Formation of Antarctic Bottom Water
Part I : General knowledge

Culture Sciences
de l'Ingénieur

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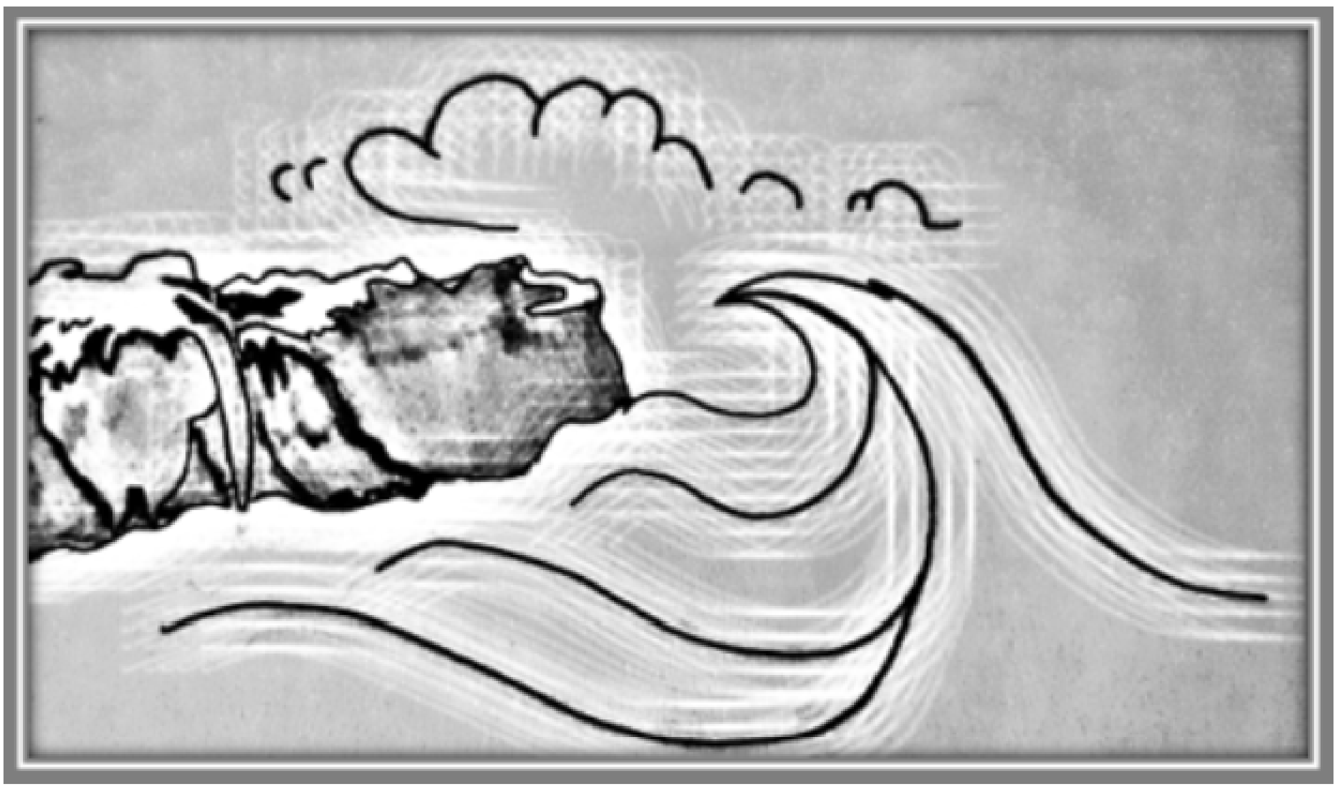
Published on :
May 2021

école normale supérieure paris—saclay



This document comes from a one-year internship at Southampton University (UK), with Mr. Alberto NAVEIRA-GARABATO and Mr. Alessandro SILVANO. Noémie SCHIFANO is a final year student at Ecole Normale Supérieure Paris-Saclay. After a first-year master degree in civil engineering, she had pursued a second-year master degree in physical oceanography at Ecole Polytechnique.

Acknowledgments I would like to thanks Mr. Alberto NAVEIRA-GARABATO and Mr. Alessandro SILVANO for all the help they have provided me during this internship. I would also like to thanks Mr. Farid BENBOUDJEMA and Mrs. Hélène HORSIN-MOLINARO for making this publication possible.

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1 Introduction

Oceans are the thermal regulators of the Earth : solar radiations warm up the ocean, whose heat storage capacity is much higher than the atmosphere's and the land's. Due to the spherical shape of the Earth, equatorial region accumulates more solar radiations than the poles. As the region close to the Equator receives the most solar radiations, a natural oceanic circulation, from the Equator to the poles, is set up. This circulation is the Meridional Overturning Circulation (MOC). The MOC is an important phenomenon for the biodiversity because it regulates the Earth thermal heating, but also because it transports nutrients, oxygen and carbon dioxide.

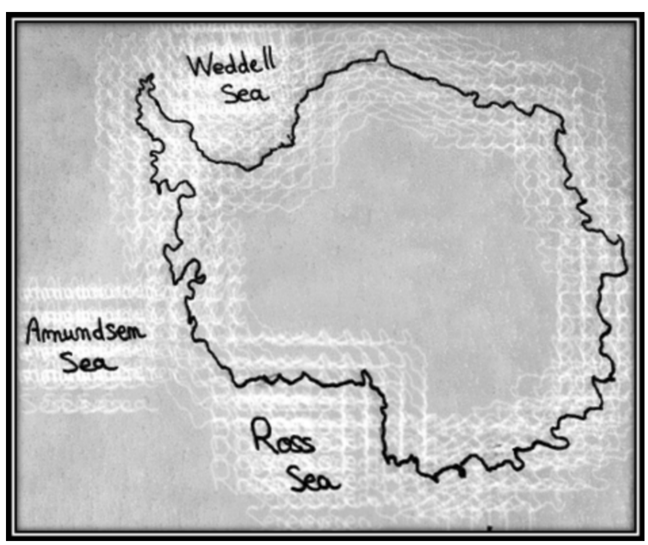
MOC is mostly composed by a surface circulation from the Equator to the Poles, and an abyssal circulation. When waters transported by the MOC reach the Poles, one part is transformed in sea ice. Because of this sea ice formation, there is a brine rejection, i.e. under-ice waters become saltier. There is a huge salinity gradient in those area, and then a density gradient, where denser water are at the surface of the Ocean. Therefore, heavy surface waters sink into the abyss : this is called "bottom water formation". Bottom water are the waters which transport oxygen, carbon dioxide and nutrients from the surface of the ocean and the atmosphere to the deep ocean.

Our knowledge about Antarctic Bottom Water (AABW) is limited, principally because of the difficulty to measure Antarctic water properties. Indeed, sea ice puts a stop to experimental studies. There are possible only in Summer, in specific area.

The purpose of this internship, topic of these publications, is to measure AABW formation thanks to satellite data. The results are then compared with in−situ data (Argo floats and one mooring). **This document presents general knowledge in physical oceanography, and more specifically in Antarctica**. Then, a document which presents satellites used, Argo floats and mooring will be published. A third document, providing this internship result, will finally be published.

Writer's Note

In this document, many handwritten drawings and schematics are used. The purpose, by linking art and science, is to offer students another way of visualisation and, hopefully, a good understanding of physical processes.



2 The team work

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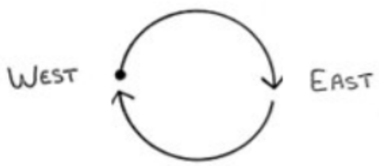
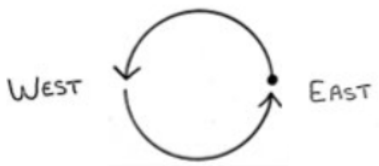
3 Oceanography basics

3.1 Vocabulary



Northern Hemisphere
Anticyclone
Southern Hemisphere
Cyclone



Northern Hemisphere
Cyclone
Southern Hemisphere
Anticyclone

Easterly = Westward

Flow from East to West

Westerly = Eastward

Flow from West to East

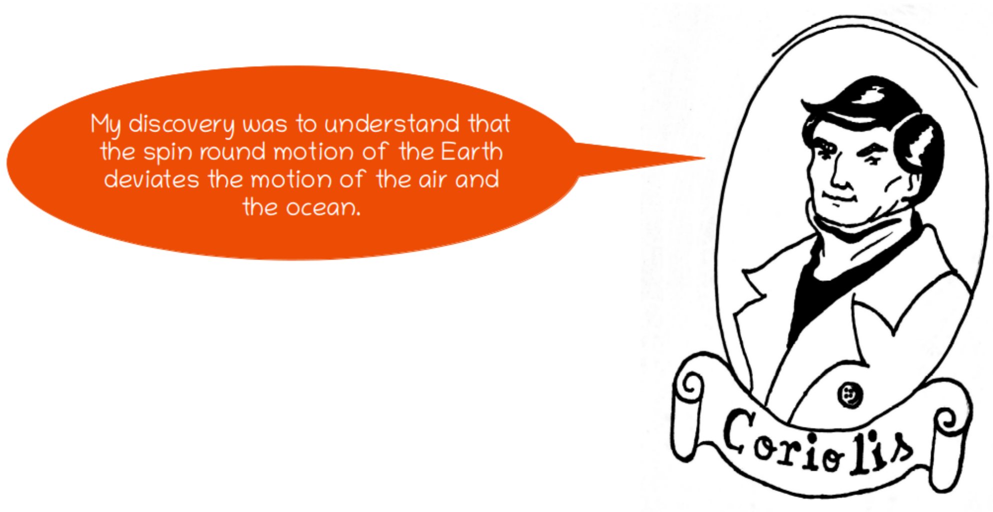
Isopycnal

Layer of waters which has the same density, but can have different combination of temperature and salinity.

Density anomaly

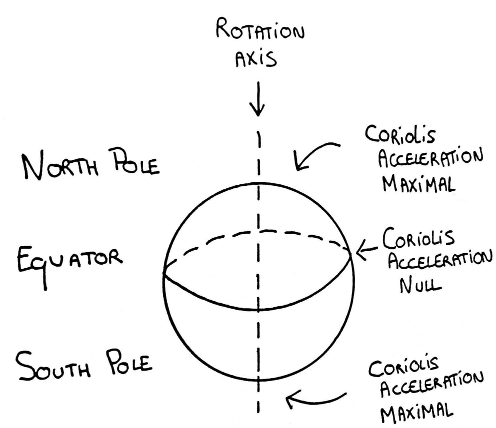
By convention, the density anomaly is the density minus 1000 $kg.m^{-3}$. It is used by oceanographers to describe waters densities.

3.2 Coriolis acceleration



In a spinning-top, the air around it will move differently than if the top does not spin. The acceleration of the top makes the air around it accelerates too. The same phenomenon occurs with the Earth. The acceleration produced by the Earth's rotation is called the <u>Coriolis acceleration</u>.

The term "Coriolis force" refer to the force due to Coriolis acceleration.
The Coriolis acceleration changes depending on where you are on Earth. The closer to the Earth rotation you are, the stronger the Coriolis acceleration is :



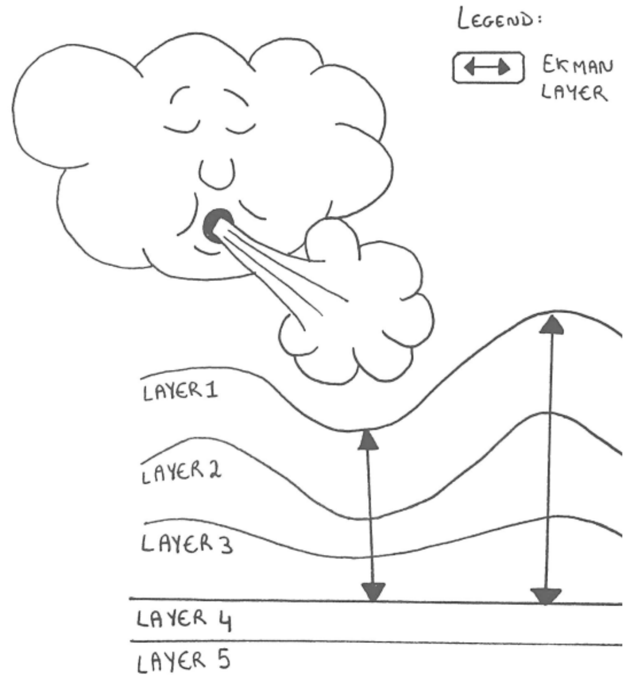
Is their a difference between Northern and Southern hemispheres ?

Yes ! The direction of the Coriolis force is opposite in Northern and Southern hemispheres.
A fluid is deviated in clockwise direction in Northern hemisphere and in counterclockwise direction in Southern hemisphere.

3.3 Effect of the wind on the ocean

The wind pushes the water on the surface of the ocean. While moving, the surface of the ocean takes (by friction) the water beneath. By this way, the effect of the wind is visible in a thin layer underneath the surface of the ocean. This layer is called Ekman's layer. Water motion due to the wind is called Ekman transport.

You can see that the wind takes layer 1 in motion, which takes layer 2, which takes layer 3. However, from layer 4, the wind does not have any effect on the ocean. The Ekman's layer is composed by layers which moves because of the wind, so here layers 1,2 and 3.



You have probably heard about cyclonic circulations and anticyclonic circulations. These two rotating winds do not have the same impact on the ocean. To understand this, we will use the the « right hand's rule».

The right hand's rule

Put your right hand in front of you, and switch your thumb to your right hand's palm. You may notice that your right arm moves away from you. If now you switch your thumb to the exterior of your hand, your arm goes closer to you (cf fig. 1).

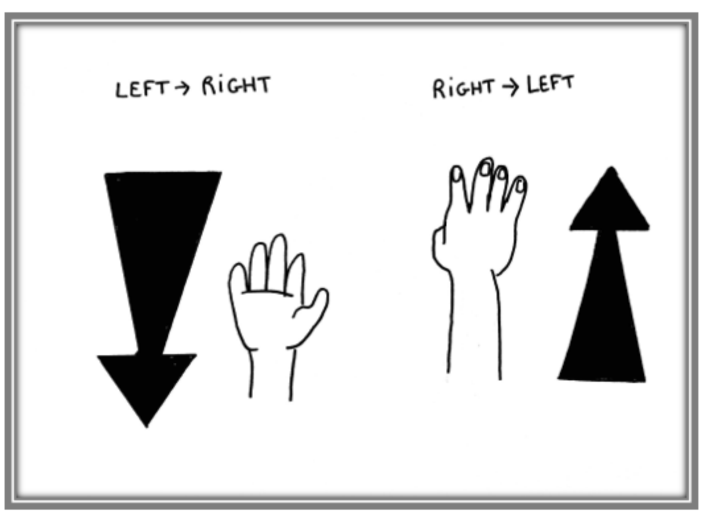


Figure 1: Schematic of the "right hand rule".
Valid in Northern hemisphere.

Links with cyclones and anticyclones ...

The figure 4 presents a summary of the effect of cyclones and anticyclones in the Southern and Northern hemispheres.

... In the Northern hemisphere

A cyclone turns from the right to the left. The cyclone produces the same effect than when you turn your right hand thumb to your hand palm, that is to say the cyclone pushes water at the center of the cyclone away from it. As the water closed to the center of the cyclone are pushed away, it creates a hole in the ocean underneath the cyclonic center. This allows deeper water to come to the surface of the ocean (fig. 2, 3). A **cyclone** makes deep waters upwell, this is called "**Ekman pumping**".
On the opposite, the anticyclone turns from the left to the right. It is similar to your right thumb when you switch it to the exterior of your hand. An anticyclone will bring the water close to its center. As the water accumulates at the center of the anticyclone, it creates a bump in the ocean underneath the anticyclonic center, and sink into the deeper ocean (fig. 2, 3). An **anticyclone** makes surface waters sink, which is called "**ventilation**".

... In the Southern hemisphere

In the Southern hemisphere, the rotation of cyclones ant anticyclones is reversed : a cyclone flows from West to East and a anticylone from East to West. Why ? It is due to Coriolis force which reversed in Southern hemisphere (see part "Coriolis acceleration"). As the Coriolis force is reversed, Ekman transport is reversed too.
Their rotation is reversed, as the Ekman transport : a **cyclone** also results in **Ekman pumping** and an anticyclone in a **ventilation**.

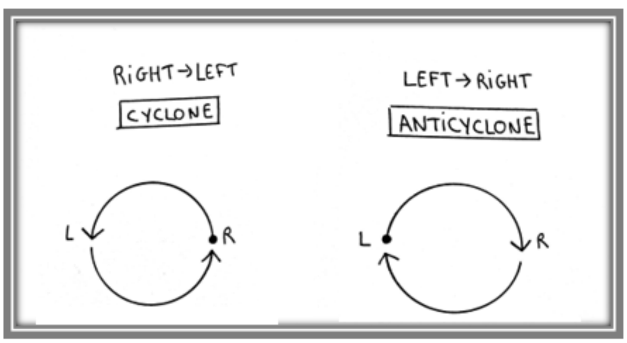


Figure 2: Schematic upper view of cyclone and anticyclone in Northern hemisphere.

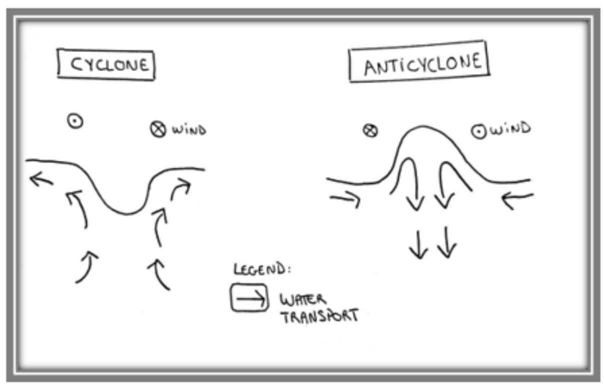


Figure 3: Schematic side view of the effect of cyclone and anticyclone on the ocean in Northern hemisphere.

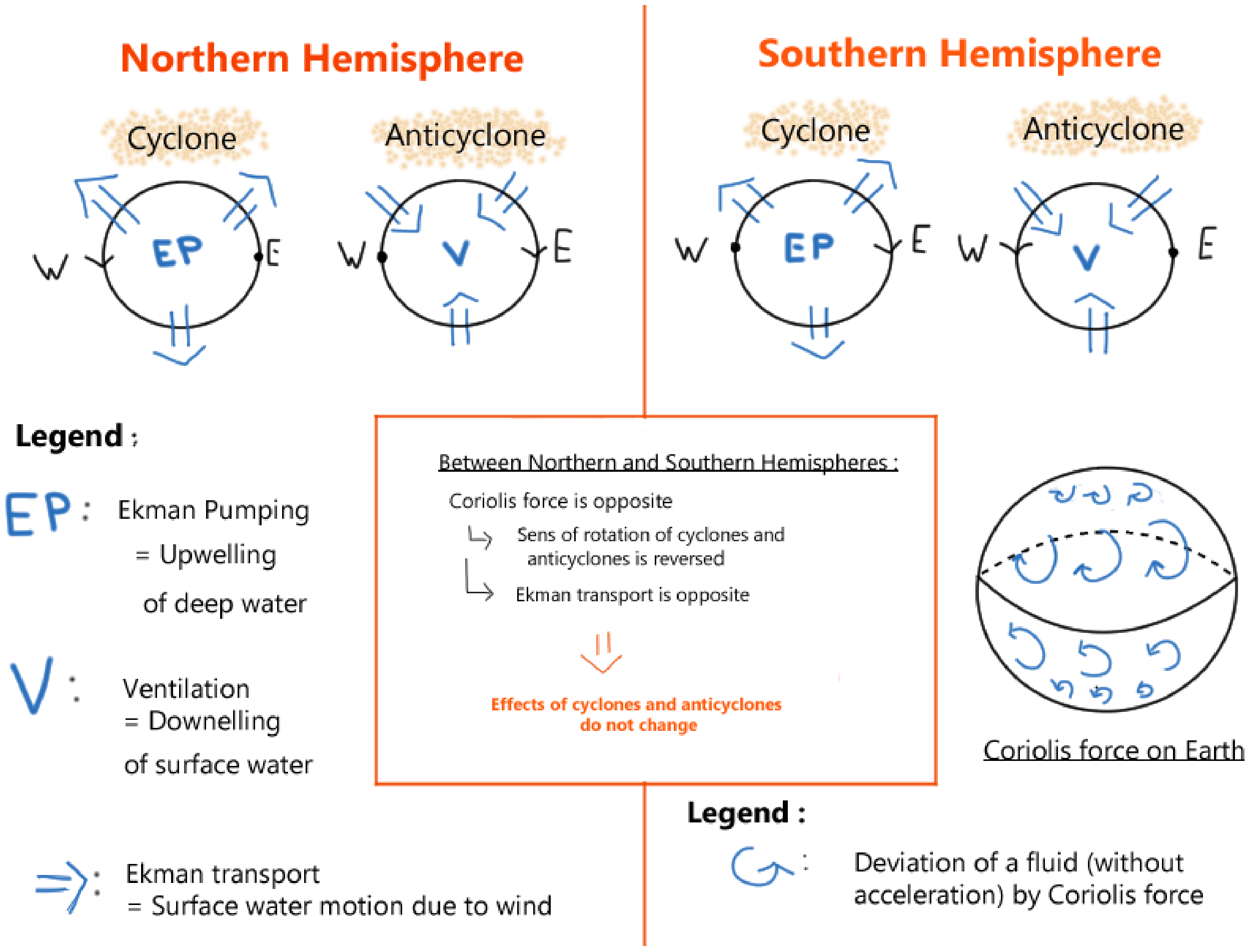


Figure 4: Summary of the effect of cyclones and anticyclones

3.4 Upwelling

Upwelling happens when deep waters rise to the ocean surface. Because strong sea winds pushes away surface waters, deep waters are able to reach the surface of the ocean (fig. 5). Places where upwelling occurs, see Fig. 6, are associated with a **strong fishery**. Indeed, deep waters bring a lot of nutrients from the abyss to the surface. These nutrients are required for phytoplankton to develop, and phytoplankton are the base of marine food chain.

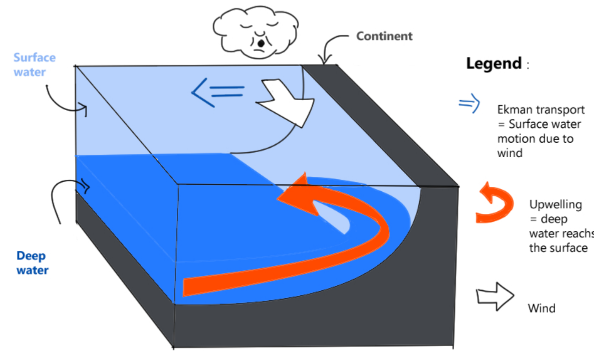


Figure 5: Schematic of upwelling

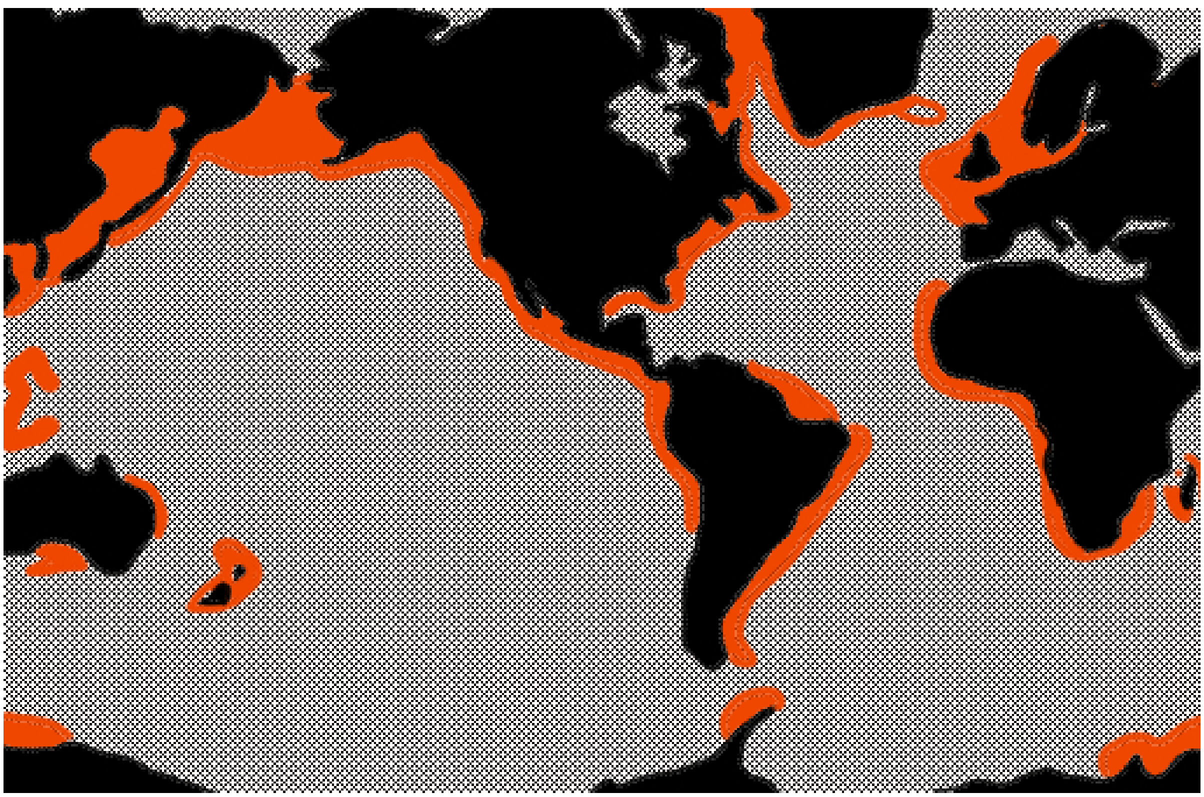


Figure 6: Upwelling areas (orange areas)

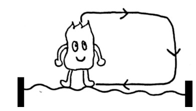
3.5 El Niño - La Niña

3.5.1 What are El Niño - La Niña ?

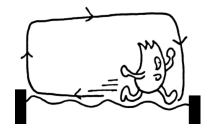
El Niño and La Niña are a sea-water temperature perturbation in tropical Pacific ocean. Those phenomena are **cyclic**, they both occur every few years. Their origin is not known, but it has been shown that they are linked with the Southern Oscillation. Southern Oscillation is a meteorological phenomenon in which the pressure at the sea surface of the Pacific ocean is periodically reversed (from "high" to "low" pressure and vice versa).

El Niño

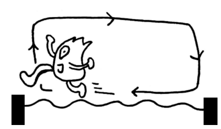
Specific winds in Pacific ocean, called **"Trade winds", become weaker**. Trade winds weakening redirect sea-water current : a hot sea-water current, initially in central tropical Pacific ocean, moves south-eastward. Clouds are created above hot sea-water. If hot sea-water moves, the location of clouds formation and precipitations also moves. The precipitations, now in eastern South-America, modifies marine winds, which **impede upwelling to occur**. Therefore, phytoplankton can not be developed (see part "Upwelling"). El Niño **limits fishing activities**.



(a) Normal conditions



(b) El Niño conditions



(c) La Niña conditions

Figure 7: Clouds formation in central pacific at the Equator. *Left black rectangle is Asia, right black rectangle is South-America. Arrow represents atmospheric circulation.*

La Niña

On the opposite of El Niño, La Niña appears when the **Trade winds strengthen**. This results in cooling Eastern Pacific ocean because the hot sea-water current is now in Western Pacific ocean. Clouds can not be created in the East of South-America, where **upwelling becomes stronger** than usual. During La Niña, **fishing is abundant** in eastern South-America!

Trade Winds

Trade winds are the permanent east-to-west prevailing winds that flow in the Earth's equatorial region (fig. 8). They were discovered by Portuguese in 15th century. Portuguese used this wind for trading. Trade winds discovery had been considered as a state secret by the spanish government until the 19th century - end of business by sail boats (Arte, Francis Drake).

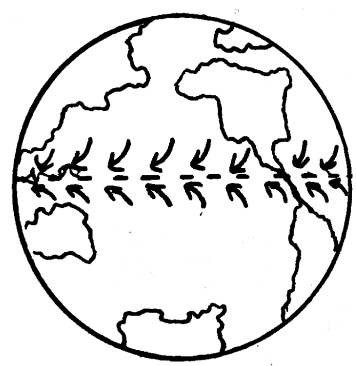


Figure 8: Trade winds (represented by arrows). *Dashed line is the Equator.*

3.5.2 Climatic impacts of El Niño and La Niña

El Niño and La Niña have a worldwide climatic impact, see figures 9 and 10. **El Niño Southern Oscillations (ENSO)** is the name of the cycle of warm El Niño and cool La Niña episodes that happen every few years in the tropical Pacific ocean.

How will ENSO be affected by climate change ?

"Extreme El Niño and La Niña events may increase in frequency from about one every 20 years to one every 10 years by the end of the 21st century under aggressive greenhouse gas emission scenarios. The strongest events may also become even stronger than they are today.", said Michael McPhaden, Senior Scientist with NOAA's Pacific Marine Environmental Laboratory in Seattle.

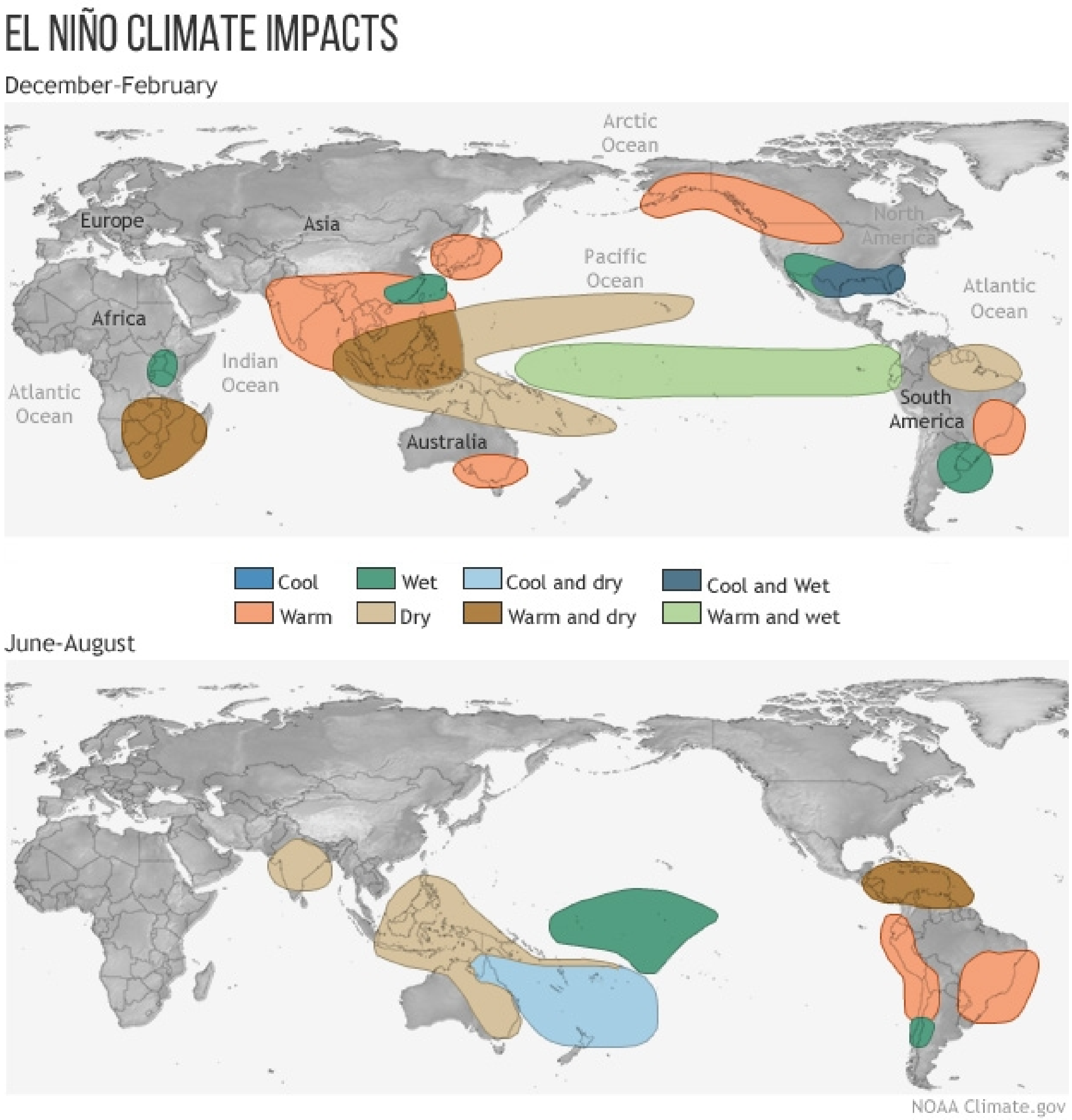


Figure 9: Impacts of El Niño (Globe Program)

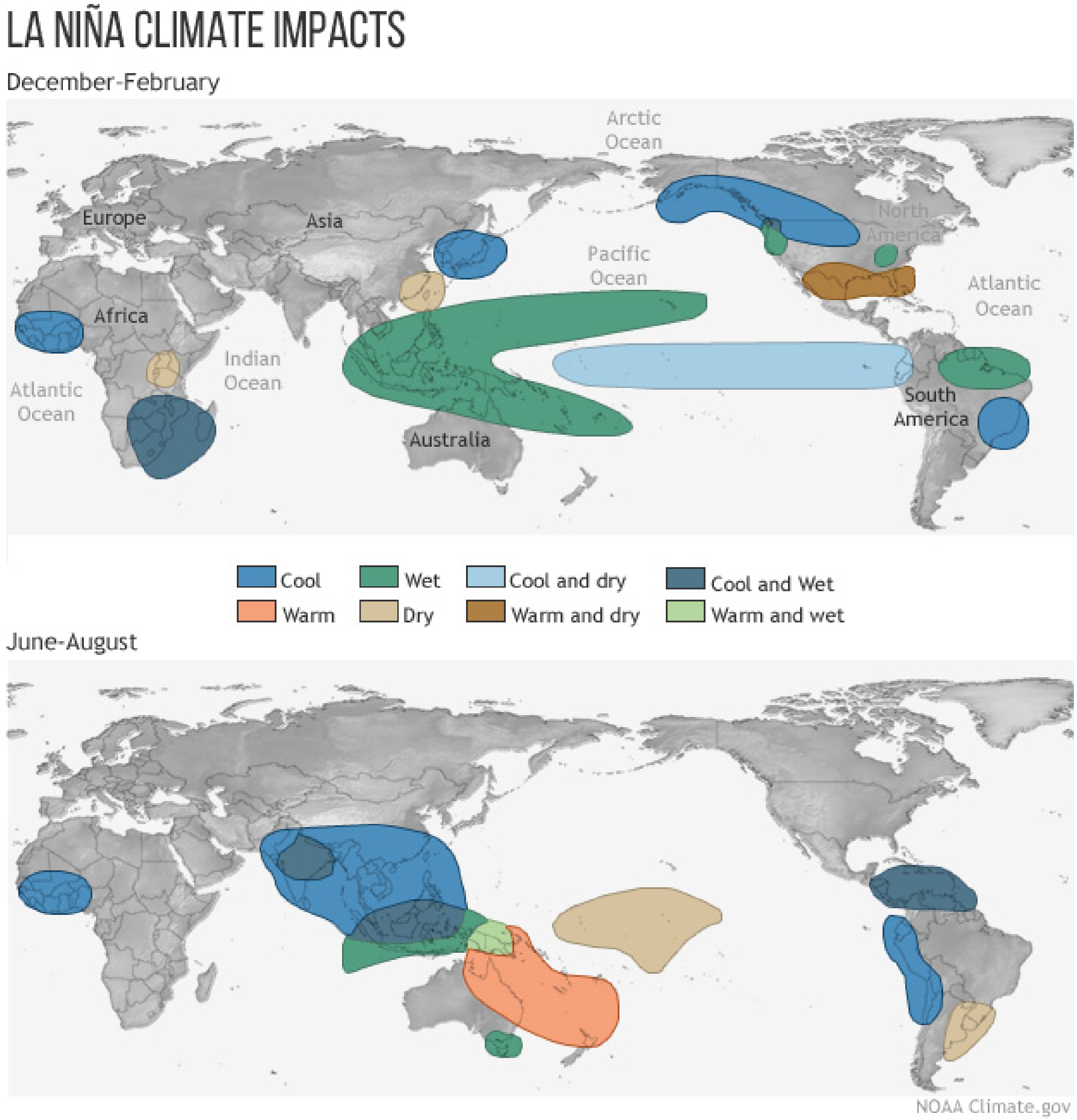


Figure 10: Impacts of La Niña (NOAA)

Do you know ?

South-american fisherman have discovered El Niño phenomenon : about every 5 years, there were no fish at Christmas period. The name "El Niño", which means "little boy" in spanish, is a reference to Jesus.

The Moche civilization, who lived in Peru from about 100 to 700 AD, was used to do human sacrifice to avoid strong rain, i.e. El Niño effect (Bourget 2016).

4 Introduction to Antarctica characteristics

4.1 What are the properties of Antarctica water ?

Before understanding the physical phenomena that comes about in Antarctica, let me introduce you the several kind of water masses that can be found. It is important to notice that in Antarctica, what drives water deeper is its salinity and not its temperature, because salinity gradient is stronger than temperature gradient. The saltier a water is, the heavier it is. Likewise, the colder a water is, the heavier it is. There are 4 varieties of water (Morrison and al., 2020)(Jenkins and al.,2016) :

Antarctic Surface Water
(ASW)

ASW is in the surface of the ocean near Antarctica. It is in contact with ice shelves and/or atmosphere. Therefore, ASW is cold and fresh water.

Circumpolar Deep Water
(CDW)

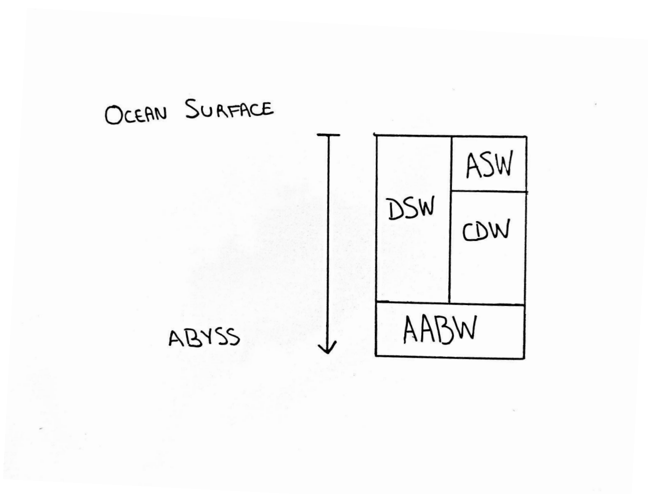
CDW is found in the deep ocean, it is salty and hot water. This kind of water is usually offshore, i.e. the CDW core is located far away from the continent.

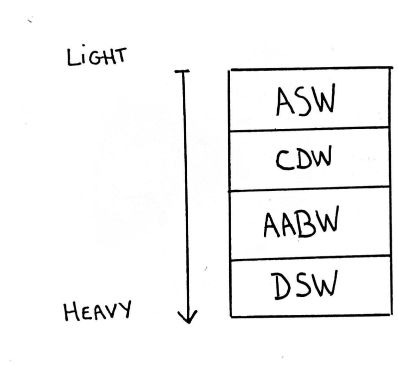
Dense Shelf Water
(DSW)

DSW does not form everywhere around Antarctica. DSW is created when ASW freezes and becomes ice, ejecting all its salt in the ocean. So, salty and cold water is formed : this water is DSW. It is formed in the upper ocean, and sinks into the deep ocean because of their weight. It is the heaviest water of the world !

Antarctic Bottom Water
(AABW)

Antarctic Bottom Water (AABW) is heavy abyssal waters in Antarctica. AABW is defined as waters with a density anomaly superior at 28,27 kg.m-3 (Jacobs and al., 2004).





4.2 What are the main ocean currents around Antarctica ?

Two main currents, cf fig. 12, are found around Antarctica (Dotto and al., 2019, 2020):

Antarctic Slope Current (ASC)

It is a quasi-circumpolar current, which flows westward around Antarctica. This current is closed to the continent, and separates the continent shelf from open ocean waters.

Antarctic Cicumpolar Current (ACC)

This flow is offshore (far away from the continent), and goes eastward. It separates tropical and Antarctic waters.

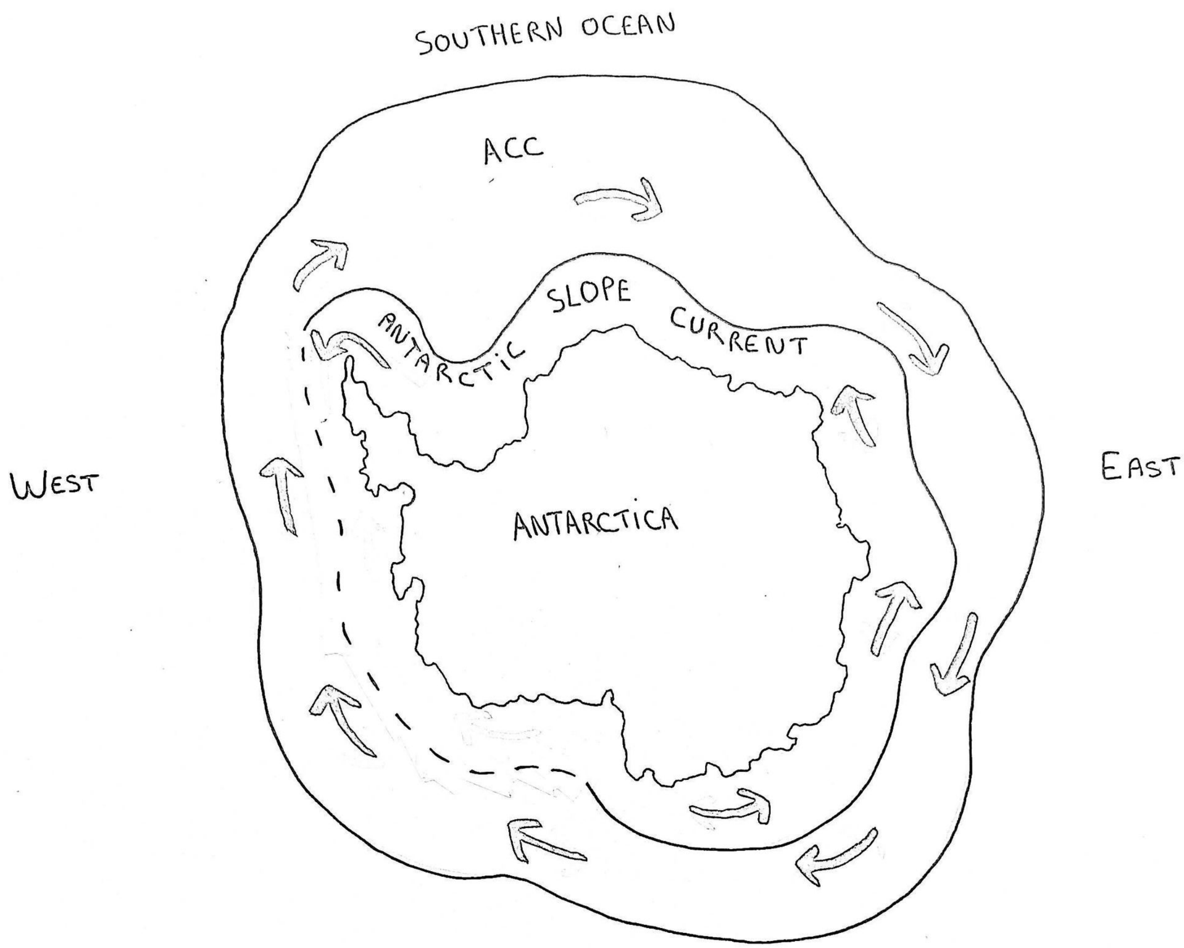


Figure 12: Main currents around Antarctica
Dot line : the ASC is not observed everywhere (e.g western Antarctic Peninsula). Its temporal and spatial variability are poorly known.

Strongest exchange between the Antarctic Slope current and the ACC occurs in two gyres (fig. 13): the Weddell gyre in the Weddell sea, and the Ross gyre in the Ross sea. These gyres allows water from the open ocean (i.e. from the ACC) to mix with the Antarctic Slope Current waters.

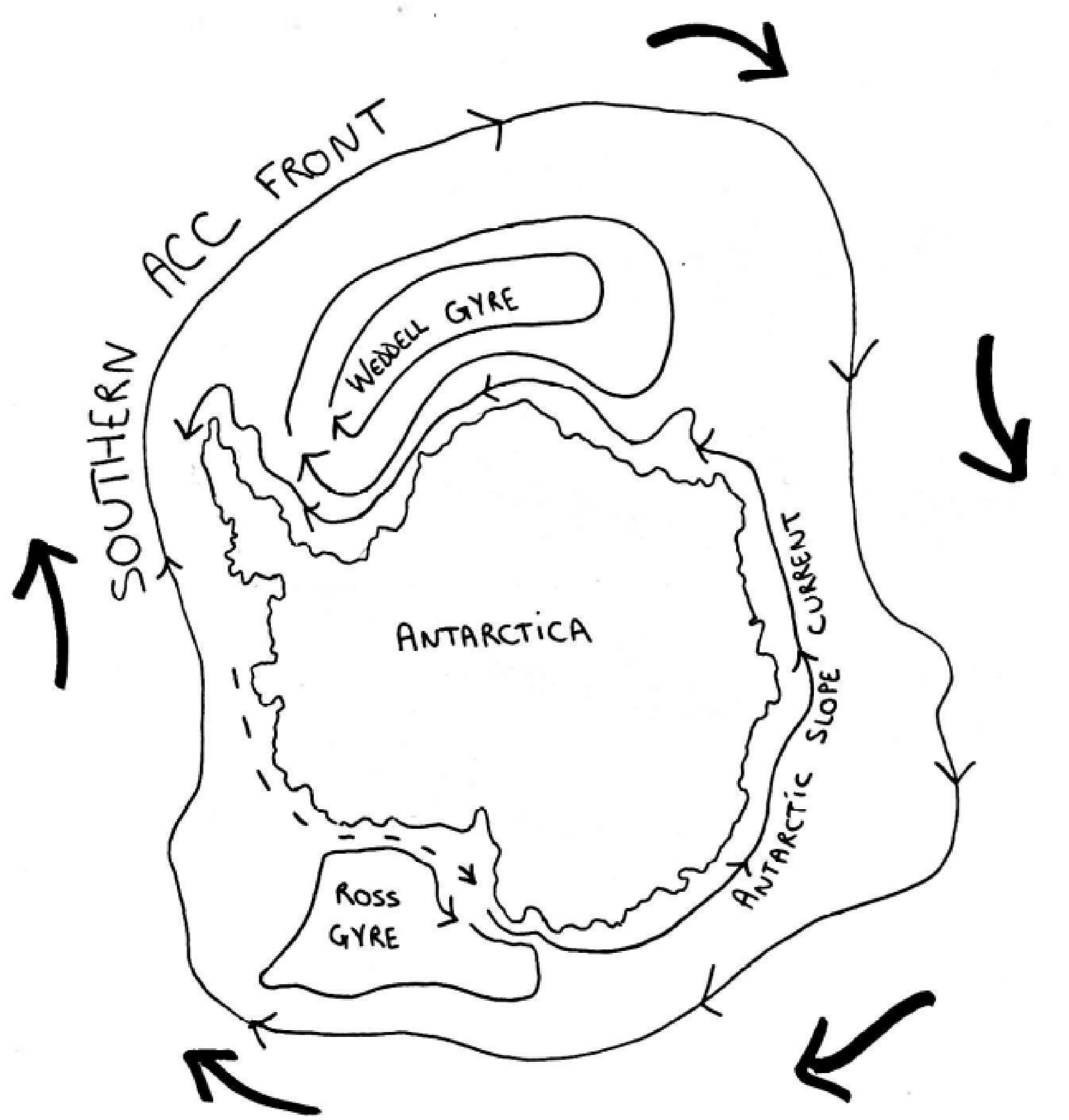


Figure 13: Interactions of the main currents around Antarctica
Dot line : the ASC is not observed everywhere (e.g western Antarctic Peninsula). Its temporal and spatial variability are poorly known.

4.3 One Antarctica, three continental shelves

Around Antarctica, three kind of interactions between ASW, CDW and DSW are found. Figures 14-16 present these interactions. Figures are a view side of the Antarctic continental slope : right side is open ocean and left side is Antarctica. Dashed area is the Antarctic Slope. There are three types of continental shelves (Thompson and al., 2018)(Silvano and al., 2016) :

Fresh Shelf

Fresh Shelf is shelf where there are strong easterly winds, resulting in a lot of ASW in the continental shelf(Ekman transports). In these shelves, the front which separates ASW from CDW is very important. The hot and salty CDW can not enter onto the continental shelf (or can in a very little proportion).

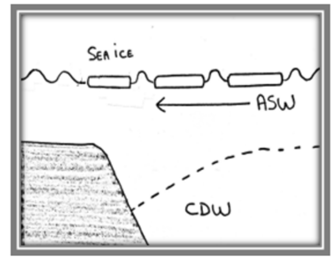


Figure 14: Interactions of ASW and CDW on Fresh Shelf

Warm Shelf

In the West Antarctica, the westward flowing ASC is weak or is absent, and the ACC is very close to the continental shelf. Therefore, the CDW transported by the ACC have access to the continental shelf, warming it.

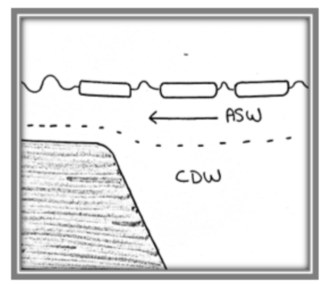


Figure 15: Interactions of ASW and CDW on Warm Shelf

Dense Shelf

Dense Shelf is associated with a strong and constant formation of ice, enabled with a katabatic wind which pushes away the ice already formed. DSW is formed, and sinks along the continental shelf until it reaches the abyss and forms AABW. While DSW sinks, CDW can enter into the continental shelf and warm it.

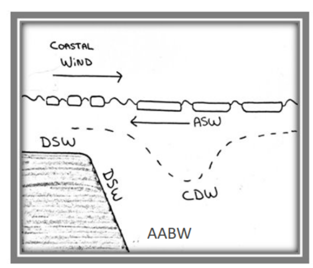


Figure 16: Interactions of ASW, DSW and CDW on Dense Shelf

Legend :

ASW motion due to Ekman transport

Front separating ASW from CDW

4.4 Locations of these three continental shelves

Fresh Shelf

They are over large parts of Eastern Antarctica, and in the western Amundsen/ eastern Ross seas (fig. 17).

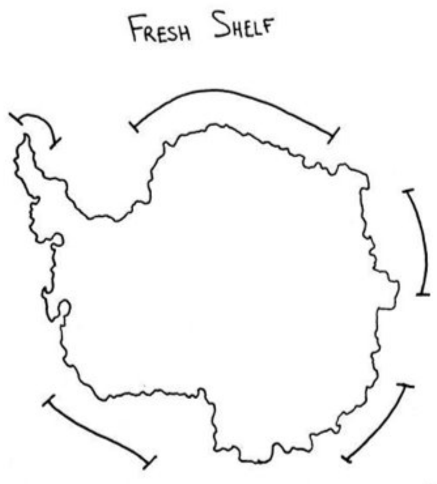


Figure 17: Fresh Shelf location

Warm Shelf

They are along the West Antarctica Peninsula and in the Bellingshausen sea (fig. 18).

Figure 18: Warm Shelf location

Dense Shelf

They are in the western Ross sea, the Weddell Sea, the Adelie coast and in the Cape Darnley (fig. 19).

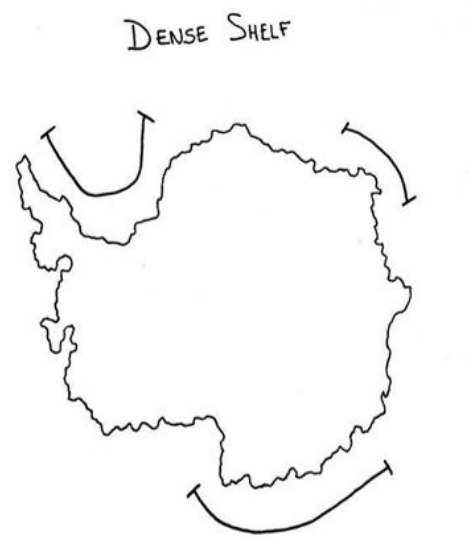


Figure 19: Dense Shelf location

5 Glaciers melting in Antarctica

Glaciers thinning in the Amundsen Sea is the most extensive and rapid among Antarctica. The Amundsen Sea ice shelf has undergone intense mass loss since at least 1990 (Jenkins and al. 2016). Why do glaciers melt ? Is it because a warming of the ocean or of the atmosphere ?

5.1 Morphology of the Amundsen Sea

The Amundsen sea shelf is a Fresh Shelf, where hot deep CDW are separated from cold surfacic ASW (see part "One Antarctica, three shelves"). It has been recently highlighted that an undercurrent, flowing eastward beneath the westward Antarctic Slope Current, is present only in the Amundsen Sea. This undercurrent transports CDW (fig.20).

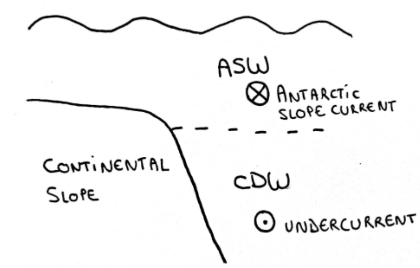
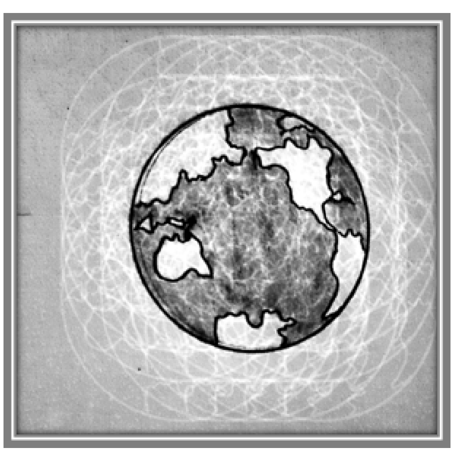


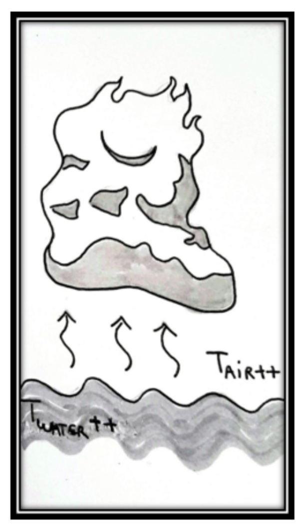
Figure 20: Schematic of the Amundsen Sea

5.2 Tropospheric height anomaly

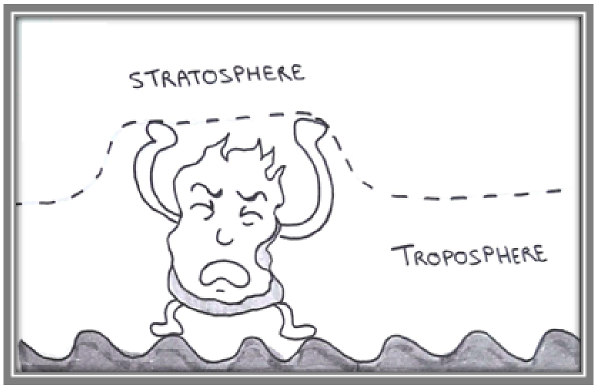
All begins in the central tropical Pacific Ocean. As all the Earth, Central Pacific Ocean experiences surface warming because of greenhouse gases ejection.



Surface warming enhances atmospheric convection, which results in a bigger number of clouds.



This high number of clouds creates tropospheric height anomalies (Jenkins and al. 2016).



This height anomaly will spread as Rossby wave, until it reaches the Amundsen Sea.

5.3 Effect of the tropospheric height anomaly

Trospopheric height anomaly modifies the zonal wind direction in the Amundsen sea (Dotto and al. 2019, 2020):

Westerly wind anomaly

Westerly wind anomaly strengthens the undercurrent transporting CDW : CDW upwells and reachs the shelf. Here, hot CDW mixes with cold ASW, warming the shelf. Because the shelf temperature increases, ice melting is enhanced.

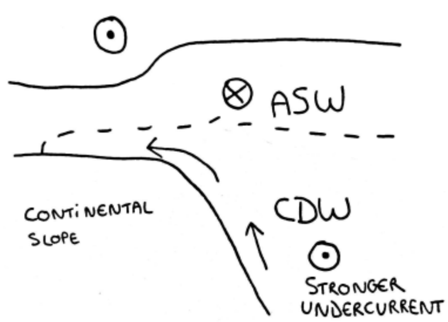


Figure 21: Schematic of an westerly wind anomaly in the Amundsen sea

Easterly wind anomaly

Easterly wind anomaly creates a downwelling motion of the waters : CDW still reaches the continental shelf, but its intrusions are reduced with easterly anomalies, and the undercurrent is weaker. This wind anomaly cools the Amundsen Sea.

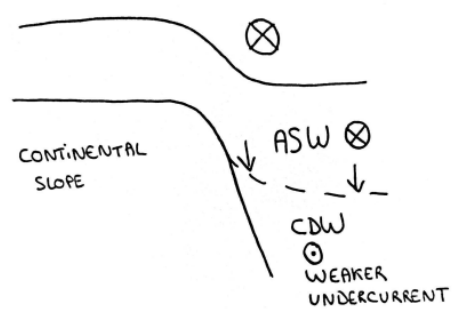
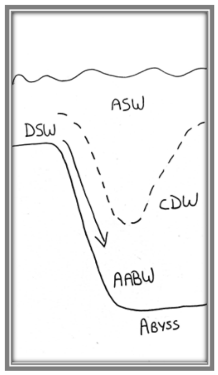


Figure 22: Schematic of a easterly wind anomaly in the Amundsen sea

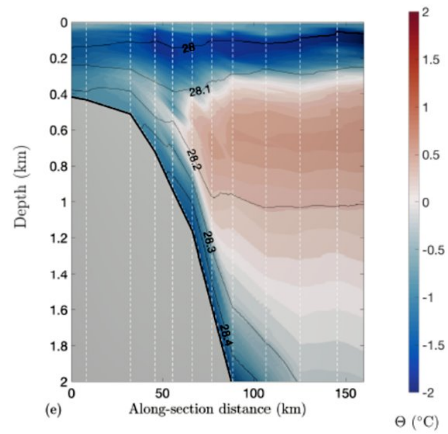
6 Antarctic Bottom Water

6.1 Focus on the Dense Shelf

In the dense shelf, the frontal structure which separates ASW from CDW has a V-shapped. This V-shapped accomodates both an on-shore transport of CDW and the export of DSW (Thompson and al. 2018). Figure 23 shows the isopycnal shape in the Western Weddell Sea as function of the depth. The isopycnals tilt down towards the seafloor over most of the continental slope. DSW (layer with a neutral density superior at 28,3 kg.m-3 on fig. 23) is carried across the shelf break in a dense outflow layer. DSW will then form Antarctic Bottom Water (AABW).



(a)



(b)

Figure 23: (a) Schematic of AABW formation and (b) measurements of conservative temperature (colors) and neutral density(black contours) across the Antarctic Frontal Structure in the Western Weddell Sea (Thompson and Heywood, 2008)

6.2 Antarctic Bottom Water

How is AABW formed?

It is formed due to brine rejection when sea ice forms in the Dense Shelf (Nicholls and al., 2009). When DSW is created, it sinks into the deep ocean until it reaches the abyss : AABW is formed. At the moment where DSW reaches the abyss, it is not longer DSW, but it is AABW.

Where is AABW formed ?

The Weddell Sea is an important place of AABW production. It is viewed as a major source of AABW production, but there are potentially upstream sources that increase the amount of AABW that accumulates and then leave the Weddell Sea. (Jacobs and al., 2004)(Nicholls and al., 2009).The Ross Sea also produces AABW, where about 25 % of the total AABW formed comes from the Ross Sea (Orsi and al. 2002).

Where does AABW go ?

Densest AABW are trapped in the Antarctic abyss. AABW which mixes with lighter waters can join the Southern Oceans, via the Weddell and Ross gyres. In the Southern Ocean, AABW and CDW mix, before be spread worldwide thanks to the meridional overturning circulation, see fig. 24 (Jacobs and al., 2004). **Between 30 and 40 % of ocean waters are AABW !**

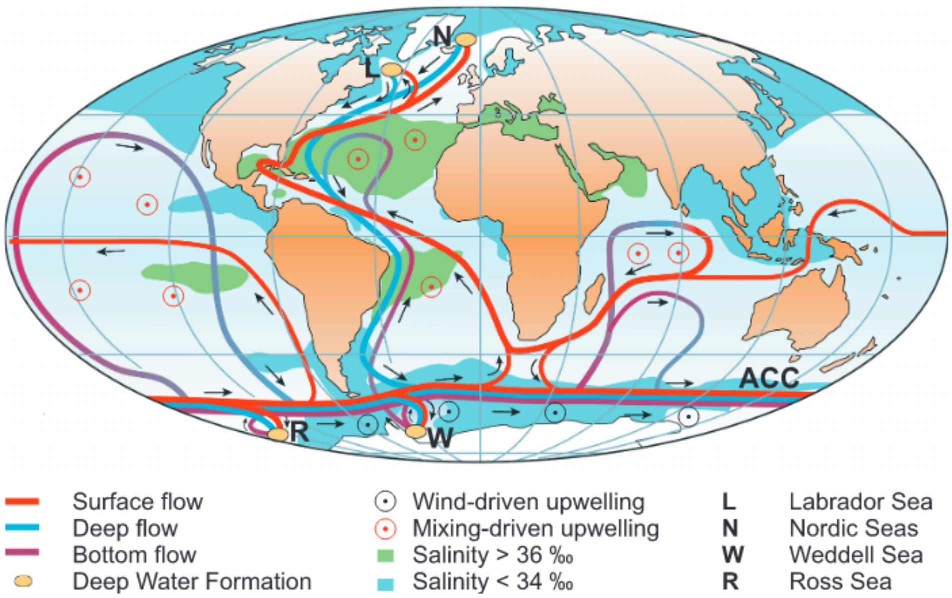


Figure 24: Meridional Overturning Circulation (Kuhlbrodt and al., 2007)

7 Purpose of this work

As you understood, formation of AABW is an important process. AABW is essential to renew worldwide ocean's water (ocean's ventilation). However, our knowledge on how and where AABW is formed is limited. This is explained by the difficulty to do experimental studies in Antarctica, due to icebergs and ice shelves.

New satellite data bases potentially allow to compute the formation of AABW. Therefore, **our aim is to calculate AABW formation using satellite data**. First, formation of AABW will be computed by joining together several satellite databases. Then, to evaluate this computation, satellite results will be compared with in situ data (Argo floats and mooring). If we succeed, it will be a great advance. It will allow researchers to quantify the important phenomenon which is formation of AABW.

How can AABW formation be measured thanks to satellites ? What are Argo floats and mooring ? How do all of this technologies work ? The next publication aims to answer those questions !

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