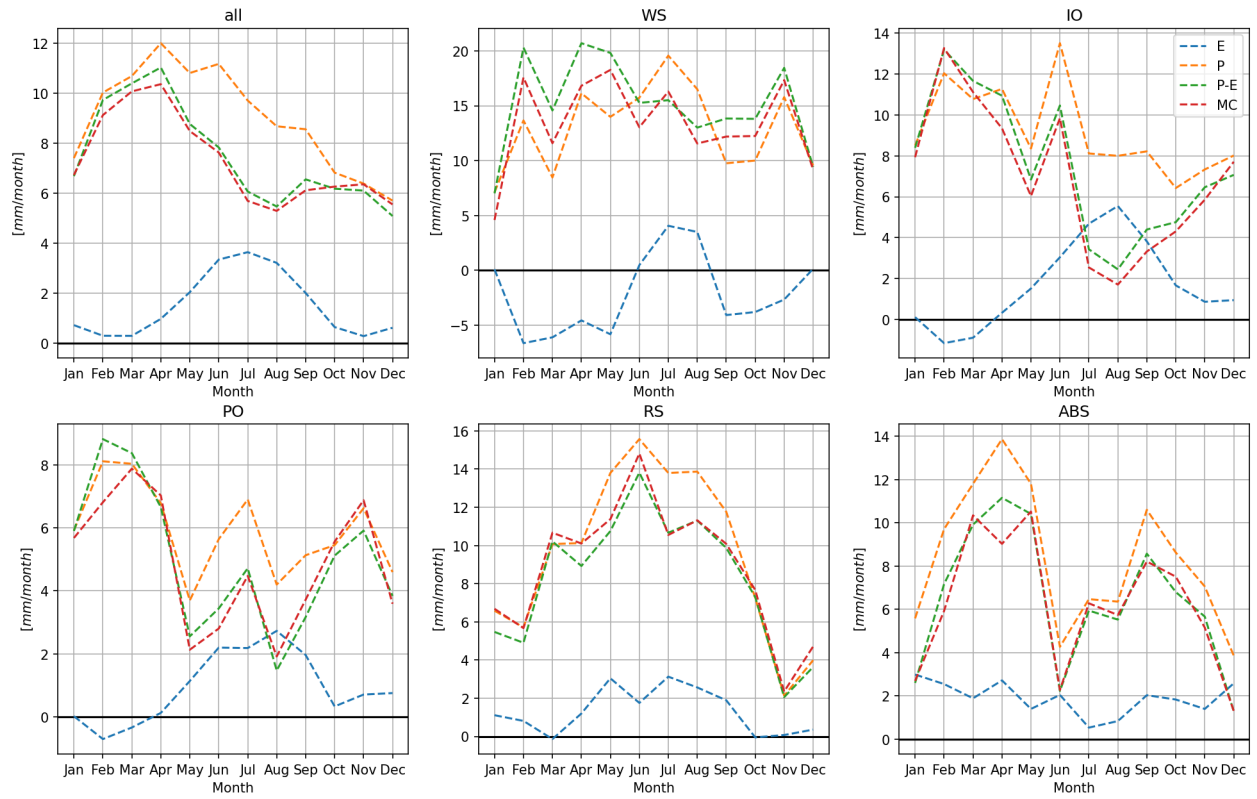


Figure 21: The difference between ACCESS SSP585 (2074-2100 mean) and historical (1979-2014) for the twelve months, each sector and each component of the atmospheric hydrological cycle (evaporation (E), precipitation (P), P-E and moisture convergence (MC)).

| Sectors        | All  | WS    | IO   | PO   | RS   | ABS  |
|----------------|------|-------|------|------|------|------|
| E [mm/month]   | 1.51 | -2.12 | 1.71 | 0.93 | 1.31 | 1.90 |
| P [mm/month]   | 9.00 | 13.02 | 9.21 | 5.92 | 9.55 | 8.33 |
| P-E [mm/month] | 7.49 | 15.14 | 7.50 | 5.00 | 8.24 | 6.44 |
| MC [mm/month]  | 7.31 | 13.39 | 6.91 | 4.87 | 8.83 | 6.25 |

Table 4: Annual mean difference between (2074-2100) mean and (1979-2014) mean of evaporation, precipitation, moisture convergence and P-E for each sector.

The first graph in Figure 21 shows the data for the entire study area. This graph shows an increase in the amplitude of the seasonal precipitation cycle, with the largest increase in autumn and the smallest in summer. Evaporation shows a significant increase centred in winter with a maximum in July, while a slight increase is observed between October and April. A thermodynamic change is to be investigated to explain this winter increase. For net precipitation, the values follow the precipitation curve with a larger decrease in winter due to the increase in evaporation this season. Moisture convergence values are close to net precipitation means that the atmospheric water balance is proper for the ACCESS-ESM1.5 model. The annual mean differences shown in Table 4 represent an increase of 10.41% for evaporation, 18.53% for precipitation, 22.6% for the net precipitation, and 22.11% for moisture convergence.

In the WS sector, a mean increase of 13.02mm/month is observed for precipitation. This increase is the largest of all sectors for precipitation. The largest values are observed in winter (July). For evaporation on average a decrease is observed ( $-2.12\text{mm/month}$ ). However, during winter, an increase in evaporation is observed. The moisture convergence rate shows a nearly similar curve to precipitation, and a large mean value is estimated. This sector exhibits the largest intensification of the atmospheric hydrological cycle, suggesting that the cycle of this sector is most affected by changes at the end of the century. And because evaporation values are particularly high in winter, this sector expects a significant thermodynamic change by the end of the century.

In the IO sector, precipitation shows larger values in autumn and winter than in spring and summer. For evaporation, a positive difference peak is observed in August. The evaporation increase in winter and decrease in spring, while it does not change much in summer and autumn. The moisture convergence shows a similar curve to precipitation until the evaporation peak, reducing the moisture convergence difference in winter.

In the PO sector, the lowest mean values for each component of the atmospheric hydrological cycle are observed and suggest that the PO cycle is less affected by changes at the end of the century. In this sector, an increase in precipitation is observed with an annual average of 5.92mm/month. An increase in evaporation is observed and takes place from April to December. For the moisture, the mean annual difference is low between May and September, while the moisture is more significant between October and April.

The RS sector shows large values of precipitation centred in winter. The maximum is reached in June and the minimum in November. A weak increase is observed for evaporation and is especially marked from April to September. The moisture convergence difference increases in autumn to peak in June and then decreases strongly in Spring. Curves variability for all processes suggests that changes occur mainly in autumn and winter while weaker changes occur in Spring and Summer.

For the ABS sector, a semi-annual cycle is observed, with two peaks centred in April and September. The annual mean for moisture convergence is 6.25mm/month, and the moisture convergence and the curve also show a semi-annual cycle. These peaks are reminiscent of the seasonal variability generated by the SAO (see section 1.4). This mode greatly impacts the low-pressure center of this sector (see section 3.2.5), which could explain this oscillation. For evaporation, a curve with a minimum centred in winter and a maximum in summer is observed conversely to others sectors. The annual mean evaporation (1.9mm/month) is the largest of all sectors, meaning evaporation increases the most in the ABS sector.

## 5.2 Spatio-temporal differences

Since the spatial variability of the various processes is large (see Figure 21), maps are provided to complete the study of the changing atmospheric hydrological cycle at the end of the century. This section is divided into six subsections. The three first subsections are included to show thermodynamics and dynamics changes, and the three last subsections present the changes in the processes involved in the atmospheric hydrological cycle. Thermodynamic changes are brought to light by temperature (subsection 5.2.1) and sea ice (subsection 5.2.2) changes, while the sea level pressure (subsection 5.2.3) illustrates the dynamic changes. Then in the three last subsections, changes in atmospheric processes are discussed with the thermodynamic and dynamic. Subsection 5.2.4 presents the evaporation changes, subsection 5.2.5 introduces the moisture convergence changes, and subsection 5.2.6 shows precipitation changes.

### 5.2.1 Temperature

The near-surface temperature of the air (2m) presents an increase in the entire study region (see Fig. 22). Considering the chosen scenario (RCP8.5), it is not disturbing to see a global temperature increase by the end of the century. However, significant spatial variability of this temperature increase is observed.

A latitudinal variability is highlighted, with a large increase of the near-surface temperature over and around the AIS. In contrast, near the circle of latitude  $60^{\circ}S$ , the temperature increase is less extreme. Near coast regions with a large positive temperature difference are regions with a decrease in sea ice concentration. Therefore the albedo in these regions is reduced by the end of the century compared to the beginning. The temperature-albedo feedback [Goosse et al., 2018] cause an amplification of the warming in these regions. Such warming is observed mainly in the Weddell Sea, around the coast, and between the Amund-

sen Sea and the Ross Sea. Temporal variability is also expressed, showing larger temperature increases in autumn and winter than in summer and spring.

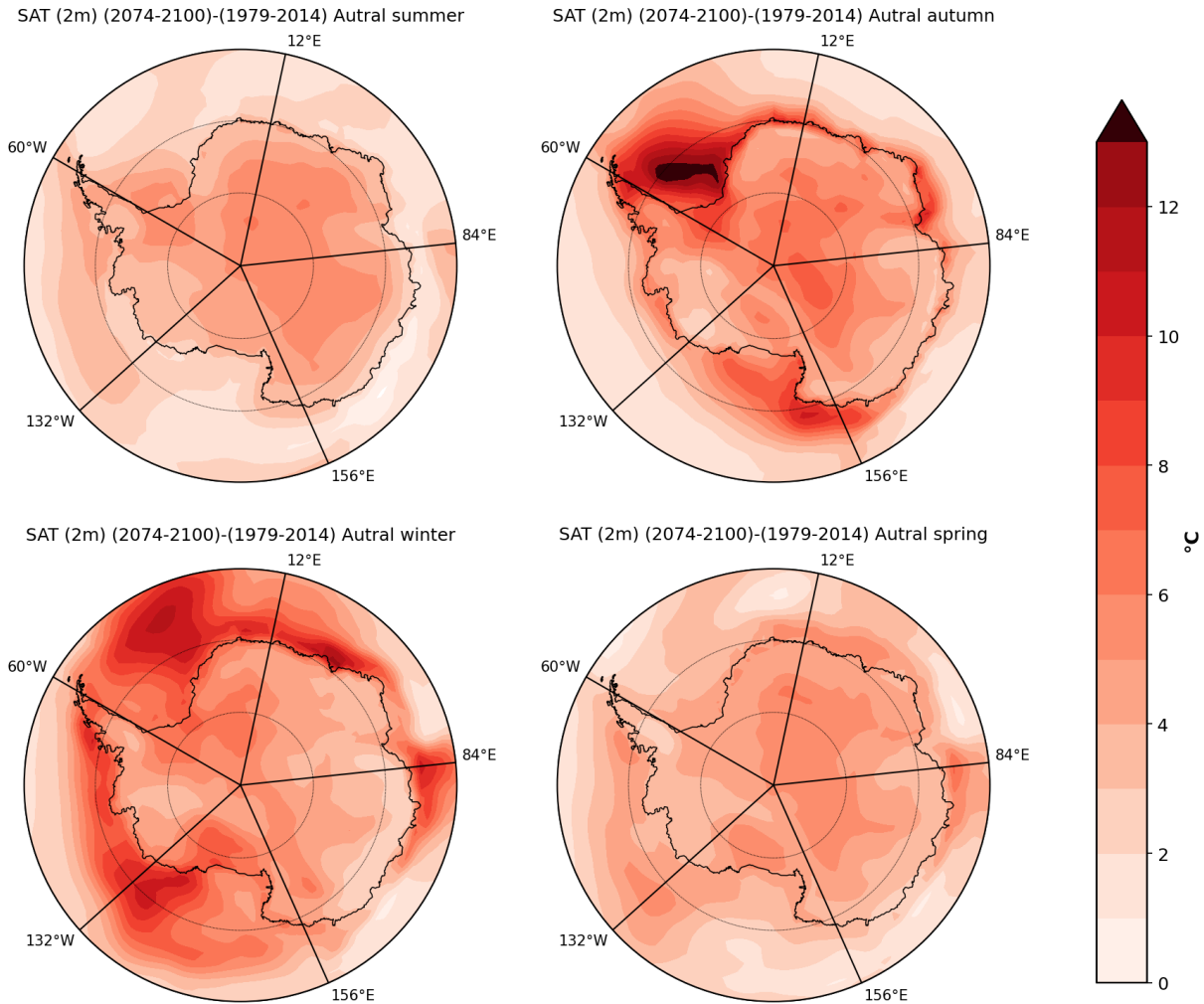


Figure 22: *The near-surface temperature difference between mean over 2074-2100 and 1979-2014 from the ACCESS-ESM1.5 monthly mean outputs. Each map represents a season such as DJF for summer, MAM for autumn, JJA for winter and SON for spring.*

### 5.2.2 Sea ice concentration

The spatial distribution of sea ice concentration difference (see Fig. 23) is similar to the near-surface temperature difference, especially in autumn and winter. Most observed differences are negative for the sea ice concentration, which is evidence of a decrease in the sea ice concentration. In summer and autumn, the sea ice concentration is extremely low, and maps exclusively show sea ice in the Weddell Sea and around the Cape Adare (not shown). For the two other seasons, sea ice extends around these two regions and the continent's coasts. During summer and autumn, the difference maps exhibit a considerable decrease in sea ice concentration, mainly near the coast. In contrast, in the winter and spring, the decrease in sea ice concentration regions is also observed offshore. In addition, in winter and spring, regions of increase in sea ice concentration are observed chiefly around Cape Adare. An explanation for the persistence of the sea ice in the Weddell Sea and around Cape Adare is the deep convection process which is well known to be present in these regions [Bullister et al., 2013; Morrison et al., 2020]. Indeed, deep water formation is associated with sea ice formation. These enormous changes in sea ice concentration could have massive consequences on evaporation.

### 5.2.3 Pressure

The sea level pressure difference maps (see Fig. 24) essentially show a deepening of the sea level pressure field. In summer and autumn, the pressure field over the AIS undergoes an evident decrease by the end of the century. In autumn, the difference reveals a negative maximum over the Peninsula. Since these changes are not focused on low-pressure centers (the three described in the previous chapters), it is challenging to conclude if these low pressures endure a strengthening or weakening. On sea level pressure (2074-2100) maps, the three low are always present, and the pressure pattern with three low pressures is best defined in autumn and spring. During winter, two main regions (the Weddell Sea and off the Cape Adare) show a deepening of the pressure field, whereas a strengthening at  $60^{\circ}S$  in the ABS sector is exhibited. Spring is the only season with no large deepening in the pressure field. Sea level pressure difference is negative in WS and RS sectors over the two regions, which display an increase in sea ice concentration. The sea level pressure difference is positive in other sectors (IO, PO, and ABS). As observed with the ACCESS data, a change of several hPa suggests a change in the atmospheric circulation. Such a change can have significant consequences on the convergence of humidity.

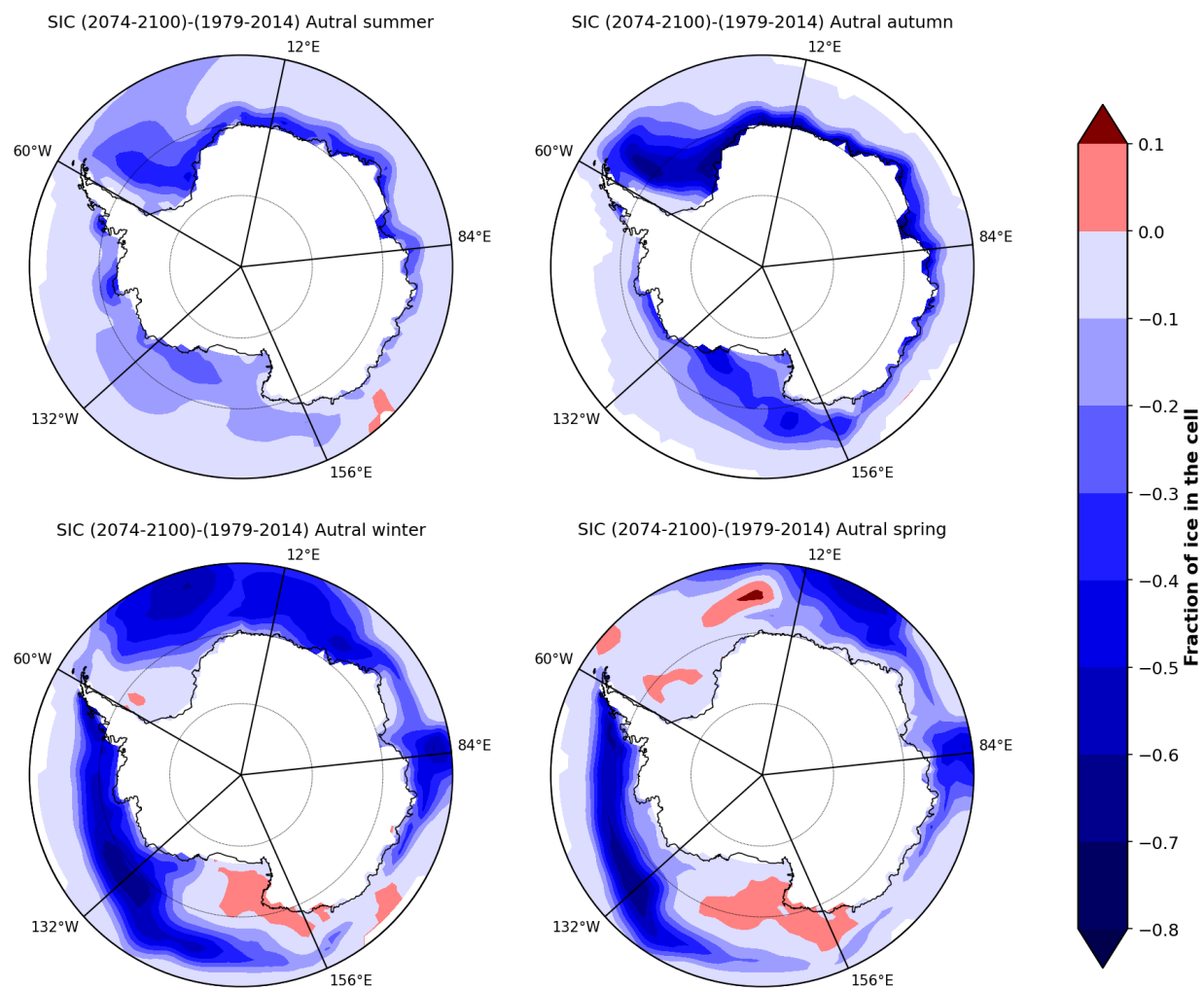


Figure 23: *The sea ice concentration difference between mean over 2074-2100 and 1979-2014 from the ACCESS-ESM1.5 monthly mean outputs. Each map represents a season such as DJF for summer, MAM for autumn, JJA for winter and SON for spring.*

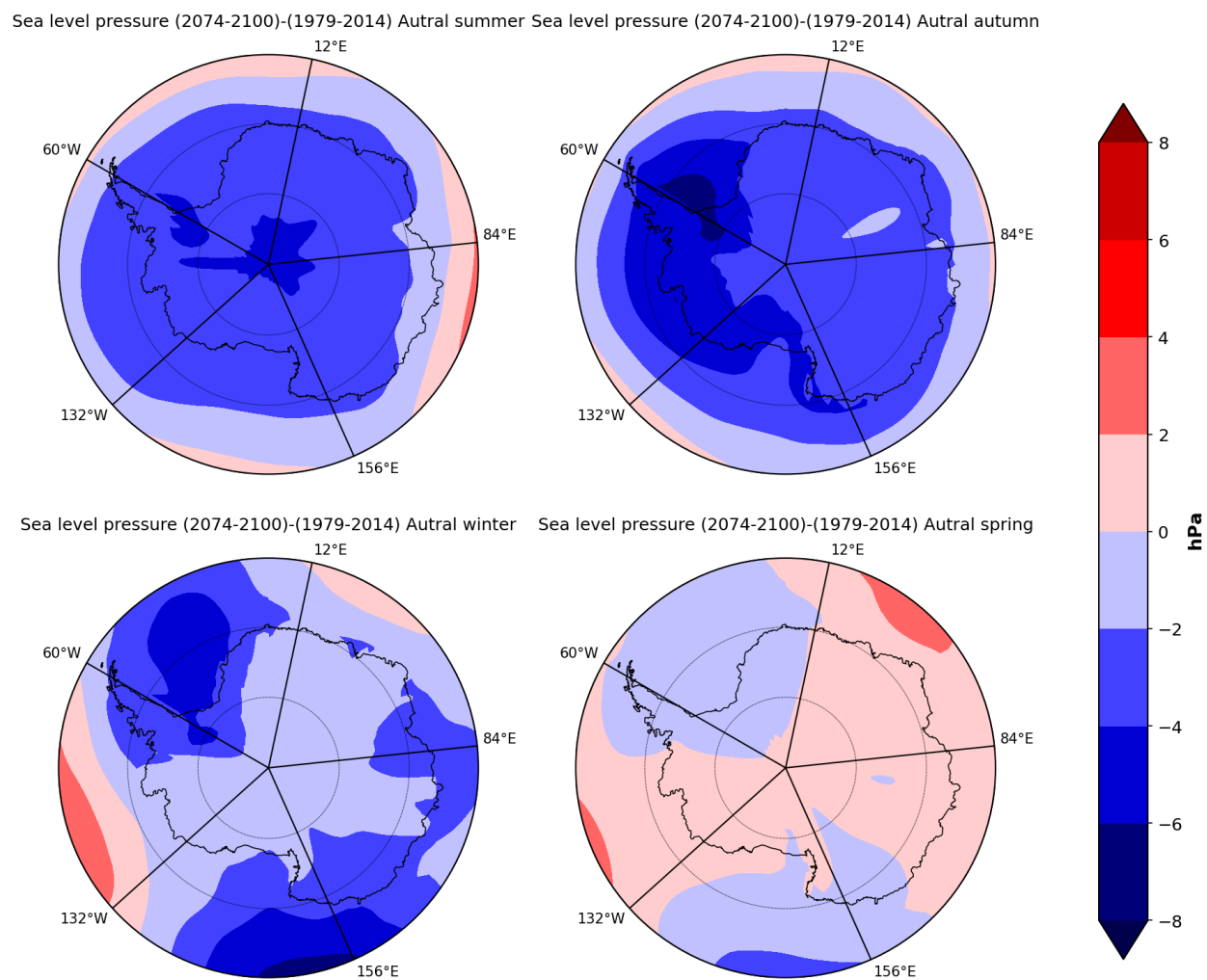


Figure 24: *The sea level pressure difference between mean over 2074-2100 and 1979-2014 from the ACCESS-ESM1.5 monthly mean outputs. Each map represents a season such as DJF for summer, MAM for autumn, JJA for winter and SON for spring.*

### 5.2.4 Evaporation

Figure 25 shows the seasonal maps of the difference between the mean evaporation over 2074-2100 and the mean over 1979-2014. Regions coloured in red show that there is an increase in evaporation. Conversely, regions are coloured blue to show a decrease in evaporation.

In summer a slight increase is observed on almost the whole continent. Only some coastal areas, such as the tip of the Peninsula, the PO sector's coasts, and Marie Byrd Land's coasts show a slight decrease. In the oceanic region, a thin band near the coast starting in the WS sector and ending in the RS sector shows a decrease in evaporation. The region of the Amundsen and Bellinghausen Sea's low pressure shows an evaporation increase. In the Weddell Sea, a small increase in evaporation is observed. The difference in sea ice between the beginning and end of the century in summer is smaller than in other seasons. Therefore, change in evaporation is caused more by the change in temperature than by the change in sea ice. The increase of evaporation in the ABS sector and the Weddell Sea could be explained by a decrease in sea ice concentration and a marked increase in air temperature compared to other regions.

In autumn, the high elevation regions of the continent show a slight decrease in evaporation, while the surrounding lower elevations show a small increase. In the oceanic region, a large increase in evaporation in the Weddell and Ross Seas is observed. These regions of increase extend along the coasts of the ABS and IO sectors. In the IO sector, a large increase is observed around the Amery ice shelf. This pattern of increase corresponds perfectly with a high decrease in sea ice concentration pattern (see Fig. 23). It suggests that the sea ice's insulation power does not work well in preventing evaporation. Regions showing a decrease in evaporation are found near  $60^{\circ}S$  in the WS, IO, and RS sectors. These regions correspond to no sea ice regions; therefore, sea surface temperature and surface air temperature are the main drivers of the evaporation process. In this case decrease in evaporation suggests that the difference between the sea surface and surface air temperature is reduced. This can be explained by the fact that the atmosphere is warming faster than the ocean.

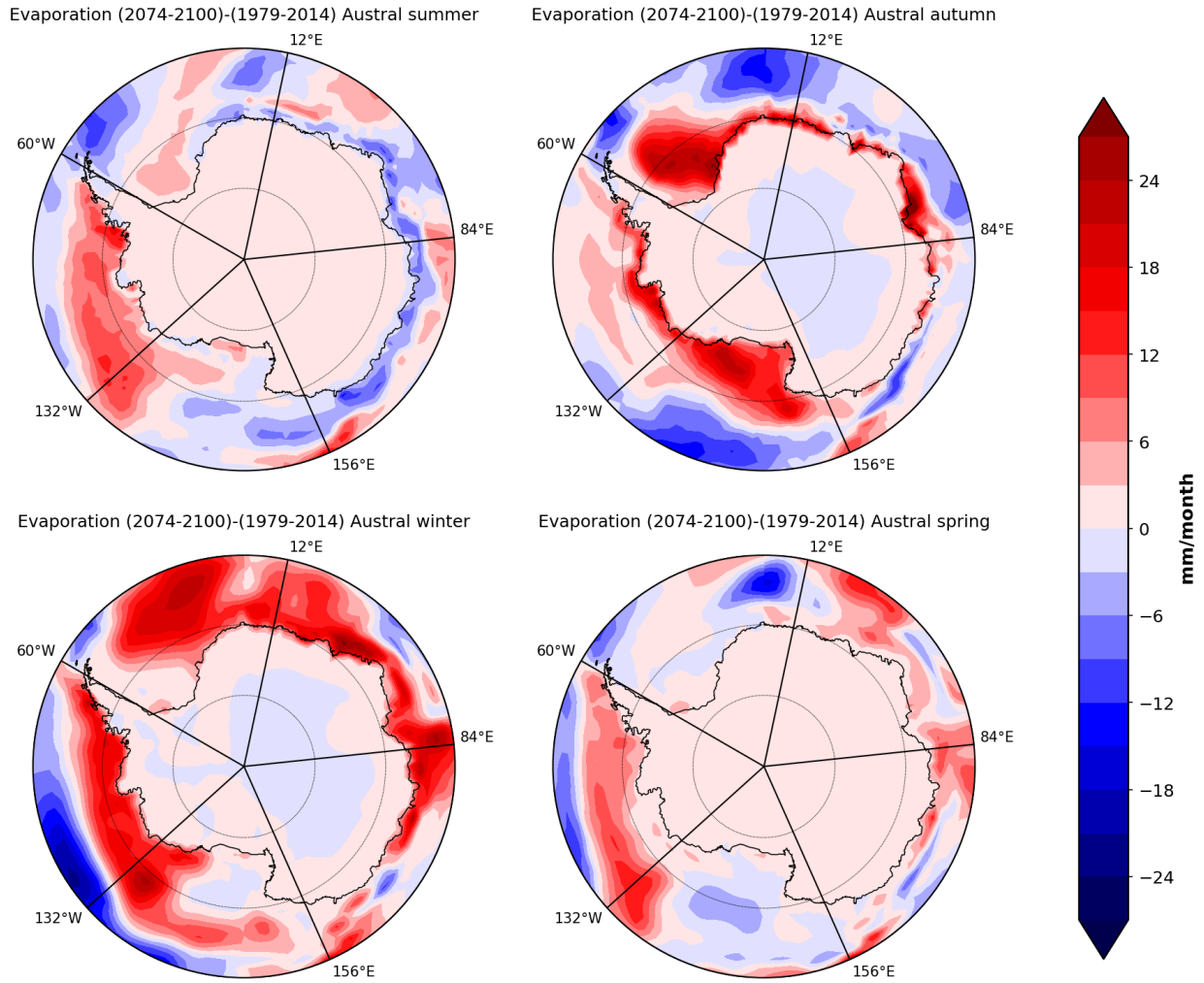


Figure 25: *The evaporation difference between mean over 2074-2100 and 1979-2014 from the ACCESS-ESM1.5 monthly mean outputs. Each map represents a season such as DJF for summer, MAM for autumn, JJA for winter and SON for spring.*

In winter, the region of decrease observed on the mainland is still linked to a high elevation, but due to the low temperature associated with this season, the negative region expands. As in the autumn, the surrounding regions of lower elevation show slightly positive values. As for each season but even more for winter, the evaporation difference is larger in the oceanic region. Regions that show an increase in evaporation are strongly linked to a decrease in sea ice concentration (see Fig. 23). The regions of increased evaporation are no longer observed near the coast in the Weddell and Ross Seas as in autumn but everywhere else around the continent. These two near coastal regions of low evaporation are explained by the high sea ice concentration still present in these regions even at the end of the century. The region near 60°S in the ABS and RS sectors is the only region showing a large decrease

in evaporation. This decreased evaporation is explained by the diminished difference between the sea surface and surface air temperature.

In spring, over the whole continental region, an increase is observed. In the oceanic region, the values are lower than those observed in autumn and winter. A region of increase off the coast of the ABS sector is observed and is mainly associated with the sea ice concentration decrease (see Fig. 23). The two other regions of increasing evaporation observed around  $25^{\circ}E$  and  $85^{\circ}E$  are also regions marked by a reduction of the sea ice concentration. Regions of decrease of around  $64^{\circ}S - 0^{\circ}E$  in the WS sector and around  $69^{\circ}S - 70^{\circ}W$  in the RS sector are linked to an increase in sea ice concentration. Finally, the region near  $60^{\circ}S$  in the ABS sector is again explained by temperature difference due to no sea ice cover at this latitude in this sector.

### 5.2.5 Moisture convergence

Figure 26 shows seasonal maps of the difference between the mean moisture convergence over 2074-2100 and the mean over 1979-2014. Regions are coloured red to show that there is an increase in the rate of moisture convergence. Conversely, regions coloured blue show a decrease in the rate of moisture convergence.

For moisture convergence, the majority of the studied region exhibits an increase at the end of the century, with only a few negative regions mainly located on the coasts. Except for a negative region near the Antarctic Peninsula, other negative regions are moisture divergence regions (not shown), which are associated with katabatic winds that explain the divergence. Therefore, the negative difference shown in Figure 26 suggests strengthening these winds, which would lead to a reinforcement of the moisture divergence.

As shown in Figure 21, the moisture convergence shows a greater increase in autumn, which is reflected in Figure 26. This large increase in autumn is consistent with the seasonal cycle studied in chapter 3. Indeed, the intensification of the temperature gradient between  $40^{\circ}S$  and  $65^{\circ}S$  in autumn (SAO) helps to explain the intensification of the atmospheric circulation at a seasonal scale. Although Figure 24 does not clearly show a deepening of the low pressure around the AIS, intense low pressure is observed (not shown) in autumn. This pressure pattern contributes to an intensification of cyclonic activity and thus increases moisture in the coastal convergence zones.

In addition to the moisture increase in convergence zones, a positive difference is observed almost everywhere in the study area. The Clausius-Clapeyron law can explain the increase in moisture. But it is still challenging to explain the spatio-temporal distribution of the moisture convergence and the divergence near the Peninsula. Studying the projections of

the internal variability modes would undoubtedly allow us to learn more about this subject. However, thanks to the study of Zheng et al. [2013] on the projections of the SAM index for the end of the century, an idea of the climate variability of the extratropical regions of the Southern Hemisphere can be made. Indeed, they show that the SAM index will follow a positive trend, suggesting an increase in convergence over West Antarctica and a decrease over the eastern part of the continent. Therefore, other dynamic processes are at play to explain the observed distribution of moisture convergence.

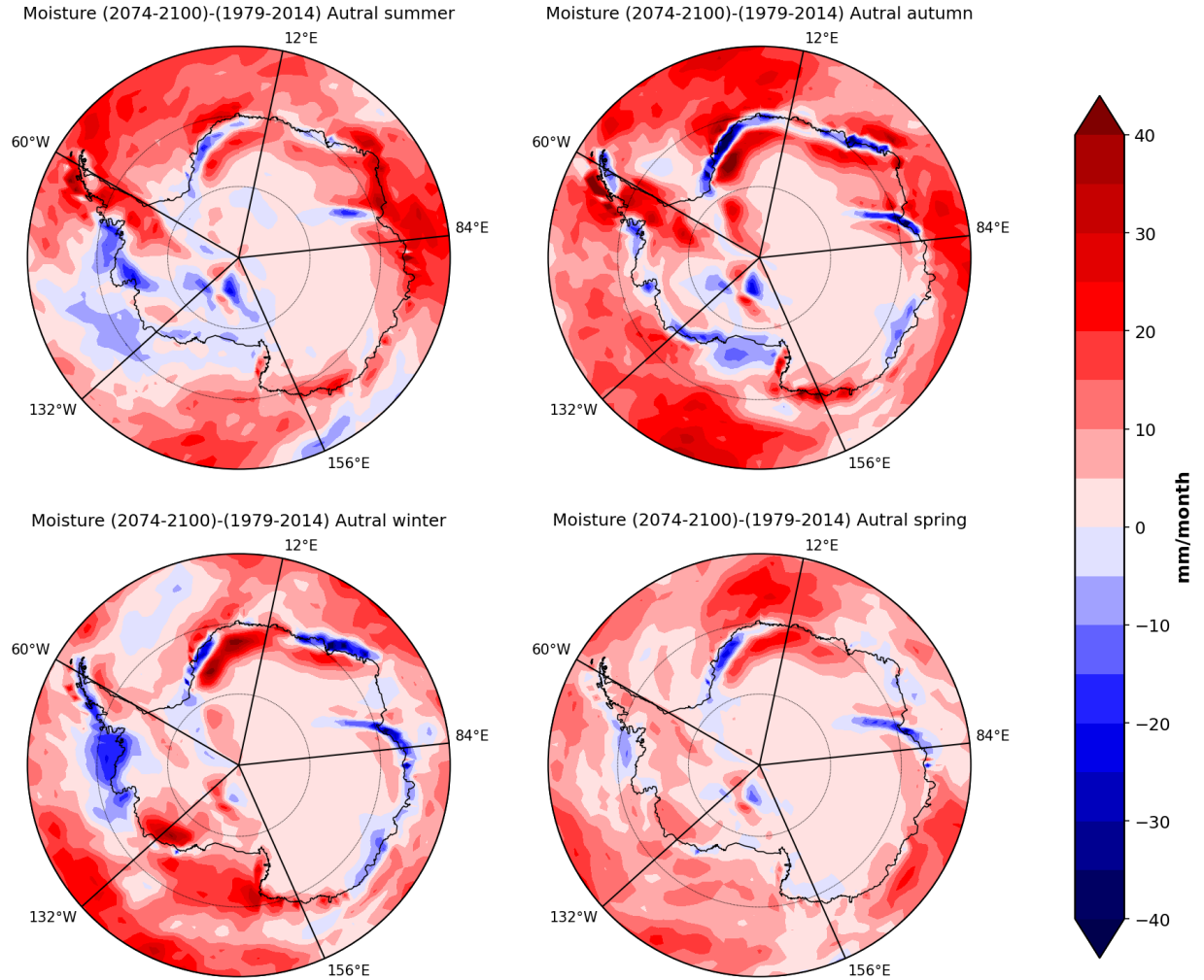


Figure 26: *The moisture convergence difference between mean over 2074-2100 and 1979-2014 from the ACCESS-ESM1.5 monthly mean outputs. Each map represents a season such as DJF for summer, MAM for autumn, JJA for winter and SON for spring.*

## 5.2.6 Precipitation

Figure 26 shows the seasonal maps of the difference between the mean precipitation over 2074-2100 and the mean over 1979-2014. Regions are coloured red to show that there is an increase in precipitation. Conversely, regions are coloured blue to show a decrease in precipitation.

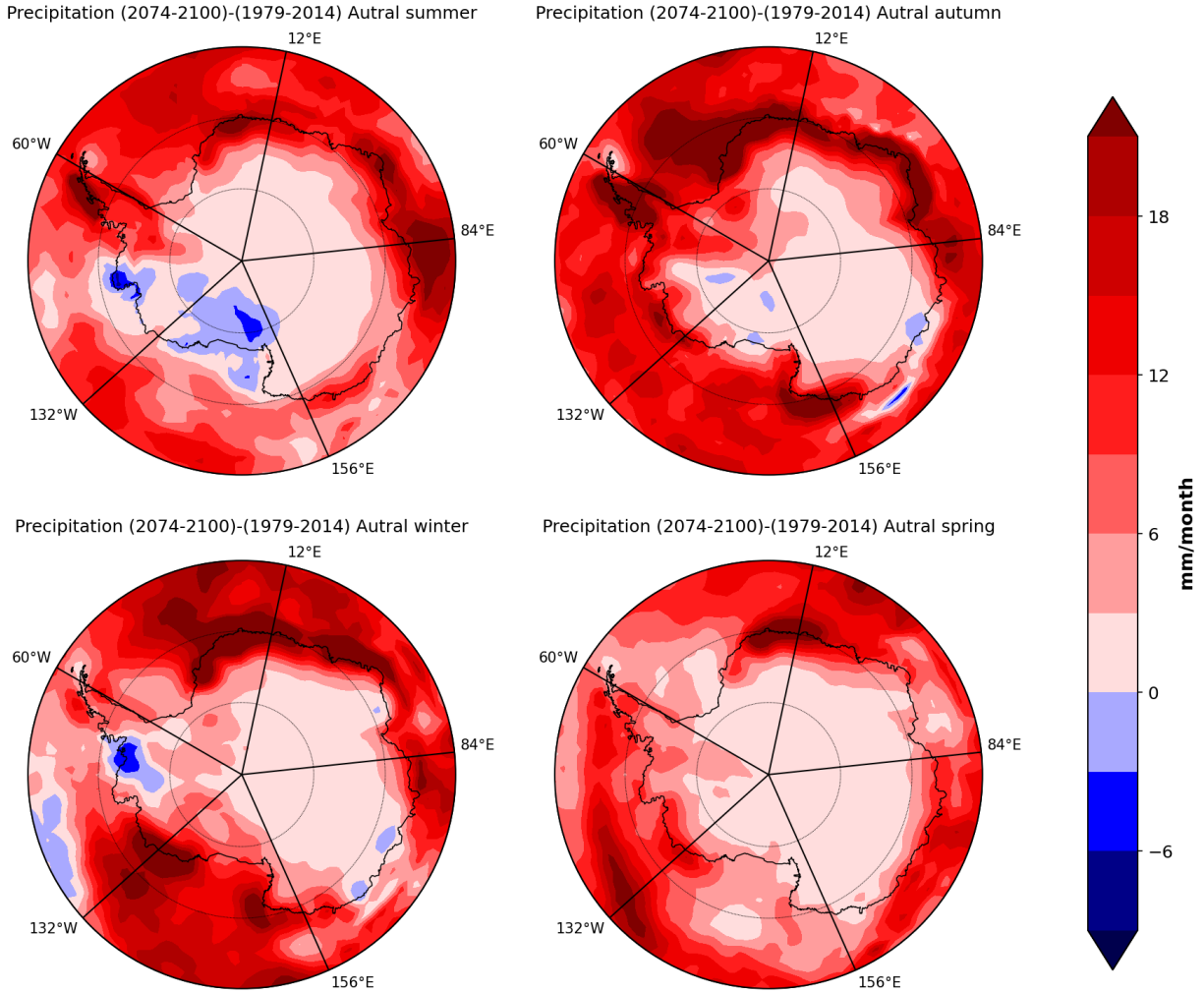


Figure 27: The precipitation difference between mean over 2074-2100 and 1979-2014 from the ACCESS-ESM1.5 monthly mean outputs. Each map represents a season such as DJF for summer, MAM for autumn, JJA for winter and SON for spring.

For precipitation, an increase is observed almost everywhere for all seasons. Some inter-seasonal changes are noticeable, with a maximum centred in autumn and a minimum in summer. First of all, the continent's interior shows smaller increases than the coastal and

maritime regions. This means that the change in precipitation is mainly on the coast and over the ocean. A larger difference is observed in the lower elevation leaving the high elevation continental regions with little change in precipitation. Negative values are observed in summer, autumn and winter over three regions: coasts of Marie Byrd Land - Ross Ice Shelf, coasts of Wilkes Land and coasts of Ellsworth Land. All these regions of negative values are associated with regions with a reduced amount of moisture convergence (see Fig. 26), which explains this decrease in precipitation. Regions over the ocean that exhibit a large increase of precipitation are directly associated with high convergence region (see Fig. 26) and are mainly coastal regions where the interaction between atmospheric circulation and orography generate precipitation.

### 5.3 Summary

The evaporation process is projected to intensify in Antarctica by the end of the century (+1.51mm/month). Winter is the period of most remarkable evaporation intensification. The different sectors react the same way with one increase in the year, except for the ABS sector, which shows the greatest intensification of the evaporation process in summer and the least in winter. This pattern contrasts with the other sectors. Small positive changes are observed on the continent, with some negative changes in the high elevation regions present in autumn and winter and are related to temperature changes. The seasonal maps highlight the main regions of intensification for evaporation. The Weddell Sea and the Ross Sea show a significant increase in autumn due to the region's high sea ice loss. The near-shore marine region of the ABS sector also shows a large increase in evaporation due to the same cause. The intensification in this region is most pronounced in winter but is present throughout the year. The larger decrease in sea ice concentration during winter can explain this. The appearance of a region of large evaporation decrease in winter in the ABS sector is why the lowest increase in the evaporation process was noted in summer in this sector. This diminution evaporation is explained by decreased evaporation rate due to temperature difference reduction. The same decrease region near  $60^{\circ}S$  is observed in the Ross Sea sector in autumn.

Moisture convergence is projected to increase in Antarctica by the end of the century (+7.31mm/month). Following the switch to another dataset (ACCESS-EMS1.5), the convergence pattern is different from the one studied in the previous chapter. The main difference of this new pattern is that it contains more pronounced regions of moisture divergence and is likely due to katabatic wind simulation. These regions of divergence exhibit a decrease in moisture convergence and suggest that katabatic winds in intensifying during the century. The peak of moisture convergence intensification observed in autumn (April) is consistent with Chap. 3 results. The SAO variability could explain the autumn maximum. The increase in the whole of Antarctica in moisture convergence can be explained as the combination

Clausius-Clapeyron law for the quantity and the atmospheric circulation changes for the spatial distribution of this increase (e.g. positive trend of SAM index). However, a thorough study of the evolution of the atmospheric circulation and its impact in Antarctica (SAM, SAO, PSA, BAM, ZW3 pattern) is required to explain moisture convergence in more detail.

Precipitation is projected to increase in Antarctica by the end of the century (+9mm/month). There is a large increase centred in autumn with a peak of precipitation in April. Only positive values are observed in all sectors and for all 12 months. A double peak of precipitation (autumn, spring) is observed for the ABS sector. It is related to ASL variability (SAO), which brings more moisture to the AIS in autumn than in other seasons. On the seasonal maps, an almost global increase is observed. The AIS shows a smaller increase in precipitation than the oceanic part. Only the Ellsworth Land (summer and winter) and the Ross Ice Shelf (summer) show large negative values, but no valid explanation has yet been found. The coastal region of the WS and IO sectors shows a large increase in precipitation, especially in autumn and winter and is explained by the interaction between the increased amount of moisture and the AIS slopes. Precipitation increases are related to moisture increases in the air and thus to the temperature. The change in the spatial distribution of precipitation is due to the intensification of atmospheric circulation.

## Conclusion

The Earth is experiencing global warming, which is reflected in increasing temperatures over the decades. The release of greenhouse gases due to anthropogenic activities is the chief cause of this increase. This temperature increase has many impacts, and the polar regions are the scene of major changes. One of the challenges is the change in the global hydrological cycle. This led to questions about the atmospheric hydrological cycle in Antarctica.

The main objective of this master thesis was to understand the atmospheric hydrological cycle in Antarctica for the past and future. Here we study the seasonal variability, the evolution during the last four decades, and the change of the atmospheric hydrological cycle by the end of the century.

The first question we tried to answer was about the seasonal variability of the processes involved in the atmospheric hydrological cycle and what explains this variability. An intensification of the general cycle in autumn is observed. Indeed, the three processes, evaporation, moisture convergence and precipitation, showed an increase in autumn. Since the spatio-temporal variability of these processes is large, a spatio-temporal study of these three processes was conducted. And a spatio-temporal study of temperature, sea ice and atmospheric circulation is carried out to explain this variability.

For evaporation, temperature and sea ice plays a major role in the variability of this process. The seasonal cycle of evaporation shows an increase in summer followed by a maximum in autumn. Evaporation then decreases in winter before rising slightly in spring. On the AIS, evaporation is always low due to low temperature and high altitude.

For moisture convergence, atmospheric circulation plays the leading role. In particular, the SAO is a semi-annual mode of climate variability that causes an intensification of the

atmospheric circulation twice a year (autumn and spring). This has helped to explain the increase in convergence during these seasons. Spatial variability has also been highlighted with three privileged regions, determined by the atmospheric dynamics of the southern hemisphere. The Foehn effect over the Antarctic Peninsula explains the lower moisture convergence in the WS sector, while the high activity of the ASL explains the large moisture convergence in the RS and ABS sectors. The steep slopes of the AIS explain the low moisture convergence over the continent.

Finally, the precipitation is mainly explained by the convergence of humidity and the region's topography. The seasonal precipitation cycle shows an increase in precipitation in summer followed by a maximum in autumn. Precipitation then decreases until early summer. The main effect observed that leads to condensation is the orographic lifting. This effect is due to the combination of topography and atmospheric circulation. The spatial precipitation variability is similar to moisture convergence variability, thus only little precipitation is observed on the continent. It was found that the RS and ABS sectors have a more significant water balance than the other sectors.

The second question we tried to answer was about the evolution of the atmospheric hydrological cycle over the last four decades and the causes of this evolution.

For evaporation, no significant trend is observed. However, an increase in evaporation over the continent and a decrease in evaporation over the ocean were observed. The trend patterns of temperature and sea ice help explain the spatial distribution of evaporation trends. A positive trend band off Marie Byrd Land was observed and explained by the decreasing sea ice concentration and increasing surface temperature in this region. In the ABS and RS sectors, negative trends were observed. These regions were partly located in the  $60^{\circ}S$  where the sea ice concentration is less than 15%. The decrease in surface air temperature in these regions is the main explanation for the existence of these negative trends. The increasing temperature on the Peninsula explains the increase of evaporation in this region. The effect of coastal polynyas is also marked by increased evaporation where they are located.

For moisture convergence, a positive trend of  $+0.48\text{mm/year/year}$  is observed, which leads to an increase of 5.6%. The intensification of the atmospheric circulation and the increase in temperature explains the increase in moisture convergence in the IO sector. Furthermore, a complementary study on the trend of the BAM mode could complete our understanding of the positive trend region in the IO sector. The convergence in the PO sector is weakened by a decrease in temperature and atmospheric circulation. Offshore of the RS and ABS sectors, an increase in convergence is observed and contributes substantially to the overall pattern of increase in convergence in these sectors. The coasts of Marie Byrd Land show a decrease in convergence, while the coasts of Ellsworth Land show an increase. A further study of the trend of PSA1 mode could be interesting to understand these regions of opposing trends

better. Indeed, the PSA1 mode creates an opposite meridional flow between the East and West of the ABS coasts, which explain the increase in the East and decrease in the West. In the WS sector, an increase is observed, especially on the eastern coasts of this sector. All sectors except the PO sector show an increase in moisture convergence, which is related to the observed global increase in Antarctica (Fig. 14).

Finally, for precipitation, a positive trend of  $+0.48\text{mm/year/year}$  is observed, leading to an increase of 4.1%. As for the moisture convergence, a majority of positive trends are found. However, two main regions show negative trends, located on the coasts of the PO sector, which extends along Cape Adare and on the coasts of Marie Byrd Land and towards the interior of this Land. The decrease over these two regions of decline is linked to the increase over Ellsworth Land and the western Peninsula by an increase in the SAM index, which modifies the atmospheric circulation. Over the east side of the Peninsula, the Foehn effect explains the small changes observed. A precipitation increase is observed due to the large increase in convergence in the IO sector. The same is true for the WS sector, which also experiences precipitation increases. Over the continent, the Clausius-Clapeyron relationship explains the observed precipitation except for the Ross Ice Shelf region. All sectors show an increase in rainfall except the PO sector. Globally, an overall intensification of the cycle has been observed in Antarctica during the last four decades.

The last question we tried to answer concerns the projections of the atmospheric hydrological cycle at the end of the century.

The evaporation process is projected to intensify by 10.41% by the end of the century in Antarctica. The evaporation change over the continent is negligible compared to the evaporation change over the ocean. The main reason for the evaporation increase is the decrease in sea ice concentration, which is directly related to the increase in temperature. Therefore, evaporation change is chiefly marked in old ice-covered regions. The oceanic part, which exhibits negative values of evaporation difference, are regions near  $60^\circ$  and the reduction of the temperature difference between sea and air can explain this. On an annual scale, winter is the season of greatest evaporation intensification, and this is explained by the significant change in sea ice that occurs during this season.

Moisture convergence is projected to increase by 22.11% by the end of the century in Antarctica. An increase in the katabatic winds can explain the diminution of the moisture convergence in the divergence regions. The projected seasonal variability is again explained by atmospheric circulation (SAO) variability. The amount of moisture in Antarctica is projected to increase due to the Clausius-Clapeyron law, and changes in atmospheric circulation explain changes in the spatial distribution of moisture. The positive trend of the SAM index over the century suggests an increase over West Antarctica and a decrease over East Antarctica. But further studies about the future impacts of modes such as SAO, SAM, BAM, and

PSA are needed to understand the future atmospheric dynamics in Antarctica better.

Precipitation is projected to increase by 18.53% by the end of the century in Antarctica. There is an increase in precipitation throughout the year, but the maximum is encountered in autumn. The AIS shows a minor increase in precipitation than the oceanic part. Only the Ellsworth Land (summer and winter) and the Ross Ice Shelf (summer) show large negative values, but no valid explanation has yet been found. The coastal region of the WS and IO sectors shows a large increase in precipitation, especially in autumn and winter and is explained by the interaction between the increased amount of moisture and the AIS slopes. Precipitation increases are related to moisture increases in the air and thus to the temperature. The change in the spatial distribution of precipitation is due to the intensification of atmospheric circulation.

The end of the century expects a general intensification of the atmospheric hydrological cycle. With a maximum intensification of moisture convergence and precipitation in autumn and winter and a maximum intensification of evaporation in winter. It should be noted that a model generated these data, and as we saw in chapter 2, the ACCESS data overestimates the data from the ERA5 reanalysis. Therefore, quantifying the projected increase may have to be revised downwards considering Chap. 2 results. However, the cycle's evolution depends on the future scenario (e.g. RCP8.5). Therefore with confidence in the ACCESS-ESM1.5 model, it can be concluded that the projection of the atmospheric hydrological cycle will take this direction.

This work provides a basis for studying the atmospheric hydrological cycle. To further understand the atmospheric hydrological cycle, a study of the evolution and impact of internal modes of variability (e.g. SAM, BAM, PSA, SAO) is essential and would be highly relevant. In addition, since the atmospheric hydrological cycle is a sub-part of the global hydrological cycle, this work could be a first step in studying the global freshwater cycle.

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