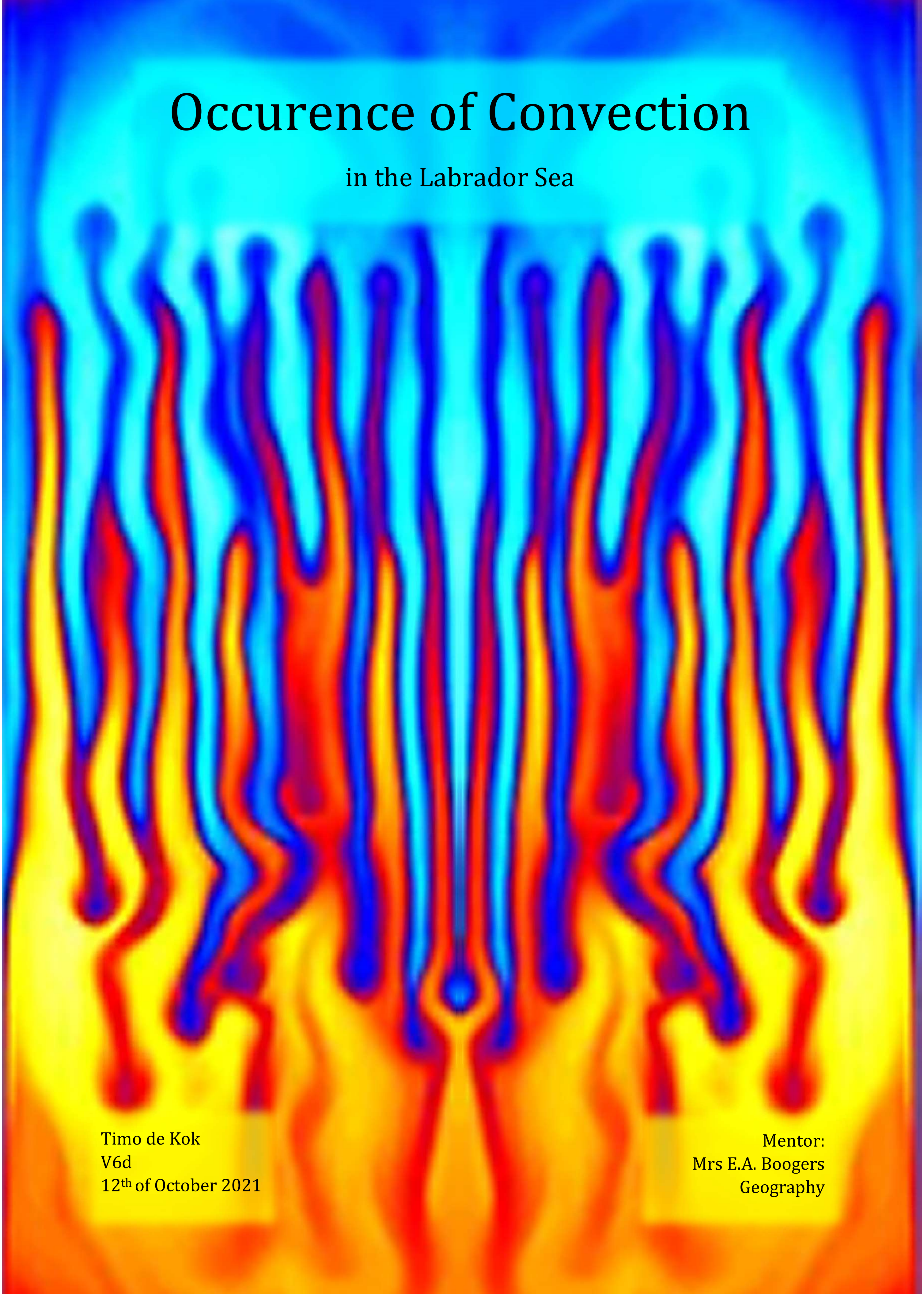

Occurence of Convection

in the Labrador Sea

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V6d
12th of October 2021

Mentor:
Mrs E.A. Boogers
Geography

Preface and Acknowledgements

Halfway the fifth school year of the VWO every student has to write a research paper to show that they have mastered the skill of doing research. In the research paper you can implement everything you have learned in the past five years. In January 2021 I started brainstorming about the subject I wanted to choose. Rather quickly I knew it had to revolve around something which had to do with physical geography.

I have always been attracted to the physical geography. During high school I was, and I still am, really intrigued by climate, ocean currents and the rock cycle. But the most interesting about the earth I find water and ocean currents. When I was in primary school, I had already made a paper which was about ocean currents and that is mainly the reason why I decided to take a subject from the branch of oceanography.

Before choosing a specific subject, I decided to contact the faculty of oceanography at the TU Delft. I am really happy that the TU was keen to help me and they immediately send my mail to the right person to answer it. The person who helped me to choose my eventual subject was Caroline Katsman. She is associate professor in oceans and climate. Through contact with her I decided to do my research about convection in the Labrador Sea as it is a relevant subject nowadays and fits in with my interests. During my research I have also talked with her via teams and zoom twice and she has provided a huge amount of information for me to use. I would therefore want to thank Caroline Katsman very much for her input and quick and in-depth help. Without her it would have been very difficult for me to make this research possible.

I would also want to thank my research paper mentor Ellis Boogers for guiding me through the process of my research.

Lastly, I would like to thank my parents for their help. They have helped me with checking my research paper text and they have listened to my endless chattering.

Abstract

The ocean currents are basically driven by density differences between the poles and equator. Near the poles, in this research the Labrador Sea, cold dense water sinks down in deep water formations. When dense cold water lies above less dense, warmer water, the denser water sinks through the less dense water which is called convection. This research has been set up to determine what the reason is for the occurrence of convection in the Labrador Sea and why the convection depth is not constant, but fluctuating.

On first sight, temperature differences between summer and winter seem to promote convection and the strength of these differences will determine the depth of convection. Differences in currents and therefore sea water temperature will therefore let the convection depth change. To test this hypothesis a lot of data has been gathered from Argo floats. These floats delivered data from the Labrador Sea from 2007 till 2021 about temperature and salinity. This data was analysed to determine the convection depth in every winter from 2007 till 2021. This data was then compared to the surface air temperature anomaly data from the same period retrieved from the WMO climate site. The graphs which came forth out of this showed interesting correlations contrary to the hypothesis.

The results showed that not the temperature of the sea, but the surface air anomaly was important for determining the convection depth. Generally, convection in winter is the deepest when the winter is cold and the previous summer is not too hot. The winter temperature anomaly is the leading factor here, whereas the summer temperature anomaly is less influencing on the convection depth. On top of this, temperature and salinity from the previous winters and summers is of importance in preconditioning the sea, which can positively or negatively influence the convection depth.

Altogether, the hypothesis can be rejected as convection in the Labrador Sea is primarily caused due to the surface air temperature and it fluctuates because of anomalies in the surface air temperature.

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1. Introduction

A huge part of our planet consists of water, but even though this is the case, barely anything is known about the oceans and seas on our planet. Seas and oceans are incredibly important in the regulation of the climate on earth and without oceans and seas the world would look very different.

Oceans are very important in regulating temperature and precipitation. The ocean functions as a large conveyor belt, transporting warmth. It is this function of the ocean which makes Europe much warmer than Canada, even though they are on the same latitude. As becomes evident from this example, the ocean plays a very important role on the climate on earth.

Modern-day climate is changing, and whether this is a good or bad thing, we have to cope with this. But to be able to supply everyone on this planet a home, food and safety, it is important we get to know more about the role the ocean plays in climate change. It is important to know in which ways the ocean is affected by climate change and in which ways it might cause or prevent climate change.

A step towards understanding the function of our oceans is looking at the conveyor belt function of the Atlantic Ocean. Through the North Atlantic Ocean runs the North Atlantic Current. This flow of warm water creates a relatively warm climate in Europe compared to the climate on the same latitude elsewhere. Gradually, when the current travels north, it cools down, because a lot of heat is lost to the atmosphere. At certain places in the North Atlantic Ocean, like the Irminger Sea and the Labrador Sea, this cold water is transported to the bottom of the sea. These deep-water formations are caused due to convection, a process which transports the once warm surface water from the equator to the cold deep ocean near the poles. The deep-water formations are crucial in the conservation of the ocean currents and a stop of convection in the Labrador Sea could have a massive effect on the climate in Europe and North-America.

But to know what causes convection, research is needed, and only when the reasons for the occurrence of convection are known, it is possible to tell what the effect of climate change might be on the deep-water formations.

It is known that convection is a process which is not constant every year, but it is a process which fluctuates in depth and place of occurrence. The research question of this paper will be:

What is the reason for the occurrence of convection in the Labrador Sea and why is the convection depth not constant, but fluctuating?

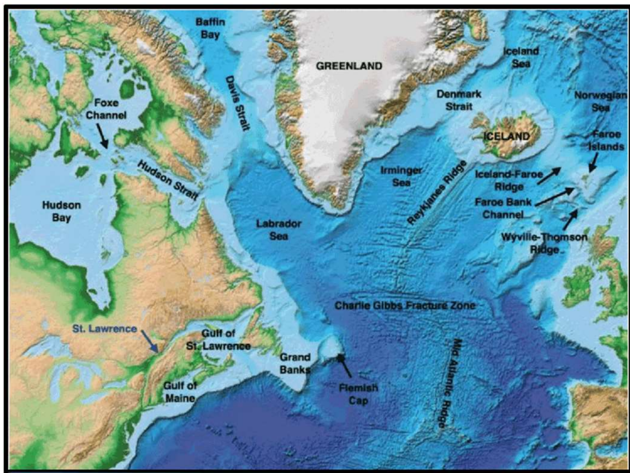
To get an answer to this research question a couple of questions will be used as a guide to the answer.

- What is convection?
- When does convection take place in the Labrador Sea?
- How deep can convection reach in the Labrador Sea?
- How does the temperature of the ocean influence convection in the Labrador Sea?
- How does the salinity of the ocean influence convection in the Labrador Sea?
- How does the temperature of the atmosphere influence convection in the Labrador Sea?

With the available knowledge at the start of the research, the reason convection might appear is due to a combination of the salinity and temperature of the ocean water. When relatively salt water from the equator enters the Labrador Sea, it will cool down and be heavier than the relatively sweet, but cold, surface water in the Labrador Sea. The cold salt water will therefore sink and set the convection process in motion. The cold salt water from the surface will drop and the sweeter deeper water will rise, eventually creating a uniform temperature and salinity.

In theory this process could happen at any time, but it would be more likely to happen when temperatures differ the most, which is in winter when warm water from the equator is cooled down the most. The convection would then be the strongest when the winter is the coldest. The incoming water is then the coldest and the difference in temperature is the biggest. The cold water will then easily sink, causing convection. A warm summer would also have a positive effect on convection as this would cause the Labrador Sea to be relatively warm in winter. The difference with the incoming cooled down water from the equator will then be the largest. The atmosphere probably does not play a huge role in convection. The occurrence of convection in the Labrador Sea would be the result of temperature and salinity differences during the winter and previous summer. Every year this difference will be different due to currents causing convection to also fluctuate.

2. Theoretical Framework



This research is about convection in the Labrador Sea. To get a better understanding of the research and it's setup, a description of the area is given and the theory behind all basic processes involved is explained.

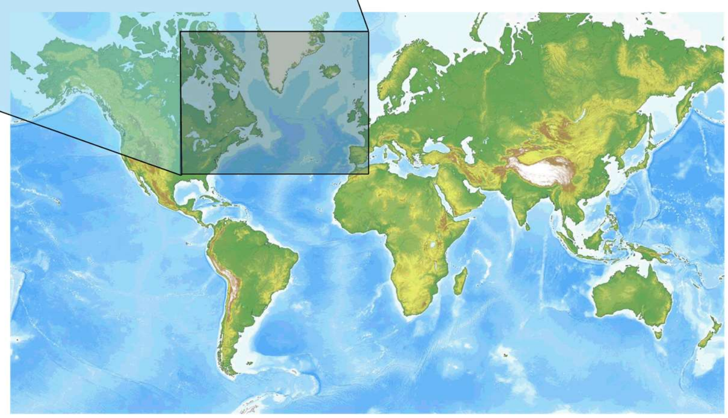


Figure 1 - Location and physical map of the Labrador Sea

2.1 The Labrador Sea

The Labrador Sea is situated between East Canada and South Greenland (Figure 1).

The Labrador Sea is an arm from the Atlantic Ocean, which lies in the south, and is connected with Hudson Bay via Hudson Strait in the west and Baffin Bay via Davis Strait in the North.

The Atlantic Ocean and Labrador Sea are divided by a line drawn between the southernmost point of Greenland (Cape Farewell) and the most eastern point of Canada (Cape St. Francis). Between these two points the sea is approximately 1500 kilometres wide and the sea narrows to only 750 kilometres at the start of Davis Strait. The sea is between 700 and 4.300 metres deep.

The sea is located just below the arctic circle which makes the water rather cold. During the winter large portions of the sea are even covered with ice. The area has no tectonic activity.

2.2 Ocean Currents

Over seventy per cent of our planet consists of water, most of which is in our seas and oceans. Even though the sea and ocean seem to stand still, they are continuously on the move. The water in seas and oceans moves in a specific direction, which has been constant for a long time now. The way water moves on our planet today, can be seen in figure 2. The patterns via which water is transported are called ocean currents and they vary in strength, size, salinity and temperature. The reason water moves in these directions is mostly due to differences in temperature, salinity and wind. The ocean currents do not only flow on the surface, but also on the bottom of the ocean. The deep ocean currents, however, are often different in direction and speed (very slow) from the surface currents. At certain points on our globe, water is transferred between the surface and deep ocean, the Labrador Sea is one of those places.

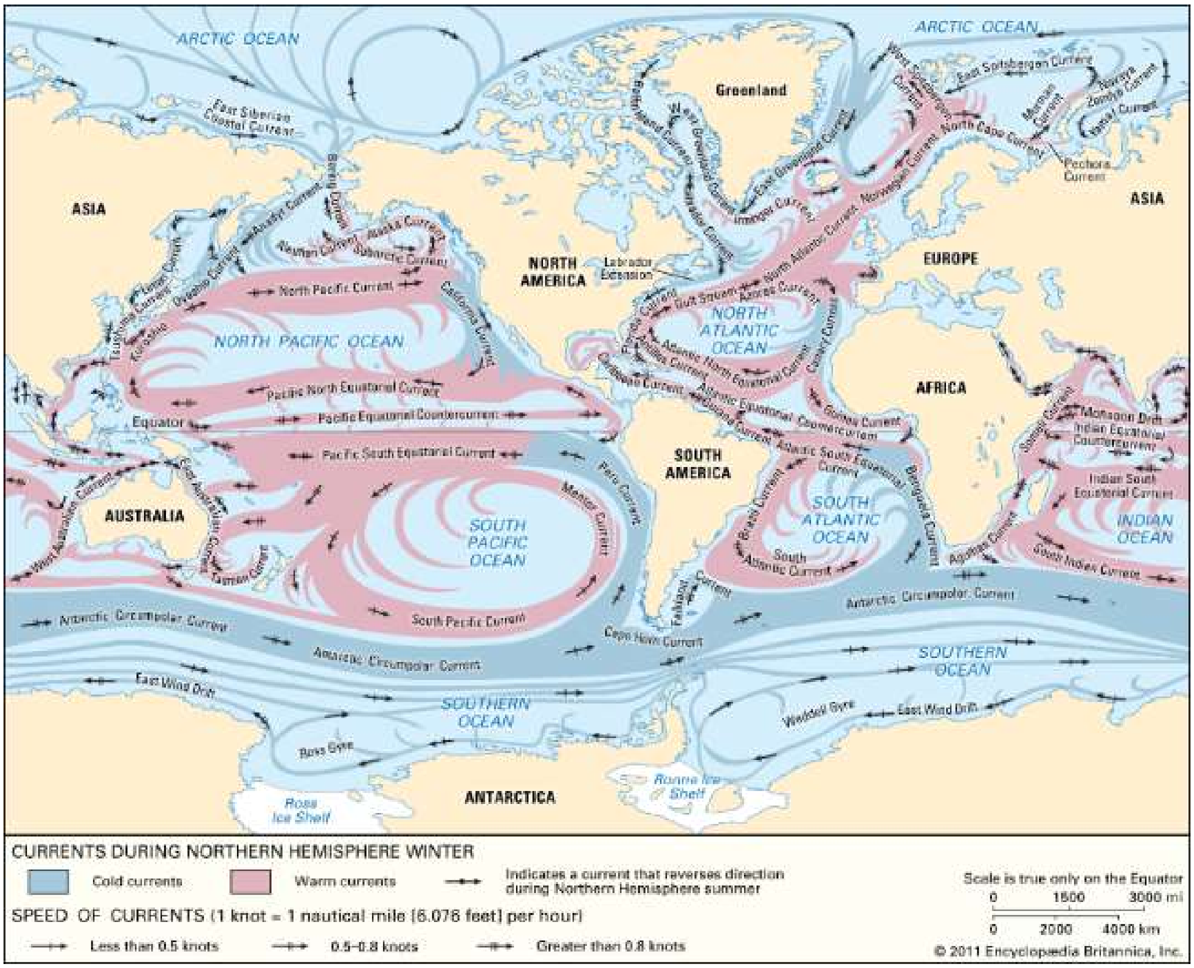


Figure 2 - Ocean currents in the world (Source: Encyclopædia Britannica, Inc. (n.d.). Major ocean current systems of the world [Map]. Consulted from https://www.britannica.com/science/ocean-current)

Temperature

Warm water is known to be lighter than cold water, the result of this is that water near the polar regions, where it is cold, will sink because of its higher density. Warmer water from the equator will then fill the gap above the cold water. The cold water will then move towards the equator again via the bottom of the ocean. Near the equator the water will rise again due to increasing temperatures. The risen water will then again move to the poles and cool down to sink and this circle will continue. Figure 3 shows this process visually.

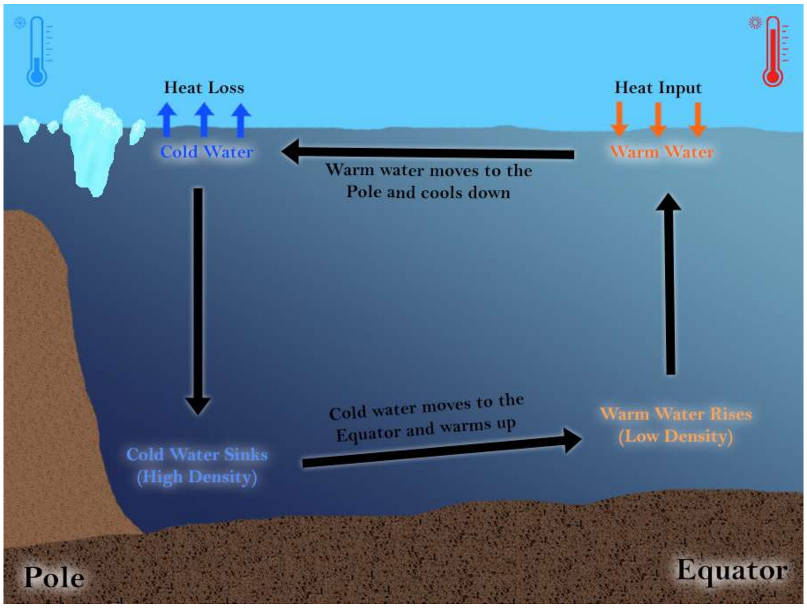


Figure 3 - Water movement initiated by temperature differences

Salinity

Salinity also plays a role in the transportation of water. The salinity shows how high the concentration of salt in water is. Differences in salinity can cause water movement, because the higher the salinity, the heavier the water.

The influence salinity has on the ocean current is actually contrary to the influence temperature has. Near the equator there is a lot of evaporation of water, but the amount of salt in the ocean will stay the same. The amount of salt per liter water will increase due to evaporation, the salinity has risen and so has the density. The water will therefore want to sink. This is contrary to the warm water which has a low density and wants to rise.

Near the poles the opposite happens. The salinity will decrease as there is little evaporation and some sweet melting water is added to the salt sea. The water will become less dense and be more buoyant. The cold temperature on the other hand creates a high density which lets the water sink.

As is evident now, the movement of water due to salinity differences actually counteracts the movement of water due to temperature differences. The two forces working together form the basics of all ocean currents and this is called the thermohaline circulation. The combination of both salinity and temperature cause density differences which determine the direction of the currents.

Winds and the Coriolis effect

A little less important role in creating ocean currents is dedicated to winds. The speed and direction of wind can influence the ocean surface to some account. As you can see in figure 2, ocean water seems to move in circles around certain spots. The rotation around these spots is caused due to the Coriolis effect.

The earth is constantly rotating around its axis. This rotation causes winds not to flow straight but curved. Winds move straight forward, but as the earth rotates at different speeds at different latitudes the winds seem to curve relative to the earth. This process is called the Coriolis effect and does not only happen with wind currents, but also with ocean currents. On the northern hemisphere this causes winds and ocean currents to curve clockwise and on the southern hemisphere this causes them to curve counterclockwise. You can see this in figure 4.

These winds together with the Coriolis effect will curve ocean currents creating the rotation around certain spots, called gyres. Deep water masses will not be influenced by the Coriolis effect as much as surface currents as they are not directly in contact with the atmosphere.

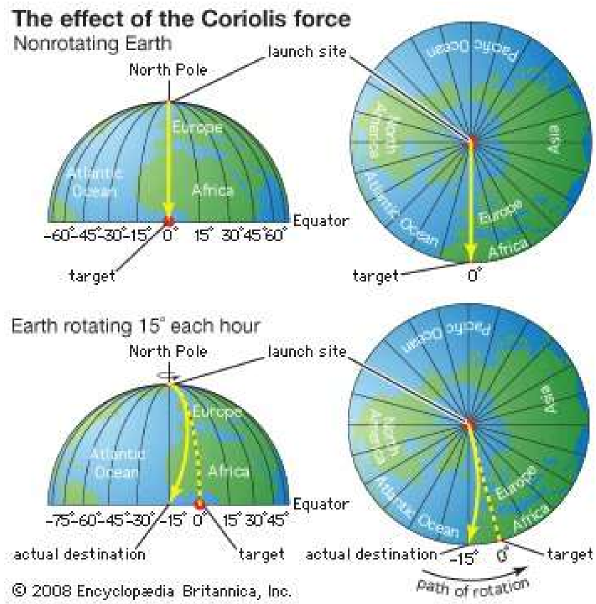


Figure 4 - The effect of the Coriolis force (Source: Britannica Editors. (n.d.). Coriolis Force [Illustration]. Consulted from https://www.britannica.com/science/Coriolis-force)

2.3 Convection

In this thesis the process of convection will be researched in the Labrador Sea. Whether convection will occur or not, depends on many factors. It is therefore difficult to predict if convection will occur.

But what exactly is convection? Most of the time in the year the Labrador Sea is structured in layers, this is called stratified. The layering is based on water properties such as salinity and temperature. Most of the time this means that heavier water (colder or saltier water) takes up most of the deeper ocean layers and the lighter water (warmer of fresher water) takes up the surface layers. All these ocean layers are relatively stable due to their different densities. Sometimes, however, it can happen that this balance is disturbed. For example, due to very cold winters or surface currents, the surface water temperature can drop. The layered water bodies are then broken up due to dense water penetrating through lighter, warmer layers and vertical mixing takes place. Water from the surface sinks down and water from the deep sea rises as a result. Figure 5 shows the sinking of colder water into warmer water like fingers pointing down. In the Labrador Sea this process cools down the warmer layers as they are mixed with the colder layers and it warms up the colder layers as they are mixed with the warmer layers. The same goes for the differences in salinity. All together, convection creates one layer with the same properties; a homogeneous layer. To conclude, the vertical mixing is what is seen as convection.

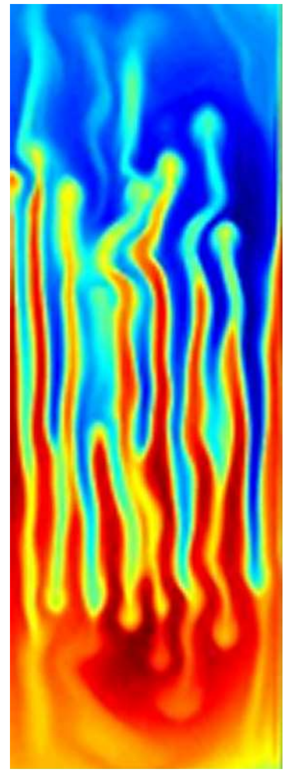


*Figure 5 - Protrusions of surface water with a higher density into water with a lower density (Source: Singh, O.P; Srinivasan, J. (2014). Effect of Rayleigh numbers on the evolution of double-diffusive salt fingers. Physics of Fluids. **26** (62104): 062104. doi:10.1063/1.4882264.)*

To make the process of convection easier to understand, figure 6 might clear things up a bit. A cross-section of the Labrador sea is being shown in this figure. In the two upper images the water is clearly stratified. Between 0 and 500 metres a lot of layers can be seen in temperature (left) as well as salinity (right). These are the properties of the water before the winter. After the winter, convection has taken place and the water has formed a homogeneous layer. The layers seen before between 0 and 500 metres are now gone due to vertical mixing; convection. As you can see, convection is known to ussually take place during the winter. As the ocean below 2.000 metres has a very thick buffer of water above it, convection does not usually get deeper than this. This research paper focusses on the 2.000 metres below the surface as this is the most interesting with regards to convection.

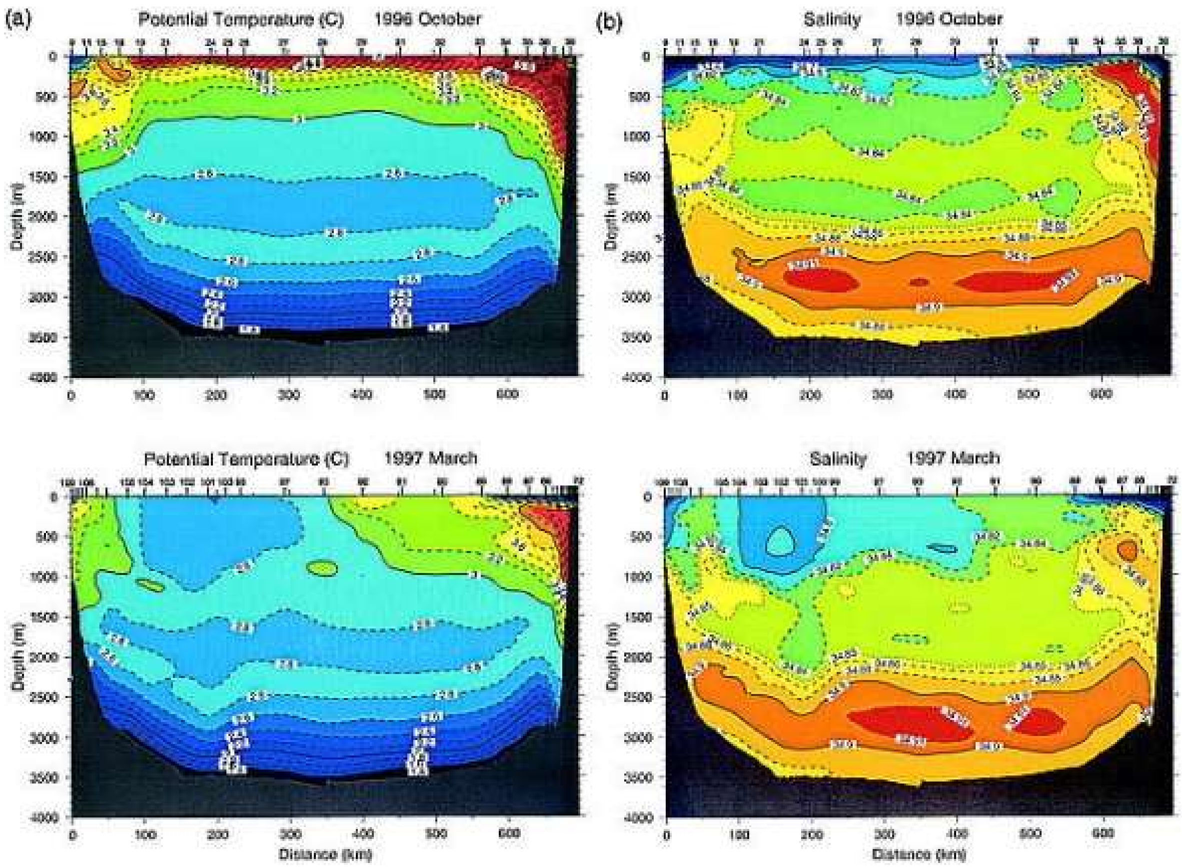


Figure 6 - Cross-section of the Labrador sea showing the temperature and salinity during October 1996 and March 1997. (Source: Pickart, Robert S., Torres, Daniel J., & Clarke ,R. Allyn. (2002) Hydrography of the Labrador Sea during active convection. Journal of Physical Oceanography 32.2, 428-457.)

The process of convection has some effect on the future and the next winter. This can also be seen in the images. In the upper two images a large relatively homogeneous layer can be seen between 1.000 and 2000 metres deep. This homogeneous layer is a remainder of convection from other years and this will also impact the chances of convection occuring the next year, as well as the atmosphere and water conditions.

In this thesis convection stands central. The factors which determine the occurance of convection are still quite uncertain and they may vary. In this thesis the initiation of convection will be researched as well as the consequences of the convection on future years. Conditions and properties of the sea and atmosphere will be researched to come to a conclusion about the forming of convection. In this research the depth of the homogeneous layer is referred to as the convection depth, even though the actual convection process will not happen in an already homogeneous layer.

2.4 Argo Floats

The data used for this research were collected and made freely available by the International Argo Program and the national programs that contribute to it (https://argo.ucsd.edu, https://www.ocean-ops.org). The Argo Program is part of the Global Ocean Observing System.

The workings of these Argo floats must be explained briefly to create an understanding of how data and information about convection has been gathered. Delivered data can be large in numbers and specific programs have been created to read it. Useful programs can be found on the Argo site. The websites used to gather data from the Argo floats in this research, fleetmonitoring.euro-argo.eu and dataselection.euro-argo.eu/view-data, have been specifically useful for this.

The Argo program has been set up worldwide to get a better understanding of our oceans. At the moment there is more knowledge about the surface of the moon than there is knowledge about our oceans. To get more knowledge the Argo program supplies crucial information to understand various ocean processes such as currents and convection.

To get all this information out of the ocean, Argo floats are deposited into our waters. These instruments are robots that cost approximately 20.000 to 150.000 USD. The Argo instrument's weight is adjusted so that it will sink to a specific depth where it will drift for ten days. Then it will sink further to its profiling depth from which it will rise to the surface to recharge its battery and send off its data. This is shown more detailed in figure 7. Most measurements are taken during the ascend from the profiling depth.

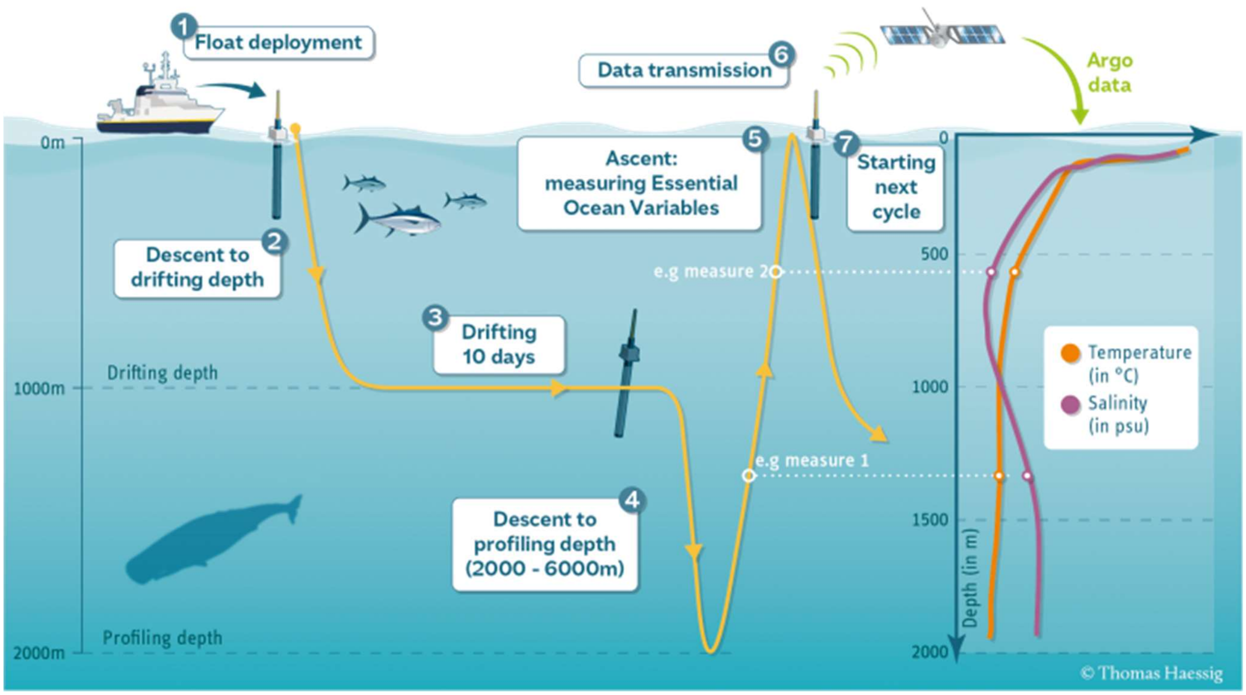


Figure 7 - Argo float cycle (Source: Argo (2000). Argo float data and metadata from Global Data Assembly Centre (Argo GDAC). SEANOE. Accessed at May 2 2021 from https://doi.org/10.17882/42182)

Most Argo floats measure pressure to determine depth and temperature and salinity. There are some, however, which measure more, such as oxygen. There are also floats which can go deeper than the regular 2.000 metres, they can sometimes go to 6.000 metres.

3. Methodology

To come to a conclusion about which factors influence convection the most, several strategies have been tried. The research has been divided in two parts in which only the second part showed real progress, therefore the first part will be covered briefly.

3.1 Research till September

During the summer holiday of 2021 a lot of time was used to figure out how to collect data. Unfortunately, the data collection manner was highly inefficient and costed a lot of time. To start off a lot of data was collected and exported to excel. In excel complicated graphs were made with the use of complex formulas. This process was tedious and heavy for the computer software. The running laptops or computers had trouble loading all data and graphs. Performing simple actions like saving and changing tabs soon started to take minutes. The formula which was used to create the graphs apparently was too difficult to perform in large numbers and therefore it was eventually decided to stop creating self-made graphs and use graphs provided by the Argo organization. This process costed around twenty hours[1].

3.2 Research in September and onwards

The start had been rough, but slowly and surely the research started to take form in September. A lot of research was done about how to collect data to get to the wanted results. Contrary to previous summer a lot of time went into searching for proper research programs. A proper structured plan had been set up to get to an answer on the research question. A lot of thinking and experiencing has created a specific plan for collecting data which, compared to each other, will hopefully answer the research question.

Controlled Variables

The first step before gathering all data is deciding what needs to be compared to get an answer. Most important here is comparing years with, and years without convection. First some controlled variables must be determined. To compare the data properly all data must be coming from the same area and from the same type of instrument. The latter will be the Argo floats, but the first one is more difficult to decide. The area must lie within the Labrador Sea, but the question is where exactly? As convection will be likely to happen in the deep parts of the Labrador Sea, the boundaries of the research area must lie within the deeper parts. As the data sets are much too big when analysing the whole area and the result becomes less specific for one spot, the area had to be split up into several smaller areas. The areas have been split up so that the chances of finding convection in one single spot are the highest and the data in each area is not too big to handle by the programs. In figure 8 you can see which areas

Figure 8 - The areas from which data has been collected.

[1] See appendix, Logbook, for exact hours

have been used. Obviously, the amount of data is also dependent on the amount of time, so the set time is 1 month.

Gathering Data

The boundaries and time span in which the data will be compared are clear now. The first question now is which data will be used to compare. To find out which factors cause convection, years with and without convection need to be compared. To collect sufficient data to compare, information from 2007 up until 2021 has been used. As convection usually takes place around winter it is important to collect information from the months January, February and March. On top of that, data from the previous summer might be interesting, so august is of use too. Then to analyse the data, the temperature and salinity will be used. In the collection of data, it is important enough data has been collected to give a realistic representation of the area. Therefore, the number of cycles per area per month have to be at least 20 to be eligible for the research. As can be seen in the results, the west Labrador Sea misses data from before 2012 due to a lack of cycles.

A lot of data gathering has been done to get all data from 2007 till 2021. Argo data delivers both adjusted and non-adjusted data, to have an as reliable as possible research, only adjusted data has been used in this research.

Analysing Data

The result of all data gathering is a lot of graphs. Every year from 2007 to 2021 has its own temperature graph and salinity graph for the months January, February, March and August. The next step now is determining the convection in every month. During the summer there usually is no convection, but during the winter a huge diversity in convection can be seen.

Figure 9 is used to show how convection has been determined. The convection depth in February 2014 was 400 metres. How can you see this?

The vertical axis shows pressure in decibar, which is approximately the same as depth in metres. On the horizontal axis stands the temperature in degrees Celsius. A characteristic of convection is a homogeneous temperature and salinity on different depths. The graph should therefore display a constant temperature till a certain depth. In the graphs this is evident in the vertical stripes downwards, because these stripes indicate that the temperature measured by one Argo float till a certain depth was a constant value. Around 400 metres deep, the vertical stripes stop and the values shift towards another temperature, so below 400 metres the sea is stratified.

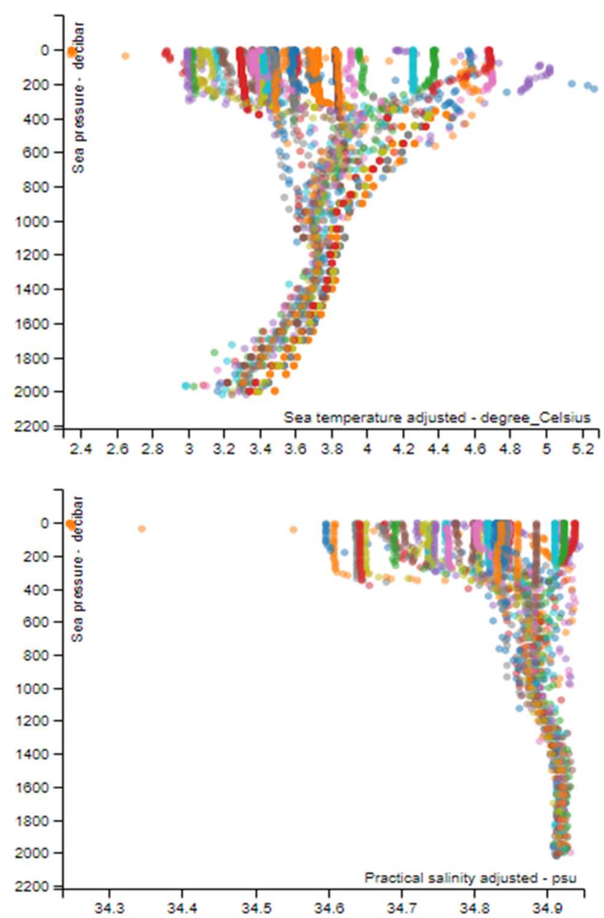


Figure 9 – Temperature and salinity graphs of the east area in February 2014. (Source: Argo (2000). Argo float data and metadata from Global Data Assembly Centre (Argo GDAC). SEANOE. Accessed at May 2 2021 from https://doi.org/10.17882/42182)

The salinity graph has also got pressure in decibar on the vertical axis, but has salinity in PSU[2] on the horizontal axis. As can be seen in the temperature graph, vertical stipes showing a homogeneous layer are also present in the salinity graph. Both graphs can therefore be used to determine convection, as in both the vertical stripes are visible. The temperature graphs however are a little easier to read due to the less diverse values on the x-axis.

When looking closely at the graphs, locally, a lot of differences can be seen in temperature. This is because every graph contains around 40 cycles from slightly different places in the Labrador Sea. To determine convection, the diversity in temperature is not of importance as a homogeneous layer does not have the same temperature at different locations. Only the temperature at one location must be the same to be recognizable as convection. Another location might have another temperature, but this temperature is also constant till a certain depth.

To determine what the depth of convection was, the deepest convection depth is taken if at least 5 Argo floats had measured convection to this depth and other cycles did not differ very much. When this is not the case, another depth which had convection shown by more than 5 cycles is taken as the convection depth instead. Not all graphs are as clear as others and therefore these rules are just guidelines. Sometimes graphs are really unorganized and the convection is a good estimation.

Surface Air Temperature Data

The last step in completing the research is to collect all convection data and plotting them in a graph. This data is compared to other data like the air temperature data from the WMO[3] website, which is also plotted in a graph. Especially the temperature anomalies[4] are useful for this, as they show which winters and summers were relatively cold and which were relatively warm.

In the Labrador Sea the surface air temperature[5] anomalies differ a lot between the coast of Greenland and the coast of Canada. In this research, anomalies from near the coast of Greenland have been taken as they seem to be more relevant to the convection. Quick data analysis shows that Canadian surface air temperature anomalies are in no way related to the convection depth. The coordinates used close to the coast of Greenland can be seen in table 1.

Table 1 – Coordinates used for collecting surface air temperature anomalies.

Area:	**East**	**Middle**	**West**
Coordinates:	-55°E to -42°E 51°N to 59°N	-54°E to -49°E 56°N to 58°N	-57°E to -50°E 61°N to 63°N

[2] Practical Salinity Unit, salinity unit equal to gram salt per kilogram water
[3] World Meteorological Organization
[4] The amount in which a value differs from the average
[5] Temperature between 2 to 10 metres above the sea surface

Proving Relations

Spearman's Rank Correlation Coefficient

After all this information has been plotted in a single graph, the only thing left to do is finding correlations between the convection depth and the surface air temperature anomaly. Firstly, Spearman's Rank Correlation Coefficient has been used to test the correlation between both data sets. The used formula is as follows:

$$r_s = 1 - \frac{6\sum d^2}{n^3 - n}$$

Here:

$\sum$ = The sum

d = The difference between the rank of the two compared data sets

n = The number of data points per set

r_s = Spearman's Rank Correlation Coefficient

To determine the rank difference of two data points, the rank of convection depth is compared to the rank of surface air temperature anomaly measured during the same time and on the same place. When for example 1.000 metres convection is the deepest depth measured in the data set, the rank number will be 1. This number is then compared to the rank number of the surface air temperature anomaly measured in the same month and place. This might be the third smallest number, for example -0,9872 K. The difference in rank would then be 3 – 1 = 2.

This number will then be squared. Doing this for every month and adding all results finds the value for $\sum d^2$. Filling in the rest of the formula will give a decimal number between 0 and 1 (if there is a correlation). The interpretation of the value (r_s) is shown in table 2.

Table 2 – The interpretation of the value r_s.

Value	Correlation Strength
Between 0,00 and 0,30	Barely to no correlation
Between 0,30 and 0,50	A weak correlation
Between 0,50 and 0,70	A reasonably strong correlation
Between 0,70 and 0,90	A strong correlation
Between 0,90 and 1,00	A very strong correlation

Observations

Statistically the correlation can be shown this way, but this is not the only thing that has to be done to show the correlation. Just by looking at the data and the graphs more relationships can be discovered.

4. Results

In the *Appendix 1, Convection Graphs Labrador Sea (2007-2021)* all plotted graphs of the salinity and temperature are collected, sorted by year, month and location. All these graphs have been closely studied to determine the convection depth. These depths are plotted in one graph which can be seen in figure 10. To see the tables and calculations made to determine the convection depth and Spearman's coefficient see *Appendix 2, Graphs and Calculations (Convection Labrador Sea 2007-2021)*.

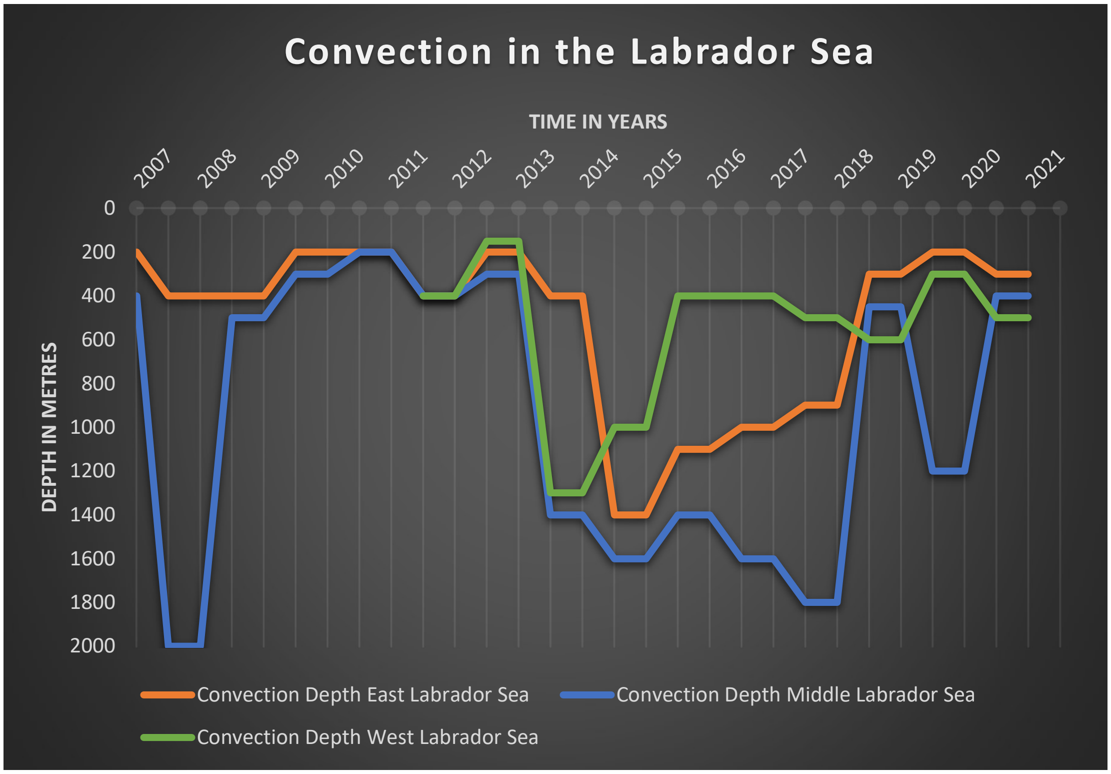


Figure 10 - Convection depths from 2007 to 2021 in the Labrador Sea.

After all data from convection has been gathered, it is compared to the surface air temperature anomaly. Both values have been plotted in three graphs, every area having a separate graph. The relation between temperature anomaly and convection depth can be seen in figures 11, 12 and 13.

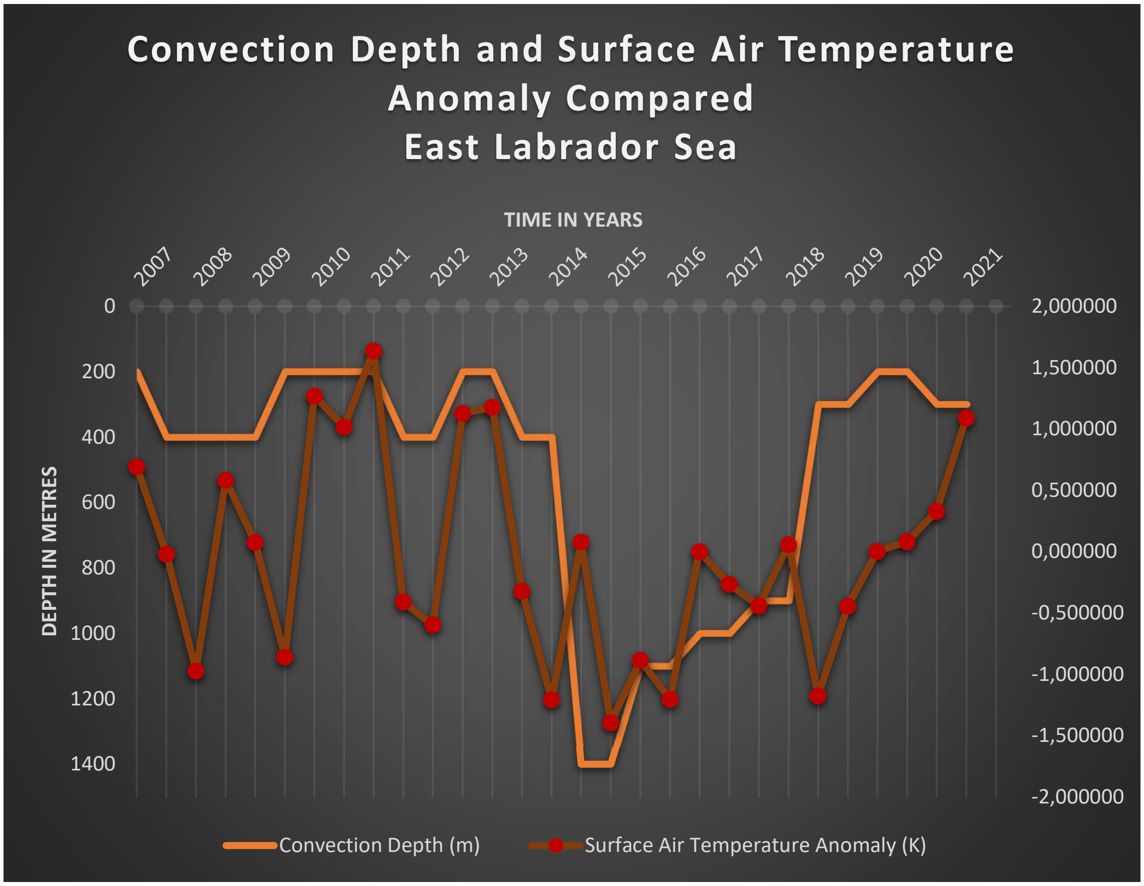


Figure 11 - Convection depth compared to the surface air temperature anomaly in the east Labrador Sea.

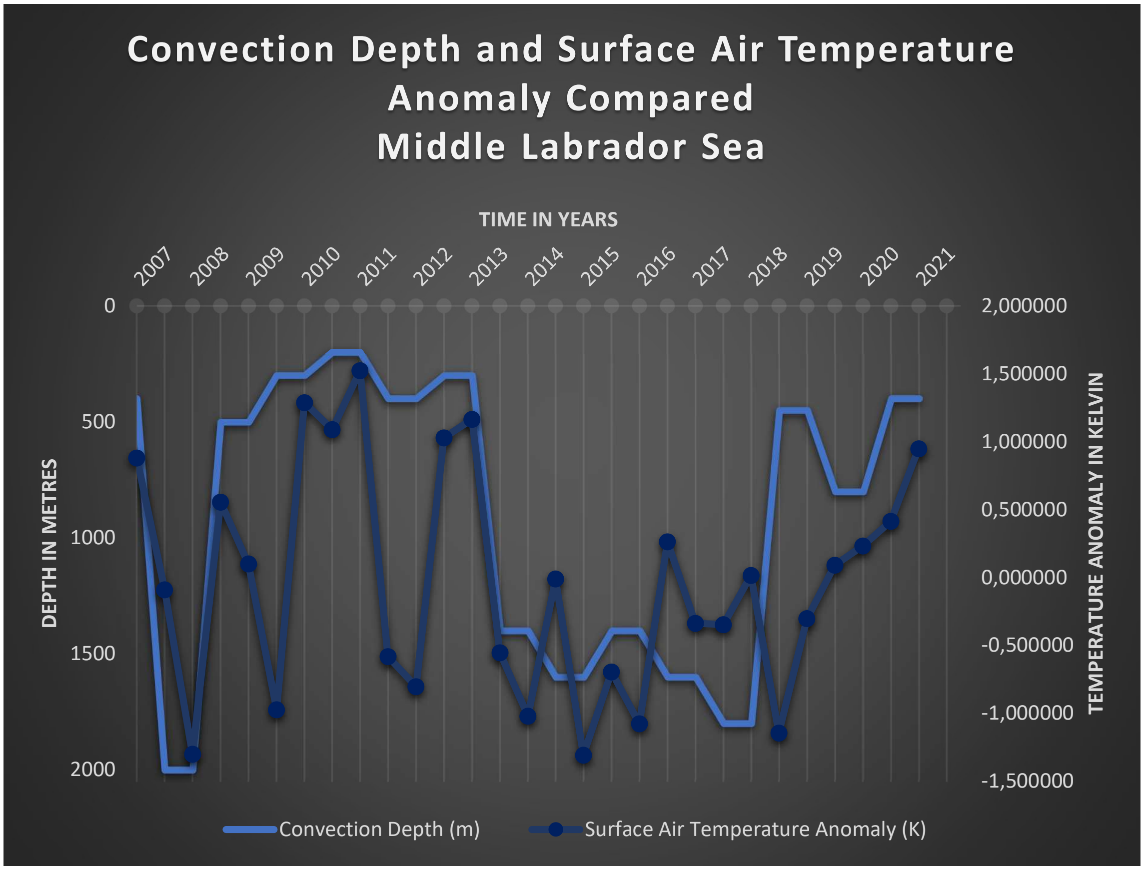


Figure 12 - Convection depth compared to the surface air temperature anomaly in the middle Labrador Sea.

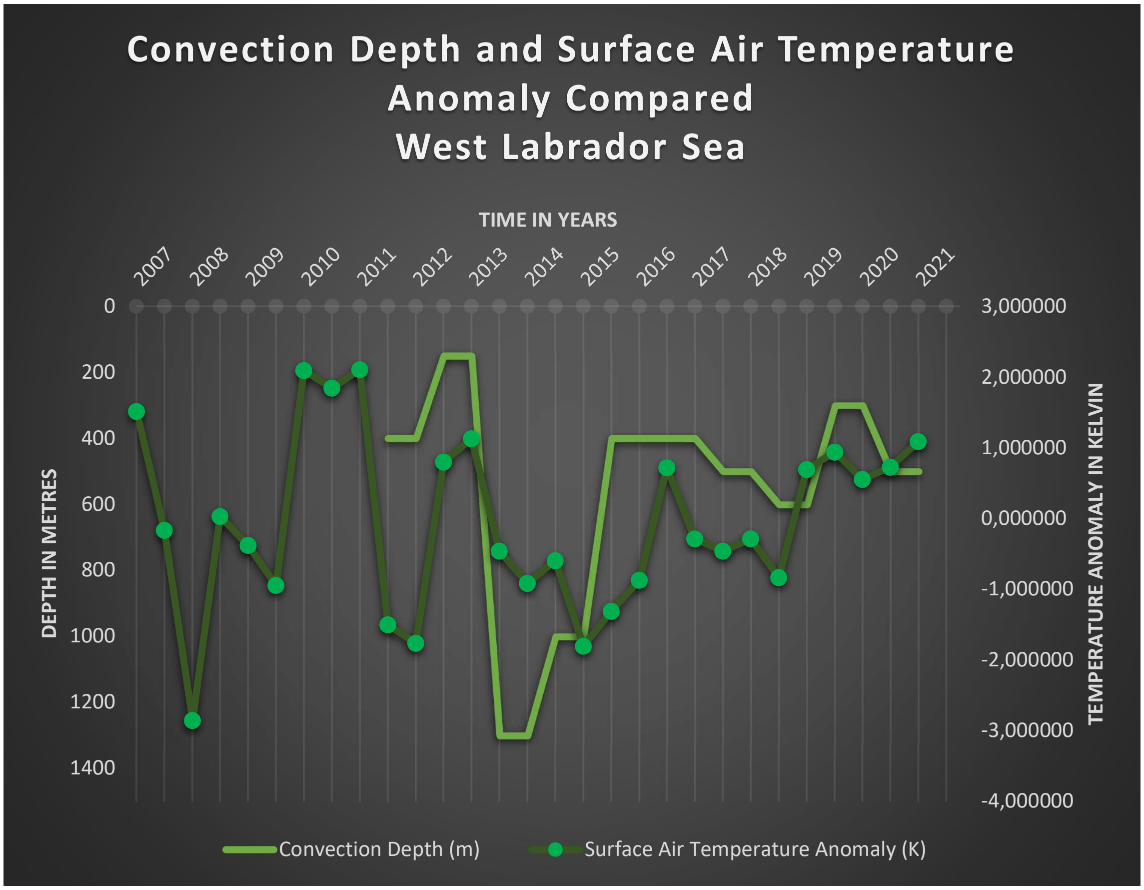


Figure 13 - Convection depth compared to the surface air temperature anomaly in the west Labrador Sea.

4.1 Statistic Correlation (Spearman's)

As can be seen in figures 11, 12 and 13, there is a relationship between the convection depth and surface air temperature anomaly. When the graph for convection depth drops, the temperature anomaly also drops. To prove this statistically, all data has been tested on their correlation with Spearman's rank correlation coefficient. The results support the assumption that the atmosphere's temperature and convection influence each other. The results can be seen in table 3:

Table 3 – Spearman's rank correlation coefficient between the convection depth and the surface air temperature anomaly for all three area's of the Labrador Sea.

Labrador sea area	east	middle	west
Spearman's rank correlation (summer + winter temperature and convection depth)	0,59	0,55	0,42
Spearman's rank correlation (winter temperature and convection depth)	0,37	0,34	0,52

As can be seen from the table, there statistically is a correlation between the convection depth and the temperature anomaly of the atmosphere near the surface. This correlation, in fact, is reasonably strong. This can also be seen in figures 11, 12 and 13. 2015 for example, has real deep convection together with a really cold winter and previous summer. Most of the data shows the same relation between the atmosphere temperature anomaly and convection depth. On average, the Labrador Sea has a coefficient of 0,52.

4.2 Correlations by observation

When looking closely at these figures 11, 12 and 13, a lot of regularities can be found from which conclusions can be drawn. All relations are based on the idea that the surface air temperature anomaly is the cause and convection depth the effect. Therefore, the previous summer's surface air temperature anomaly will have an effect on the next winter's convection depth. This also fits when both data sets are compared, because a change in surface air temperature is often followed by a change in convection depth. This would theoretically also make sense as the surface water has to have a relatively high density to set the convection process in motion. A logical cause for this would be the cooling down of the surface water due to a cold atmosphere. The relations that follow from the research will be explained and all assumptions made follow from figures 11, 12, 13 and 14.

Firstly, surface air temperature anomalies in winter seem to be more important for deep convection than surface air temperature anomalies in summer. Summer and winter anomalies seem to have a different influence on convection. To clarify this, both anomalies have been plotted separately. The separated anomalies can be seen in figure 14. When looking at 2010 for example, the previous summer is around 1 Kelvin colder than usual, whereas the winter is around 1,2 Kelvin warmer than usual. The result is little convection, which makes sense if the winter temperature would be more important in creating convection. In 2008 it can be seen the other way around, an average previous summer in combination with a very cold winter caused very deep convection instead of the usual convection. In the years 2014, 2015 and 2016 another example can be seen. According to the winter temperature anomalies, 2014 and 2016 were as cold, whereas 2015 was slightly colder. The same trend is seen in the convection depth, 2014 and 2016 are a little less deep than the colder 2015. This

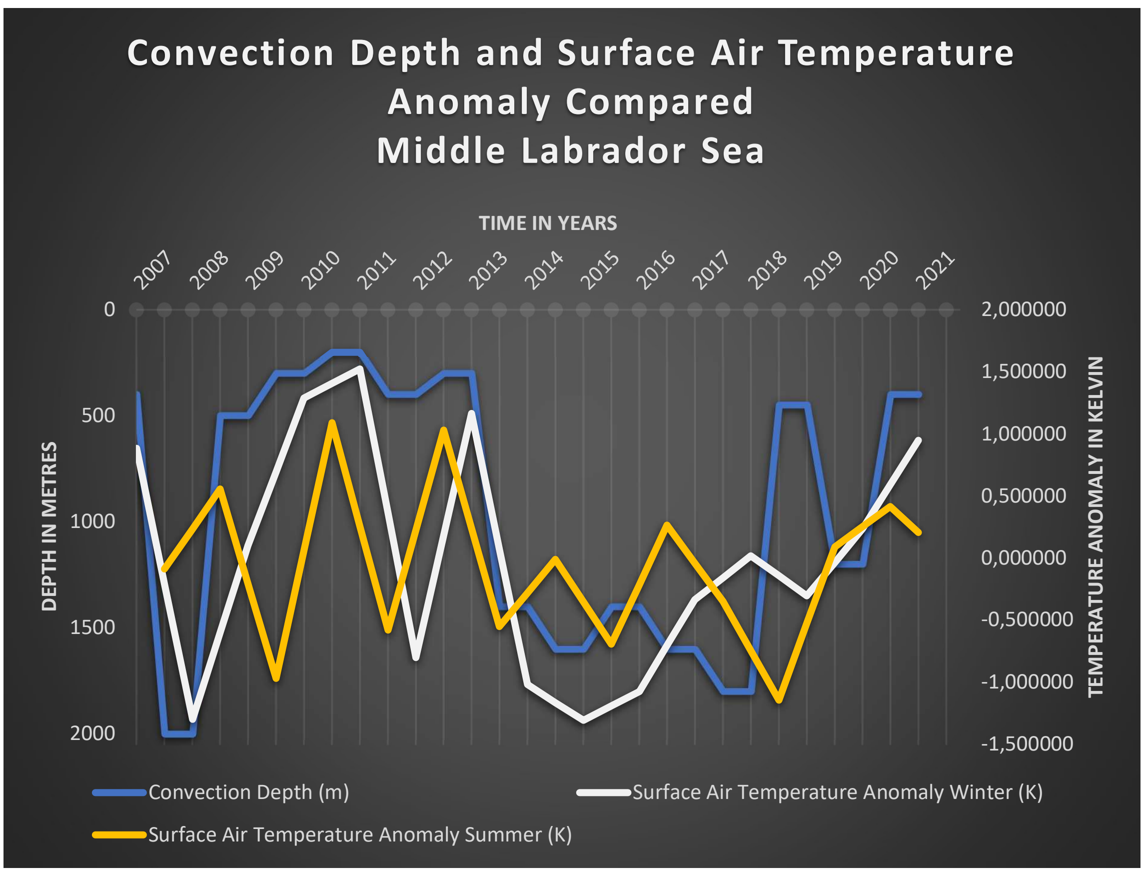


Figure 14 – The relation between the convection depth and the winter and summer surface air temperature anomaly plotted separetely.

trend can be explained with the use of the winter temperature anomaly, but not with use of the summer temperature anomaly, which shows a different pattern. As becomes evident after analysing this data, cold winters generally cause deep convection and warm winters cause little convection. The summers are not the leading factor, but less hot summers as present from 2013 to 2018 do create the possibility of very deep convection in a cold winter.

Secondly, following from the first rule, positive anomalies both in the winter and previous summer have a very little chance of causing deep convection. In the winters of 2011 and 2013 this can clearly be seen. A very positive anomaly around 1,0 or higher is present during these years. Together with this positive anomaly, the convection depth goes no deeper than 300 metres, which is very shallow compared to other years. The same can be seen in the years 2009 for the east and middle area and in 2020 and 2021 for the east and west area, but less strong. In these years the anomaly is positive, but not as strong as in 2011 and 2013, the convection does not exceed the 500 metres. Convection these years is only to a depth of 200 metres.

Thirdly, it can be deduced that deep convection often takes place when there is a cold winter in combination with a regular or cold previous summer.

Fourthly, it can also be deduced that a relatively warm winter can prevent deep convection, even if the previous summer was cold, as is evident from the winter in 2010. The winter was warmer than previous years and the previous summer was very cold, but only little convection was measured. Warm winters are therefore unfavorable for deep convection.

These four relations seem to cover most relations between the surface air temperature anomaly and the convection depth. There are however some strange phenomena's which cannot be explained with the above correlations.

Preconditioning

The first abnormality, according to previous relations, which can be seen is in the winter of 2012. The previous summer was very cold and so was the winter of 2012. All three areas show an anomaly around -0,5 or more extreme. Despite the cold air temperatures, the convection did not exceed a depth of 400 metres. This seems rather strange, but there is something which might explain this. When you look carefully at figures 11, 12 and 13, the years prior to 2012 are the exact opposite of cold. From the winter of 2010 till the winter of 2011 there was an extreme warmth in the Labrador Sea. The surface air temperature was 1 to 2 Kelvin higher than usual. In these two winters there barely was any convection and the surface water must have warmed up significantly. As can be seen in figure 15, an ocean temperature graph from January 2011, the water layer between 200 and 600 metres was extremely warm. To create a big homogeneous layer, like in figure 16 from March 2016, all this water, from 200 to 600 metres depth, has to cool down to around 3,5 degrees Celsius. As you can imagine this takes a lot of energy and is difficult to achieve in one year, even if the surface air temperature is cooler than usual. The sea was preconditioned in a way which made it very stratified.

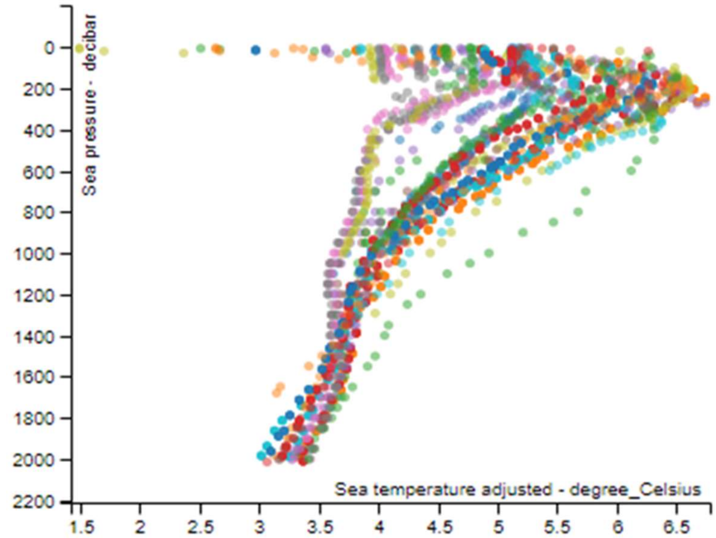


Figure 15 - Temperature graph of the west area in January 2011. (Source: Argo (2000). Argo float data and metadata from Global Data Assembly Centre (Argo GDAC). SEANOE. Accessed at May 2 2021 from https://doi.org/10.17882/42182)

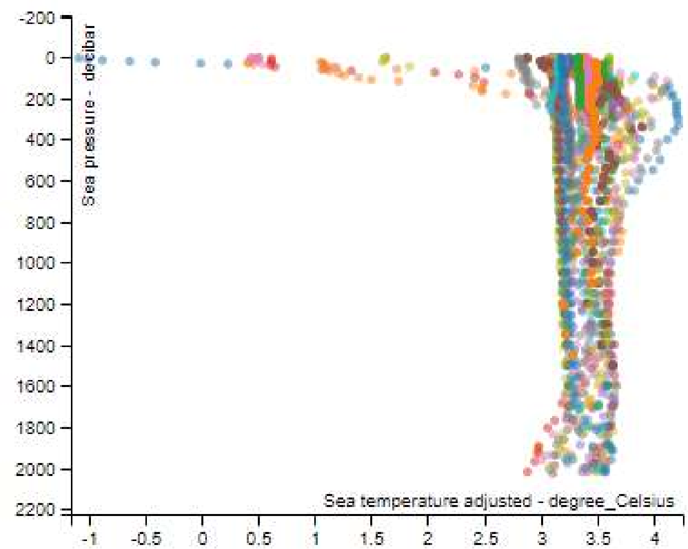


Figure 16 - Temperature graph of the middle area in March 2016. (Source: Argo (2000). Argo float data and metadata from Global Data Assembly Centre (Argo GDAC). SEANOE. Accessed at May 2 2021 from https://doi.org/10.17882/42182)

A fifth relation can be deduced from this, which is that several successing years with warmer summers and winters than usual can prevent deep convection in the next year, even though the surface air temperature seems to be enough colder than usual.

The second abnormality is the sudden decrease in convection depth in 2015 for the west area and 2018 for the east and middle area. Even though the temperature still seems colder than usual, both in the winter and previous summer, the convection did decrease. The reason for this would be that an average winter would not lead to deep convection, but that the water had been well preconditioned in the previous years. The sudden decrease in convection depth would be a delayed result of the prior warmer years. When taking the east area as an example, the winters and summers in 2017 and 2018 were rather warm, but the convection was still deep. This could have been the cause of a well preconditioned sea, which means that previous years of convection have created a homogeneous layer which has not been stratified fully in the summer. As can be seen in figure 17, January 2017 was preconditioned really well. Already in January the homogeneous layer was big and contrary to January 2015, only little convection was needed to get deep convection. In 2017 and 2018 the preconditioning was apparently enough to enable deep convection. In 2019, however, the preconditioning was not enough anymore to guarantee deep convection. Preconditioning is the reason why the convection decrease was only seen two years later than the positive anomaly.

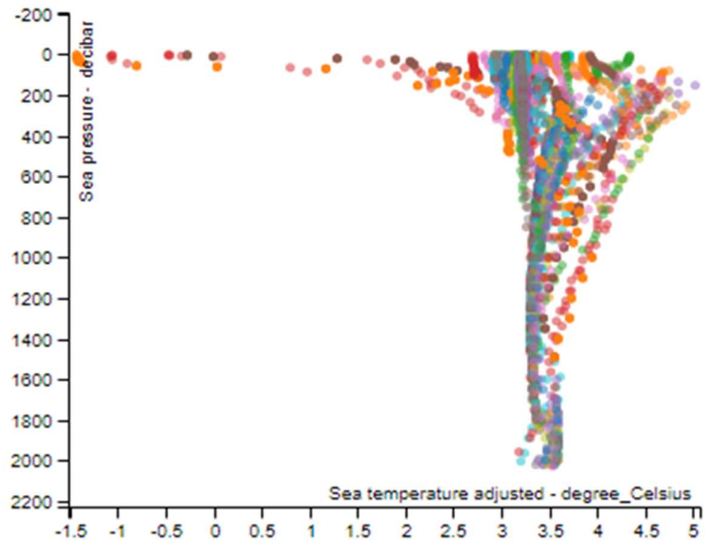


Figure 17 - Temperature graph of the middle area in January 2017. (Source: Argo (2000). Argo float data and metadata from Global Data Assembly Centre (Argo GDAC). SEANOE. Accessed at May 2 2021 from https://doi.org/10.17882/42182)

From this a sixth relation can be drawn; when deep convection took place in the previous year or years, the chance of convection in the following year is higher due to preconditioning.

5. Conclusion

To conclude, convection is a process where high density water from the surface mixes vertically with lower density water from below the surface. A stratified body of water will then turn into a homogeneous body of water, where temperature and salinity are constant to a certain depth. During winter, the surface of the Labrador Sea will get the coldest due to the cold atmosphere which creates a lot of heat loss. The surface water will therefore have a high density and cause convection. Usually, convection is the deepest in late winter, around March. Between 2007 and 2021 convection in the Labrador Sea has reached to a depth of 2.000 metres at the deepest and has not been shallower than 150 metres deep.

The primary factor which influences convection in the Labrador Sea, according to this research, is the surface air temperature. The relation between the surface air temperature anomaly and the convection depth, calculated with Spearman's rank correlation coefficient, was 0,52 in the Labrador Sea. This indicates a reasonably strong correlation. The general rule which follows from this is:

The colder the surface air temperature in the Labrador Sea during the winter and the previous summer, the deeper the convection during that same winter.

By observing all graphs, some more specific rules can be set up about the correlation between the surface air temperature and the convection depth. An important addition to the above rule is:

Surface air temperature anomalies in winter are crucial to causing deep convection, whereas surface air temperature anomalies in summer have a smaller influence on the convection depth.

Following from this, the first rule can be written more specifically:

Warm surface air temperatures in the Labrador Sea in both winter and the previous summer do not cause deep convection.

Cold surface air temperatures in the Labrador Sea in winter and average to cold surface air temperatures in the Labrador Sea in the previous summer have a large chance of causing deep convection.

Warm surface air temperatures in the Labrador Sea in winter and cold surface air temperatures in the Labrador Sea in the previous summer do not cause deep convection.

These rules cover most causes of convection, but two other rules also apply. When the ocean is preconditioned, the convection depth can be positively or negatively influenced. The relation can be summarised in the following two rules:

Warm surface air temperatures in the Labrador Sea during successive winters and summers can precondition the sea so that in the following winter the forming of a deep-reaching homogeneous layer is prevented, even though there is a cold surface air temperature.

Cold surface air temperatures in the Labrador Sea in successive winters and summers can precondition the sea so that in the following winter the forming of a deep-reaching homogeneous layer is more likely, even though there is a relatively warm surface air temperature.

With this knowledge the research question and all sub questions can be answered and the hypothesis can be rejected. The temperature of the atmosphere is the primary cause of convection as it cools down the surface water to enable convection.

Salinity and temperature of the ocean play a smaller role, but can make the occurrence of convection more or less likely. When the Labrador Sea is preconditioned so that there already is a large homogeneous layer, the chance of deep convection is higher. When the Sea is stratified instead, the chance of deep convection the next winter is smaller.

Altogether, the fluctuation of convection is due to differences in temperature of the atmosphere. Deep convection is most likely to happen when the winter and previous summer are cold and is not likely to happen when both are warm. The hypothesis can therefore be rejected, as it is not primarily the ocean temperature and salinity which determine the convection depth and a warm summer does not strengthen convection, but instead weakens it.

6. Discussion

The research question has been successfully answered, but, as in any research, there is some uncertainty about the used data and methods. Some methods are more reliable than others and in this research some parts could have gone more secure.

Firstly, manually ordering all data is a tedious and boring process. On top of that, it requires a fair amount of concentration to prevent mistakes. As a separate graph has been created for every winter month (and August) for fifteen years for the salinity as well as temperature, a lot of time has been spent on simply collecting data. In total 120 graphs have been generated by the argo website, but all controlled variables have been set manually, 120 times. Small errors could have been made here, so it can be that some argo floats too many or too less have been selected or that the period is off, due to a misclick. These errors have a very small chance of influencing the research, as one argo float too much or less makes little difference when comparing 50 cycles and misclicks in the period have little chance to go unseen as the shape of the graph chances drastically through the seasons.

Secondly, reading off the convection depth is difficult and the chosen values are arguable. A couple of times graphs have been requested again on the argo site to look at the data in more detail. The advantage of this was that the online graph could be enlarged to make the reading off easier and more accurate. This has not been done with every graph however, so small manmade mistakes are likely. The difference this makes is probably small, as it is not likely to be significantly different than the previously noted convection depth. The likelihood of big errors is even smaller as all depths have been rounded to hundreds and fifties.

Thirdly, excel is a difficult program to work with when plotting graphs and calculating formulas. When plotting graphs and calculating Spearman's coefficient it often took several attempts to get the shape or calculation wanted. Errors were easily made in the distribution of data in tables and the setting up of formulas to make calculations. In the end, many checks have decreased the chance on errors, but did not rule all errors out. For other researchers the graphs and calculations with tables are in *Appendix 2, Graphs and Calculations (Convection Labrador Sea 2007-2021).*

In conclusion, to improve this research, it would be useful to use better hardware and software. This would have enabled the collection of data to go more smoothly and reliable and the data could be processed better. The determination of convection depth for example, could have been calculated by a computer or the read off could be more precisely.

7. Recommendations

For future researchers, redoing this study with more data and better software and hardware could be beneficial in checking all correlations stated in this research.

Further, going more into depth about the results of preconditioning could be useful. It seems that the longer the atmosphere has a negative anomaly, the bigger the preconditioning effect is, but further research would be necessary to confirm this.

Lastly, with the knowledge gained in this research the relation between convection and climate change could be researched. In what ways is convection influenced by the changing climate? Convection is all about temperature anomalies. Does it matter when climate changes, as there will always be temperature anomalies? Or is, for example, the rapid melting of Greenland ice a disturbance for convection in the Labrador Sea, as the sweet, light water may prevent convection.

Appendix

Appendix 1, Convection Graphs Labrador Sea (2007-2021)

Appendix 1 is a separate digital excel document which shows all ocean temperature and salinity graphs from 2007 till 2021 for the months January, February, March and August. The graphs are separated per area in the Labrador Sea.

Appendix 2, Graphs and Calculations (Convection Labrador Sea 2007-2021)

Appendix 2 is a separate digital excel document which shows all tables used to generate figures 10 till 14, some additional graphs which did not make it into the research paper and the table used to calculate Spearman's rank correlation coefficient. The graphs are separated per area in the Labrador Sea.

Appendix 3, Logbook

Week	Day	Date	Time	Purpose	Minutes
48	Wednesday	25-11-2020	09.00 – 09.50	Introduction to profile paper	50
48	Thursday	26-11-2020	20.30 – 21.00	Start paper Brainstorm	30
48	Friday	27-11-2020	18.45 – 19.30	Brainstorm, word cloud	45
51	Monday	14-12-2020	16.00 – 16.45	Writing Motivational Letter to get Ms Boogers as my mentor	45
02	Monday	11-01-2021	9.00-9.30	Discussing the topic with Ms Boogers	30
03	Monday	18-01-2021	9.00-9.15	Discussing the topic with Ms Boogers	15
04	Friday	29-01-2021	21.00-21.30	Reading replies to an e-mail sent to Caroline Katsman and Brian from Wageningen University	30
09	Saturday	06-03-2021	21.00-21.30	Trying to narrow down my topic	30
10	Monday	08-03-2021	9.00-9.30	Discussing topic with Ms Boogers	30
10	Thursday	11-03-2021	10:00-10.40	Writing E-mails to Caroline Katsman	40
12	Monday	22-03-2021	18:00-18:30	Reading E-mails from Caroline and making my research and time plan.	30
15	Sunday	18-04-2021	21:30-22:30	Preparing for Thesis and conversation with Caroline Katsman	60
16	Monday	19-04-2021	8:00-9:00	Preparing conversation with Caroline Katsman and finishing research questions and hypothesis.	60
16	Tuesday	20-04-2021	16:00-17:00	Conversation with Caroline Katsman We discussed data collection and how to find convection	60
17	Sunday	02-05-2021	15:00-17:00	Getting Argo Float Data into Excel and making graphs	120
18	Monday	03-05-2021	13:45-15:45	Improving Argo Float Data in Excel and creating proper graphs	120
18	Tuesday	04-05-2021	10:00-11:00	Reading Vage_2008 and the start of Gelderloos_2012.	60
18	Wednesday	05-05-2021	9:45-10:30	Reading Gelderloos_2012	45
19	Thursday	20-05-2021	11:10-11:50	Discussion Boogers about layout paper	40
20	Sunday	23-05-2021	11:00-12:00	Start Introduction Labrador Sea	60
21	Tuesday	25-05-2021	14:10-15:30	Continue Labrador Sea and Sea currents	80
22	Tuesday	01-06-2021	14:30-15:20	Finish introduction sea currents, send for first check	50
27	Thursday	08-07-2021	8:40-9:30	Finisch introduction convection	50
29	Sunday	25-07-2021	13:30-15:10	Research Argo Float Data and plot into graphs	100
30	Tuesday	27-07-2021	8:00-9:20	Deciding how to plot graphs and manage data	80
30	Wednesday	28-07-2021	8:00-11:45	Deciding how to plot graphs and manage data	225
30	Thursday	29-07-2021	8:00-10:30	Plotting data from a second argo float	150
30	Friday	30-07-2021	8:00-9:50	Plotting data from three different argo floats	110

Week	Day	Date	Time	Purpose	Minutes
31	Tuesday	03-08-2021	9:30-11:00	Plotting Data from three argo floats	90
31	Wednesday	04-08-2021	8:20-10:20	Plotting 4 argo floats	120
35	Wednesday	01-09-2021	14:25-14:55	Wanted to plot salinity, but had trouble opening files on school computers, did plot range	30
35	Thursday	02-09-2021	9:10-9:10	Plot salinity graphs, 3 done, come to the realization that plotting the graphs isn't actually really that useful as I can find them online as well)-: So I should continue	60
35	Thursday	02-09-2021	14:00-15:00	Finding Data	60
36	Monday	06-09-2021	19:00-21:00	Starting new plan of collecting data, worked great. I do it manually now and I have created a table with all comparison numbers, this works a lot more efficient, but has more uncertainties	120
36	Tuesday	07-09-2021	9:00-10:40	Finishing another period of information	100
36	Wednesday	08-09-2021	11:10-11:50	Finding sources for later years of convection	40
36	Wednesday	08-09-2021	17:20-18:50	Finding sources for later years of convection	30
36	Thursday	09-09-2021	9:00-10:40	Having found a great program to analyse large scale data and finding the right periods and locations	100
36	Saturday	11-09-2021	19:30-21:00	Restructuring my thesis and writing my process and research plans	90
36	Sunday	12-09-2021	12:00-12:30	Writing introduction Argo Floats	30
36	Sunday	12-09-2021	19:00-20:00	Writing research plan	60
37	Monday	13-09-2021	18:00-18:30	Planning meeting with Caroline Katsman and looking for convection data in 2014/2015	30
37	Monday	13-09-2021	19:00-19:30	Writing research plan	30
37	Tuesday	14-09-2021	9:10-10:40	Starting gathering data from 2021	90
37	Wednesday	15-9-2021	9:30-9:50	Gathering Data	20
37	Wednesday	15-9-2021	11:20-11:50	Gathering Data	30
37	Thursday	16-09-2021	17:20-18:20	Gathering Data	60
37	Sunday	19-09-2021	10:55-13:05	Gathering Data	130
38	Monday	20-09-2021	17:45-18:45	Gathering Data	60
38	Monday	20-09-2021	19:30-20:30	Gathering Data	60
38	Tuesday	21-09-2021	9:00-10:40	Gathering Data	100
38	Tuesday	21-09-2021	18:15-18:35	Gathering Data	20
38	Wednesday	22-09-2021	7:30-8:25	Finishing Data	55
38	Wednesday	22-09-2021	9:00-9:50	Finishing Data	50
38	Wednesday	22-09-2021	16:40-17:10	Finishing Data	30
38	Thursday	23-09-2021	7:25-8:35	Making Data ready to print	70
38	Thursday	23-09-2021	9:00-9:40	Making Data ready to print and sending it off	40

Week	Day	Date	Time	Purpose	Minutes
38	Thursday	23-09-2021	16:00-16:50	Talking with Caroline Katsman about collecting data and recognising convection.	50
39	Tuesday	28-09-2021	9:30-10:00	Talking with Vlot, about structure of PWS in English	30
39	Wednesday	29-09-2021	11:00-11:50	Analysing Data	50
39	Wednesday	29-09-2021	16:00-18:00	Analysing Data and looking for an air temperature graph	120
39	Thursday	30-09-2021	15:55-18:35	Analysing Data and comparing it to air temperature	160
39	Friday	01-10-2021	18:55-20:55	Overlaying temperature graphs with convection graphs	120
39	Sunday	03-10-2021	16:30-18:00	Structuring research paper and adding appropriate headings, also managing sources and adding APA-norm sources.	90
40	Monday	04-10-2021	9:20-11:30	Improving theoretical framework. Writing Methodology	130
40	Monday	04-10-2021	13:40-16:00	Writing Methodology and finishing graphs with data	140
40	Monday	04-10-2021	17:50-18:20	Finishing middle area with air temperature	30
40	Tuesday	05-10-2021	8:50-9:50	Finishing west area with air temperature	60
40	Tuesday	05-10-2021	11:30-12:45	Finishing methodology and starting results	75
40	Tuesday	05-10-2021	13:30-15:30	Finishing Results and writing introduction	120
40	Wednesday	06-10-2021	14:40-18:30	Calculating Spearman's coefficient and writing results	230
40	Thursday	07-10-2021	14:00-14:50	Writing results, what I see myself	50
40	Thursday	07-10-2021	17:00-18:35	Making source Labrador Sea and source Water Circulation	95
40	Friday	08-10-2021	13:30-15:30	Finishing Results	120
40	Saturday	09-10-2021	13:45-14:30	Writing conclusion	45
40	Saturday	09-10-2021	17:30-18:45	Finishing Conclusion and writing and finishing Discussing and recommendations	75
40	Sunday	10-10-2021	13:00-13:30	Writing full preface and abstract	30
40	Sunday	10-10-2021	15:00-18:30	Checking document on spelling	210
40	Sunday	10-10-2021	21:00-22:00	Checking document on spelling	60
41	Monday	11-10-2021	19:40-21:30	Checking document on spelling and finalising the research paper	110
41	Wednesday	13-10-2021	9:00	Handing-in document	
					97h30

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