Hydrographical History of 7 Fjord Basins Along the Norwegian Sognefjorden with Emphasis on Oxygen Conditions

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ABSTRACT

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Oxygen concentration, temperature and salinity within the Barsnesfjorden, Sogndalsfjorden, Nærøyfjorden, Ikjefjorden, Østerbøvatn, Fuglsetfjorden and Finnabotn in Western Norway were profiled over time and along the water column of each basin. Bathymetric maps for each fjord were presented and the locations of wastewater plants and hydropower plants along the Sognefjorden were identified.

The basin water of the Barsnesfjorden, Sogndalsfjorden, Nærøyfjorden, and Ikjefjorden was found to be getting more anoxic over time. Temperature was found to be increasing over time, and results regarding salinity were varied. While the data available for the Østerbøvatn, Fuglsetfjorden and Finnabotn was not comprehensive enough to observe long-term trends, the baseline conditions of these fjords were found to be anoxic. Oxygen depletion was tied to increasing temperatures resulting from climate change and decreasing salinity associated with positive North Atlantic Oscillation trends and hydropower activities that resulted in reduced inflow frequencies. Increased temperatures had more negative effects on oxygen levels than salinity including warmer water containing less oxygen than cooler water, warmer temperatures decreasing water density which reduces inflow frequencies, and increased temperatures resulting in increased oxygen consumption rates.

It was suggested based on these findings that the EU Water Framework Directive classifications for these fjords should be revisited due to how the changing climate and anthropogenic impacts have affected fjord processes. Additionally, classification systems for fjords such as LENKA need to take these factors into account as well. The effects seen in these fjords are likely analogous to those occurring in other Western Norwegian fjords, and it was suggested that future studies should continue to monitor changing oxygen levels across coastal waters and fjords.

Keywords: Fjord, Basin, Anoxia, Hydrography, Climate Change, Hydropower, Foraminifera

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1.0 Introduction

1.1 General Fjord Morphology & Hydrography

Fjords can be considered very unique water bodies, and as such they have unique ways of functioning (Gade and Edwards, 1980). In 2004 Gade described fjords as "blue lungs" which are of vital importance to both humans and microorganisms alike. As discussed by Gade (2004), in the absolute simplest terms a fjord can be pictured as an "underwater valley". Fjord formation occurs through the act of glacial arms carving them out (Strøm, 1936; Gade, 2004). A key aspect of fjord morphology is the presence of sills. Sills are formed where glacier arms temporarily ceased calving, and end moraines were laid down. This creates a sort of underwater barrier known as a "sill". These sills are important as they restrict water exchange between the fjord and coastal waters (Gade, 2004). Sills are largely responsible for the distinctive stratification present in fjords due to the role they play in limiting water exchange between the fjord and the ocean. There are some fjords with multiple sills and occasionally there are fjords with no fjord limiting exchange at all. As a result of sills, the water in many Norwegian fjords may be prone to stagnation (Strøm, 1939). Most fjords in Norway have deep sills that are greater than 100 meters in depth (Gade, 2004).

In addition to water exchange between the fjords and coastal waters, fjords also receive a large supply of freshwater from rivers and meltwater runoff. This freshwater mixes with seawater and forms an outgoing brackish water current. This brackish water current originates as shallow and fresh but mixing with denser seawater below occurs quickly, and generates an undercurrent of new seawater located outside the fjord (Gade, 2004). This is known as a counter-current. It tends to be 2-3 times denser than the brackish water current, and carries nutrients and oxygen from the coastal waters. Together, the counter-current and brackish water current play an important role in fjord circulation patterns (Gade, 2004).

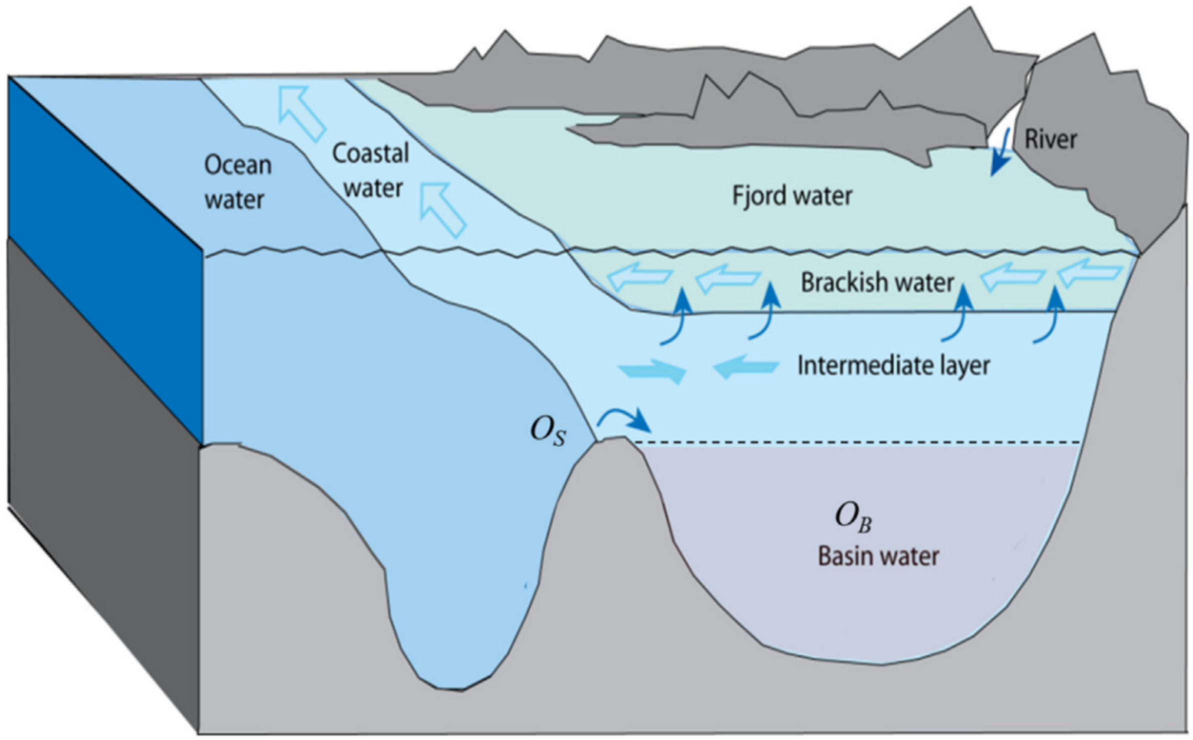


Figure 1: Vertical layering of a Norwegian fjord. Reprinted from "Multi-decadal warming of Atlantic water and associated decline of dissolved oxygen in a deep fjord"*,* by Aksnes et al., 2019, *Estuarine, Coastal and Shelf Science, 228.*

Fjords tend to have 3 distinct layers along the water column as shown in figure 1 above. The first layer is a brackish water layer that is seldom thicker than a few meters and normally made up of fresh or semi-fresh water from the local watershed. Salinity in this layer tends to be very variable due to varying freshwater supply (Strøm, 1936). For example, a prolonged rainfall event may supply freshwater to this layer for days, skewing the salinity. This surface layer is generally saturated or supersaturated with oxygen (Strøm, 1939). This is due to factors such as constant atmospheric exchange, absorption through wave action (Strøm, 1936) and photosynthesis occuring in the euphotic zone. This layer is heavily influenced by meteorological conditions and surface temperature is constantly changing (Strøm, 1936).

Directly below the brackish layer is the intermediate layer that extends to the depth of the sill (Aksnes et al., 2019). This layer generally contains Norwegian coastal water and sometimes also North Atlantic ocean water depending on the depth of the sill. It tends to be sealed off from the atmosphere (Strøm, 1939) and as such its properties are almost entirely based on the outside sources supplying it. The circulation in this layer is largely governed by wind patterns along the coast and the Norwegian Coastal Current (Aksnes et al., 2019; Gade, 2004). Tides also play a role in renewal and mixing of fjord water as they are known to cause eddies and turbulence that are important for gradual mixing of the water masses (Gade, 2004).

The base layer located below the intermediate layer is known as the basin water. This basin water may contain Norwegian coastal water, North Atlantic water or some combination of the two (Aksnes et al., 2019). This deep basin water located below the sill is especially vulnerable to pollution and influxes of organic matter that consume oxygen as it is isolated from free exchange with the coastal water (Gade, 2004). The meteorological factors that are known to strongly influence the surface waters do not have any pronounced effect in the basin waters and influence the deep water in only an indirect way (Strøm, 1936). In contrast to surface salinities, basin salinity values are very constant (Strøm, 1936). Even if a new water inflow is saltier than the layers being replaced, salinity tends to remain fairly constant during the mixing process. The basin water generally contains the lowest concentration of oxygen along the water column as it requires an influx of dense water for ventilation that may sometimes take years to occur.

Ventilation may occur in one of two ways: convection currents during cold or dry seasons or by dense aerated waters entering the basin and lifting the bottom waters that require ventilation (Strøm, 1939). In this thesis, such an occurrence is referred to as an "inflow". The frequency of ventilation determines the degree of stagnation. Dense oxygenated water seeps over the sill and renews the basin water only when the density of the shallower layers of coastal water are higher than those of the basin water. This generally occurs from mid- to late winter (Gade, 2004). Fjords have combined density stratification (Strøm, 1936) meaning that density is governed by both salinity and temperature with water of high salinity and cold temperature generally being densest. For renewal to occur the oxygenated water may be saltier than the basin water, or if the salinities are similar even a colder temperature may suffice for ventilation to occur successfully (Strøm, 1936). Pending failure of water renewal, basin water usually becomes depleted of oxygen which leads to the formation of hydrogen sulfide (Gade, 2004). Sometimes quantities of ventilated waters carried in are too small to affect oxygen concentration for any more than a short time, soon giving way to the formation of hydrogen sulfide (Strøm, 1936). As such, partial renewals that do not reach all depths along the water column cannot affect waters that have developed very high hydrogen sulfide concentrations.

1.2 Deriving Links Between Anoxia and its Causation

There are many indicators that fjords are becoming more anoxic over time, and several suggestions in the literature around possible causation. A publication by Pakhomova et al. (2014) noted that areas of anoxia in coastal zones have increased exponentially since the 1960s, and this occurrence is expected to continue to increase in extent, frequency and intensity. Fjords are especially sensitive to anoxia due to a restricted exchange with sea water (Pakhomova et al., 2014). The main possible causes that are to be discussed in this publication are global temperature increases as a result of climate change, organic matter input (through both sewage and aquaculture activities), and hydropower production. Oxygen depletion tends to first develop in bottom waters, and then spread upwards (Strøm, 1939).

Once all oxygen is consumed, hydrogen sulfide production begins. Hydrogen sulfide conditions exist in many fjords. There are cases of these conditions being both permanent and sporadic. In some cases these conditions can occur due to nutrient runoff into fjords from agriculture, industry or other human pollution, which results in eutrophication. An influx of organic matter through sewage introduction can have similar effects. In other cases it happens due to an imbalance between oxygen supply & oxygen consumption.

The main cause of stagnation is inadequate ventilation and basin water renewal. Overall, the key to stagnation is a prolonged density difference between surface and bottom water layers, which prevents basin water renewal. Without ventilation, oxygen is consumed and hydrogen sulfide gradually begins to accumulate (Strøm, 1939). Bottom waters and sediments containing hydrogen sulfide develop a total lack of plant and animal life with the exception of some bacteria. Often the only signs of life are dead planktonic organisms and organic detritus. An implication of this is that when stagnant bottom waters are renewed and lifted to the surface sometimes a catastrophic death of fauna in upper waters may occur (Strøm, 1939).

Temperature is known to play a role in fjord stagnation. Increased temperatures cause increased oxygen consumption rates & force oxygen concentration to decrease. Additionally, water of increased temperature is able to retain less oxygen. Although fjords are mostly chemically stratified due to the mixing of ocean water from the coast, temperature does play a role in stratification as well. As water temperatures increase, this results in less dense cold water that can penetrate the depths of fjord basins and oxygenate the water. This definitively leads to less frequent inflows which contribute to anoxia.

In terms of organic matter input, decomposition is a process that routinely consumes oxygen. Decomposition is the breakdown of organic matter into somewhat simple and inorganic compounds (Gade, 2004). The implications of this is that a large influx of organic matter can cause all oxygen in the water to be consumed during the breakdown process. Some possible sources of organic matter introduction include aquaculture activities, wastewater treatment plants and cruise ships. The Sognefjorden contains 15 aquaculture stations from its outer regions towards Sognesjøen which may be significant contributors to organic matter in the fjords (Manzetti and Stenersen, 2010). In addition to aquaculture stations, the Sognefjorden also has 67 wastewater treatment plants as shown in figure 5 (Manzetti and Stenersen, 2010). Of these sewage treatment stations, only 3% treat the sewage biologically before discharging it into the fjord. The other 97% apply mechanical processes such as decantation, sedimentation and centrifugation before discharging the sludge directly into the fjord. This sludge poses significant issues to the Sognefjorden related to its environmental protection (Manzetti and Stenersen, 2010). Analogously, 10 plants do not apply any sewage treatment at all and discharge it directly into the fjord. While this may have been fine in prior years, it is within the realm of possibility that with the influx of anthropogenic factors such as climate change & hydropower development the fjords no longer have the capacity to process this amount of organic matter without going into anoxic states. Additionally, the Sognefjorden and its side arms are known to be popular tourist destinations and may receive over 200 visits from cruise ships annually (Manzetti and Stenersen, 2010). Cruise ships have been found to be significant sources of many different types of pollution. It is estimated that ships generate between 1-3.5 kg of solid waste per passenger and up to 50 tons of sewage per day (Manzetti and Stenersen, 2010). Much of this waste is then discharged into the fjords. In combination with other factors, this is quite concerning.

Salinity is a factor that can cause very stable stagnant conditions in an isolated basin (Strøm, 1936). The largest anthropogenic factor influencing salinity is the influx of hydroelectric power plants. The concept behind hydropower is a conversion of the potential energy of water into electrical energy (Øystein et al., 2010). Typically water is stored in a reservoir and this water is released to either meet changing electricity needs or maintain a constant reservoir level (Øystein et al., 2010). The first hydropower station in Europe was constructed in Norway in 1882 (Øystein et al., 2010). Between 1945-1961 more than 200 hydropower stations were constructed in Norway (Øystein et al., 2010). Many large hydropower projects were completed from the years of 1961-1980 (Øystein et al., 2010). In the past 40 years, the building of plants has increased substantially (Manzetti and Stenersen, 2010). Generally, there are two types of hydropower plants in Norway. The first type utilises a dam in order to control when water is released to generate hydroelectric power (Øystein et al., 2010). The second type is without a dam and follows the natural seasonal inflow rate. This type is less common.

Studies have shown that hydropower production modifies runoff patterns to fjords; additionally, temperature and current changes can also be induced by hydroelectric power plants (Kaartvedt and Nordby, 1992; Kaartvedt and Svendsen, 1990; Manzetti and Stenersen, 2010). This practice is disturbing the natural equilibrium of the fjords' salinity and temperature. Norway is releasing reservoir water in the winter to meet a higher demand for electricity at this time. Seeing as most hydropower plants in Norway have large reservoirs (Øystein et al., 2010), this is largely disrupting the natural water cycle as freshwater is normally only released into the fjords in early spring with the influx of meltwater. Surface salinity has been known to decrease as a result of increased freshwater discharge from hydropower plants (Kaartvedt, 1984). Additionally, hydropower production is causing less variation in temperature as it has been known to make water temperature lower in summer and higher in winter (Øystein et al., 2010). It cannot be disputed that 50-60 years of increasing hydroelectric activity in the Sognefjord has significantly altered the salinity and spawning conditions in this area (Manzetti and Stenersen, 2010). There is a confirmed phenomenon of reduced fish stocks in fjords with the presence of a large amount of hydroelectric activity, with the salinity fluctuations directly destabilized via a supply of large amounts of exogenous freshwater injected into these poorly circulated marine systems (Manzetti and Stenersen, 2010). This increased input of low density freshwater influences stratification along the water column and is proven to extend the residence time of bottom water, preventing aeration (Pakhomova et al., 2014).

1.3 Implications of Fjord Anoxia

Oxygen depletion in water bodies has been shown to be a serious environmental issue worldwide (Pakhomova et al., 2014). Effects of this depletion can have effects ranging from entire community displacements such as loss of fisheries or species invasions to altered microbial activity such as enhanced sulphate reduction and denitrification (Pakhomova et al., 2014). Furthermore, fluxes of contaminants such as mercury can vary as a direct result of redox changes/methylation of mercury or the formation of metal sulphides which can significantly alter water quality in connection with worsening anoxia.

Fjords are especially sensitive to anoxia because of their restricted exchange with the sea water. Fjord anoxia can have severe implications for flora, fauna and even for humans living around fjords that can be considered anoxic. General guidelines for oxygen levels in aquatic environments are indicated in figure 2. The main issue with anoxia is the formation of hydrogen sulfide after periods of stagnation (Strøm, 1939). Bottom waters and sediments containing hydrogen sulfide develop a total lack of plant and animal life with the exception of some bacteria. The only signs of life in these basins are dead planktonic organisms and organic detritus. An implication of this is that when stagnant bottom waters are renewed and lifted to the surface, sometimes a catastrophic depth of fauna in upper waters may occur (Strøm, 1939).

Additionally, there have been some accounts of severely anoxic basins “outgassing” and resulting in negative health effects to humans living around them. In some instances this has resulted in the evacuation of homes located around outgassing basins. Even when anoxic basins are ventilated, sometimes the quantities of oxygenated waters carried in are too small to affect sulphuretted hydrogen content for any more than a short time (Strøm, 1936).

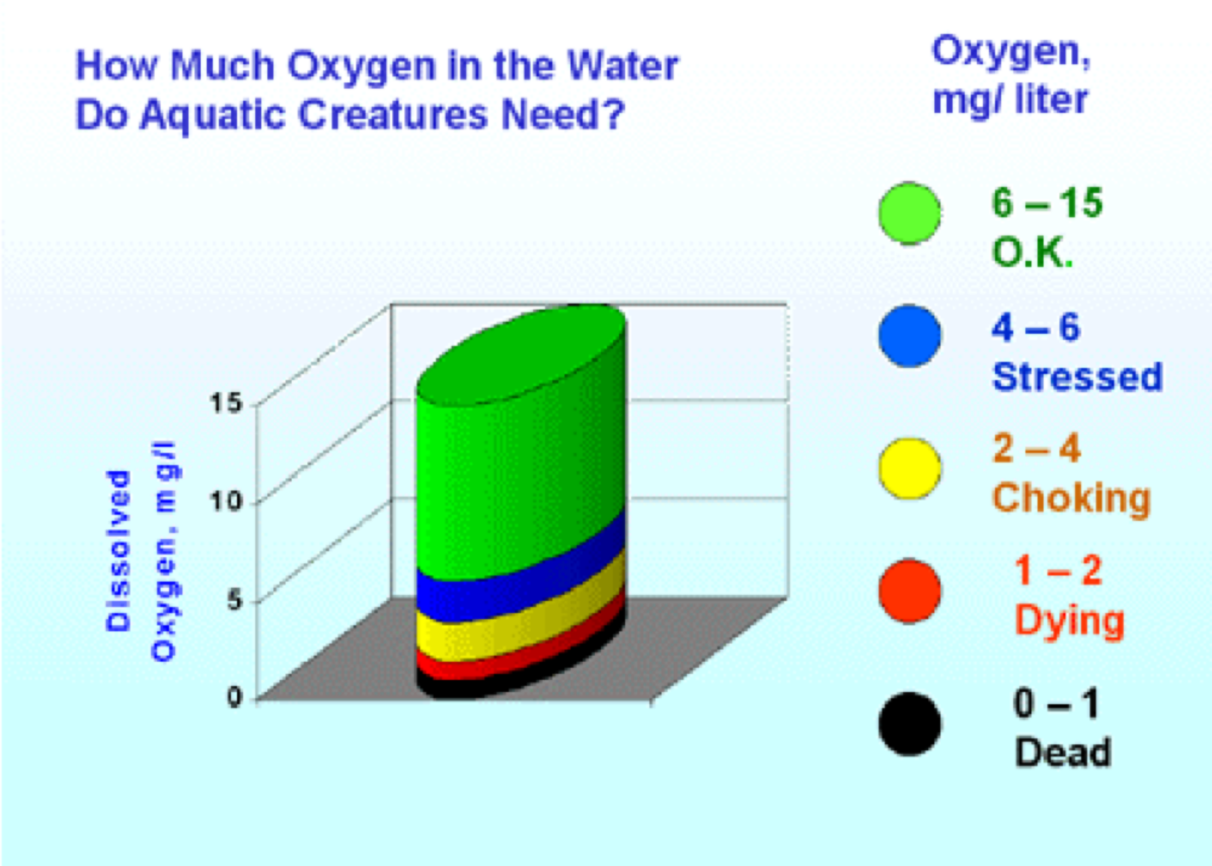


Figure 2: Oxygen guidelines for aquatic organisms. Reprinted from the *Environmental Protection Agency*. 2012.

1.4 Foraminifera Background and Relevance

Foraminifera are amoeboid protists that have existed since the Cambrian period (Goldstein, 1999). Since then they have diversified to exist in a wide variety of environmental conditions. They tend to be abundant and diverse in both coastal settings and in the deep sea (Goldstein, 1999). Though unicellular, they eat, defecate, grow, move, reproduce, and respond to a variety of stimuli. Nearly all foraminifera also possess a shell that separates them from the surrounding environment. These shells may be agglutinated, organic, or composed of compounds such as calcium carbonate or silica (Goldstein, 1999). These carbonate shells can be preserved in fossil records and used for monitoring environmental changes over long periods of time (Frontalini and Coccioni, 2011).

Foraminifera (particularly of the benthic variety) are widely regarded as effective bioindicators. The presence of pollutants such as pesticide residues, aluminum, cadmium, arsenic, copper, mercury, nickel, lead, selenium, silver and zinc may result in sediments becoming toxic to benthic and epibenthic organisms (Frontalini and Coccioni, 2011). Additionally, foraminifera are effective in acting as bioindicators for other aquatic conditions, such as oxygen depletion. Since foraminifera have short reproduction and life cycles, they react quickly to both short and long-term changes in water quality (Frontalini and Coccioni, 2011). Although there are some foraminifera that have evolved to be able to inhabit oxygen-poor or anoxic environments for weeks at a time, most species do not possess this ability (Bernhard and Gupta, 1999). A general rule is that decreasing oxygen concentrations are associated with an increase in the abundance of arenaceous foraminifera and a decrease in the abundance of calcareous foraminifera (Scott et al., 2011).

1.5 Research Question, Objectives, and Hypothesis

This thesis is aiming to answer the following question: is the basin water in seven side fjords of the Sognefjord (namely the Barsnesfjorden, Sogndalsfjorden, Nærøyfjorden, Finnabotn, Østerbøvatn, Fuglsetfjorden and Ikjefjorden) becoming more anoxic over time? “More anoxic” includes either longer periods of anoxia or anoxia extending to shallower depths.

The objectives of this study are as follows:

1) Determine whether the side fjords are becoming more anoxic over time through:
    a) Analysis of oxygen, temperature and salinity data (both historical and collected through the course of this study)
    b) Analysis of historical depth profiles (e.g. time series measurements from the last century) or benthic foraminifera where applicable
2) Create a bathymetric description of each side fjord with the highest degree of detail possible; this also includes a hydrographical description of oxygen, salinity and temperature along the water column
    a) Additionally, locations of wastewater plants and hydropower plants should be identified relative to the study sites

It has been hypothesized that the basin water in the side fjords of the Sognefjorden (namely the Barsnesfjorden, Sogndalsfjorden, Nærøyfjorden, Finnabotn, Østerbøvatn, Fuglsetfjorden and Ikjefjorden) is becoming more anoxic over time as a result of increasing temperatures due to climate change, organic matter introduction through anthropogenic activities, and hydropower production changing hydrography outside the basins, which influences inflow.

2.0 Methods

2.1 Study Area

This project focused on the basins of seven side fjords located along the primary Sognefjorden in Western Norway. These fjords include the Barsnesfjorden, Sogndalsfjorden, Nærøyfjorden, Finnabotn, Østerbøvatn, Fuglsetfjorden, and Ikjefjorden. As visible in figure 3 (located below), the Barsnesfjorden and Sogndalsfjorden are located to the North of the Sognefjorden while the other five fjords are located to the South. These locations were selected in order to provide a representative overview of basin water conditions around the Sognefjorden, and are spread across most of its length, close to 200 km.

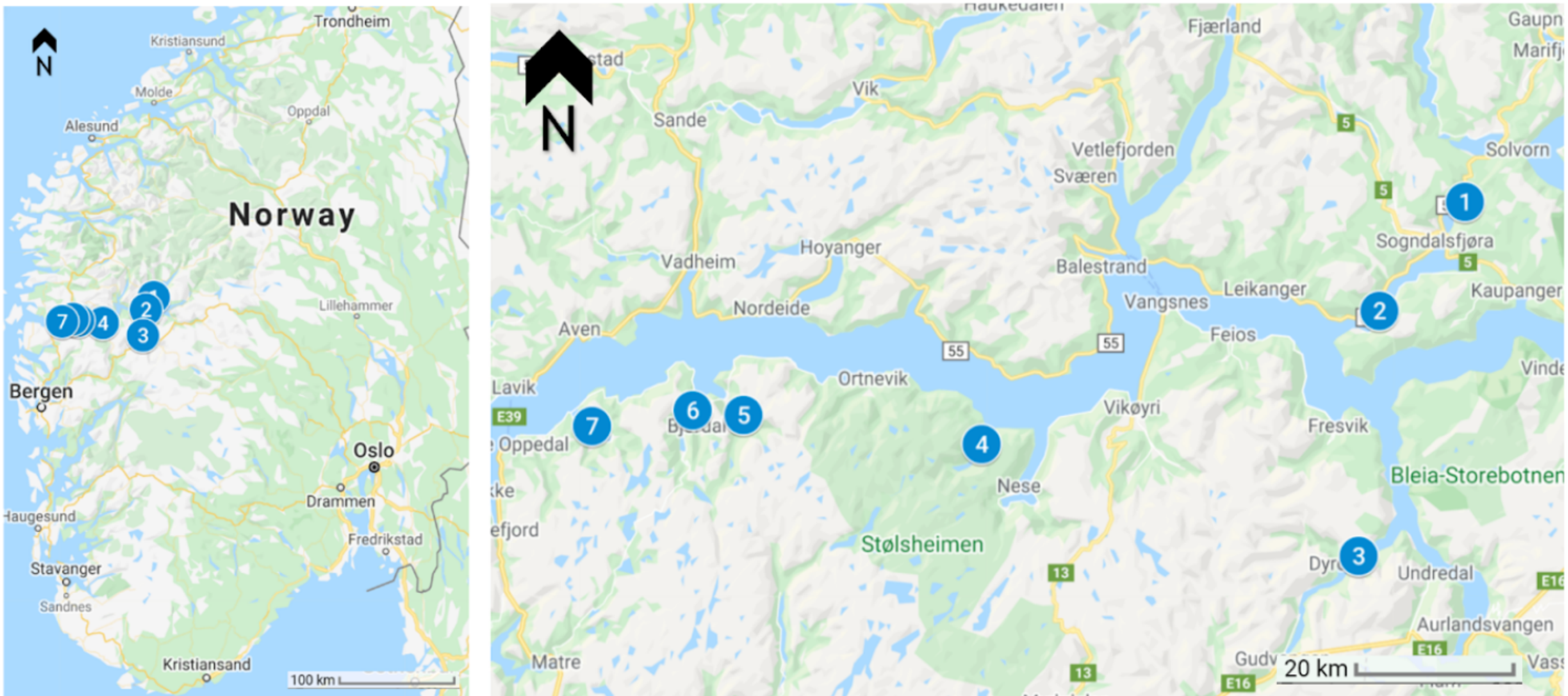


Figure 3*:* Map of study sites located around the Sognefjord in Western Norway (1) Barsnesfjorden, (2) Sogndalsfjorden, (3) Nærøyfjorden, (4) Finnabotn, (5) Østerbøvatn, (6) Fuglsetfjorden and (7) Ikjefjorden

Most of these fjords are directly impacted by factors such as aquaculture sites, hydropower plants (figure 4), wastewater plants (figure 5) and other anthropogenic activities.

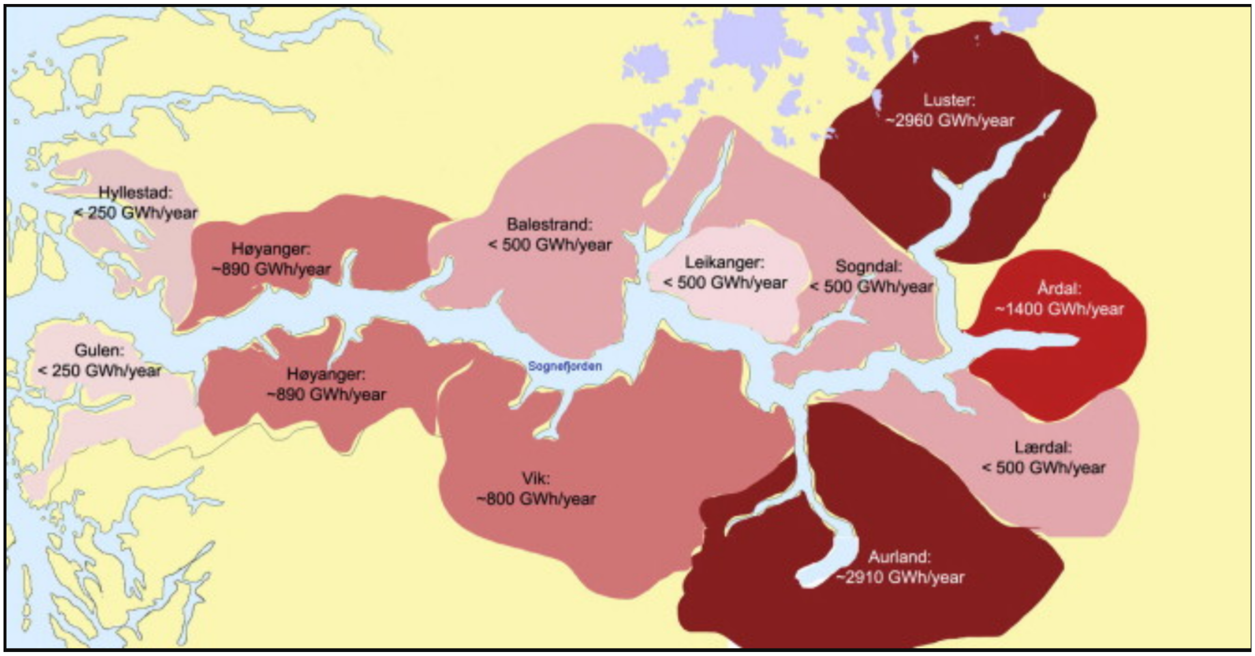


Figure 4: Hydropower production areas on the shores of the Sognefjorden, with an increase in hydroelectric production indicated by colour intensifying from pink to red. Reprinted from "A critical view of the environmental condition of the Sognefjord," by S. Manzetti and J. H. Stenersen, 2010.

Many towns along the shore of the Sognefjorden rely on the generation and export of hydroelectric power to major cities in Norway to maintain booming economies. This area is the densest hydroelectricity production area in Norway and production in this area only continues to increase along with the population and growth of the capital, Oslo (Manzetti and Stenersen, 2010). Since the early 1900s, there have been 79 hydropower plants constructed alongside the Sognefjord (Berg et al., 2017). Of these, 32 are hydropower plants with reservoirs. As indicated in figure 4, the Barsnesfjorden and Sogndalsfjorden are located in an area that produces <500 GWh/year. The Nærøyfjorden is located in an area that produces ~2910 GWh/year. Finnabotn is located in an area that produces ~800 GWh/year, and Østerbøvatn & Fuglsetfjorden are located in an area that produces ~890 GWh/year. It is estimated that 8TW h is produced at hydropower stations in the Sognefjorden annually (Manzetti and Stenersen, 2010). As a direct result of this, it is estimated that 248% more freshwater is entering the Sognefjorden in the winter than would occur if the fjord was not regulated (Berg et al., 2017). However, some side fjords are more affected than others.

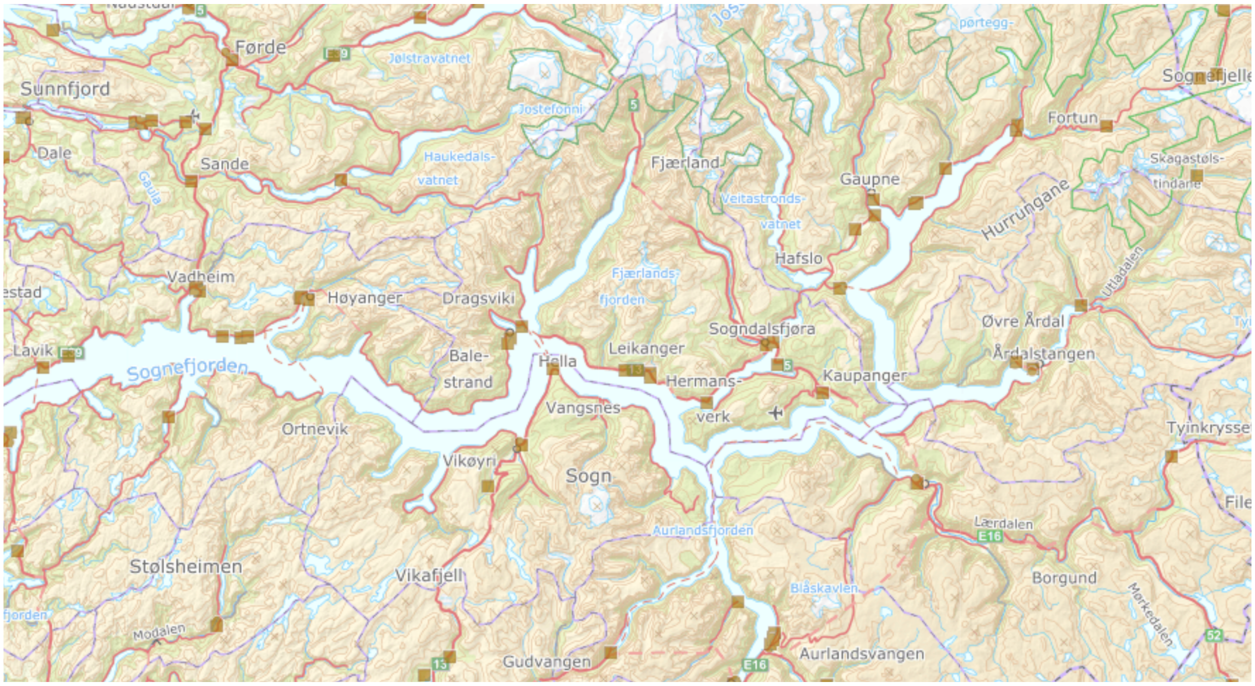


Figure 5: Locations of wastewater treatment plants (indicated by squares) along the Sognefjorden. Reprinted from the *Miljøstatus* website.

Figure 5 exhibits the existence of many wastewater treatment plants located around the study sites in addition to the hydropower gradient displayed in figure 4. Along the Sognefjord there are 55 stations utilising mechanical methods of wastewater treatment, 2 utilising biological methods of treatment & 10 with no treatment (Manzetti and Stenersen, 2010). Of the 10 wastewater plants not treating the wastewater, 7 are located in the immediate area of the study sites. Additionally, it is estimated that the Sognefjord contains 15 aquaculture stations from its outer regions towards Sognesjøen (Manzetti and Stenersen, 2010).

The Barsnesfjorden is impacted by hydropower as it is located directly beside the Årøy-river hydropower plant, which is a riverine power plant that has been in operation since 1983 (Kaufmann, 2014). Despite this regulation, the annual freshwater flow rate has been deliberately kept at a similar level as it was before construction (Paetzel and Dale, 2010). There were also multiple bridges built between the Barsnesfjorden and Sogndalsfjorden that have resulted in some shallowing and constrictions of the sound. The first of these bridges was built in 1958 (Kaufmann, 2014) followed by a new one constructed in 2018 (Holz, 2017). The Barsnesfjorden is connected to the Sogndalsfjorden by a shallow inlet (figure 6). Additionally, there are many farms around the Barsnesfjorden and Sogndalsfjorden so it cannot be disregarded that agricultural runoff could have a minor influence on fjord water chemistry.

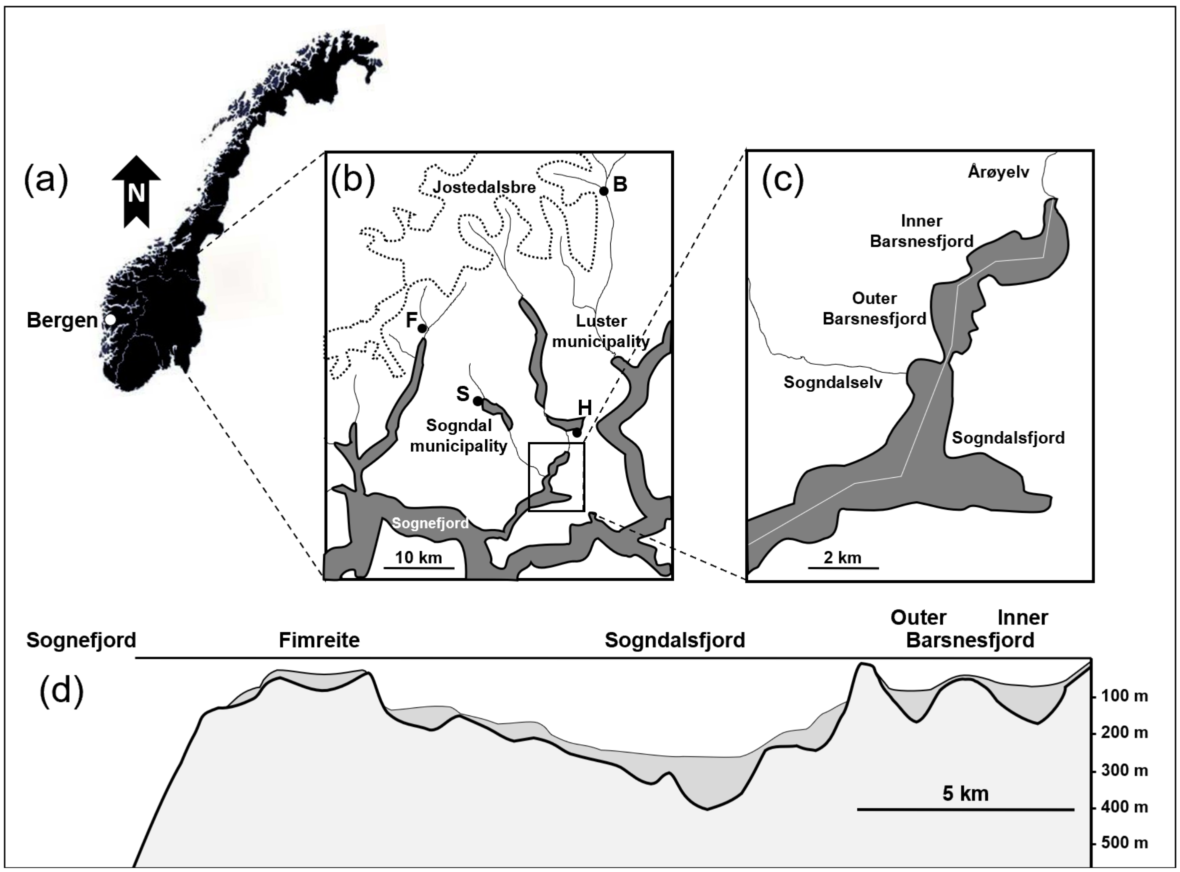


Figure 6: Depth profile for the Sogndalsfjorden and Barsnesfjorden. Reprinted from "Climate proxies for recent fjord sediments in the inner Sognefjord region, western Norway", by M. Paetzel and T. Dale, 2010, *Geological Society London Special Publications, 344*(1).

While the Sogndalsfjorden does not have the direct influence from hydropower that the Barsnesfjorden does, it does have a small aquaculture operation located near the town of Sogndal at Skjær. From the years of approximately 1985-2010 the premises were used for salmon farming followed by cod farming. From 2015 on the farm has transitioned into the farming of lumpfish

(*Cyclopterus lumpus*) for their use as “cleaner fish”. These operations occur on land and are likely less damaging to the local environment than the years of cod and salmon farming. It is also worth noting that before the 1990s Sogndal did not have a sewage treatment plant, meaning that the sewage ran directly into the fjord (Dale & Hovgaard, 1993). Treatment plants were installed in the mid-1990s, however an estimated 1480 pe (person equivalent) of sewage is still untreated (Brekke et al., 2014). There are six sewage discharge points located in the Sogndalsfjorden (Brekke et al., 2014).

In terms of the Nærøyfjorden (figure 7), it does not appear to have constructions at the fjord entrance, aquaculture activities, or agricultural runoff. It is located the furthest from the coastal water and in an area that is known to produce large amounts of hydroelectricity (Manzetti & Stenersen, 2010), but does not appear to have any hydropower plants directly influencing it. In the 1960s/1970s approximately 7% of the watershed was transferred to another river not draining into the Nærøyfjorden (Berg et al., 2017). This can be expected to have an effect on the surface hydrography and the current system. Additionally, there is likely some impacts from sewage entering the basin water, especially since it is a fjord that harbours many ferries and cruise vessels that are releasing sewage on a regular basis (Øystein et al., 2010).

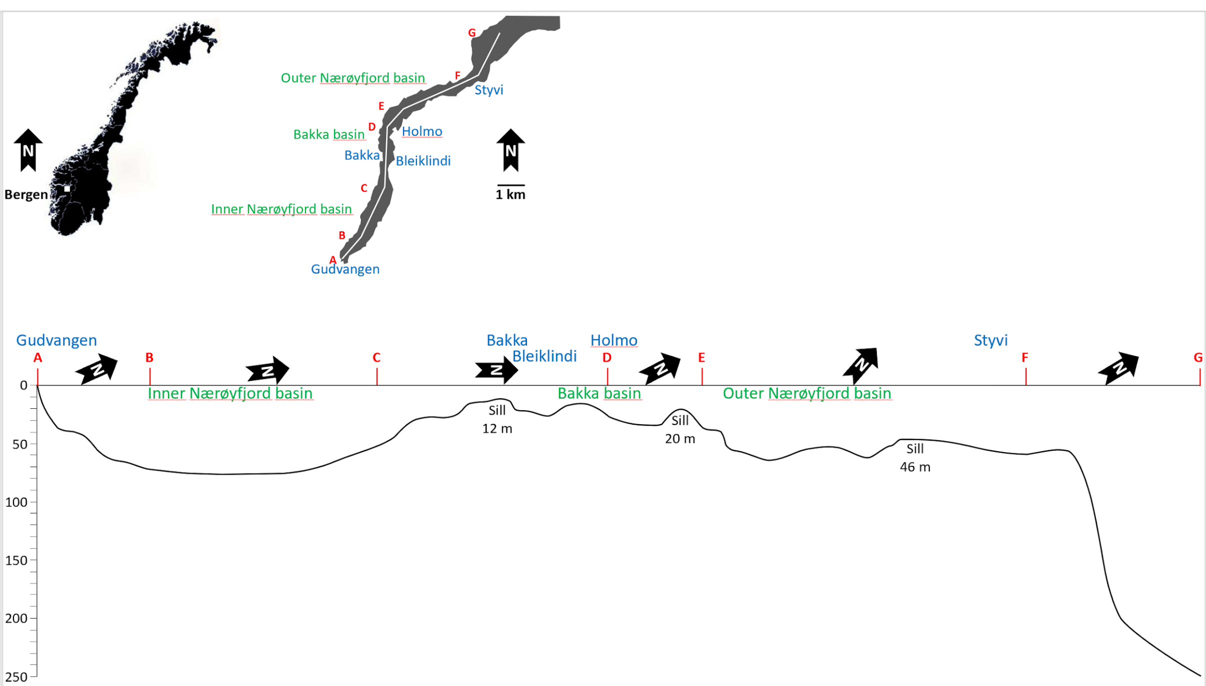


Figure 7: Depth profile for the Nærøyfjorden. Reprinted from “Analyse av resente sedimentkjerner i den anoksiske Nærøyfjorden, Vest-Norge”, by Dybo et al., 2016.

The Ikjefjorden has also been impacted by anthropogenic activities (figure 8). It has been estimated that as a result of hydropower activities, 50% of the natural freshwater supply was removed from the watershed in the 1970s (Gladsø and Hylland, 2005). The Øystrebøelva and Storelva rivers that drain into the Ikjefjorden were regulated for the purpose of increasing the hydropower production of the Matre M hydropower plant, which is one of the plants affecting the Ikjefjorden along with Stordal (Berg et al., 2017). Since 1971 when the rivers were regulated, their freshwater discharge relies entirely upon hydropower production. This has changed the patterns of freshwater flow received by the Ikjefjorden. The Ikjefjorden also receives freshwater from the Snjogilet river (Van Rossum, 2018). This primarily has effects on the hydrography and water currents, indirectly affecting oxygen supply to the basin water. The Ikjefjorden also has a bridge that was constructed at its entrance in 1977 (Koek and Van Doorn, 2018; Van Rossum, 2018). The successful construction of this bridge required a reduction of the deepest sill point by approximately 5 m (Koek and Van Doorn, 2018). Part of this endeavour was the closing of a 50-100 m sound, allowing a sound of 300 m to remain. It can be assumed that these influences have an effect on oxygen supply to the basin.

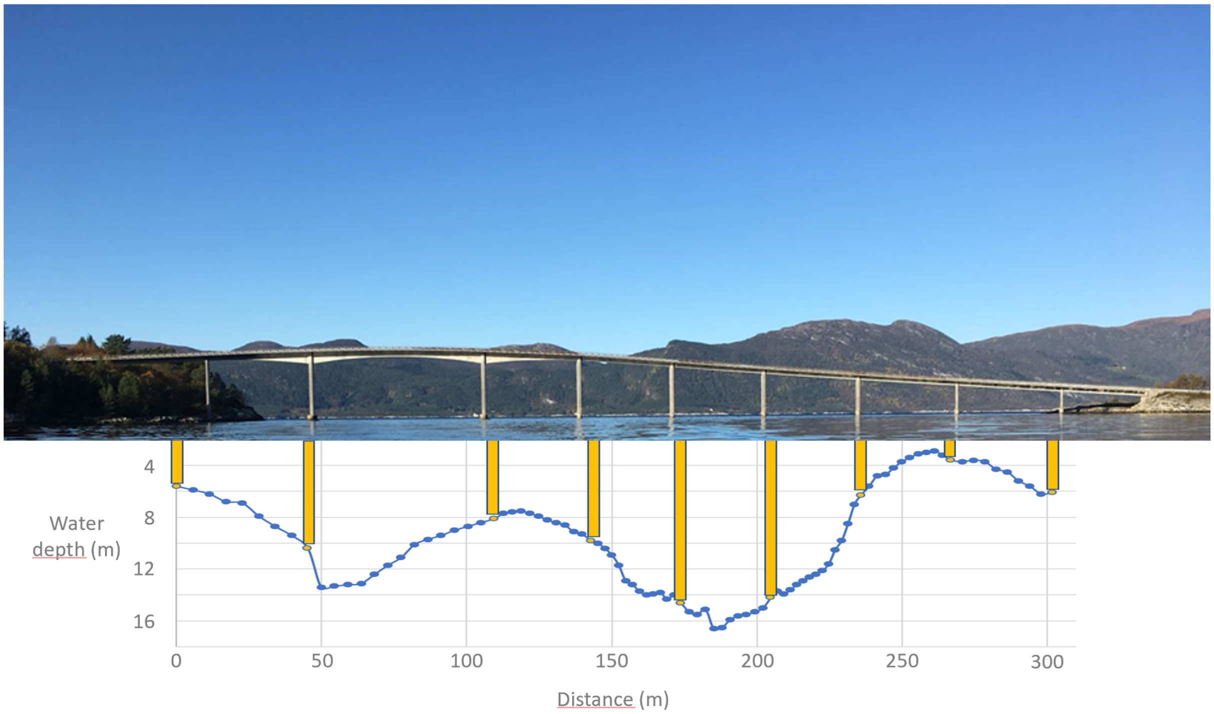


Figure 8: Depth profile for the Ikjefjorden. Reprinted from "Investigating environmental change in the micro-organism distribution of anoxic Ikjefjord sediments since the 1960s, Western Norway", by Koek and Van Doorn, 2018.

The Østerbøvatn (figure 9) can be considered a unique water body in this study. It was previously a lake that was situated just above sea level. In the 1860s a small river that was located between the lake and Fuglsetfjorden was excavated and the lake evolved into an integrated part of the fjord system (Johnsen & Tveranger, 2016). This has several implications for the hydrology of the basin, such as the possibility of increased oxygenation due to an increased frequency in basin water exchanges. Additionally, the Østerbøvatn has a production site for smolt (young salmon or trout) that is land-based. It is known as "Sørebø" and drains wastewater to Østerbøvatn (Lode et al., 2013). Runoff from this farm likely contains organic matter which could cause an increased rate of oxygen consumption in the fjord. As the smolt production plant is looking to expand its hatcheries, there are plans in place to increase the depth of the opening from 2 m to 7-8 m and widen it from 11 m to 20 m to facilitate this expansion (Johnsen & Tveranger, 2016). Additionally, the Østerbøvatn has some direct influence from hydropower activities. The Matre M hydropower plant runs into the Østerbøvassdraget which drains into the Østerbøvatn. There is also a hydropower plant under construction in the Østerbøvatn area. Johnsen et al. (2016) states that this planned hydropower plant will increase freshwater flow to the Østerbøvatn by 21% annually due to transfer of water from a neighbouring watershed.

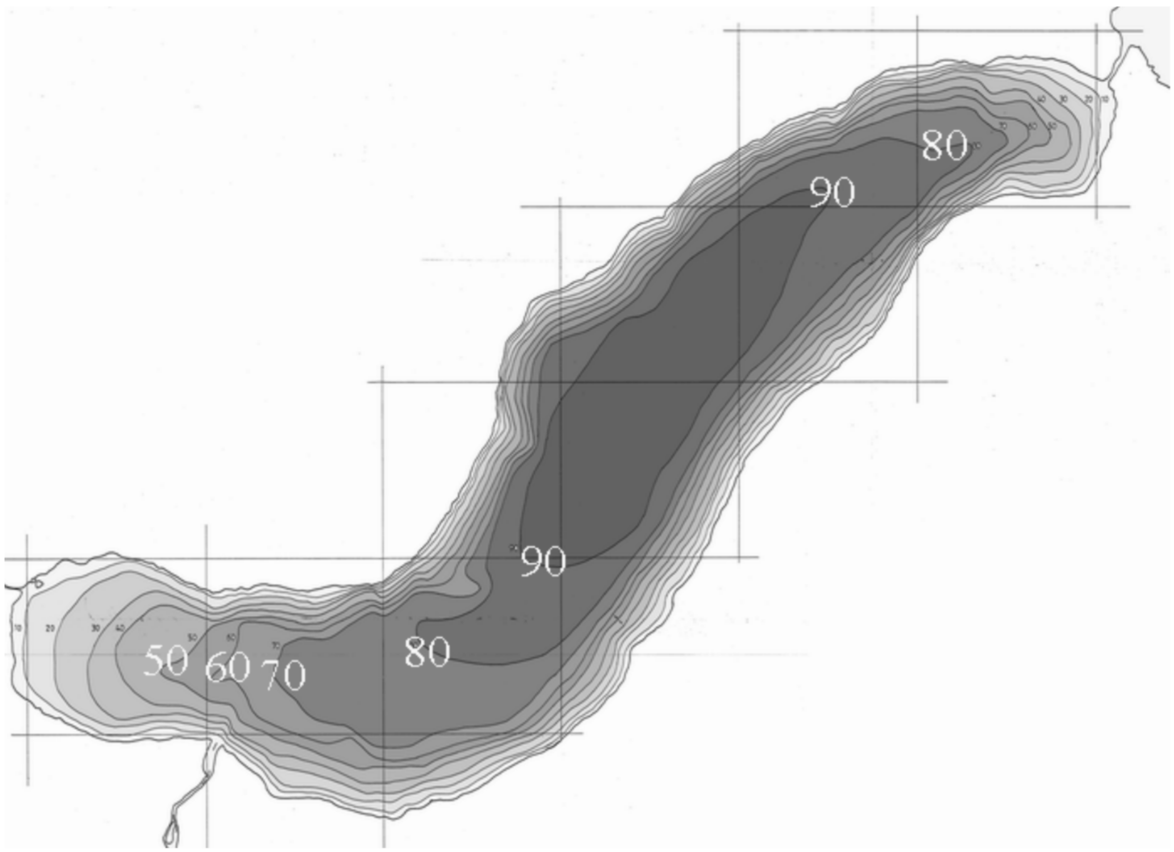


Figure 9: Bathymetric map of the Østerbøvatn. Reprinted from "Konsekvensutredning for Østerbø og Randalen kraftverk, Høyanger kommune.", by G.H Johnsen and S. Kålås, 2005.

The Fuglsetfjorden (figure 10) also has some factors that may be influencing its water chemistry. In the 1970s there was a salmon farm operating in the entrance to the Fuglsetfjorden. This farm has since been moved away from the entrance. However, the water supplying the Fuglsetfjorden will still be influenced by the fish farm even though it has been moved. It is possible that some organic matter related to the fish farm such as feces and excess food may have been transported to the inner part of the fjord through tidal currents, which could result in an increased oxygen consumption. Additionally, if the fish farm has caused a general decrease in oxygen concentration in the area directly influenced by it then it is possible that inflows into the

Fuglsetfjorden may not ventilate the fjord as much as previously expected. There is also a bridge located at the entrance to the fjord that was constructed in 1963. The construction likely constricted the sounds somewhat which may have influenced oxygen supply to the basin. The Fuglsetfjorden has some impact from hydropower production as well. The Matre M, Vestrebotn and Vemundsbotn power plants affect the Førdeelva and Bjordalselva which run directly into the Fuglsetfjorden (Berg et al., 2017).

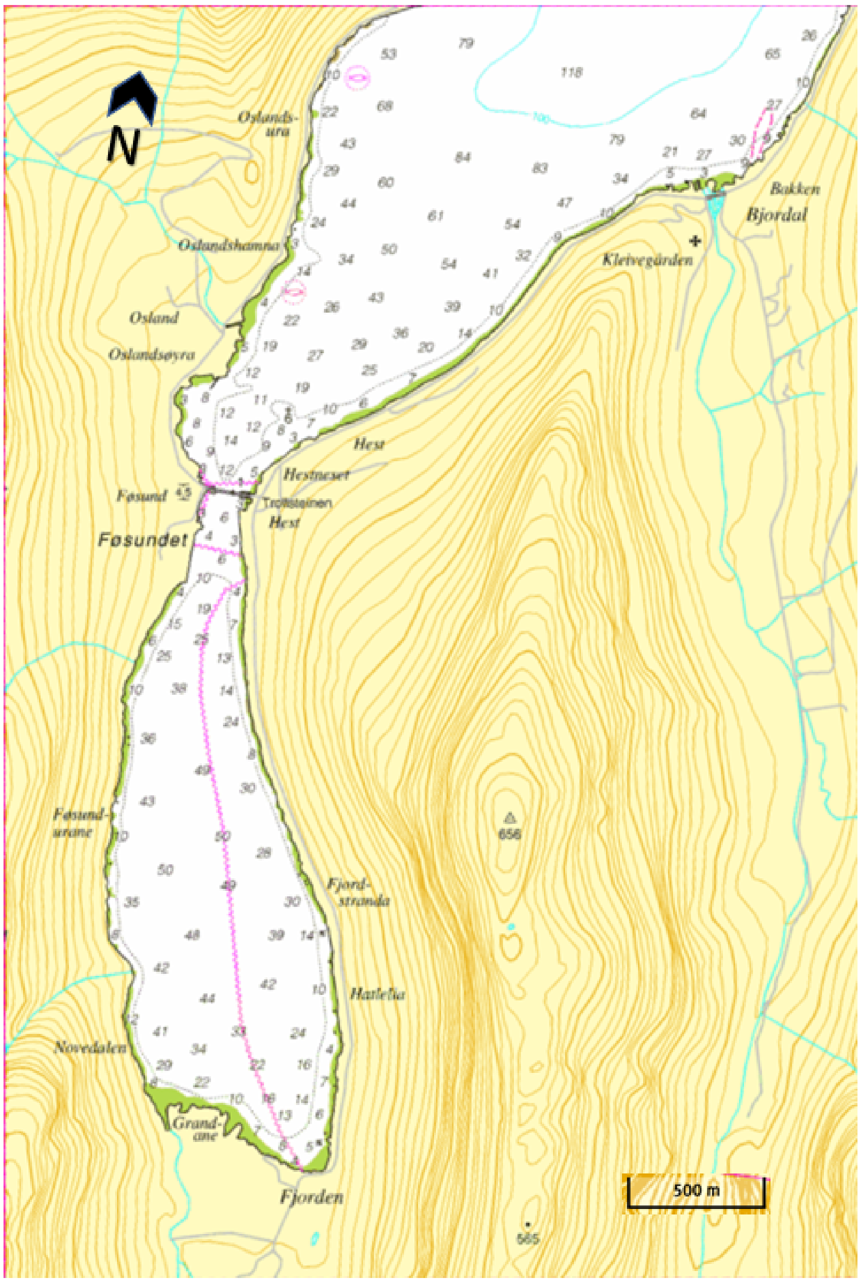


Figure 10: Bathymetric Map of the Fuglsetfjorden. Adapted from the *Norgeskart* website.

Although the Finnabotn (figure 11) has no hydropower plants, aquaculture activities or local agriculture facilities, it does have some anthropogenic modifications. Aquatic travel is imperative to life in Norway as water bodies are plentiful, and around the 1950s or 1960s the entrance to Finnabotn was deepened from 0.5 m to 2 m for the facilitation of small boat traffic (Personal communication between Dale & Finden, 2021). This carries the implication that oxygen supply to the basin water may have been altered as well.

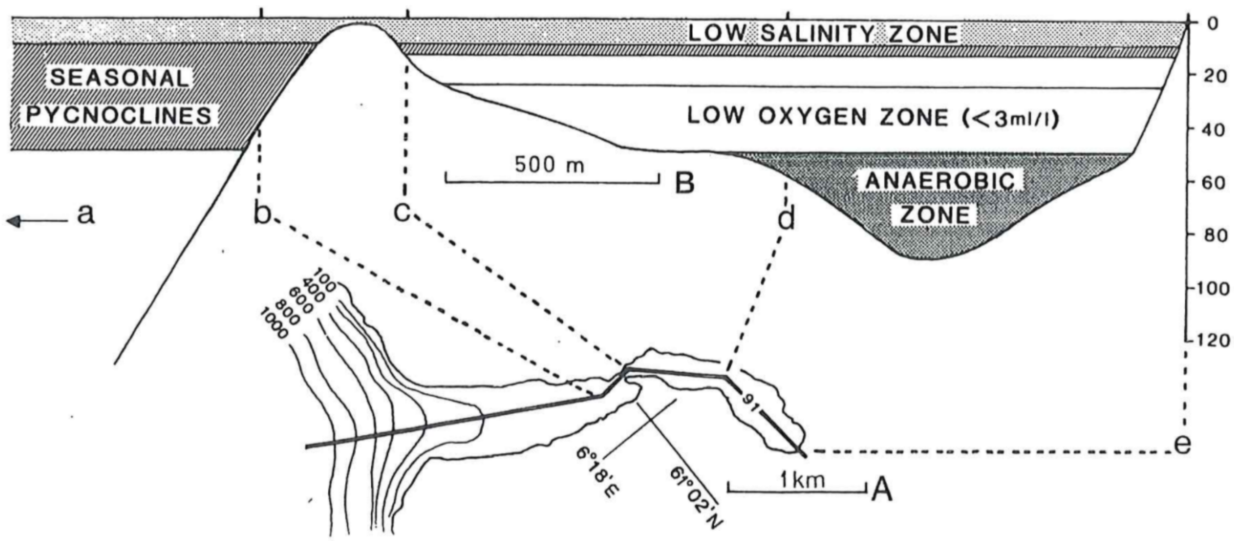


Figure 11: Hydrography of the Finnabotn. Reprinted from “Radiolaria in the plankton of some fjords in western and northern Norway: The distribution of species”, by K.J Bjørklund and N.R Swanberg, 2020, *Sarsia: a Nordic journal of marine biology, 72*(3-4).

While the Barsnesfjorden and Sogndalsfjorden have been studied extensively (Holz, 2017; Kaufmann, 2014; Bøen et al., 2015; Klakken, 2015; Golmen et al., 2003; Paetzel & Dale, 2010, Swanberg & Bjørklund, 1987) there is less information available regarding the Nærøyfjorden, Finnabotn, Østerbøvatn, Fuglsetfjorden and Ikjefjorden. As such, current data was extracted from the latter five fjords through some field work sessions and amalgamated with the pool of historical data available. Analysis of the former two fjords was executed exclusively utilising historical data. It must be noted that since the Barsnesfjorden, Nærøyfjorden, and Fuglsetfjorden had multiple basins, this thesis focused on only one of the basins in each of these fjords. Thus, the presented results are focused upon the Outer Barsnesfjorden, Inner Nærøyfjorden, and Inner Fuglsetfjorden. Sampling conditions for the five fjords in the study area that underwent data collection are indicated in Table 1 below.

	Nærøyfjorden	Finnabotn	Østerbøvatn	Fuglsetfjorden	Ikjefjorden
Date	10/20/2020	12/09/2020	10/23/2020	10/23/2020	10/23/2020
Time	10:17	13:30	14:00	12:31	11:37
Weather	Rainy, no sun		Clear sky	Clear sky	Clear sky
Secchi Depth (m)	8	20	10	14	14
Depth at Sampling Point (m)	77.0	87.0	90.0	51.3	122.0

Table 1*:* Sampling conditions for the Nærøyfjorden, Finnabotn, Østerbøvatn, Fuglsetfjorden and Ikjefjorden

The basic physiographic characteristics of the seven side fjords included in the study were also profiled. This data is presented in Table 2 below.

	Outer Barsnesfjorden	Sogndalsfjorden	Inner Nærøyfjorden	Ikjefjorden	Østerbøvatn	Inner Fuglsetfjorden	Finnabotn
Maximum Depth (m)	~80[a]	263[a]	77[a]	120[d]	~100[b]	50[a]	90[c]
Sill Depth (m)	7.5[a]	25[a]	15[a]	16[i]	2[a]	6[a]	2.5[c]
Length (km)	4.5[g]	15[f]	17.5[e]	~5[i]	~3[b]	~2.5	~2
Width (km)	1.4[f]	1.6[f]	2.5[h]	~1.5[i]	~1	~1	~1
Area (km^2)	4.5[f]	17.5[f]	709[h]	4[i]	2.2[b]		1.3[c]
Volume (m^3)	~165[f]	~1934[f]			~128[b]		

Table 2*:* Basic physiographic characteristics of seven side fjords located along the Sognefjorden in Western Norway**;** *Note:* Data are from a Personal Communication with Dale (2021)[a], Johnsen & Kålås (2007)[b], Swanberg & Bjørklund (1987)[c], Koek (2018)[d], Vassenden et al., (2007)[e], Dale & Hovgaard (1993)[f], Reβ (2015)[g], Claudino-Sales (2018)[h], Van Rossum (2018)[i]

2.2 Field Methods

Field work was completed at the Inner Nærøyfjorden, Finnabotn, Østerbøvatn, Inner Fuglsetfjorden, and Ikjefjorden. Dissolved oxygen was measured at the deepest point in the basin of each side fjord through the use of a Conductivity-Temperature-Depth (CTD) sonde. This CTD was a model SD204 produced by the Norwegian company *Saiv*. It was equipped with a Dissolved Oxygen (DO) sensor of type SAIV205. This sensor contains a Clark type electrode which operates by allowing oxygen levels to modify electrical currents flowing between an anode and cathode; this provides an indication of ambient oxygen levels. At each sampling location the depth was noted, as were the geographical coordinates, field conditions, and time of sampling. A CTD attached to approximately 200 m of rope was slowly lowered into the water until it hit the bottom of each location, and automatically recorded measurements every 2 seconds. This CTD recorded measurements for oxygen (mg/L), salinity (‰), temperature (^{0}C), density (mg/l), chlorophyll (µg/l) and turbidity (FTU). Secchi depth was measured on the shady side of the boat utilising a white Secchi disk that was ~25 cm in diameter.

2.3 Data Collection

The data presented in this thesis is an amalgamation of historical data and data collected in the field. Historical dissolved oxygen, temperature and salinity data collected from year to year were synthesized to evaluate change over time. Historical records were obtained through various reports, theses and scientific journals. The data in question was CTD records for the Inner Nærøyfjorden, Østerbøvatn, Ikjefjorden, Inner Fuglsetfjorden, Outer Barsnesfjorden and Sogndalsfjorden. Additionally, foraminifera data in the form of time series measurements over the last century are available for the Inner and Outer Barsnesfjorden, Sogndalsfjorden, Inner Nærøyfjorden and Ikjefjorden. Field work was carried out in the Inner Nærøyfjorden, Finnabotn, Østerbøvatn, Inner Fuglsetfjorden and Ikjefjorden.

Seeing as some of the data goes back as far as 1916, not all parameters have been determined through the same techniques throughout the past century. Additionally, some data was collected by experienced researchers while some was collected by students. It must be noted that this use of various techniques and the differing experience levels of researchers could be a potential source of error in the data. Oxygen was either determined through use of the Winkler method or a CTD electrode. The Winkler method was performed on-site and utilised titration to determine dissolved oxygen concentration in the water sample. This method was first developed by Winkler in 1888 and has been found to produce values with an accuracy of 3-5% (Carpenter, 1965). Some historic data presented their oxygen values with units of mL/L, so these values were converted to mg/L.

Salinity was determined in one of three ways: Mohr titration, use of a densimeter or with a CTD electrode. The Mohr method was developed by Karl Friedrich Mohr in 1856 and involved the titration of a water sample with a silver nitrate solution of known concentration in order to determine the salinity of the sample. Temperature was measured with either a reversing thermometer or with a CTD electrode. It must be noted that the Winker method, Mohr titration method and reversing thermometer all utilised Nansen bottles for collection of the water samples.

A full account of which method was used for each dataset is included in Appendix A.

2.4 Data Analysis

All relevant CTD data was tabulated and presented in the form of scatter plots, which allowed for conclusions to easily be drawn and presented. These plots displayed depth (m) along the x-axis, the parameter being analysed (either oxygen concentration, salinity or temperature) along the y-axis and featured different time series with the data from various years as a visual representation of how the anoxia has progressed over time. Scatter plots of this sort were produced for each of the seven study sites. Additionally, timelines were produced with time on the x-axis and the parameter being analysed on the y-axis in order to show exactly how these parameters have changed over time. Trendlines were only present in timelines that were proven to have statistically significant data.

Historical depth profiles (e.g. time series measurements from the last century) of benthic foraminifera were available for the Barsnesfjorden, Sogndalsfjorden, Inner Nærøyfjorden and Ikjefjorden. Minor modifications were made to most of these profiles for the purpose of consistent formatting.

A paper authored by Aure & Stigebrandt (1989) found that oxygen consumption can be related to mean sill basin depth, and a formula was derived in this article. This formula was used to calculate the theoretical oxygen consumption at each location. This formula is presented as follows:

$$Consumption\ Rate = (a - b \cdot H_t) \cdot 2.43/H_b (ml^{-1} month^{-1})(H_t \leq 50) \qquad [1]$$

In this equation, a=5.38, b=0.070, H_t represents sill depth (m), and H_b represents sill basin mean depth (m) (Aure & Stigebrandt, 1989). It is also important to note that in this model, $H_t \leq$ 50 m. Utilising this formula provided the theoretical oxygen consumption rate for each fjord in the study. Each theoretical rate was then multiplied by a factor of 1.423 so that the consumption rate was in units of mg/L/month. Additionally, the actual oxygen consumption rate was calculated by selecting one point at the start of an inflow in the dissolved oxygen data, selecting a second point at the end of the inflow and assuming a linear relationship between them. In that case, actual oxygen consumption is represented by the slope between the two points. This must be calculated directly after an inflow in order to get the most accurate oxygen consumption rate. For datasets where multiple inflows were visible, consumption rates were calculated for each inflow and then averaged. For each basin, one consumption rate was calculated at a shallower basin depth and a second rate was calculated at a deeper basin depth. Depths varied for each basin. Upon calculation, a comparison of theoretical and actual oxygen consumption rates was presented in the form of a table.

Additionally, one way analysis of variance tests were utilised to determine whether statistically significant differences were present between the datasets over time for each location. A full account of the results of these tests is presented in Appendix B. Independent sample t-tests were also conducted for the Outer Barsnesfjorden and Sogndalsfjorden timelines to determine whether statistically significant differences were present in the first and second periods. The full results of these tests are available in Appendix C. These tests were imperative in verifying the hypothesis with statistically significant data.

3.0 Results

3.1 Hydrographical results for the Outer Barsnesfjorden

3.1.1 Salinity, Temperature and Oxygen Depth Profiles

The Barsnesfjorden depth profiles contained between 42-54 observations. They consisted entirely of measurements taken in the summer, which was defined as any data occurring in the months of June, July or August. The presented data was limited to these months as the comprehensive totals included 122 salinity observations, 124 temperature observations and 107 oxygen observations. These datasets were too large to include all seasons in one graph for each parameter.

The salinity data in the Barsnesfjorden all follows the same trend with a definite cluster visible in figure 12. This trend is encompassed by salinity steadily increasing from 0-10 m, a slower increase visible from 10-20 m and then a salinity stabilization at approximately 20 m where the hypolimnion begins. From 20 m on salinity remains relatively stable.

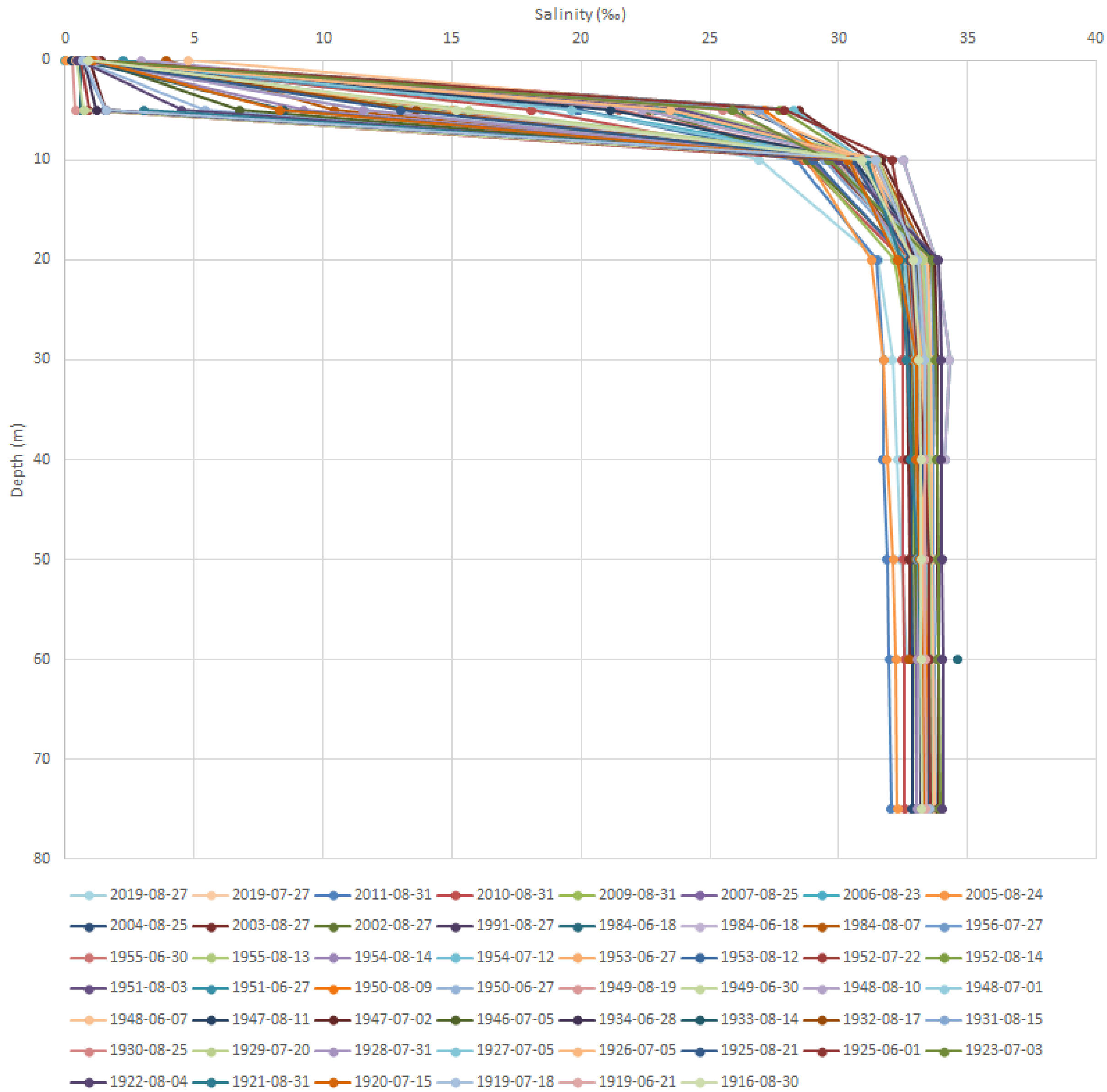


Figure 12*:* Salinity (‰) throughout the water column of the Outer Barsnesfjorden during summers (June-August) from the years of 1916-2019

It is worth noting that many of the most recent values appear to be reflective of lower salinity. However, a one way analysis of variance showed that this data was not statistically significant *[F(53, 395)=0.098, p=1]*. As such, no conclusive conclusions can be drawn from this figure.

In regards to the temperature data (figure 13), the earlier years display lower temperatures along the water column while more recent years exhibit higher temperatures. Although the majority of the data is clustered together, there is a tendency for the more recent years to be increasing.

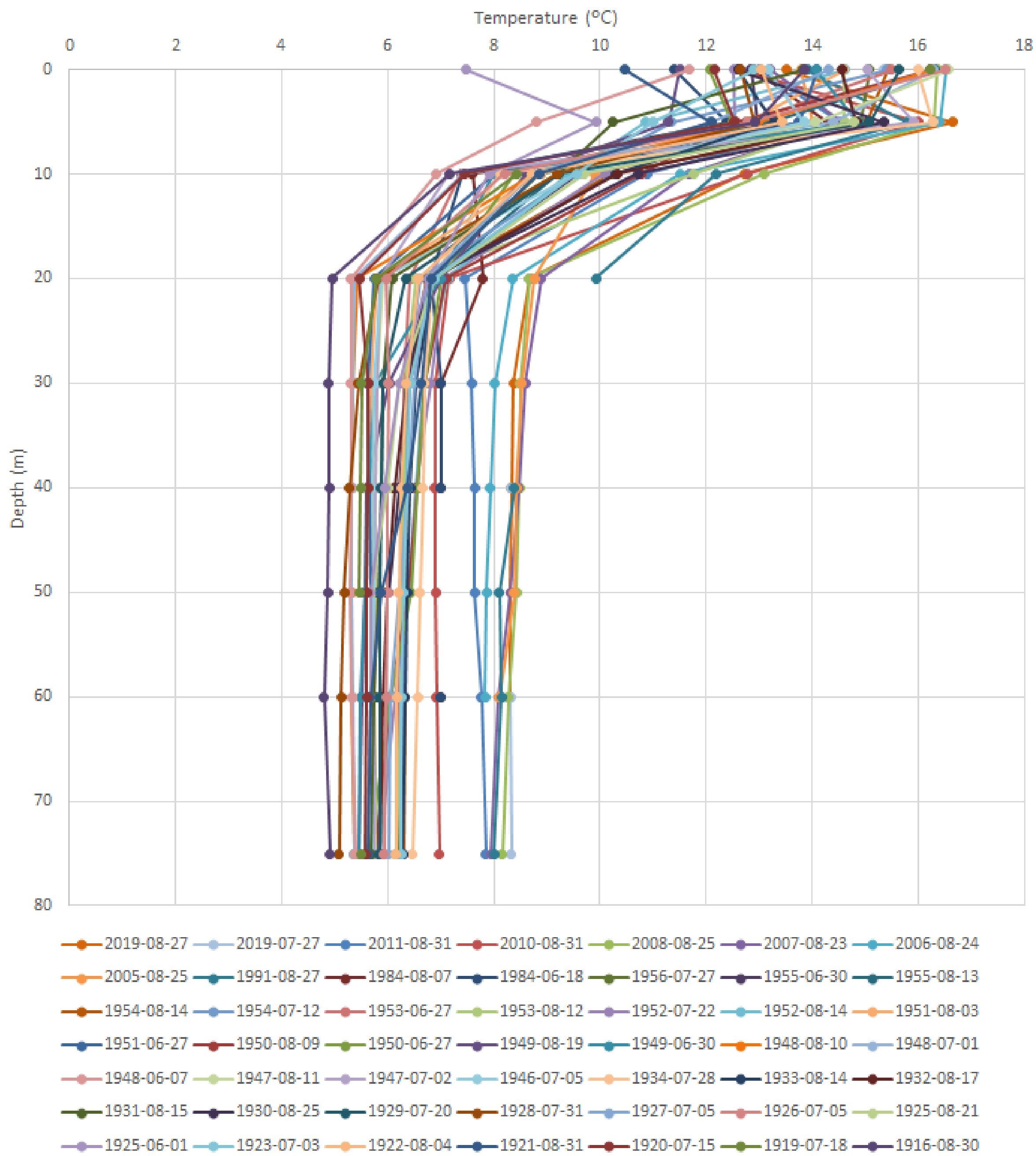


Figure 13*:* Temperature (ºC) throughout the water column of the Outer Barsnesfjorden during summers (June-August) from the years of 1916-2019

Notably, all data from the past 50 years is located outside of the main cluster in the right wing of the depth profile which shows pretty definitively that temperature is increasing over time in the basin water. It is also notable that the data with the lowest temperature along the water column occurred in 1916 which is the earliest year available in the dataset. There is a very clear gradient here. A one way analysis of variance deemed this data to be statistically significant $[F(115, 807)=1.75, p=9.54E\text{-}06]$. As is also supported by figure 12, the hypolimnion begins at 20 m. The thermocline appears to begin at approximately 5 m where the epilimnion ends.

Although difficult to definitively interpret whether the Barsnesfjorden is becoming more anoxic over time from its oxygen profile (figure 14) alone, this depth profile does serve an important purpose. It is evident from this figure that anoxia is tending to occur at shallower depths in the water column in more recent years than previously seen.

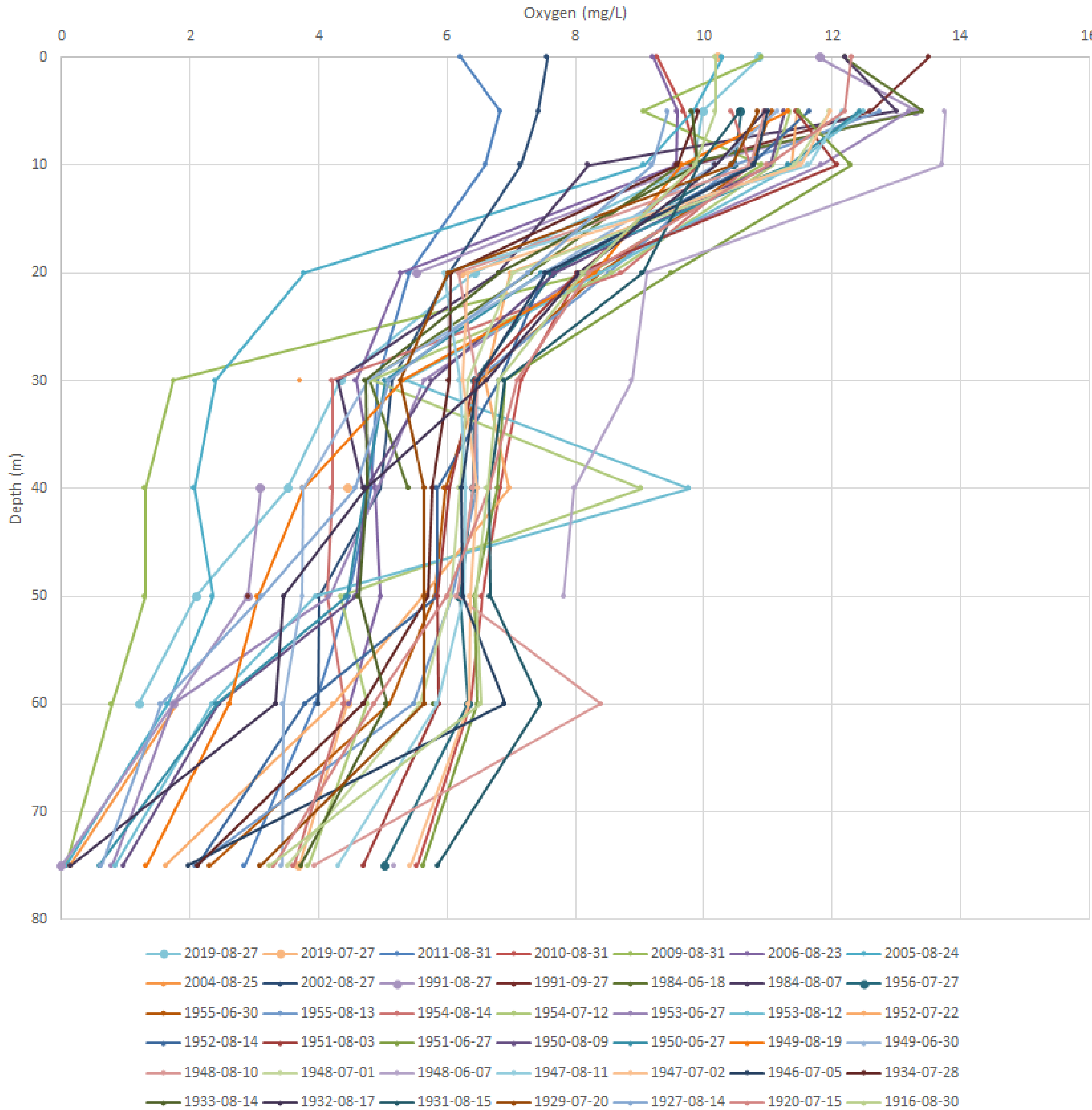


Figure 14*:* Oxygen concentration (mg/L) throughout the water column of the Outer Barsnesfjorden during summers (June-August) from the years of 1916-2019

As an example, in 2009 the oxygen concentration at 30 m is already lower than 2 mg/L. This is highly unusual as most datasets do not indicate a concentration this low until at least 60 m, and only 14 of the 42 observations reach 2 mg/L or below. In 2005 the oxygen concentration at 30 m was already 3.5 mg/L, and only deteriorated further from there. It is worth noting that the oxygen concentrations in 2011 and 2002 were likely underestimated as it is not possible that the oxygen could have been that low at the surface.

Notably, peculiar oxygen spikes at 40 m are visible in the 1953 and 1954 data along with an oxygen spike visible at 60 m in 1948. A one way analysis of variance found this data to be statistically significant *[F(119, 678)=1.47, p=0.0021]*.

3.1.2 Salinity, Temperature and Oxygen Timelines

The Barsnesfjorden timelines go back as far as 1916 for all parameters and contain data from all seasons, providing an illuminating wealth of data exhibiting how conditions along the water column have changed over time. The depths profiled include 0 m, 20 m, 40 m, 60 m and 75 m. The overall trends seem to indicate that salinity is decreasing over time, temperature is increasing over time and oxygen is decreasing over time.

In terms of the salinity data (figure 15), a large amount of variation is visible in the 0 m dataset, which can be attributed to seasonality. There is less variation visible in the data from 1976-2019. The salinity at 0 m, 20 m, 40 m, 60 m and 75 m appears to be decreasing over time. Independent samples t-tests were conducted at each depth to verify whether this decrease was statistically significant and to compare 1916-1956 trends to 1978-2019 trends.

There was not a significant difference at 0 m in the 1916-1956 *(M=6.33, SD=9.40)* and 1978-2019 *(M=4.97, SD=7.48)* datasets *[t(118)=-0.80, p=0.43]*. A significant difference was not observed between 1916-1956 *(M=33.0, SD=0.39)* and 1978-2019 *(M=32.93, SD=0.70)* at 20 m either *[t(116)= -0.72, p=0.47]*. Similarly, a statistically significant difference was not found in the 1916-1956 *(M=33.33, SD=0.34)* and 1978-2019 *(M=33.17, SD=0.66)* data at 40 m *[t(116)= -1.75, p=0.084]*. However, a statistically significant difference could be found at a depth of 60 m between the 1916-1956 *(M=33.44, SD=0.21)* and 1978-2019 *(M=33.28, SD=0.63)* datasets *[t(113)= -2.01, p=0.047]*. The 75 m 1916-1956 *(M=33.48, SD=0.207)* and 1978-2019 *(M=33.05, SD=0.57)* data was also found to have a statistically significant difference.

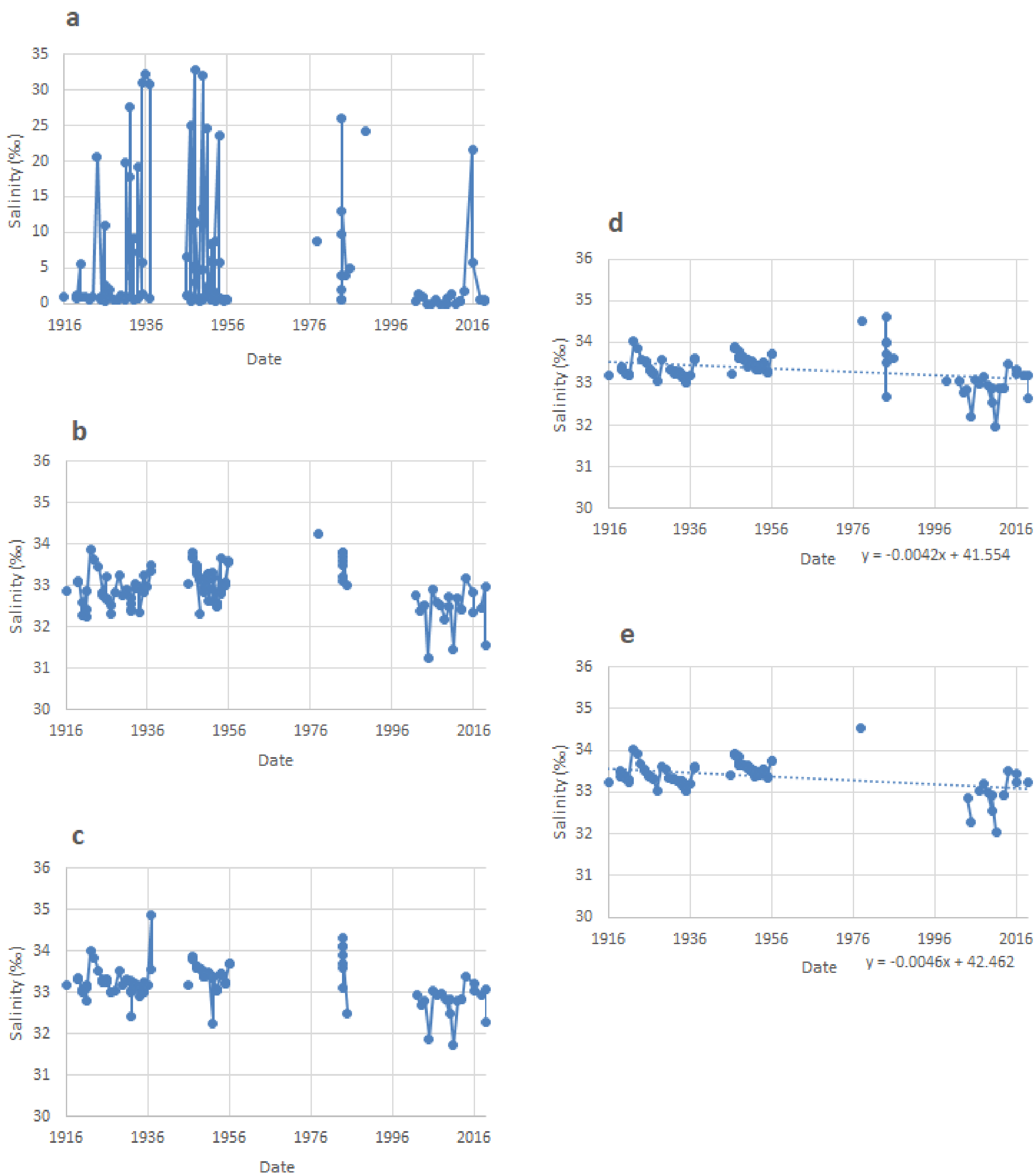


Figure 15: Progression of salinity (‰) from 1916-2019 at depths of (a) 0 m, (b) 20 m, (c) 40 m, (d) 60 m and (e) 75 m in the Outer Barsnesfjorden

Not only are the differing means at 60 m and 75 m indicative of salinity decreasing over time in the basin, but the trendline slopes support this as well. At 60 m the slope of the trendline was -0.0042 and at 75 m the trendline slope was -0.0046.

It is notable that the salinity data in 1984 appears to be extremely varied at all depths with the exception of 75 m, which does not contain data in this year. There also appears to be an outlier in 1978 at all depths except 0 m and 40 m.

Analogous to the 0 m salinity data in figure 172, the temperature values at 0 m (figure 16) are heavily influenced by seasonality. This is evident in the data from 1916-1956 *(M=9.42, SD= 4.88)* which contains representative data from all seasons, but not as evident in the data from 1978-2019 *(M=10.17, SD=4.77)* which is mostly comprised of observations made in late summer and early fall. Regardless, an independent samples t-test did not find the difference in these periods to be statistically significant *[t(109)=0.73, p=0.47]*.

At 20 m there is far less variation than there is at 0 m. While the 0 m dataset contains values ranging from 0 mg/L to 16.57 mg/L, the 20 m dataset only has a range from 4.96 mg/L to 9.70 mg/L. This indicates there is already less of a seasonal influence at this depth. A temperature increase over time is reflected in both the trendline and respective averages for each period. There was a significant difference found in the 1916-1956 *(M=6.50, SD=0.85)* and 1978-2019 *(M=8.10, SD=0.83)* datasets *[t(129)=10.50, p=5.18E-19].* Additionally, the slope of the trendline is 0.0264.

At 40 m the slope of the trendline is 0.0271, which is the same as the slope of the trendline at 60 m. At 75 m the slope of the trendline is 0.0268. Not only is there a palpable increase in temperature indicated by the trendline slopes, there is also a pronounced increase in averages between the first and second periods at all depths. At 40 m there is a statistically significant difference of 1.67ºC between the average temperature from 1978-2019 *(M=7.73, SD=0.71)* and 1916-1956 *(M=6.07, SD=0.52)*, *[t(126)=15.18, p=3.13E-30]*. There is a statistically significant difference of 1.72ºC at 60 m between the average temperature from 1978-2019 *(M=7.62, SD=0.62)* and the average temperature from 1916-1956 *(M=5.90, SD=0.38), [t(120)=19.04, p=4.59E-38]*. At 75 m, a statistically significant difference between the averages from 1916-1956 *(M=5.86, SD=0.35)* and 1978-2019 *(M=7.81, SD=0.56)* was found to be 1.95 ºC *[t(103)=20.86, p=9.29E-39]*. There does not appear to be any significant outliers in this set of timelines.

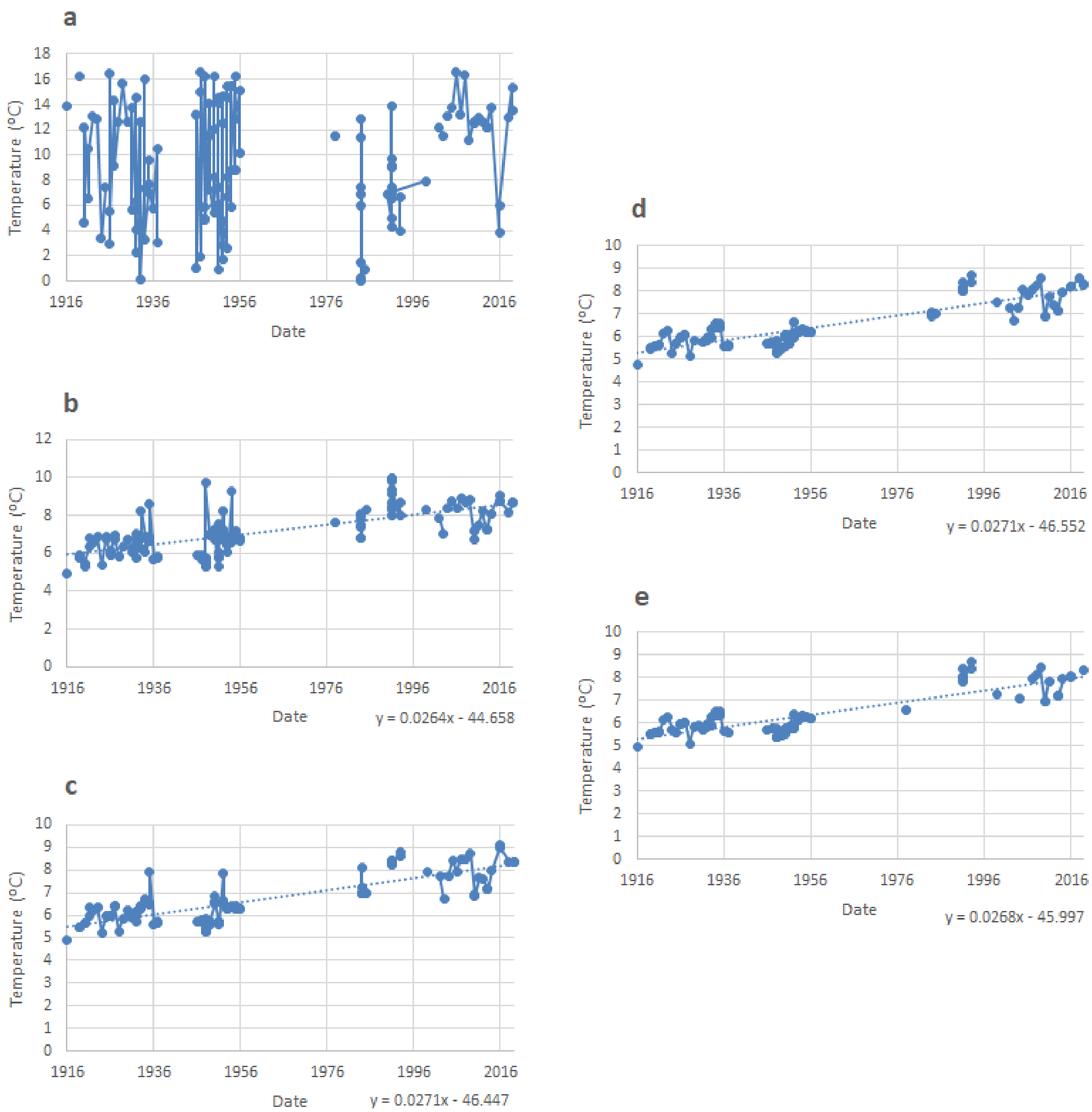


Figure 16*:* Progression of temperature (ºC) from 1916-2019 at depths of (a) 0 m, (b) 20 m, (c) 40 m, (d) 60 m and (e) 75 m in the Outer Barsnesfjorden

Furthermore, it is evident that the oxygen concentration in the Barsnesfjorden is decreasing over time. This is apparent at all depths shown in figure 17. Although the 0 m dataset appears to be somewhat lacking in data compared to the other depths, it does provide a good baseline for oxygen concentration comparison. Seeing as 0 m is located far above the threshold depth (which is located at 7.5 m as specified in table 2) and heavily influenced in terms of seasonality, it is important to note that it cannot be considered a reliable indicator of oxygen concentration progression. The average oxygen concentration at 0 m is 11.5 mg/L.

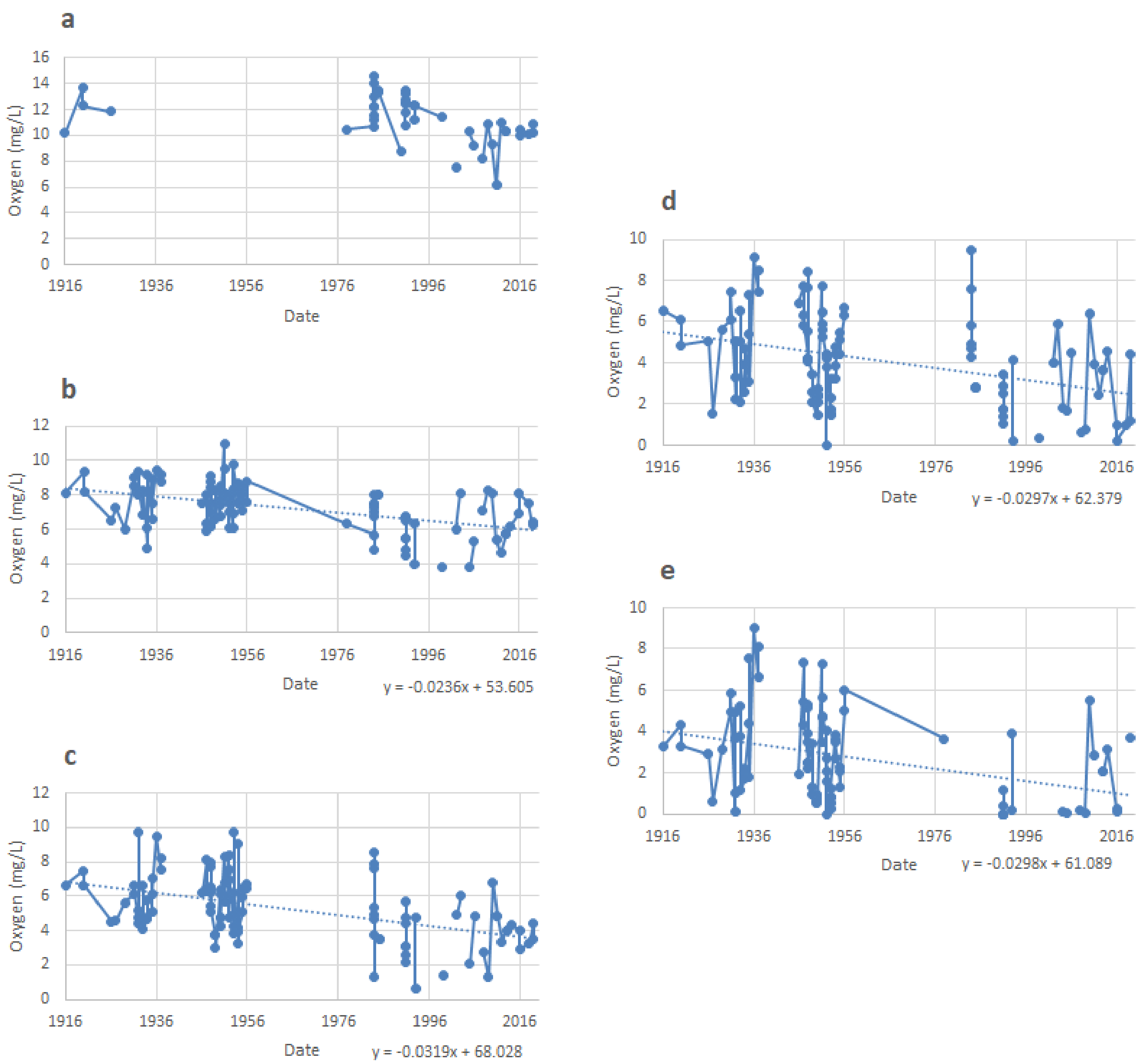


Figure 17*:* Progression of oxygen concentration (mg/L) from 1916-2019 at depths of (a) 0 m, (b) 20 m, (c) 40 m, (d) 60 m and (e) 75 m in the Outer Barsnesfjorden

The oxygen concentration at 20 m has a notable difference in the oxygen concentration averages between the earlier data and the later data. This difference between the 1916-1956 *(M=7.83, SD=1.13)* data and the 1978-2019 *(M=6.42, SD=1.26)* data was deemed statistically significant by means of an independent samples t-test *[t(111)= -6.23, p=8.66E-09]*. The decreased average in the second period along with the trendline slope of -0.0236 indicates that oxygen concentration is decreasing over time at this depth.

The 40 m dataset has the steepest trendline of the dataset with a slope of -0.0319. Additionally, the 1978-2019 *(M=4.35, SD=1.99)* oxygen concentrations tend to be significantly lower than those of 1916-1956 *(M=6.01, SD=1.56), [t(110)= -4.92, p=3.11E-06]*. From 1916-1956 the lowest concentration is 3.0 mg/L. From 1978-2019 there are 8 values that are lower than the previously determined minimum and the average is 1.65 mg/L lower than that of 1916-1956.

Similar evidence of an oxygen concentration decrease is visible in the 60 m dataset. The increased anoxia at 60 m appears to begin in approximately 1930 and only deteriorates further from there. The average oxygen concentration from 1978-2019 *(M=3.58, SD=2.39)* is 1.08 mg/L lower than that of 1916-1956 *(M=4.65, SD=2.05)*, a difference that was deemed statistically significant by an independent samples t-test *[t(106)= -2.50, p=0.0014]*. It is notable that the 60 m dataset also contains the first observed occurrence of total anoxia in this figure. This event occurred in 1952. There are some points following this observation that also come close to 0 mg/L, namely in 2016, 2008, 1999 and 1993. Following the first occurrence in 1952 these events increased in frequency.

On initial inspection of the 75 m dataset it can be noted that the trendline slope is not much steeper than those of the other depths. However, it must be taken into account that although some of the oxygen concentration values are appearing as 0 mg/L, they could actually be even lower. In reality anoxia is a sliding scale, with hydrogen sulfide production beginning after oxygen concentration reaches 0 mg/L. As a result, the values from 1978-2019 in this dataset could very well be lower than is represented, meaning that the slope in this trendline is likely underestimated. It is worth noting a statistically significant difference was found in the 1916-1956 *(M=3.22, SD=2.15)* data and the 1978-2019 *(M=1.34, SD=1.71* data, *[t(87)= -3.73, p=3.41E-04]*, so even without valid trendlines to compare there is proof that the oxygen concentration is decreasing over time at this depth based on the decreased average in the second period. Additionally, from 1978-2019 there are 8 observations of anoxia (occurring in 2016, 2009, 2005, and 5 months in 1991). From 1916-1956 there is only one occurrence which happened in 1952 and was also visible in the 60 m dataset.

In addition to the oxygen concentration decreasing over time at each depth, this figure also shows that the oxygen concentration tends to be higher in the surface values and lower deeper in the basin.

3.1.3 Foraminifera

The foraminifera data for the Inner Barsnesfjorden (figure 18) followed a different trend than that seen in the Outer Barsnesfjorden (figure 19).

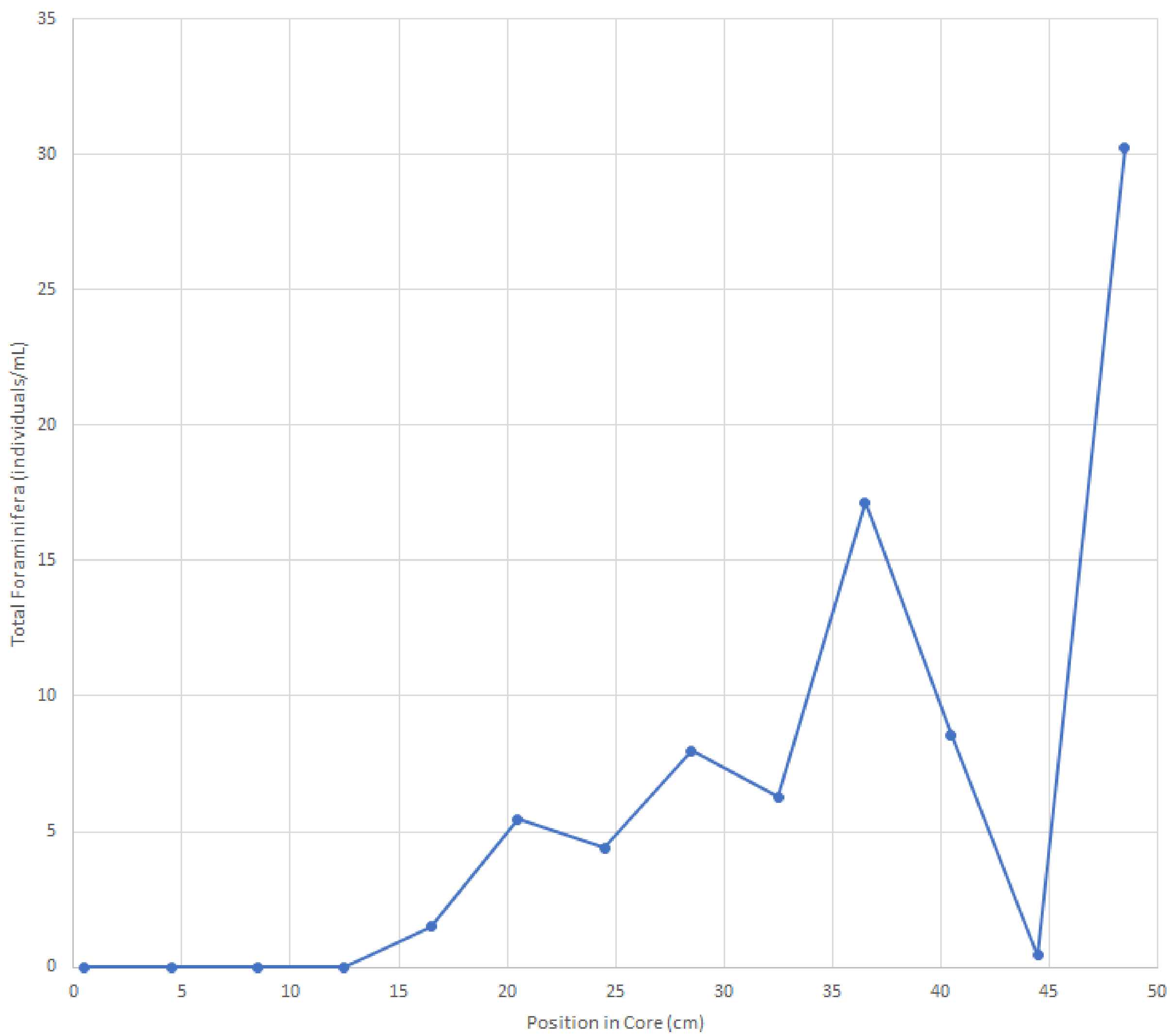


Figure 18: Total foraminifera (individuals/mL) found in an Inner Barsnesfjorden sediment core in 2019. Graph adapted from Dufner et al., 2019, unpublished data.

It is evident in figure 18 that as core depth increases, total foraminifera is increasing as well. Additionally, there is quite a substantial range with 0 individuals found from 0-12 cm in the core and 30 individuals found at the end of the core. This lack of individuals from 0-12 cm can be directly attributed to anoxic conditions in the basin, and the fact that there is a clear increase as depth increases means that the Inner Barsnesfjorden has gone from being periodically anoxic to permanently anoxic.

Conversely, the Outer Barsnesfjorden core tells a different story (figure 19). There does not appear to be any distinctly evident trend in the foraminifera data.

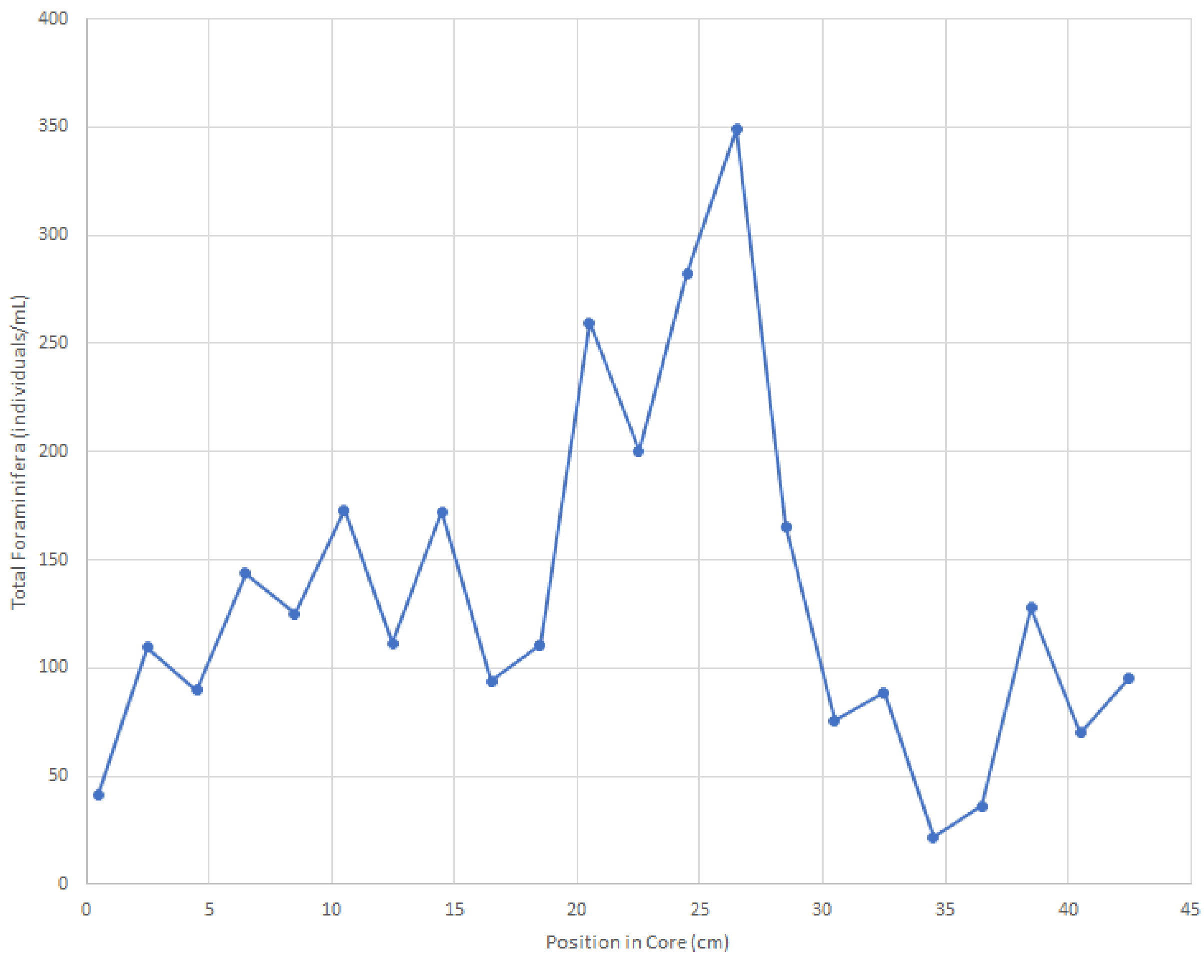


Figure 19: Total foraminifera (individuals/mL) found in an Outer Barsnesfjorden sediment core in 2019. Graph adapted from Dufner et al., 2019, unpublished data.

From 0-18 cm in the core there is a range of 40-175 individuals. From 18-30 cm there is a large spike in foraminifera with the presence of anywhere from 75-350 individuals. A dip is seen from 30-43 cm with only 22-128 individuals present in this section of the core. It can be deduced that the spike in foraminifera from 18-30 cm is indicative of an oxic period in the basin when the fjord was well ventilated, and the lower amounts of individuals on either side of this spike can be attributed to lower amounts of oxygen present in the fjord.

3.2 Hydrographical results for the Sogndalsfjorden

3.2.1 Salinity, Temperature and Oxygen Depth Profiles

The Sogndalsfjorden depth profiles contained between 36-52 observations. Analogously to the Barsnesfjorden depth profiles, these figures consist entirely of measurements taken from the months of June-August. The comprehensive Sogndalsfjorden totals included 147 salinity observations, 153 temperature observations and 128 oxygen observations.

The Sogndalsfjorden salinity data (figure 20) appears to follow the same trend seen in the Barsnesfjorden salinity depth profile (figure 12). The main difference is that the Barsnesfjorden salinity did not have a statistically significant difference between the data, and the Sogndalsfjorden salinity data does *[$F(147, 365)=4.45$, $p=4.59E-31$]*.

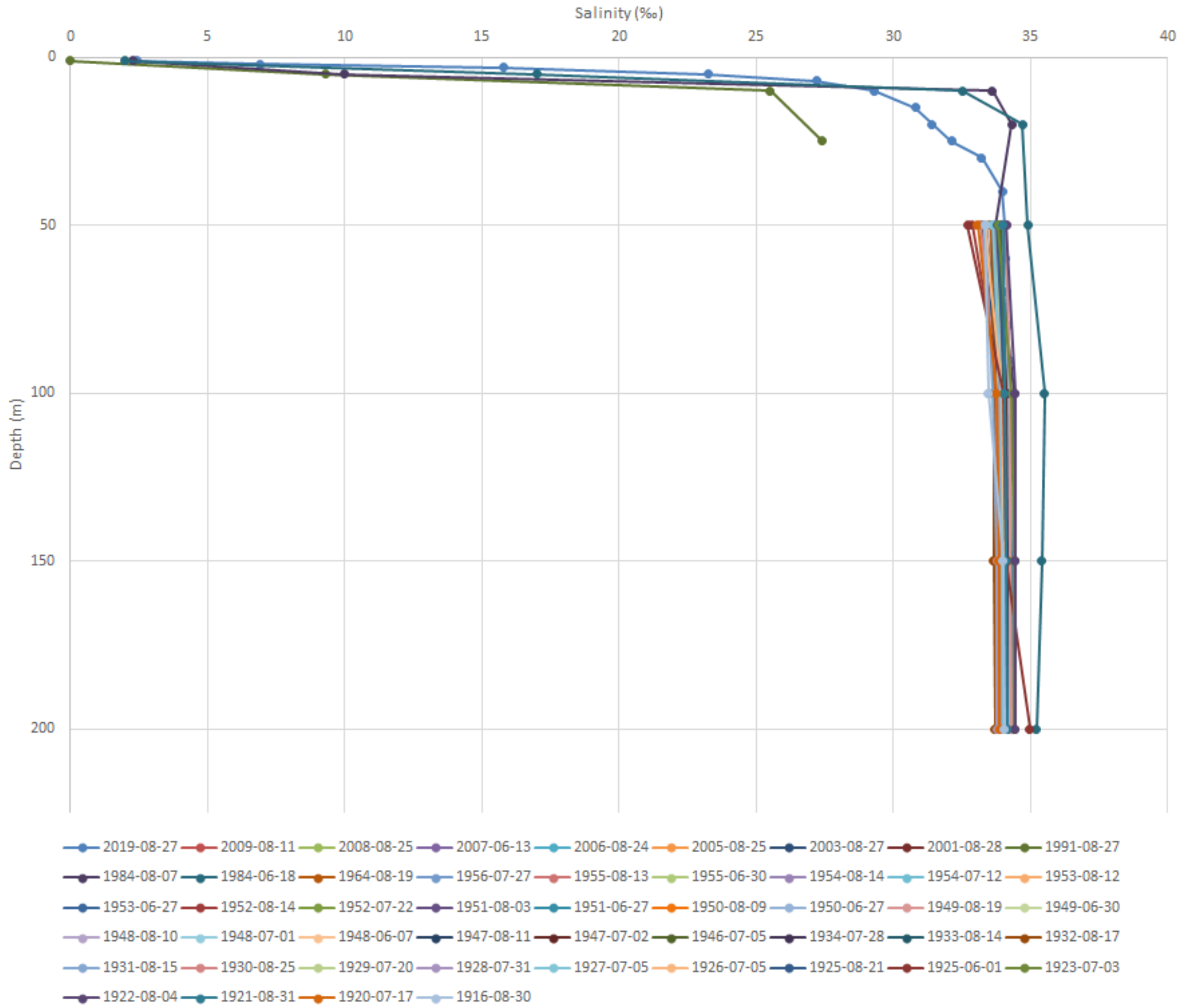


Figure 20: Salinity (‰) throughout the water column of the Sogndalsfjorden during summers (June-August) from the years of 1916-2019

Although the data in this figure does appear to be somewhat clustered, the historic data is mostly confined to the left side of the cluster towards the lower salinity values while the more modern data falls on the right. The most saline dataset occurs in 1984, and is somewhat of an outlier as it is the only dataset that stands alone away from the cluster. This spike in salinity is indicative of an inflow at this time. The hypolimnion appears to begin at approximately 30 m, but it is difficult to ascertain this in definitive terms as most of the datasets do not begin until a depth of 50 m.

There is a clear gradient visible in the temperature depth profile (figure 21). The more recent data tends towards warmer temperatures while the older data tends towards cooler temperatures. This is indicated by the cluster of historical data located along the left wing of the graph, with most of the data from the past 40 years visible on the right.

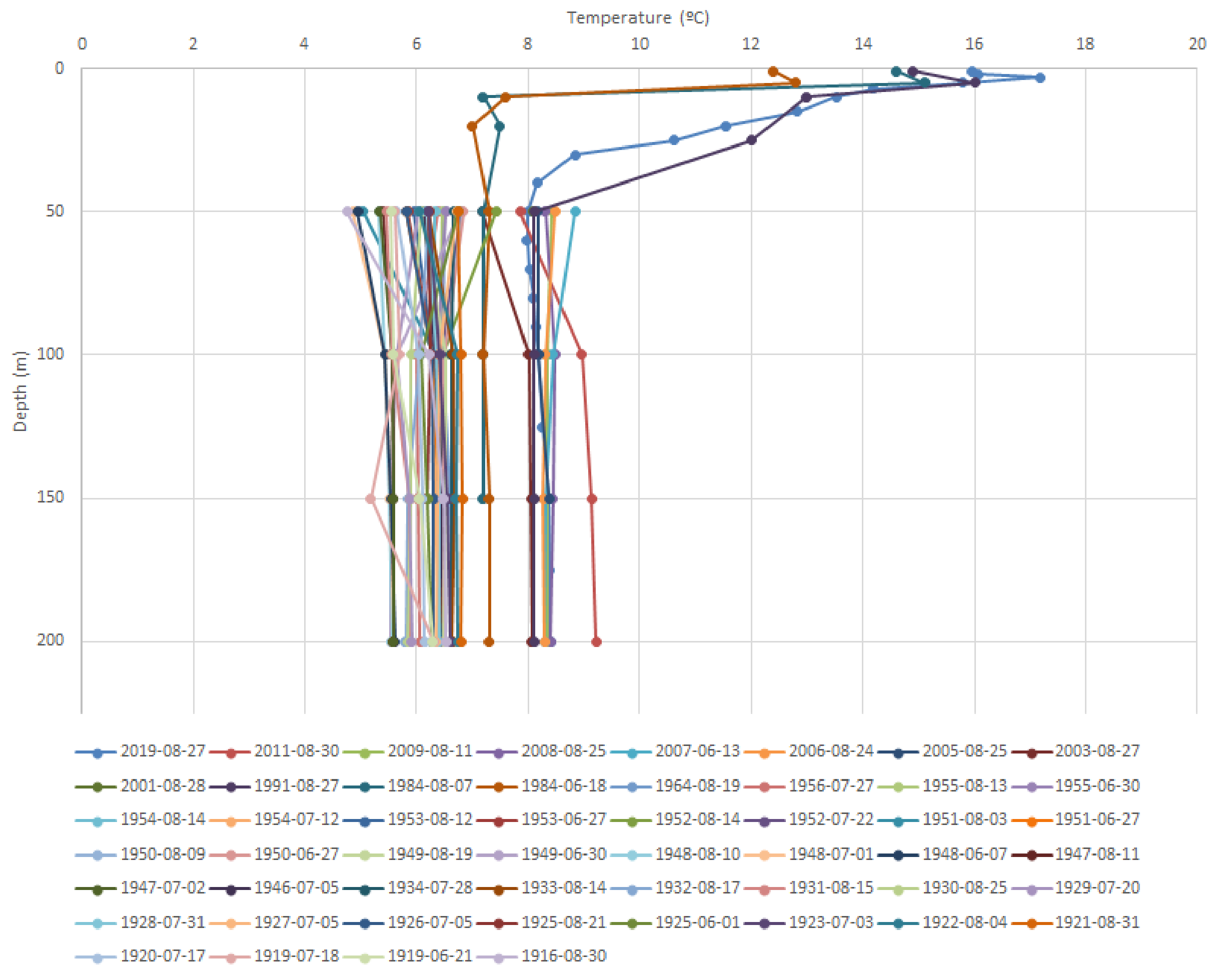


Figure 21: Temperature (ºC) throughout the water column of the Sogndalsfjorden during summers (June-August) from the years of 1916-2019

The hypolimnion appears to begin at approximately 30 m, although it is once again difficult to ascertain due to the lack of data available from 0 m-50 m. The highest temperature data along the water column appears to have occurred in 2011. It is also notable that there is a sudden temperature decrease in the 1919 dataset at 150 m before the temperature increases again at 200 m. This may have been due to a partial inflow of cold water at this time that did not extend to all depths of the water column. A one way analysis of variance test found this data to be statistically significant *[F(153, 432)=38.38, p=2.3E-183]*.

The Sogndalsfjorden oxygen data is extremely varied and appears somewhat sporadic, with no clear trend visible on initial inspection (figure 22). The three most anoxic measurements along the water column occurred in the past 15 years (these measurements were from 2006-2008). The most oxic measurements occurred in 1933 and 1934, and these measurements appear to be outliers to some degree. A one way analysis of variance did find a statistically significant difference in this dataset *[F(127, 370)=10.95, p=6.58E-73]*.

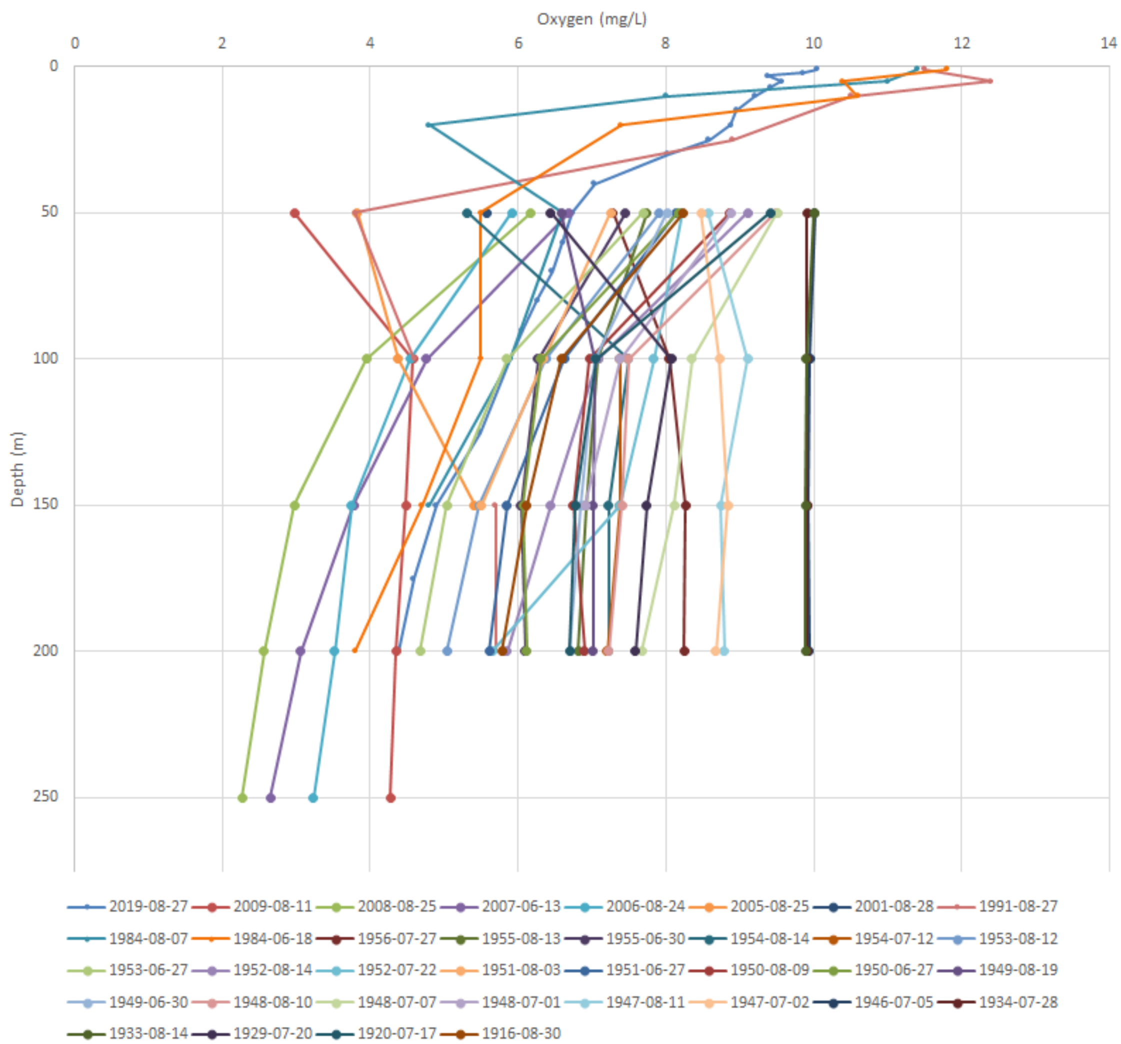


Figure 22: Oxygen concentration (mg/L) throughout the water column of the Sogndalsfjorden during summers (June-August) from the years of 1916-2019

3.2.2 Salinity, Temperature and Oxygen Timelines

The Sogndalsfjorden timelines exhibit data from 1916-2019 for all parameters. The profiled depths include 50 m, 100 m. 150 m and 200 m. Seeing as it was previously determined in the depth profiles that the hypolimnion begins at approximately 30 m, these timelines are only representative of conditions within the basin water. The overall trends in the Sogndalsfjorden appear to be that salinity is increasing over time, temperature is increasing over time and oxygen is decreasing over time.

Regarding the Sogndalsfjorden salinity timelines (figure 23), there is not a large amount of variation visible at each depth. Generally all values are within approximately 3 ‰ of eachother.

With that being noted, there does appear to be far more variation from 1978-2019 at each depth than from 1916-1965. The bulk of the variation at each depth occurs from the years of 1978-1990. Salinity values during these years range from 32.3 ‰ to 35.6 ‰ across all depths.

Salinity appears to be slowly increasing over time at all depths. This increase is the most pronounced at a depth of 50 m as it has a corresponding trendline slope of 0.0042 which is approximately twice that of the slope found at other depths. Additionally, the average from 1916-1965 *($M=33.61$, $SD=0.26$)* was significantly lower than what was found from 1978-2019 *($M=33.86$, $SD=0.43$), [$t(131)=4.06$, $p=8.34E-05$]*. The slopes at all other depths are relatively similar and range from 0.002 at 200 m to 0.0023 at 150 m. At 100 m, there was not a statistically significant difference found between the 1916-1965 *($M=33.92$, $SD=0.19$)* average and that of 1978-2019 *($M=34.03$, $SD=0.60$), [$t(127)=1.51$, $p=0.13$].* At 150 m the average during 1978-2019 *($M=34.15$, $SD=0.66$)* was higher than that of 1916-1965 *($M=33.98$, $SD=0.18$)* by 0.17 ‰ *[$t(124)=2.27$, $p=0.025$].* There was less of a difference found between the average of 1978-2019 *($M=34.17$, $SD=0.64$)* and 1916-1965 *($M=34.02$, $SD=0.21$)* at a depth of 200 m *[$t(123)=2.03$, $p=0.045$]*.

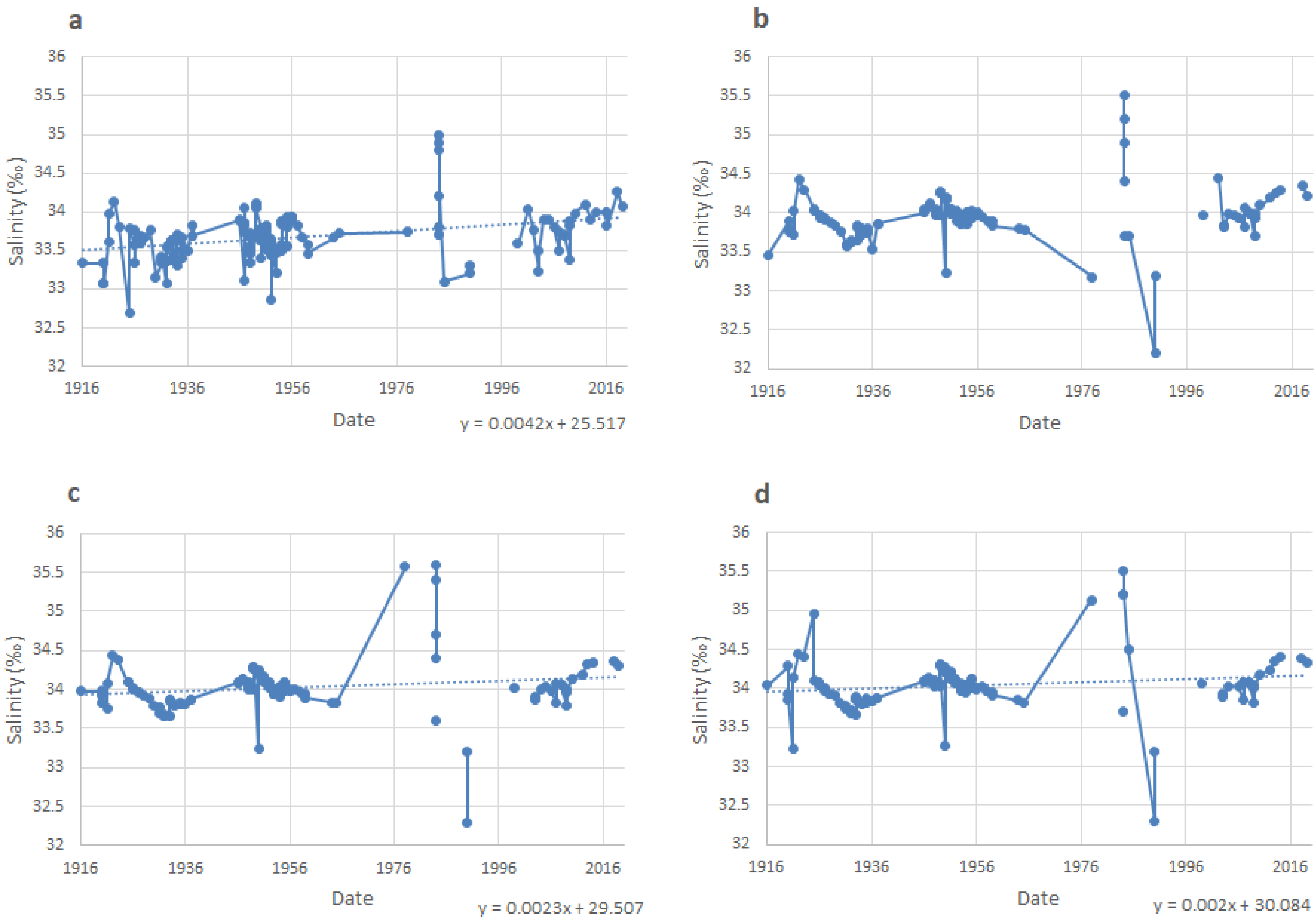


Figure 23: Progression of salinity (‰) from 1916-2019 at depths of (a) 50 m, (b) 100 m, (c) 150 m, and (d) 200 m in the Sogndalsfjorden

The same trends that were visible in the Barsnesfjorden temperature data (figure 16) are also evident in the Sogndalsfjorden temperature timelines (figure 24). The general trend is that temperature is distinctly increasing over time. At 50 m, the slope of the trendline is 0.0315 indicating an increase over time. This was a statistically significant finding with the average from 1978-2019 *(M=8.22, SD=0.56)* being higher than the average from 1916-1965 *(M=6.20, SD=0.67)* by 2.02 ºC *[t(149)=18.07, p=2.18E-39]*. At 100 m the slope of the trendline is 0.0279. Additionally, the average from 1978-2019 *(M=8.00, SD=0.39)* is 1.81 ºC higher than the average from 1916-1965 *(M=6.19, SD=0.38), [t(147)=26.11, p=4.52E-57]*.

At 150 m the slope of the trendline is 0.0275. Furthermore, the average from 1978-2019 *(M=8.05, SD=0.37)* is higher than the average from 1916-1965 *(M=6.24, SD=0.39)* by 1.81 ºC *[t(141)=24.86, p=2.20E-53]*. Additionally, at 200 m the slope of the trendline is 0.0266. It is also worth noting that the average from 1978-2019 *(M=8.01, SD=0.41)* is higher than the average from 1916-1965 *(M=6.27, SD=0.38)* by 1.74 ºC *[t(141)=24.05, p=9.39E-52]*. There does not appear to be any distinct outliers in these timelines.

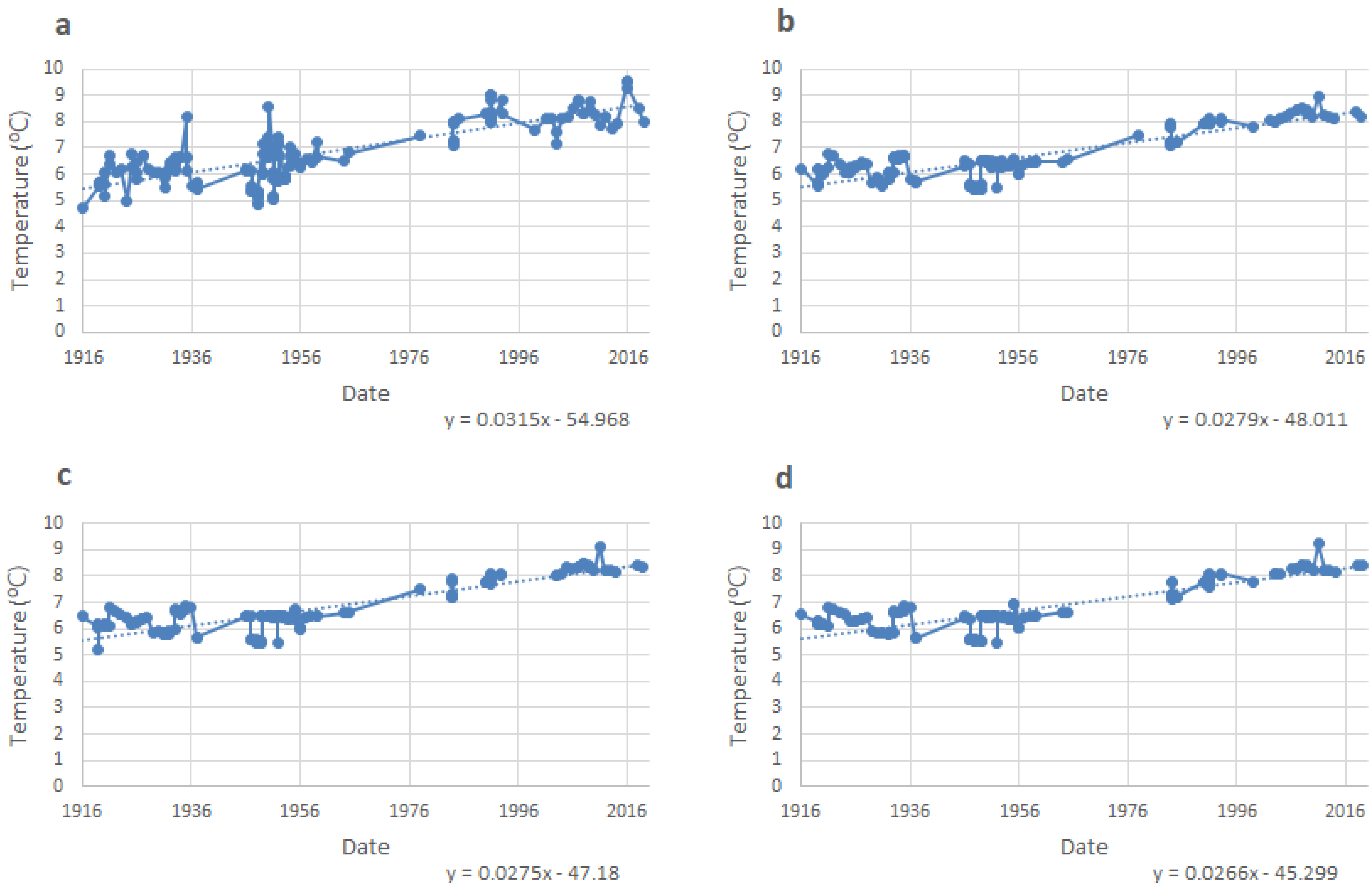


Figure 24: Progression of temperature (ºC) from 1916-2019 at depths of (a) 50 m, (b) 100 m, (c) 150 m, and (d) 200 m in the Sogndalsfjorden

Regarding the Sogndalsfjorden oxygen timelines (figure 25), it is apparent that oxygen concentration is decreasing over time at all depths. Additionally, as depth increases, the oxygen concentration is decreasing at a faster rate over time. This is indicated by the trendline slopes decreasing as depth increases. At 50 m the trendline slope is -0.04. At 100 m it is -0.0446, at 150 m it is -0.0492 and at 200 m it is -0.0499. It is also worth noting that all maximum values at all depths occurred before 1940 and all minimum values at all depths occurred after 2005. This is also indicative of conditions becoming more anoxic over time.

The maximum at 50 m was 10.19 mg/L in 1936 and the minimum was 2.97 mg/L in 2008. A statistically significant difference was found between the 1916-1965 *(M=8.08, SD=1.16)* data and the 1978-2019 *(M=5.88, SD=1.42)* data *[t(125)= -9.48, p=2.18E-16].* At 100 m the maximum was 10.1 mg/L in 1936 and the minimum was 3.61 mg/L in 2008. Additionally, the average from 1978-2019 *(M=7.23, SD=1.31)* was found to be significantly higher than that of 1916-1965 *(M=4.88, SD=0.88), [t(122)=-10.35, p=2.15E-18].* At 150 m the maximum was 10.06 mg/L which occurred in both 1932 and 1933. The minimum at 150 m occurred in 2008 and was 2.78 mg/L. The average from 1916-1965 *(M=6.98, SD=1.44)* was higher than that of 1978-2019 *(M=4.39, SD=0.90)* by 2.59 mg/L *[t(117)= -10.07, p=1.50E-17].* At 200 m the maximum was 10.08 mg/L in 1932 and the minimum was 2.46 mg/L in 2008. A statistically significant difference was found between the period of 1916-1965 *(M=6.80, SD=1.59)* and 1978-2019 *(M=4.23, SD=1.24)*, *[t(113)= -8.40, p=1.51E-13].*

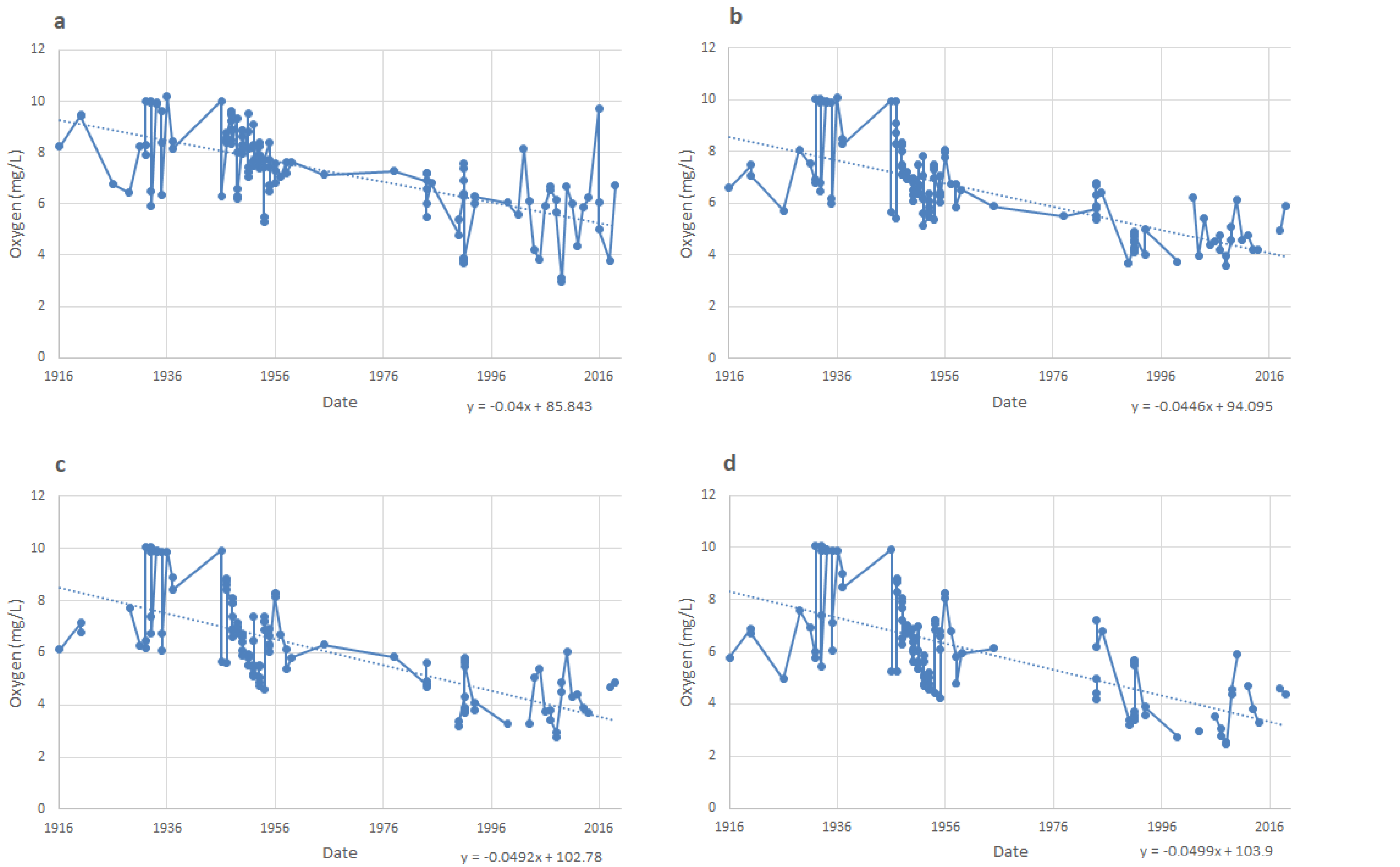


Figure 25: Progression of oxygen concentration (mg/L) from 1916-2019 at depths of (a) 50 m, (b) 100 m, (c) 150 m, and (d) 200 m in the Sogndalsfjorden

3.2.3 Foraminifera

The Sogndalsfjorden foraminifera data (figure 26) appears to display a trend of individuals slowly decreasing as sediment depth increases. The maximum number of individuals is 534.5 at 0 cm and the minimum is 58.3 individuals at 190 cm.

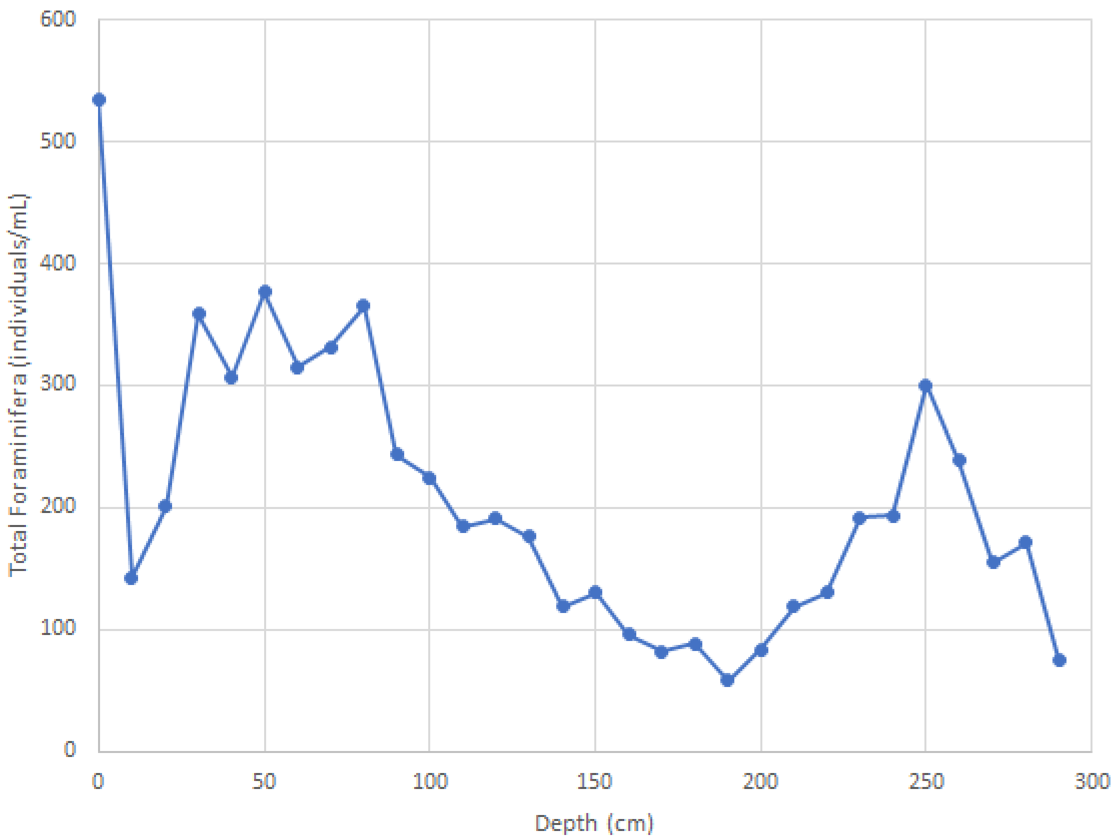


Figure 26: Total foraminifera found in a Sogndalsfjorden sediment core in 2021. Graph adapted from Bollingberg, in prep.

3.3 Hydrographical results for the Inner Nærøyfjorden

3.3.1 Salinity, Temperature and Oxygen Depth Profiles

There are 7-10 observations included in the Nærøyfjorden depth profiles. These consist of measurements taken during all seasons due to the limited amount of data available. Despite the limited datasets, measurements along the water column are available from 1920-2020 in the salinity and temperature depth profiles and from 1987-2020 in the oxygen depth profile.

It is evident in the salinity depth profile (figure 27) that the hypolimnion begins at a depth of approximately 20 m. The highest salinity along the entire water column appears to occur in 2015. The 2019 data is also somewhat high, but this is likely due to an inflow. The 2020 data is actually the least saline (along the hypolimnion), indicating the effects of the inflow in 2019 were short lived. The second least saline data is that of 2006, although the data does still appear to be highly clustered along the hypolimnion. A one way analysis of variance test found this data to be statistically significant *[F(6, 563)=6.89, p=4.51E-07]*.

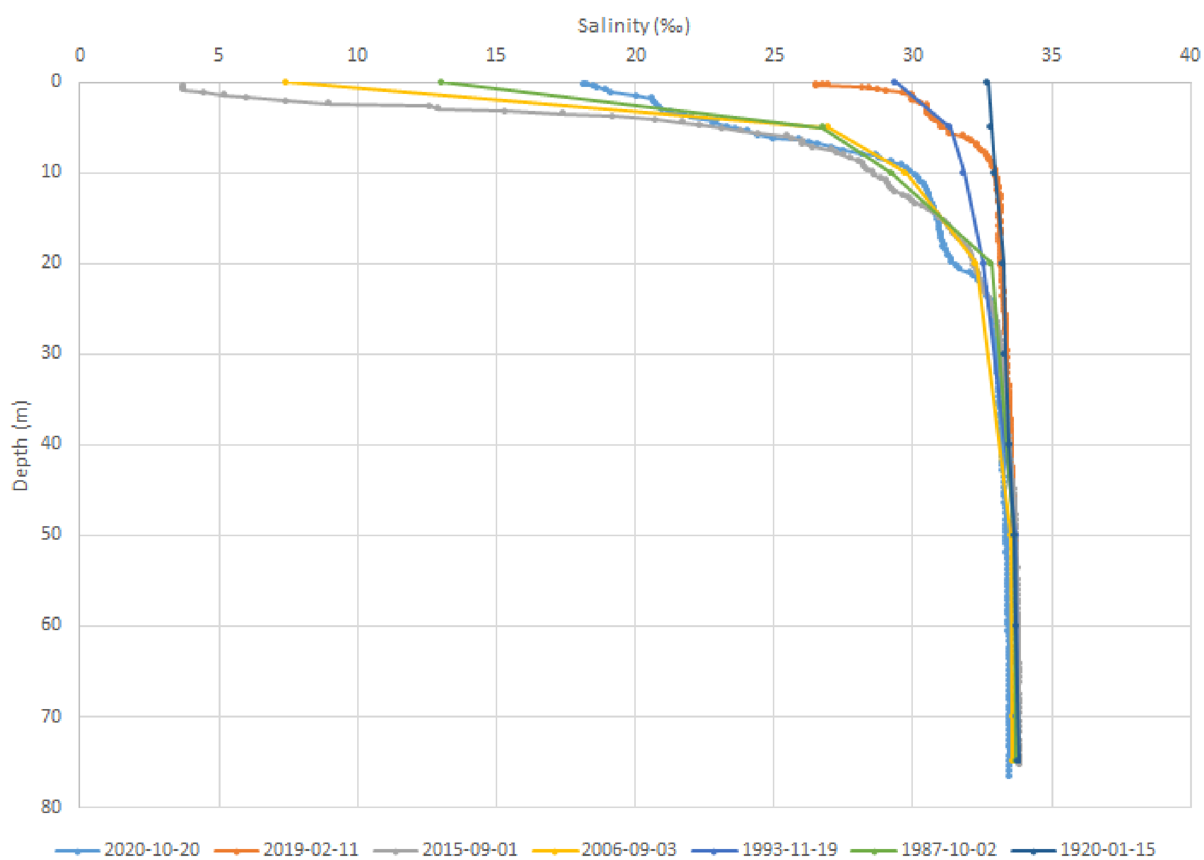


Figure 27: Salinity (‰) throughout the water column of the Inner Nærøyfjorden from the years of 1920-2020

The Nærøyfjorden temperature depth profile (figure 28) exhibits data that seems rather unstable along the hypolimnion in many of the datasets. The 2006 data in particular has a sharp decrease in temperature that exists from 70 m to the bottom of the basin. This could be due to a measurement error or possibly due to bottom water heating from mud, which is known to happen in some instances (Strøm, 1936). Conversely, (and quite peculiarly) the 1994 dataset appears to increase by approximately 1.5 ºC from the start of the hypolimnion to the bottom of the basin. Many of the other observations display decreases in temperature along the hypolimnion.

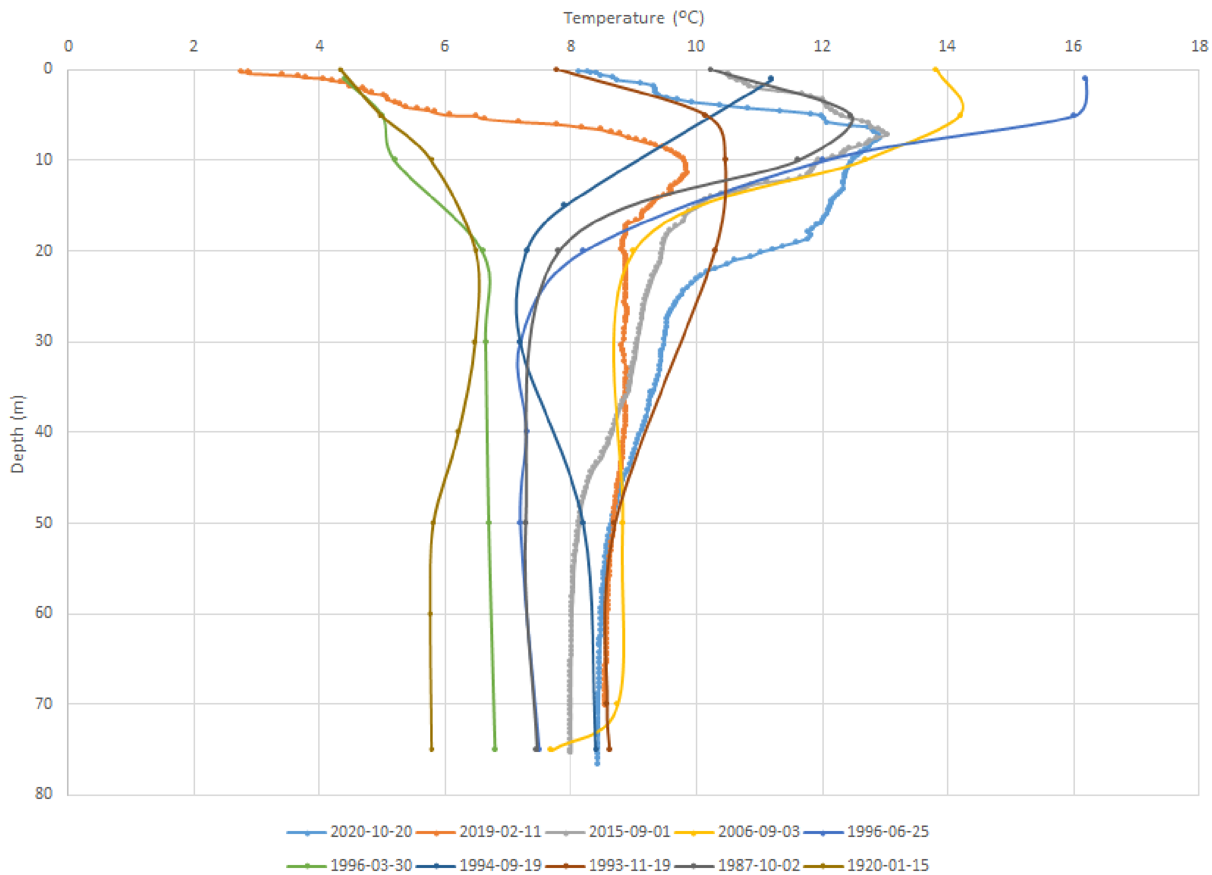


Figure 28: Temperature (ºC) throughout the water column of the Inner Nærøyfjorden from the years of 1920-2020

The 1920 data is the coldest along most of the water column with the exception of the surface data. The 2020 data is not the warmest, but is among the warmest data along with 2019, 2006 and 1993. The second coldest data is found in 1996 which makes sense as this coincides with an inflow that can be seen in figure 32**.** A one way analysis of variance test deemed this data statistically significant *[F(9, 581)=19.36, p=1.86E-28]*.

The Nærøyfjorden oxygen depth profile (figure 29) exhibits data that is representative of a fjord that is becoming more anoxic over time. The anoxia extends to shallower depths as time goes on, and the data from more recent years appears to be indicative of less oxygen content than data from past years. The data collected in 2020 is the lowest oxygen values ever recorded below the threshold in the Nærøyfjorden, and the anoxia in this series extends to 50 m. There appears to have been an oxygen inflow in 2019 which is why there is a temporary increase in oxygen concentration in this series, but the 2015 data is more reflective of a lower oxygen concentration and represents the second most anoxic data in this figure. On the other end of the spectrum, the highest oxygen concentrations can be found in the data from 1996. This is due to an inflow that extended to all depths as supported by the data in figure 32. This is the ONLY inflow that extended to all depths in the data available. A one way analysis of variance test found this data to be statistically significant *[F(8, 570)=6.27, p=8.7E-08]*.

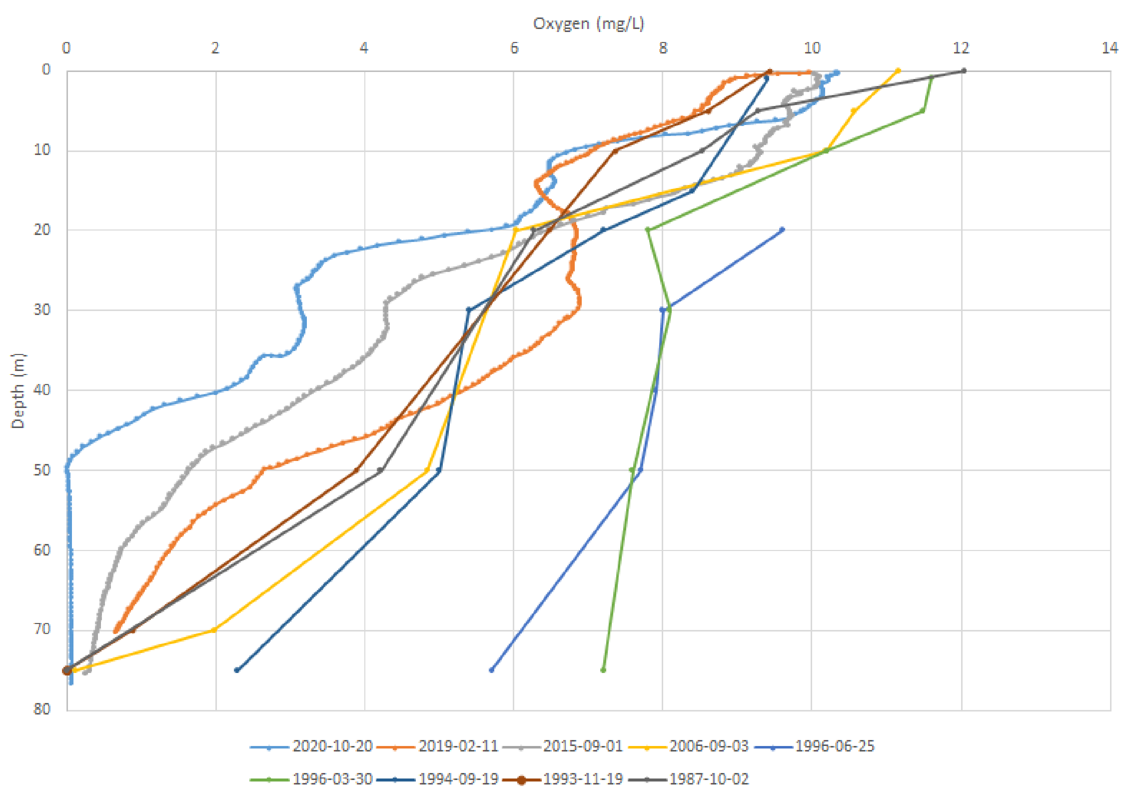


Figure 29: Oxygen concentration (mg/L) throughout the water column of the Inner Nærøyfjorden from the years of 1987-2020

3.3.2 Salinity, Temperature and Oxygen Timelines

The Nærøyfjorden timelines contain data extending back to 1920 for all parameters except oxygen, which goes back to 1987. The depths profiled include 0 m, 20 m, 40 m and 70 m. The overall trends appear as follows: salinity is decreasing over time, temperature is increasing over time and oxygen is decreasing over time.

In terms of the salinity timelines (figure 30), decreasing trends are displayed at all depths. The 0 m dataset contains a large amount of variation with values ranging from 3.73 ‰ to 33.25 ‰. The 20 m dataset has a trendline slope of -0.00003 and values ranging from 31.497 ‰ to 33.25 ‰ with the lowest value occurring in 2020 and the highest value occurring in 2019. The 40 m dataset corresponds to a trendline slope of -0.000003. Its minimum occurs in 2006 with a value of 33.12 ‰ and the maximum occurs in 2019 with a value of 33.57 ‰. This maximum in 2019 coincides with a partial inflow that only extended to a depth of 40 m and is visible in figure 32. The trendline slope for the 70 m dataset is the same as that of the 40 m dataset. At 70 m the minimum is 33.12 ‰ in 2006 and the maximum is 33.83 ‰ in 2019, closely followed by 33.73 ‰ in 1920.

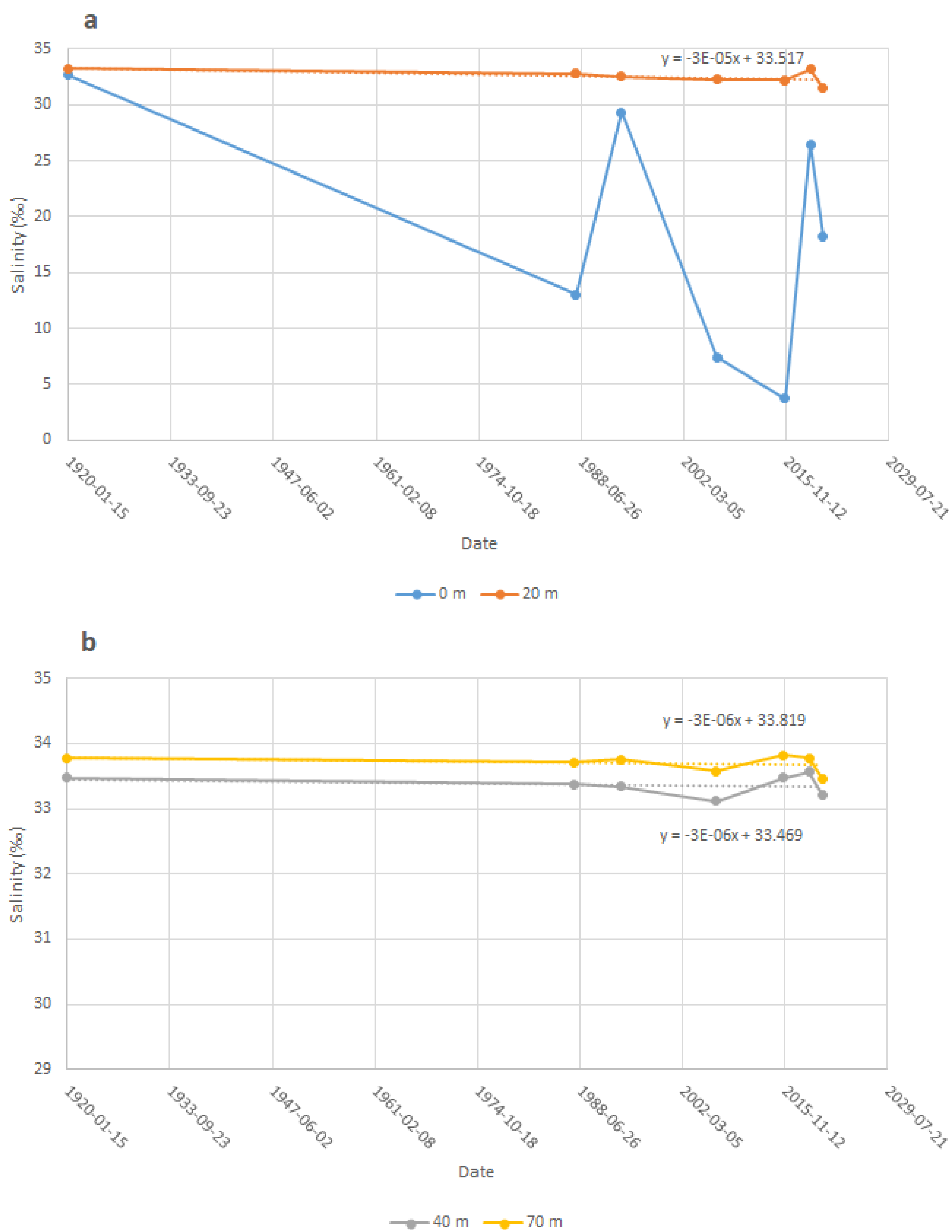
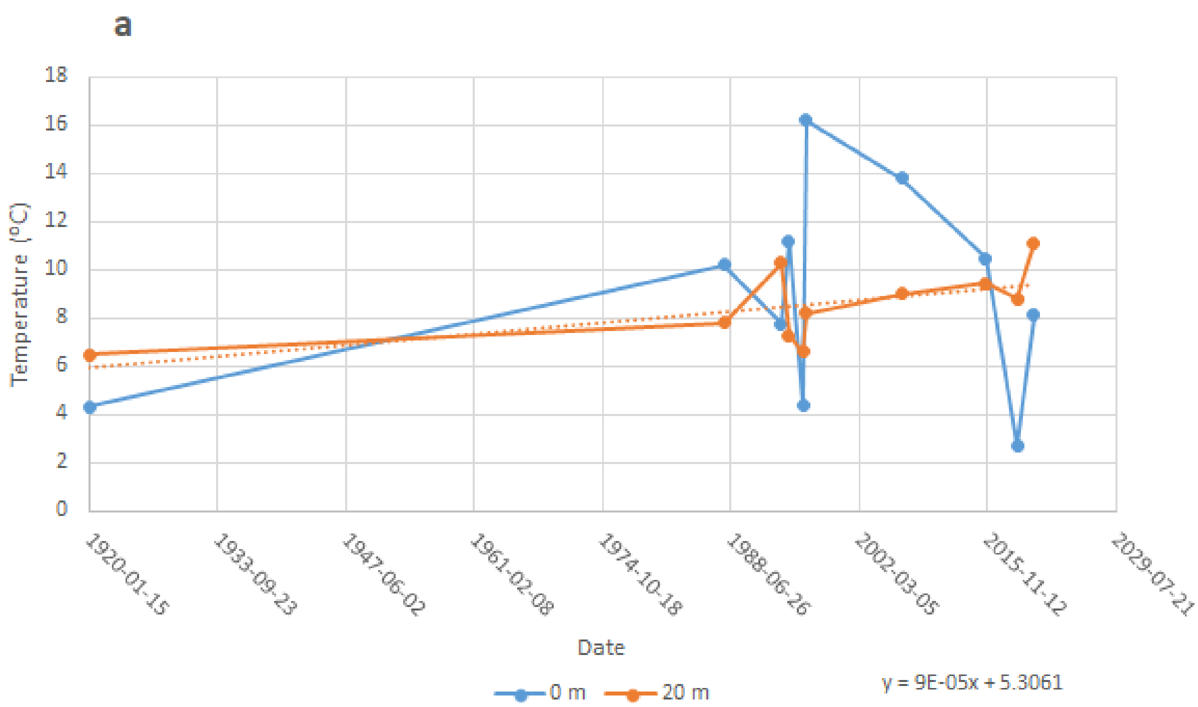


Figure 30: Progression of salinity (‰) from 1920-2020 at (a) surface depths of 0 m and 20 m and (b) basin depths of 40 m and 70 m in the Inner Nærøyfjorden

Regarding the temperature timelines (figure 31), there are positive trendline slopes at all depths indicating a definitive increase in temperature over time. This includes a slope of 0.00009 at 20 m, 0.00008 at 40 m and 0.00007 at 70 m. Although small, these all indicate there had been a steady increase in temperature over time at both surface and basin depths. The surface data is more variable than the basin data, which can be attributed to seasonality having a strong influence on temperature at these shallow depths. The 0 m data has a minimum of 2.75 ºC and a maximum of 16.2 ºC. The 20 m data has a minimum of 6.49 ºC and a maximum of 11.1 ºC. This equates to ranges of 13.5 ºC and 4.63 ºC respectively. Conversely, the 40 m dataset has a range of 3.01 ºC while the 70 m dataset has an even lower range of 2.96 ºC. At all depths other than 0 m the lowest measured temperature occurred in 1920 which was the earliest data available.



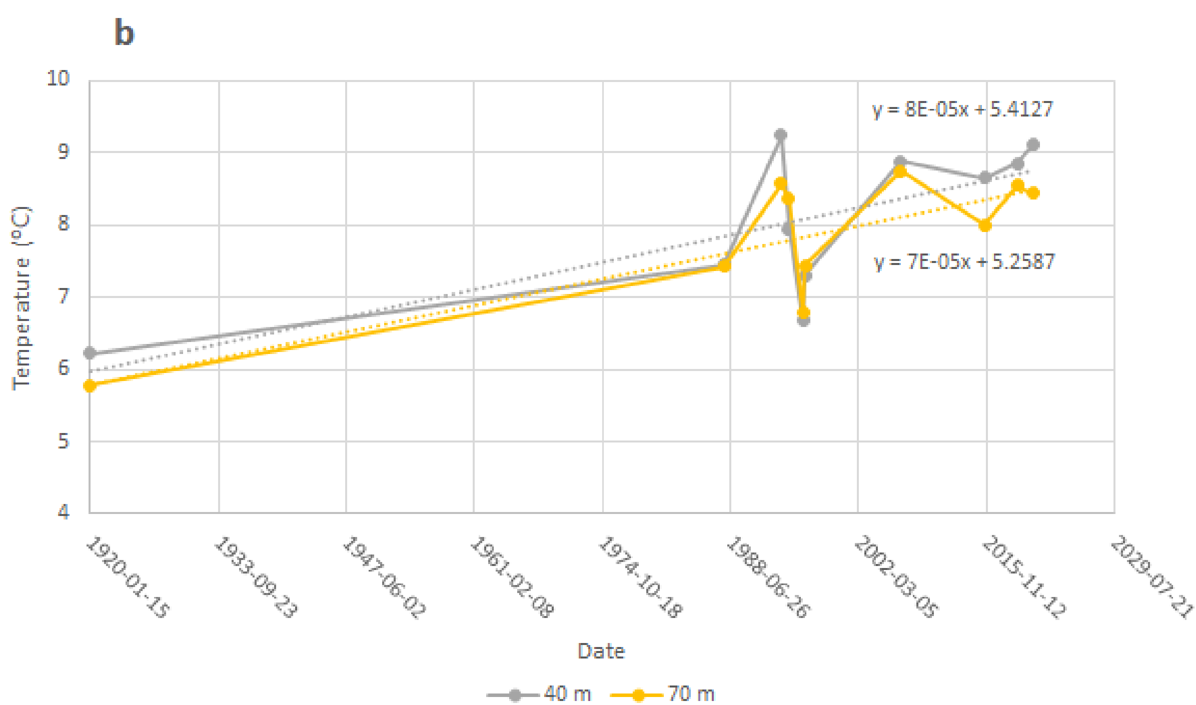


Figure 31: Progression of temperature (ºC) from 1920-2020 at (a) surface depths of 0 m and 20 m and (b) basin depths of 40 m and 70 m in the Inner Nærøyfjorden

The Nærøyfjorden oxygen timelines tell a story of a fjord steadily becoming more anoxic over time. Additionally, this decrease over time is more pronounced as depth increases. The most pronounced decrease in oxygen concentration over time appears to be at 70 m which is associated with a trendline slope of -0.0003 and least pronounced at 20 m which is associated with a trendline slope of -0.0001 (the 0 m dataset has been omitted from this trendline slope analysis as it is too influenced by seasonality). The 40 m dataset falls in the middle with a corresponding trendline slope of -0.0002.

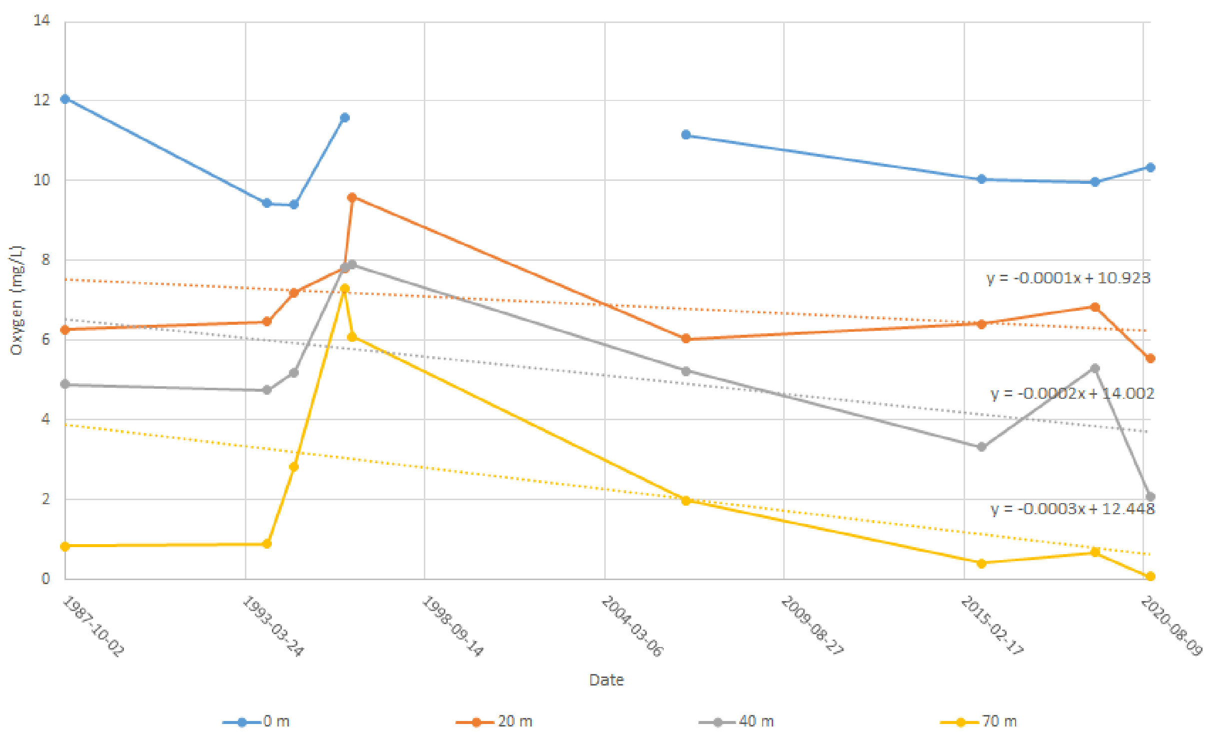


Figure 32: Progression of oxygen concentration (mg/L) from 1987-2020 at depths of 0 m, 20 m, 40 m, and 70 m in the Inner Nærøyfjorden

There appears to be an inflow of oxygenated water after 1993 which is visible at all depths in the water column. Additionally, a partial inflow in 2019 is also visible, although this inflow only had a minimal impact at 70 m.

3.3.3 Total Foraminifera

In terms of the Nærøyfjorden foraminifera data (figure 33), there appears to be slightly elevated numbers of individuals present in the deeper depths of the core than the shallower ones, which suggests that numbers may be decreasing over time. Most notably, there is a large spike in individuals at 15.5 cm. This declines to just one individual at 5.5 cm, which is the lowest observation in the entire core.

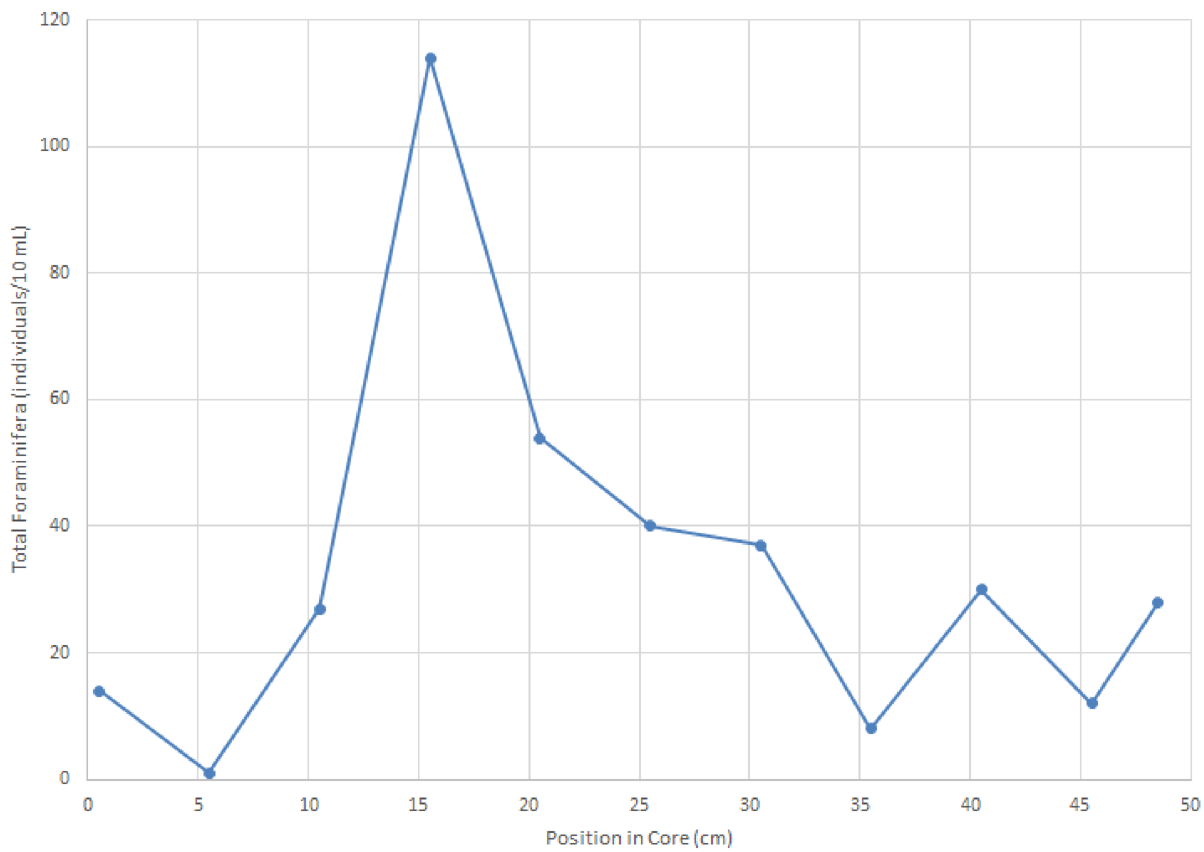


Figure 33: Total foraminifera (individuals/10mL) found in an Inner Nærøyfjorden sediment core in 2015. Graph adapted from Becker et al., 2015, unpublished data.

3.4 Hydrographical results for the Ikjefjorden

3.4.1 Salinity, Temperature and Oxygen Depth Profiles

The Ikjefjorden depth profiles contain 6 observations for each parameter. These observations are not limited by season. The data goes back to 2015 and extends to 2020.

As indicated by the Ikjefjorden salinity depth profile (figure 34) the hypolimnion appears to begin at approximately 30 m. The highest consistent salinity along the water column in this figure is associated with 2019, which was due to the inflow that occurred at this time and is visible in figure 39. With the exception of 2019, the remainder of the data exhibits a clear gradient of salinity decreasing over time. 2015 is the most saline after 2019, the 2017 data is clustered together and the 2020 series is the least saline overall. It is somewhat astounding that the 2020-10-23 data is the least saline out of all the data when you consider the fact that 2019-02-21 was the most saline and this salinity decrease occurred over the course of just 20 months. Despite the clustered datasets, a one way analysis of variance test found this data to be statistically significant *[$F(5, 1247)=28.42$, $p=2.34E-27$]*.

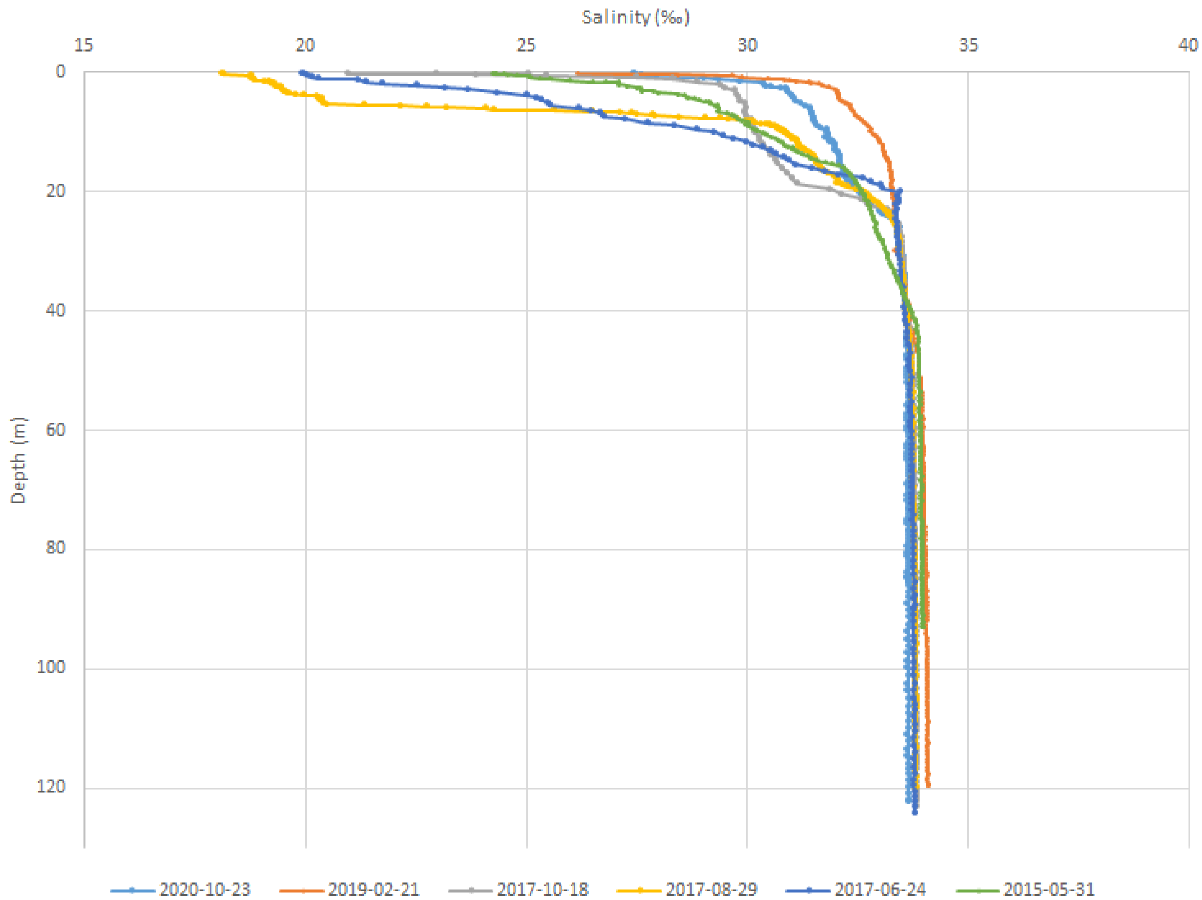


Figure 34: Salinity (‰) throughout the water column of the Ikjefjorden from the years of 2015-2020

The Ikjefjorden temperature data appears to be somewhat varied (figure 35). The lowest overall temperature along the water column in this figure is associated with the 2015 dataset. The 3 datasets that originated in 2017 appear to be similar in temperature as they are all clustered together, and happen to be the second coolest after the 2015 data. The 2020 data is the second warmest with the 2019 data being the absolute warmest. The 2019 data displays a peculiar trend of temperature increasing as depth increases. A one way analysis of variance deemed this data to be statistically significant *[F(5,1247)=72.98, p=3.99E-67]*.

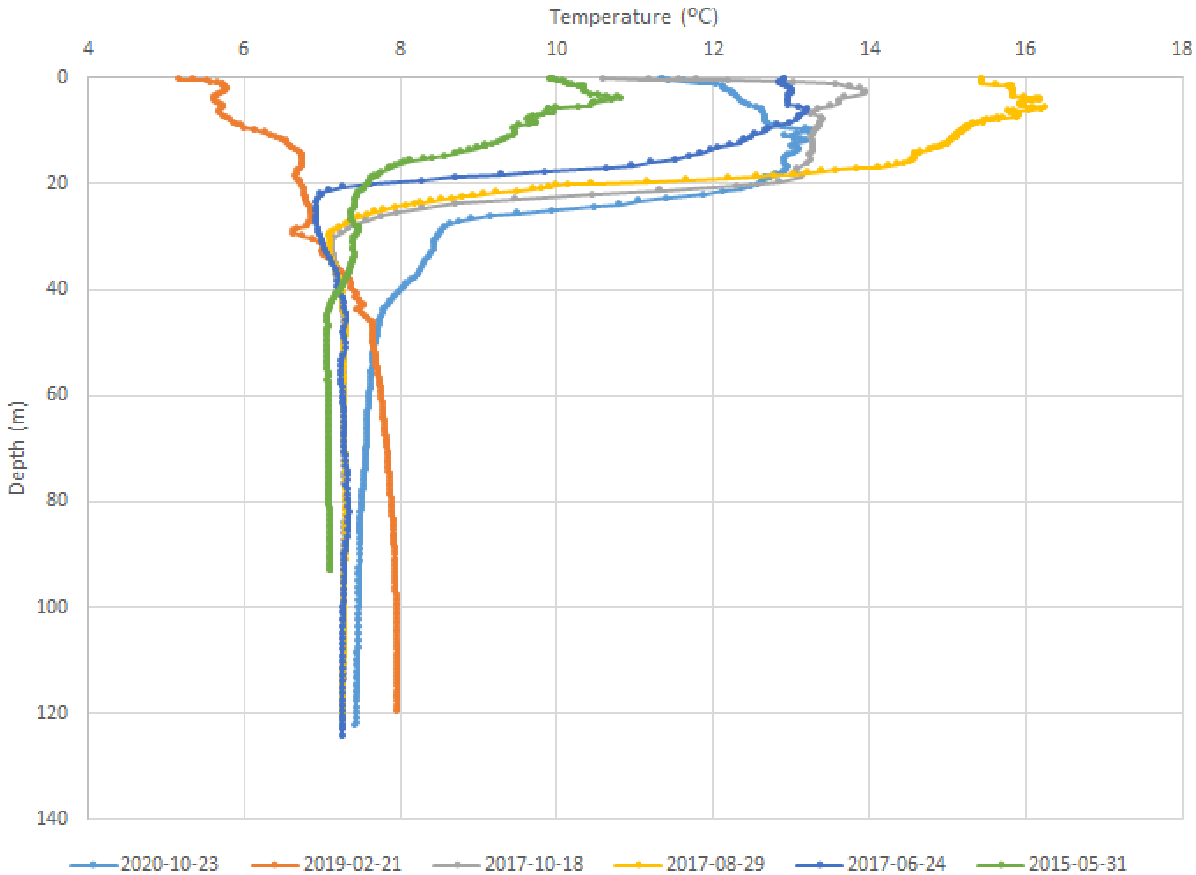


Figure 35: Temperature (ºC) throughout the water column of the Ikjefjorden from the years of 2015-2020

In the oxygen depth profile, 2020 appears to have the lowest oxygen concentration throughout the water column and also has a state of anoxia beginning at approximately 85 m, which is the earliest depth of this state in the dataset. All the 2017 datasets appear to end up anoxic as well, with the 2017-10-18 dataset displaying anoxia beginning at 90 m followed by 2017-08-29 displaying anoxia at ~97 m then 2017-06-24 displaying anoxia at ~110 m. As there was an inflow in 2019 this series has the highest oxygen concentration. A one way analysis of variance test found this data to be statistically significant *[F(5, 1247)=13.30, p=1.19E-12]*.

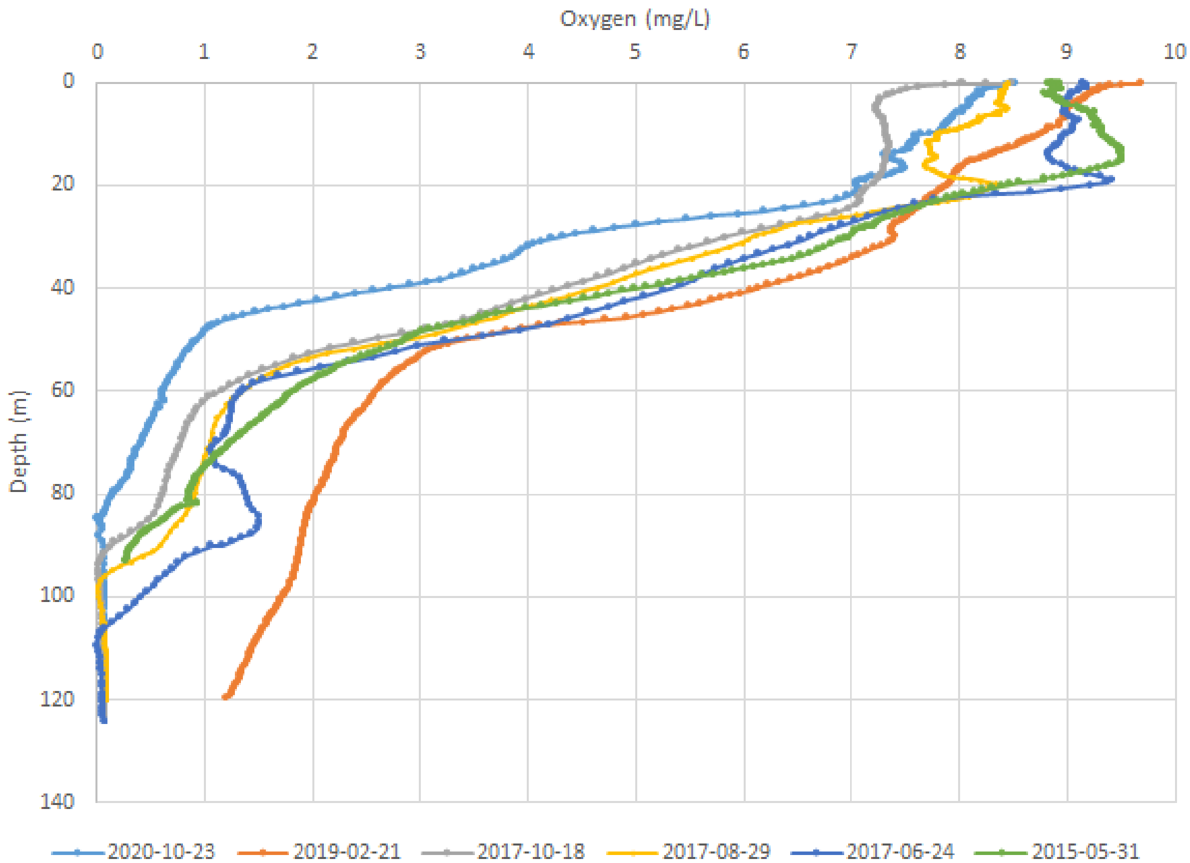


Figure 36: Oxygen concentration (mg/L) throughout the water column of the Ikjefjorden from the years of 2015-2020

3.4.2 Salinity, Temperature and Oxygen Timelines

The Ikjefjorden timelines contain data extending back to 2015 for all parameters. The depths profiled included 0 m, 25 m, 50 m, 75 m and 100 m. The overall trends appeared as follows: salinity is decreasing over time, temperature is increasing over time and oxygen is decreasing over time.

In regards to the salinity timelines (figure 37), it appears as though the 0 m salinity is increasing over time while the 25 m salinity is staying relatively constant with a small increase over time, as indicated by the 0.0002 trendline slope. However, the perceived increase at 0 m is likely just due to the fact that the later measurements are late fall and winter values while the earlier measurements are summer values. Since the surface salinity is affected by seasonality, this is creating the illusion of a salinity increase over time. However, in the basin depths that are unaffected by seasonality there is a very clear decrease in salinity over time. The trendline slopes at 50 m, 75 m and 100 m are -0.00008, -0.00007 and -0.00009 respectively. The drastic upswing in salinity in 2019 can be attributed to the inflow that occurred then. Salinity values in the basin depths range between 33.64 ‰ to 34.07 ‰.

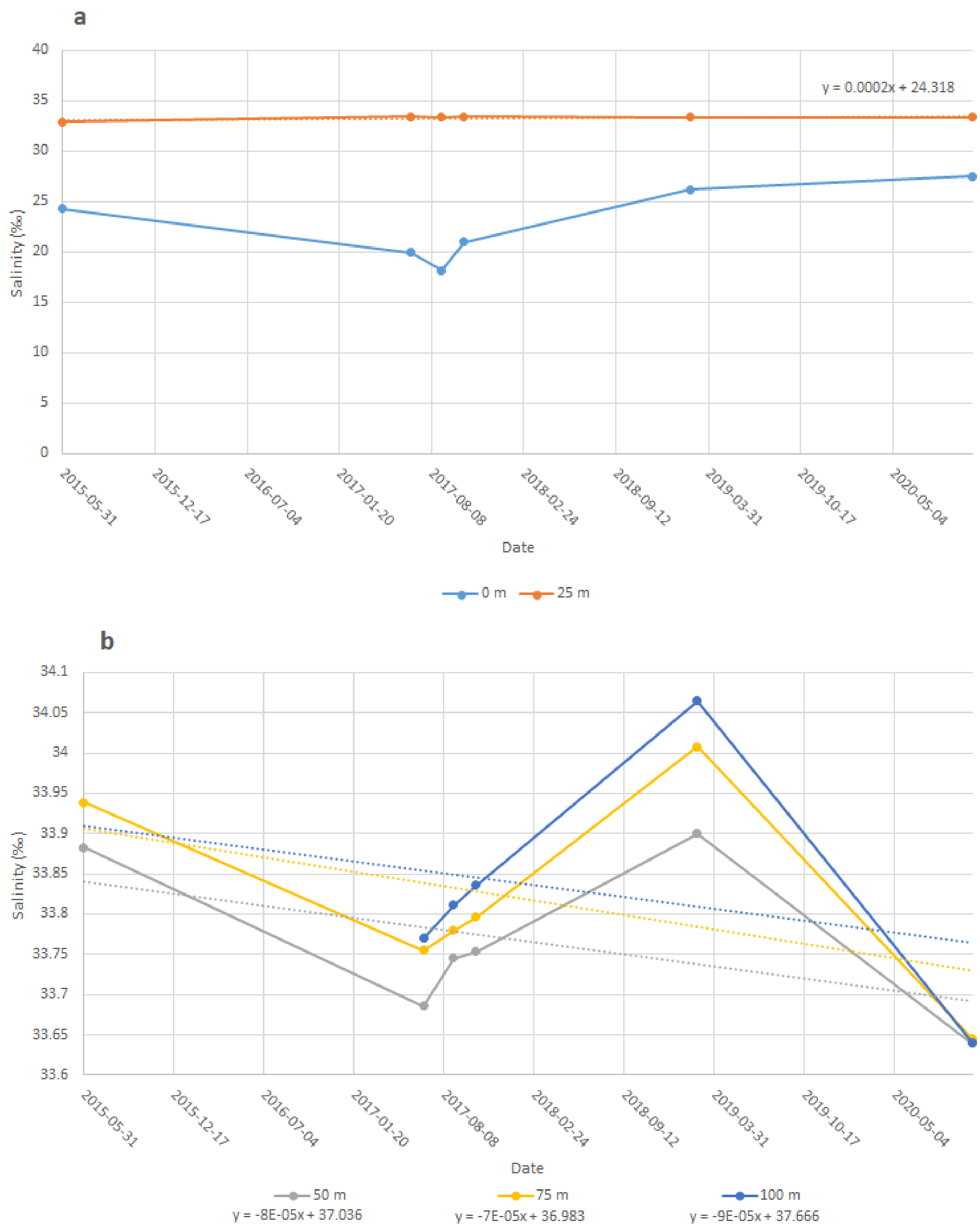


Figure 37: Progression of salinity (‰) from 2015-2020 at (a) surface depths of 0 m and 25 m and (b) basin depths of 50 m, 75 m and 100 m in the Ikjefjorden

In terms of the temperature timelines (figure 38), it is evident that temperature in the Ikjefjorden is increasing over time. This is indicated by the slopes of the trendlines. The slope of the trendline at 25 m is 0.0011, 0.0004 at 50 m, and 0.003 at 75 m and 100 m. This may seem like a miniscule increase, but it must be taken into consideration that this data only shows the past 5 years. At surface depths the temperatures range from 5.17ºC to 15.32ºC. At basin depths this range is lower with a minimum temperature of 7.06ºC and a maximum temperature of 7.96ºC. This equates to a range of just 0.9ºC.

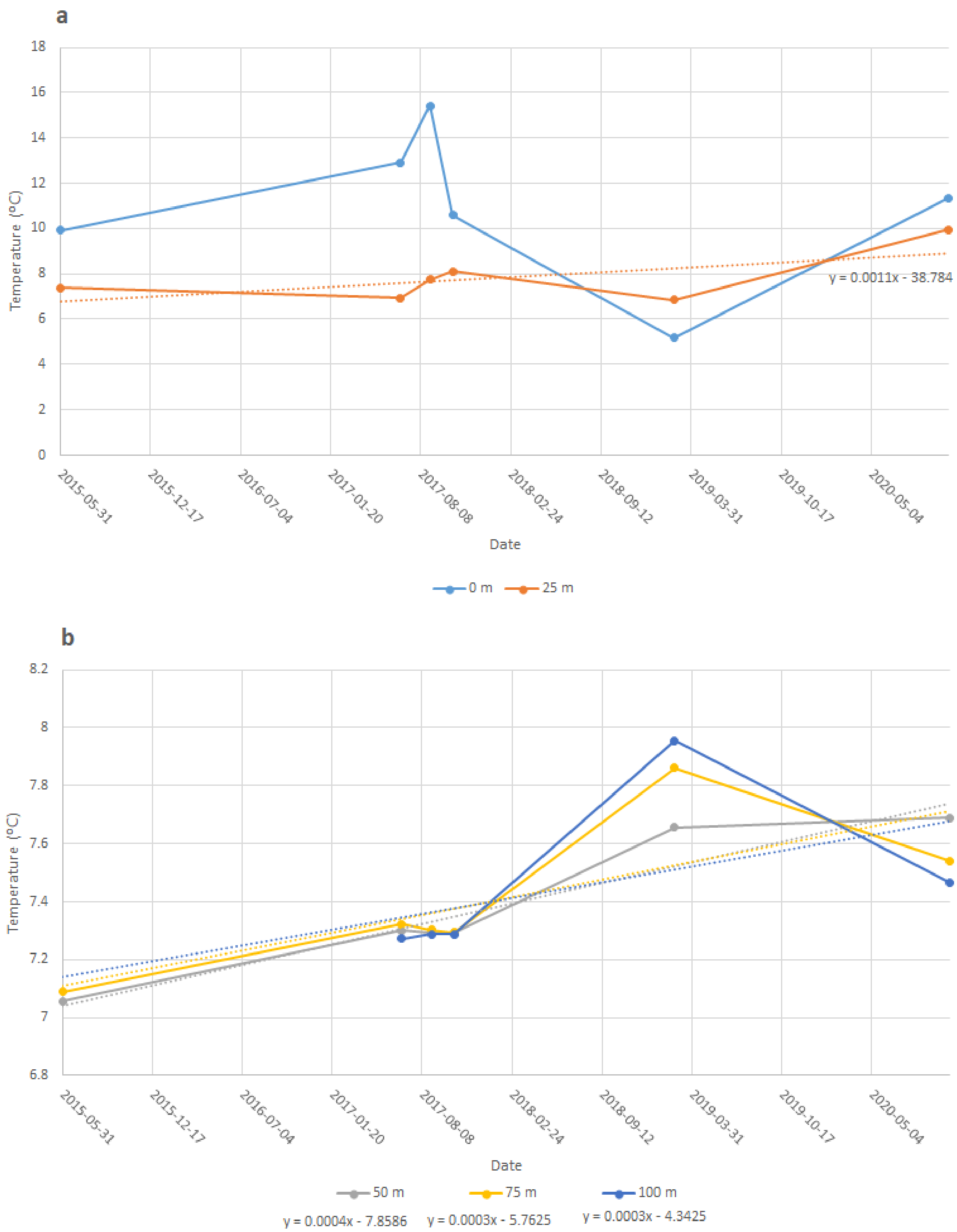


Figure 38: Progression of temperature (ºC) from 2015-2020 at (a) surface depths of 0 m and 25 m and (b) basin depths of 50 m, 75 m and 100 m in the Ikjefjorden

The oxygen timeline (figure 39) displays trends of oxygen decreasing over time at all depths except for 100 m. This is likely due to a lack of data available at this depth. At 25 m, 50 m, and 75 m there are corresponding trendline slopes of -0.0005, -0.0008 and -0.0001. There appears to be a definite inflow in 2019 indicated by the increased values along the entire water column. The lowest oxygen values at depths of 25 m, 50 m and 75 m occurred in 2020. The dip before 2017 visible at all depths could be due to a lack of calibration. At basin depths the oxygen ranges from 0.019 mg/L to 3.40 mg/L and at surface depths this range is from 6.18 mg/L to 9.68 mg/L.

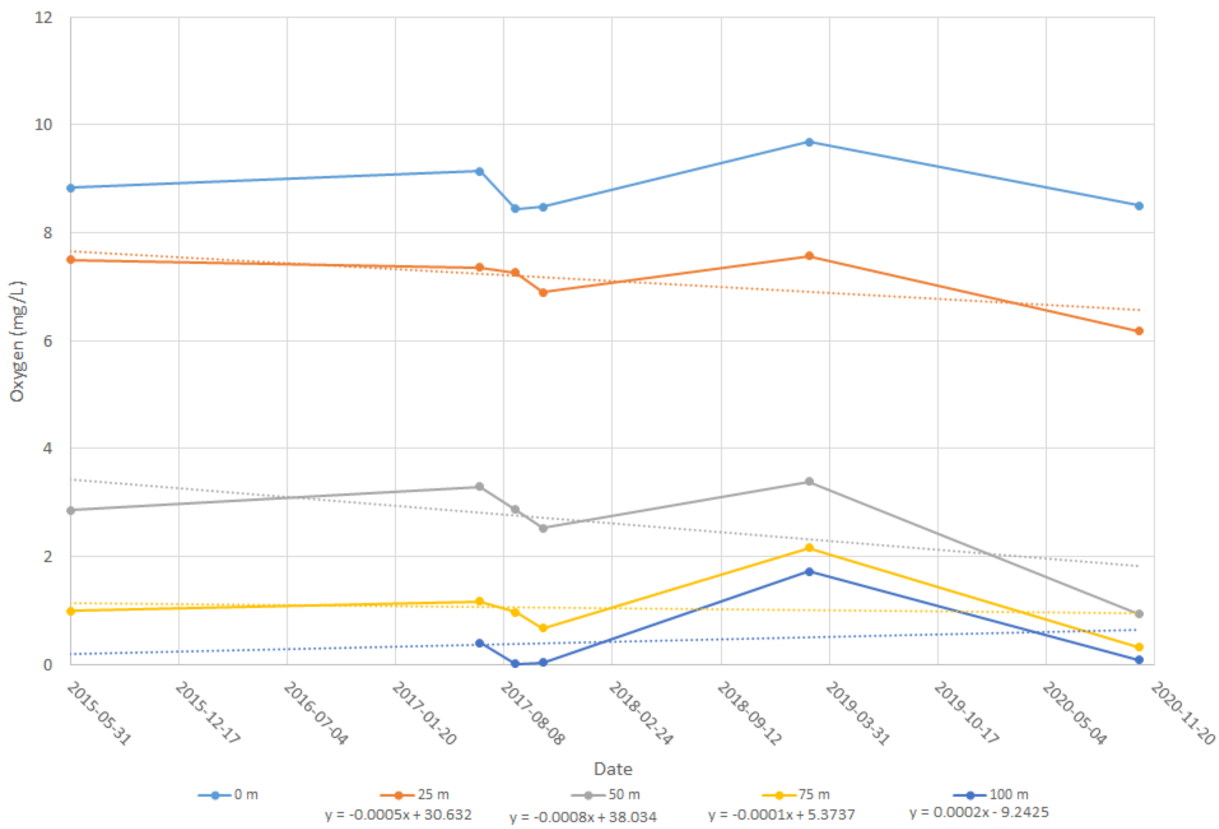


Figure 39: Progression of oxygen concentration (mg/L) from 2015-2020 at depths of 0 m, 25 m, 50 m, 75 m and 100 m in the Ikjefjorden

3.4.3 Total Foraminifera

Regarding the Ikjefjorden foraminifera data (figure 40), it is evident that foraminifera populations from all species profiled are decreasing over time, indicating that there has also been a decrease in oxygen concentration over time. From the mid 1950s on there was a large decrease in foraminifera abundance. There appears to be a total lack of foraminifera from the 1980s to the 1990s. The population appears to rebound somewhat from the late 1990s onward, but not by much. From 2015 on there appears to be a decrease in foraminifera abundance which is reflected in the Ikjefjorden oxygen data available in figure 39.

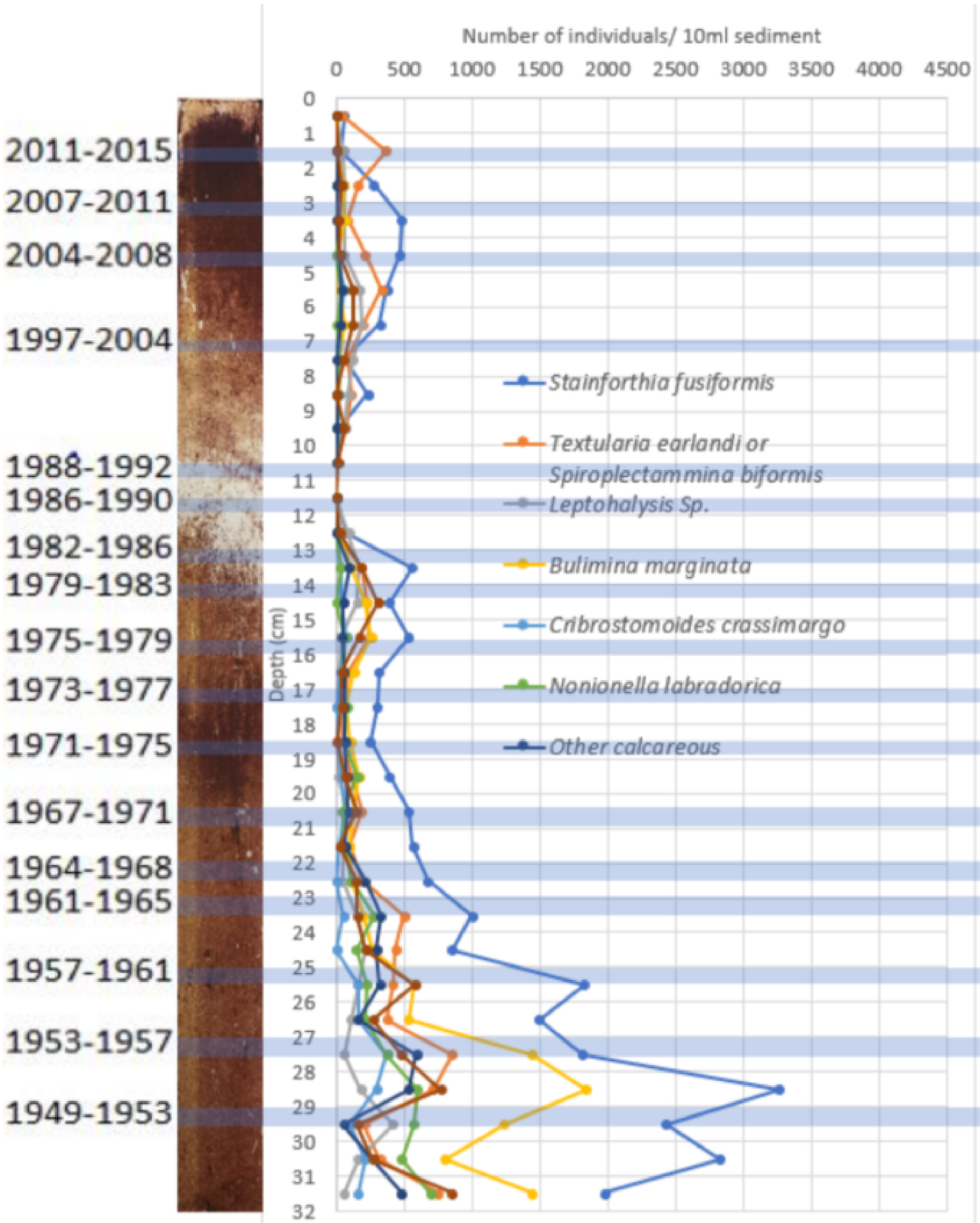


Figure 40: Total foraminifera (individuals/10 mL) found in an Ikjefjorden sediment core in 2018. Adapted from "Investigating environmental change in the micro-organism distribution of anoxic Ikjeford sediments since the 1960s, Western Norway", by Koek and Van Doorn, 2018.

3.5 Hydrographical results for the Østerbøvatn

3.5.1 Salinity, Temperature and Oxygen Depth Profiles

The Østerbøvatn depth profiles contain 4 observations for each parameter, with this data going back to 2005 and extending to 2020. The salinity data (figure 41) appears to be quite sporadic with unique patterns displayed along the water column. There does not appear to be a distinct hypolimnion visible in this dataset. This dataset was not deemed to be statistically significant after a one way analysis of variance was performed *[F(3, 228)=1.60, p=0.190]*.

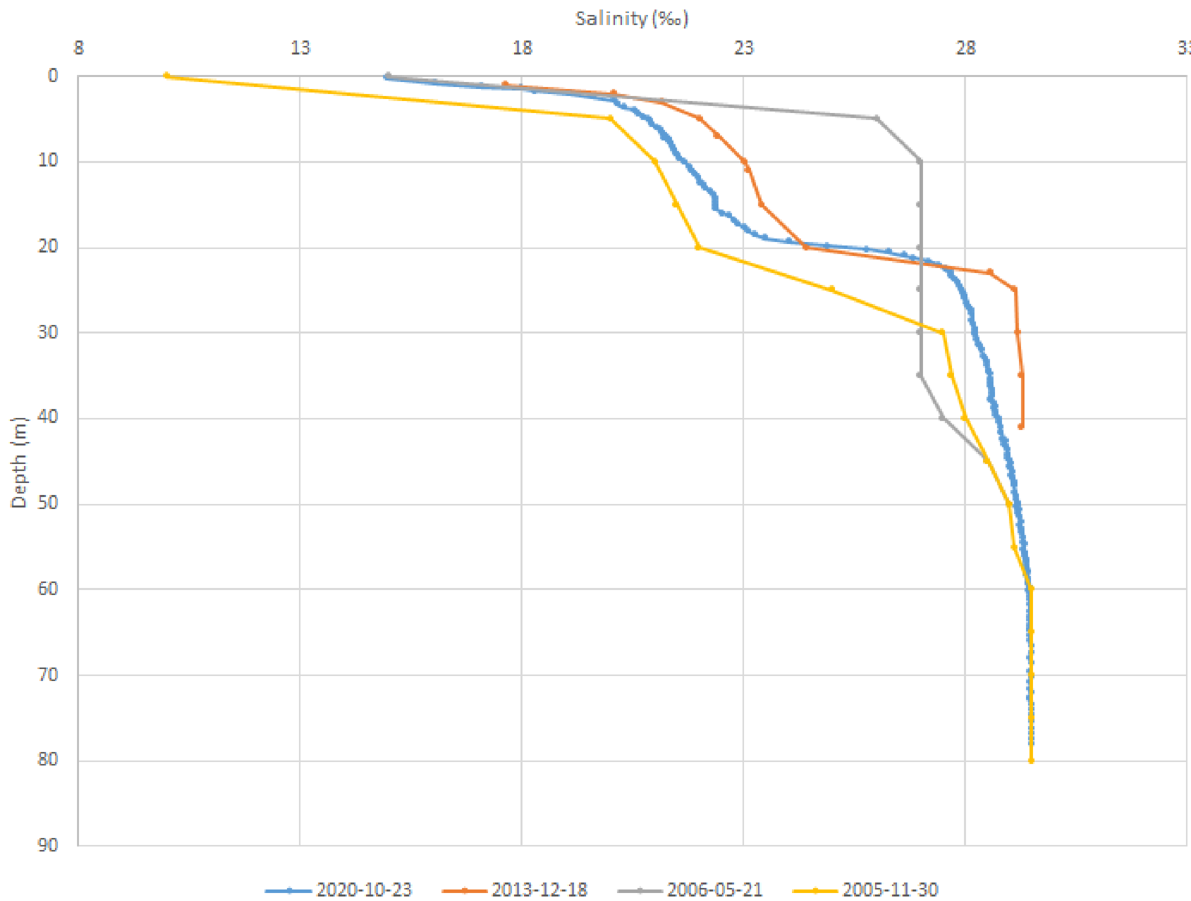


Figure 41: Salinity (‰) throughout the water column of the Østerbøvatn from the years of 2005-2020

The Østerbøvatn temperature depth profile (figure 42) appears to be just as sporadic as its salinity data. Analogously, the data was not found to be statistically significant from the results of a one way analysis of variance test *[F(3, 228)=0.53, p=0.663]*.

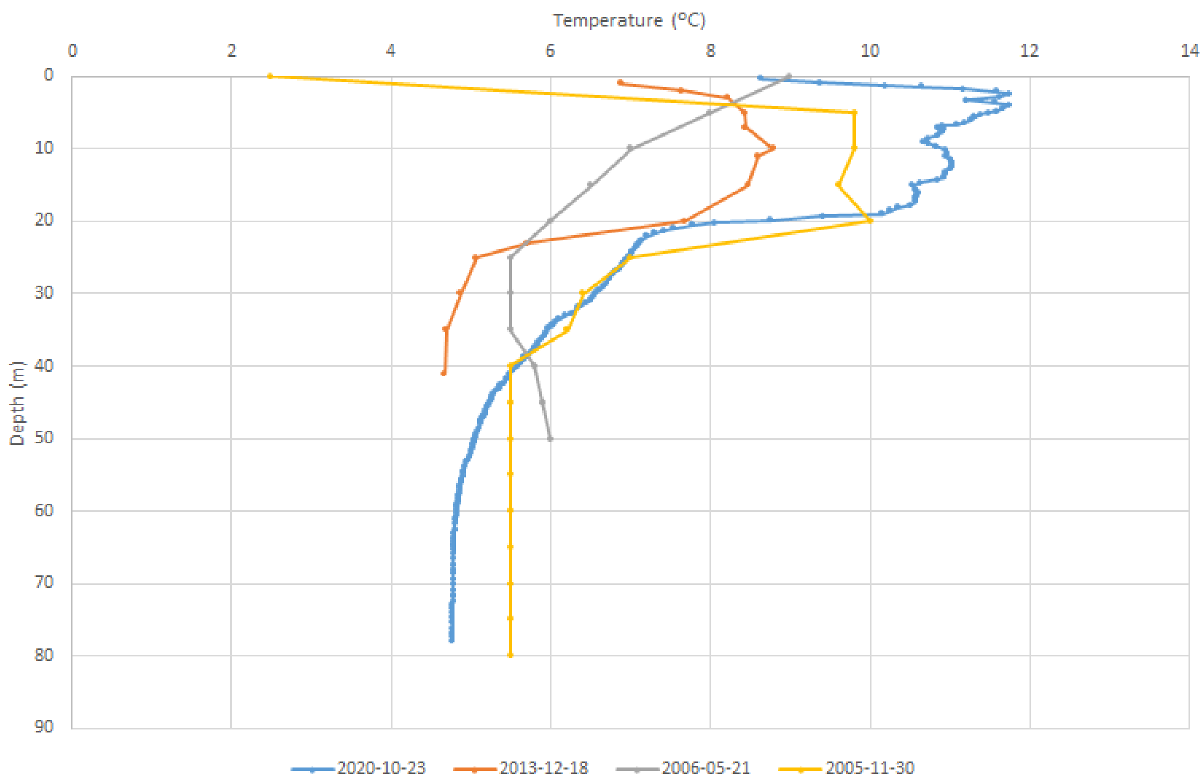


Figure 42: Temperature (°C) throughout the water column of the Østerbøvatn from the years of 2005-2020

In regards to the Østerbøvatn oxygen depth profile (figure 43), there appears to be a clear pattern of worsening anoxia along the water column. The 2020 series encompasses the most anoxic measurements taken in this fjord. Not only is the 2020 series consistently the most anoxic along the water column, its anoxia begins around 34 m which is the shallowest in the figure. In 2005 the anoxia did not begin until approximately 60 m. The least anoxic data is that of 2006, which coincides with an inflow as seen in figure 46. A one way analysis of variance test deemed this data to be statistically significant *[F(3, 228)=8.25, p=3.1E-05]*.

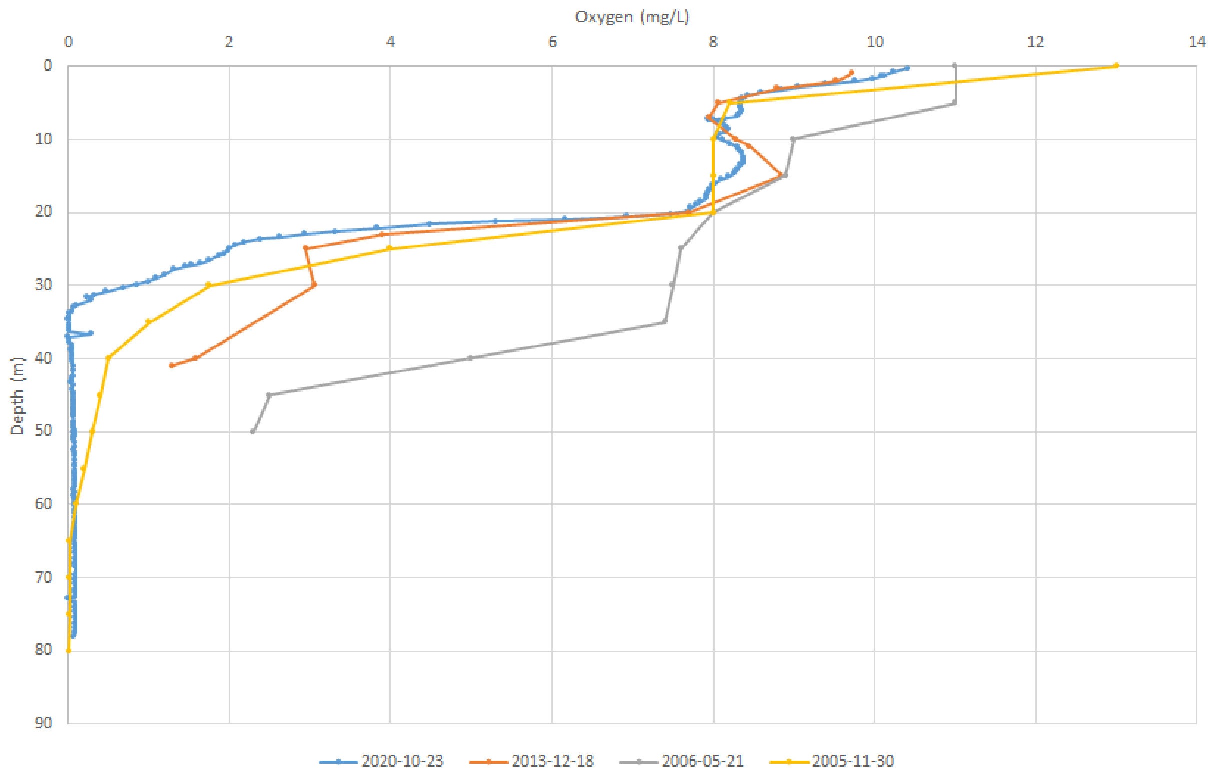


Figure 43: Oxygen concentration (mg/L) throughout the water column of the Østerbøvatn from the years of 2005-2020

3.5.2 Salinity, Temperature and Oxygen Timelines

The Østerbøvatn timelines contain data extending back to 2005 for all parameters. The depths profiled included 0 m, 20 m, 50 m and 70 m. There did not appear to be any distinct trends visible for the salinity or temperature timelines and oxygen appeared to be decreasing over time.

Regarding the salinity timeline (figure 44) a one way analysis of variance test deemed the data to not be statistically significant *[F(3, 228)=1.60, p=0.190]*. Despite the test results, it would have been difficult to draw conclusions from this figure as it does appear to be lacking in data. Salinity along the water column appears to range from 10 ‰ to 29.5 ‰.

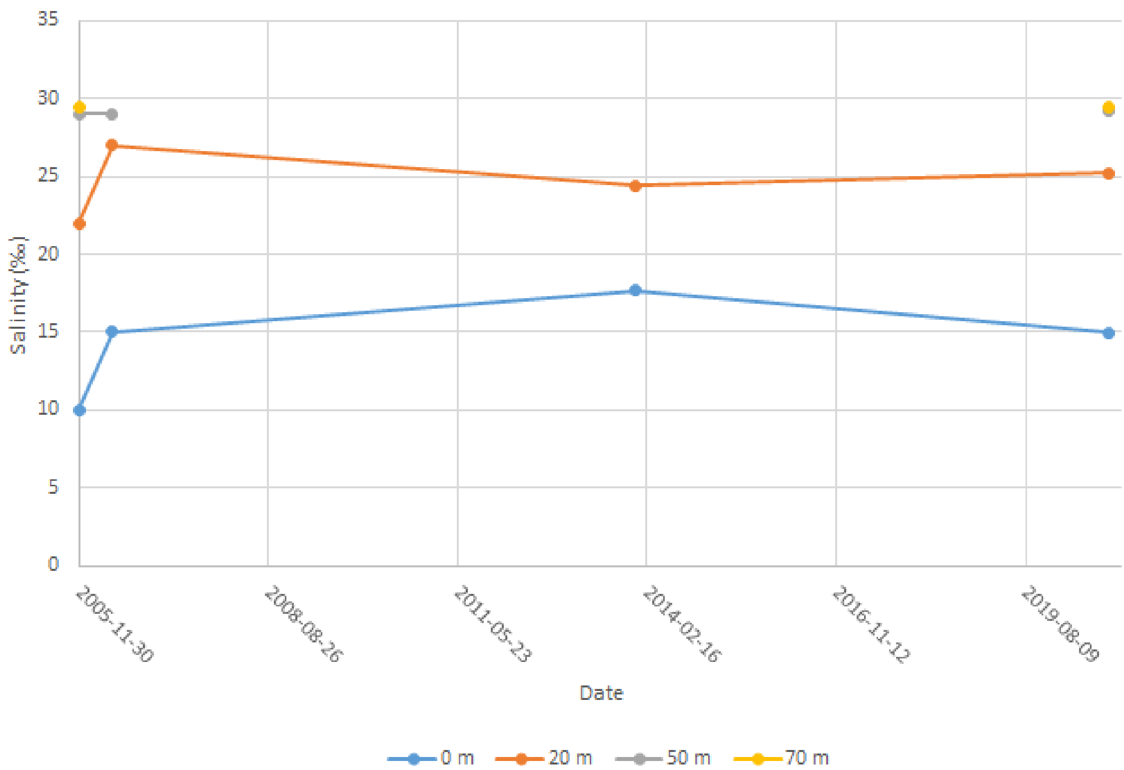


Figure 44: Progression of salinity (‰) from 2005-2020 at depths of 0 m, 20 m, 50 m and 70 m in the Østerbøvatn

Similarly to the salinity timeline, the temperature timeline (figure 45) does not appear to display any clear trends and was not deemed to contain statistically significant data from the results of a one way analysis of variance test *[F(3, 228)=8.25, p=3.1E-05]*. Temperature along the water column appears to range from 2.5ºC to 10ºC.

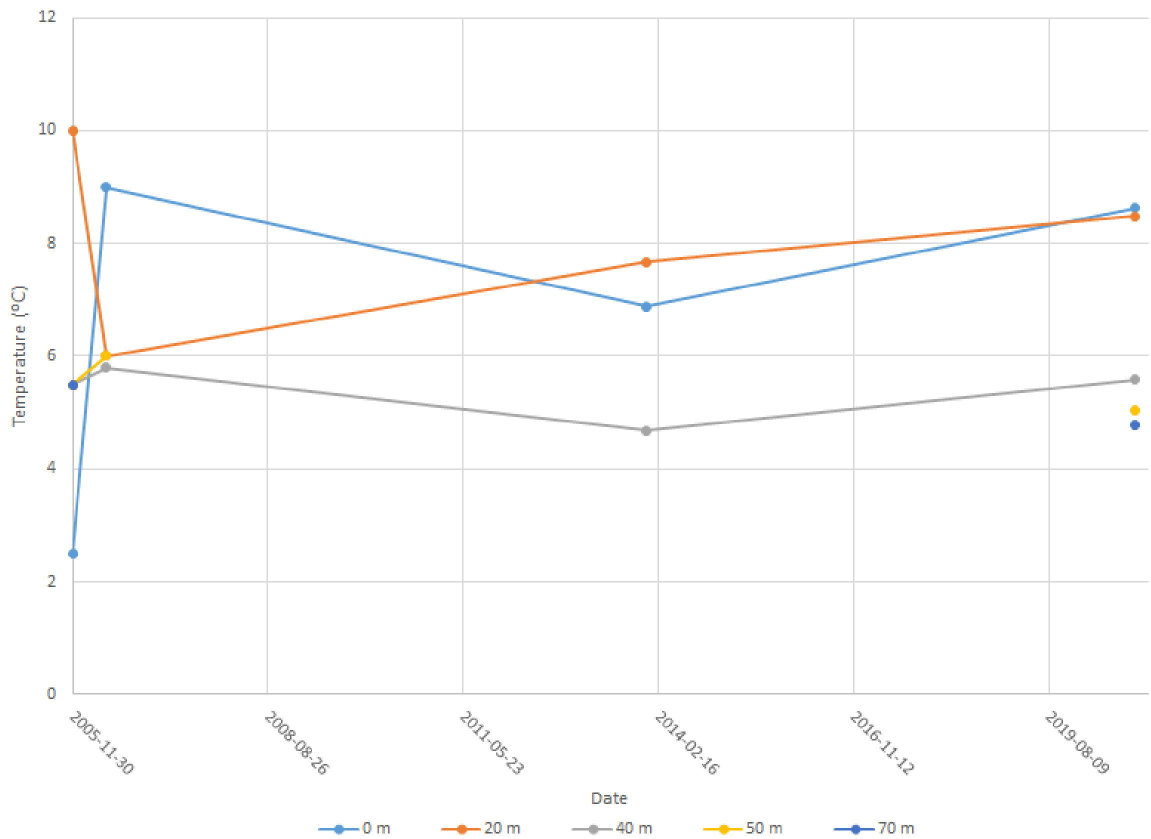


Figure 45: Progression of temperature (ºC) from 2005-2020 at depths of 0 m, 20 m, 40 m, 50 m and 70 m in the Østerbøvatn

The oxygen timeline (figure 46) was the only Østerbøvatn timeline that contained statistically significant data as indicated by the results of a one way analysis of variance test *[F(3, 228)=0.53, p=0.663]*. It is apparent that oxygen concentration is decreasing over time at all depths. The 20 m data appears to be the most stable with minimal variation and only a slight decrease in oxygen concentration over time, but there appears to be more of a decrease at 40 m and 50 m over time. The exception to this is the 70 m dataset, which starts off with an oxygen concentration of 0.015 mg/L in 2005 and ends with a value of 0.09 mg/L in 2020, suggesting there has been a slight increase in oxygen over time. More data would be required in order to deduce if there is a real increase or if the 2020 data at this depth is simply within the realm of reasonable variation. Many of the other basins experienced an inflow in 2019, so it is possible that one also occurred in the Østerbøvatn at this time as well. There appears to have been the occurrence of an inflow in 2006.

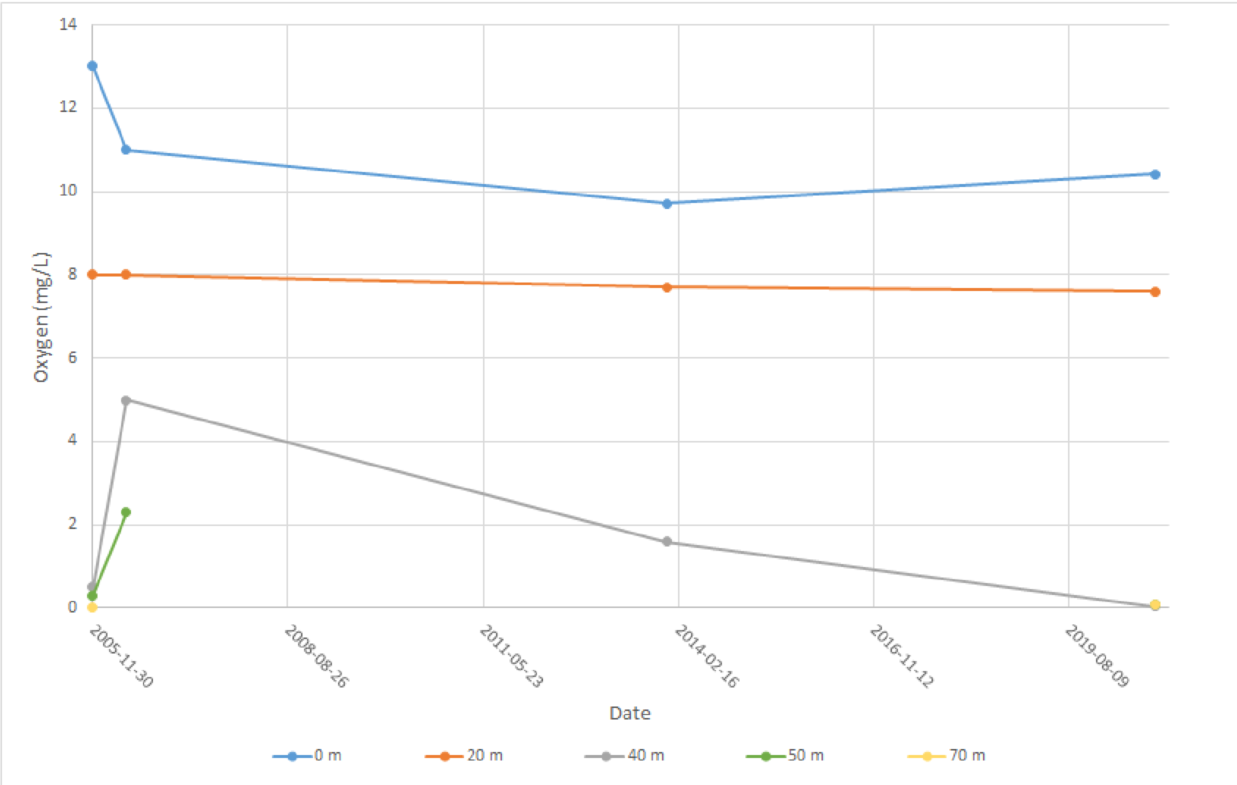


Figure 46: Progression of oxygen concentration (mg/L) from 2005-2020 at depths of 0 m, 20 m, 40 m, 50 m and 70 m in the Østerbøvatn

3.6 Hydrographical results for the Inner Fuglsetfjorden

3.6.1 Salinity, Temperature and Oxygen Depth Profiles

The Fuglsetfjorden depth profiles contain 5 observations occurring between 2018 and 2020 for each parameter. Regarding the salinity depth profile (figure 47) salinity appears to be highest along the thermocline in 2019, strongly implying an inflow of high salinity and high density water. The hypolimnion appears to begin at approximately 30 m. Salinity was highest along the hypolimnion in 2018-03, and the other 2018 data appears to be clustered near the 2018-03 data. The least saline data along the hypolimnion occurred in 2020. In 2018-08 a freshwater layer is visible along the surface. A one way analysis of variance test deemed this data statistically significant *[F(4, 555)=6.61, p=3.35E-05]*.

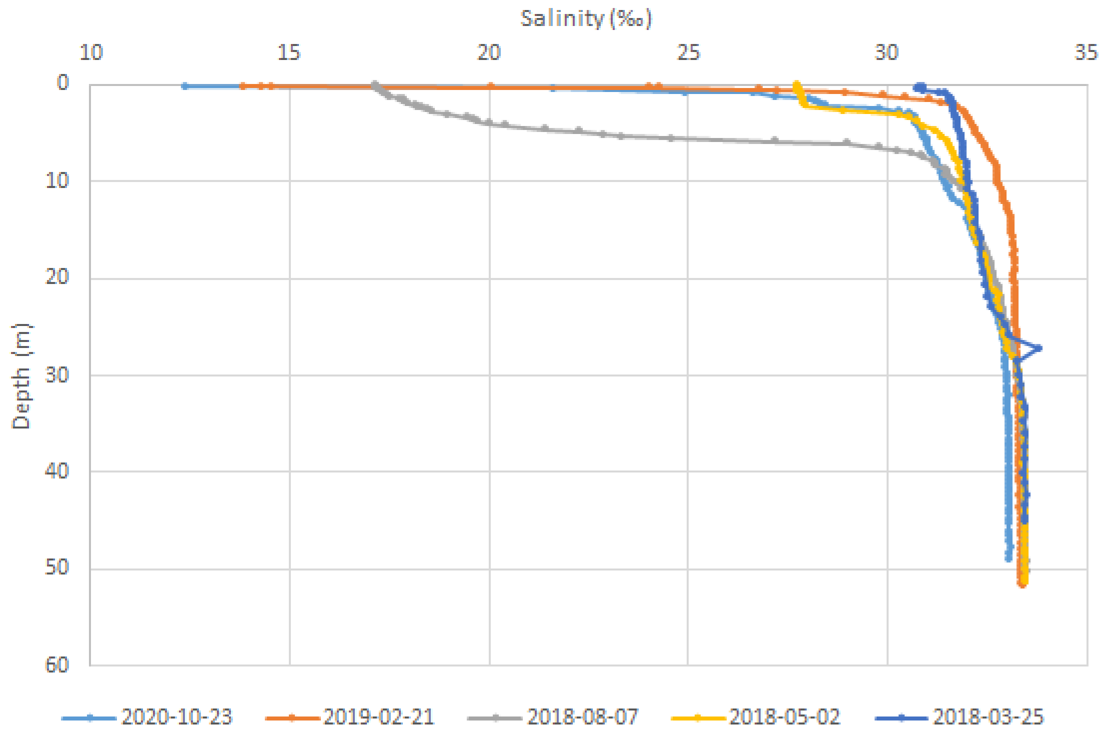


Figure 47: Salinity (‰) throughout the water column of the Inner Fuglsetfjorden from the years of 2018-2020

Inspection of the temperature depth profile (figure 48) shows that all data from 2018 appears to be clustered along the hypolimnion, and has the highest temperature in the dataset below the threshold. The 2019 data appears to be the coldest along most of the water column, which is presumably due to the inflow that occurred at this time. The 2020 dataset does end up being colder than the 2019 data towards the bottom of the basin, but is the warmest along the thermocline. Analogously to the salinity profile, the hypolimnion appears to begin at approximately 30 m. A one way analysis of variance test found that this data could be considered statistically significant *[F(4, 555)=55.57, p=2.05E-39]*.

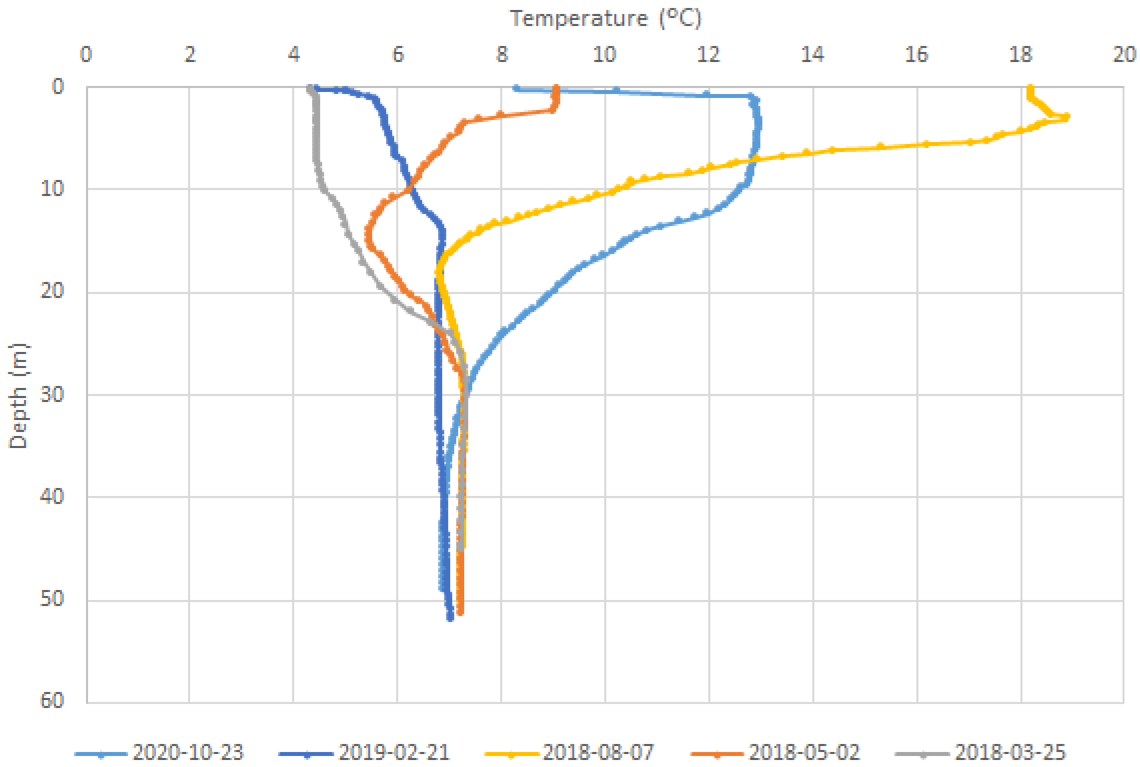


Figure 48: Temperature (ºC) throughout the water column of the Inner Fuglsetfjorden from the years of 2018-2020

In terms of the oxygen depth profile (figure 49), the datasets appear to fall in chronological order getting more anoxic over time with the exception of the 2019 data. This can be attributed to an inflow that occurred in 2019. The 2020 dataset is the most anoxic by far with the anoxia beginning at approximately 25 m. The results of a one way analysis of variance test proved this data to be statistically significant *[F(4, 555)=12.99, p=4.09E-10]*.

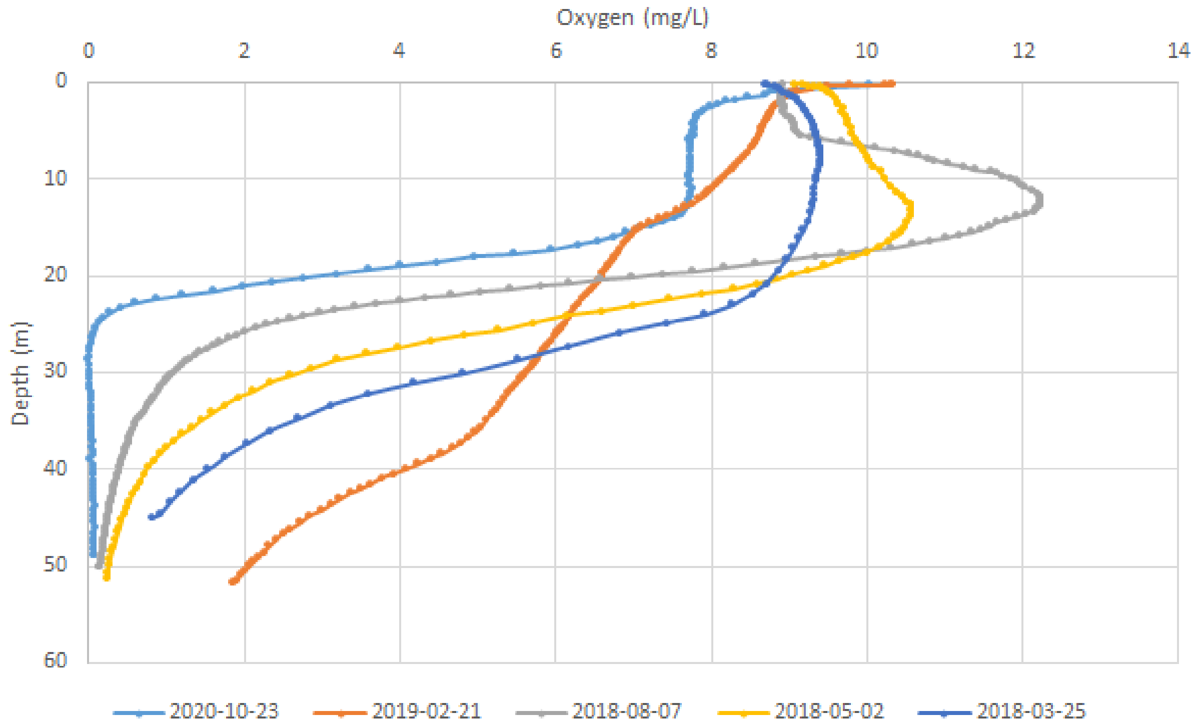


Figure 49: Oxygen concentration (mg/L) throughout the water column of the Inner Fuglsetfjorden from the years of 2018-2020

3.6.2 Salinity, Temperature and Oxygen Timelines

The Fuglsetfjorden timelines contain data extending back to 2018 for all parameters. The depths profiled included 0 m, 15 m, 30 m, and 45 m. The overall trends appeared as follows: salinity is decreasing over time, there were no distinct temperature trends and oxygen is decreasing over time.

Salinity appears to be decreasing over time at most depths, although this decrease is not as distinct at 15 m which appears to have been relatively stable over time (figure 50). The 30 m and 45 m series both have trendline slopes of -0.0004. Additionally, in the basin depths the minimum values occur in 2020 at both 30 m and 45 m.

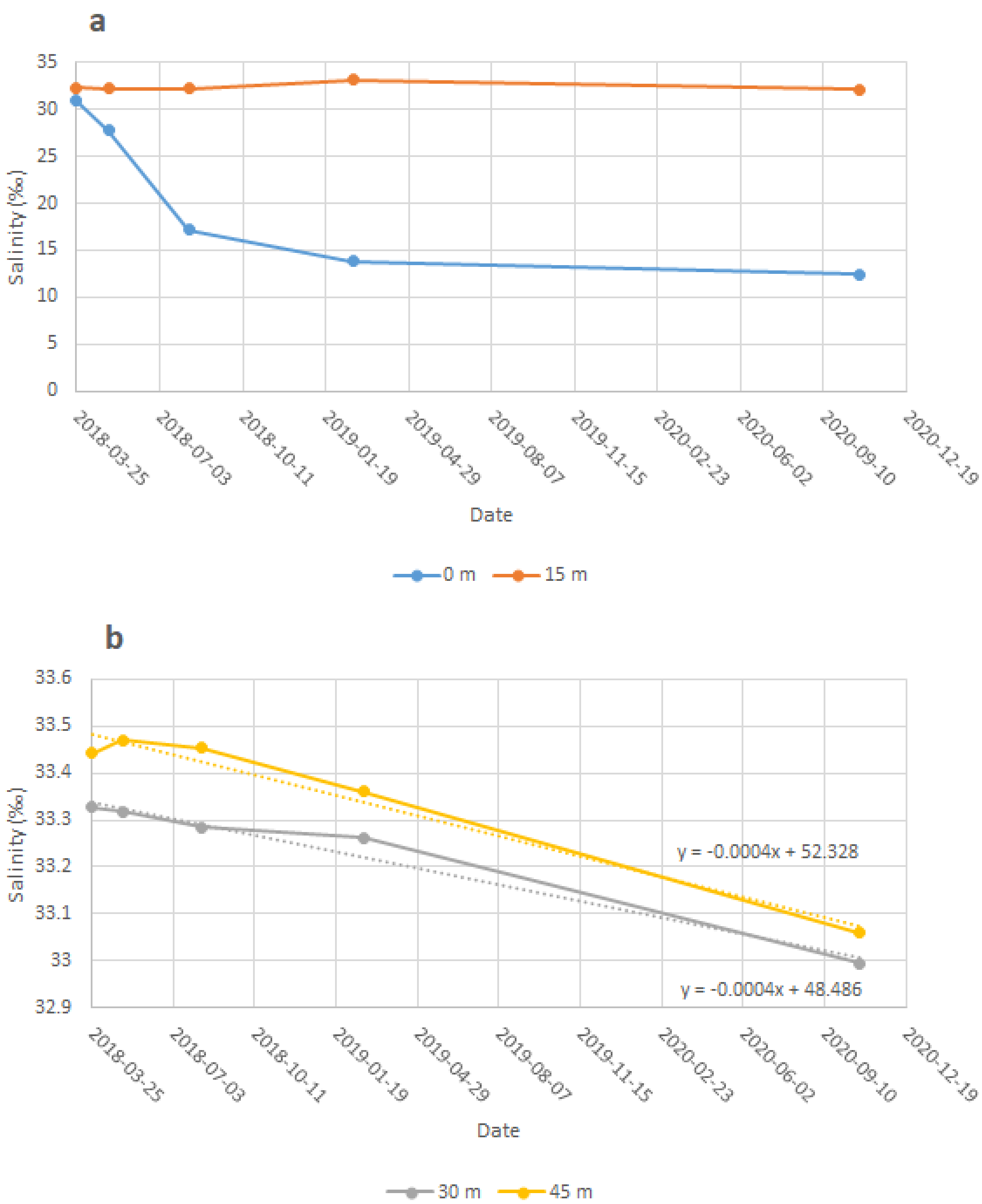


Figure 50: Progression of salinity (‰) from 2018-2020 at (a) surface depths of 0 m and 15 m and (b) basin depths of 30 m and 45 m in the Inner Fuglsetfjorden

The temperature trends in figure 51 are varied. The 15 m dataset appears to be increasing over time as supported by the 0.0052 trendline slope. There does not appear to be a clear trend at 30 m. At 45 m there is a decrease over time as indicated by the trendline slope of -0.0004. The perceived decrease in 2019 at 30 m and 45 m is likely due to the inflow that occurred at this time. Seeing as the data available for the Fuglsetfjorden is extremely limited, this 2019 inflow presumably skewed the data to make it appear as though the temperature is decreasing in the basin over time. This is especially applicable for the 30 m dataset, which actually has a maximum temperature of 7.32 ºC occurring in 2020.

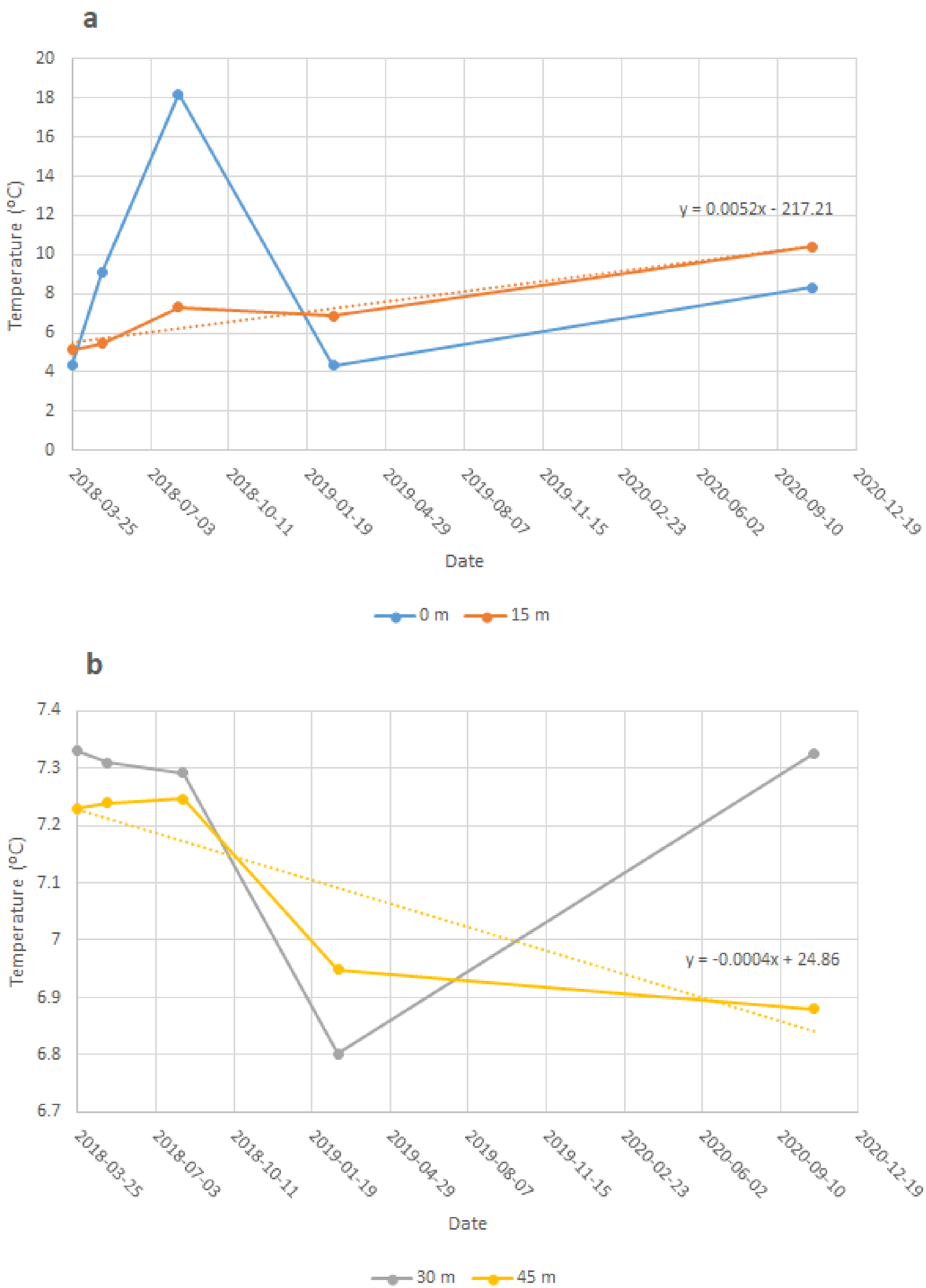


Figure 51: Progression of temperature (ºC) from 2018-2020 at (a) surface depths of 0 m and 15 m and (b) basin depths of 30 m and 45 m in the Inner Fuglsetfjorden

Oxygen concentration appears to be decreasing at all depths with the exception of the 0 m dataset (figure 52). This decrease is evident from the trendline slopes. The slope at 15 m is -0.0036, the slope at 30 m is -0.0033 and the slope at 45 m is -0.004. There appears to have been an inflow in 2019 which is indicated by the sudden increase at this date in the 30 m and 45 m datasets. The decline in the 15 m dataset in 2019 is likely due to the uplifting of oxygen deficient water that occasionally occurs along with inflows.

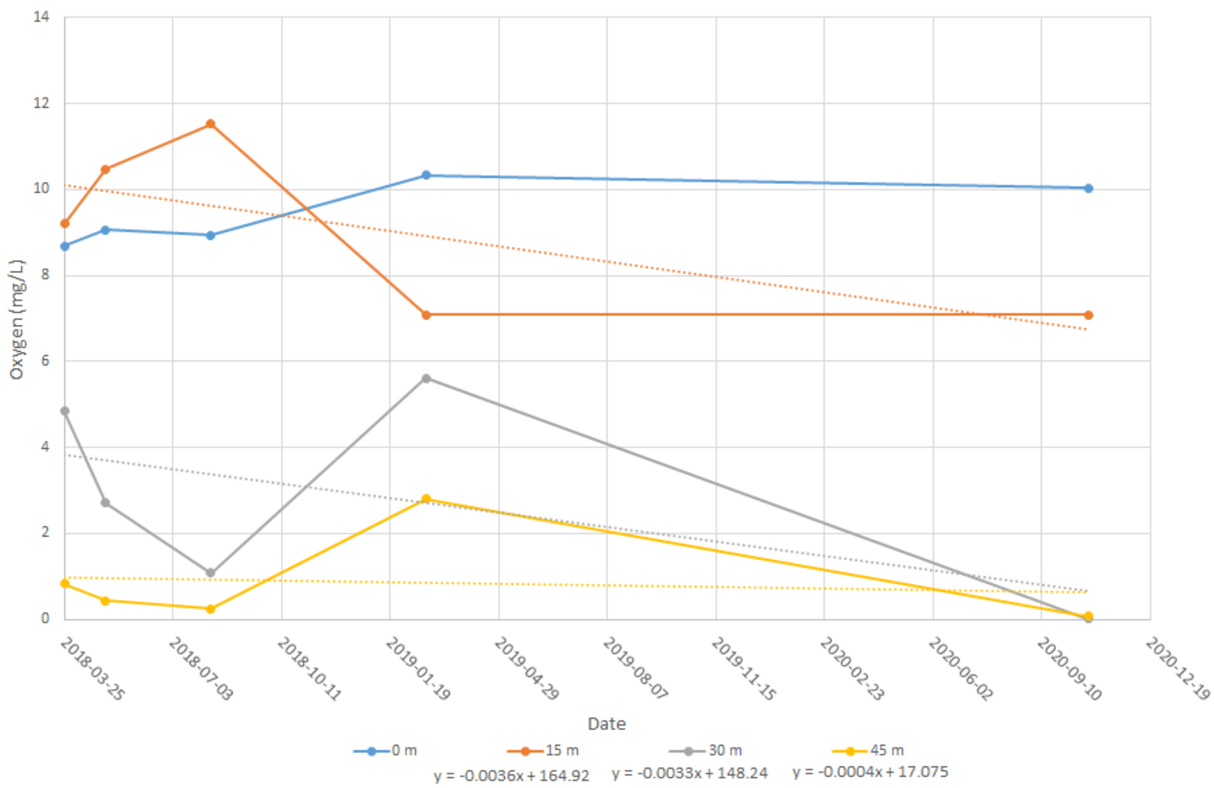


Figure 52: Progression of oxygen concentration (mg/L) from 2018-2020 at (a) surface depths of 0 m and 15 m and (b) basin depths of 30 m and 45 m in the Inner Fuglsetfjorden

3.7 Hydrographical results for the Finnabotn

3.7.1 Salinity, Temperature and Oxygen Depth Profiles

The Finnabotn depth profiles contain one observation that occurred on 2020-12-09 for each parameter. The data in the salinity depth profile (figure 53) takes a shape that can be expected for a salinity profile. There is a steady increase in salinity along the pycnocline until a sudden stabilization that begins around 40 m and continues to the bottom of the basin. The salinity holds a value of approximately 33 ‰ from 40 m on.

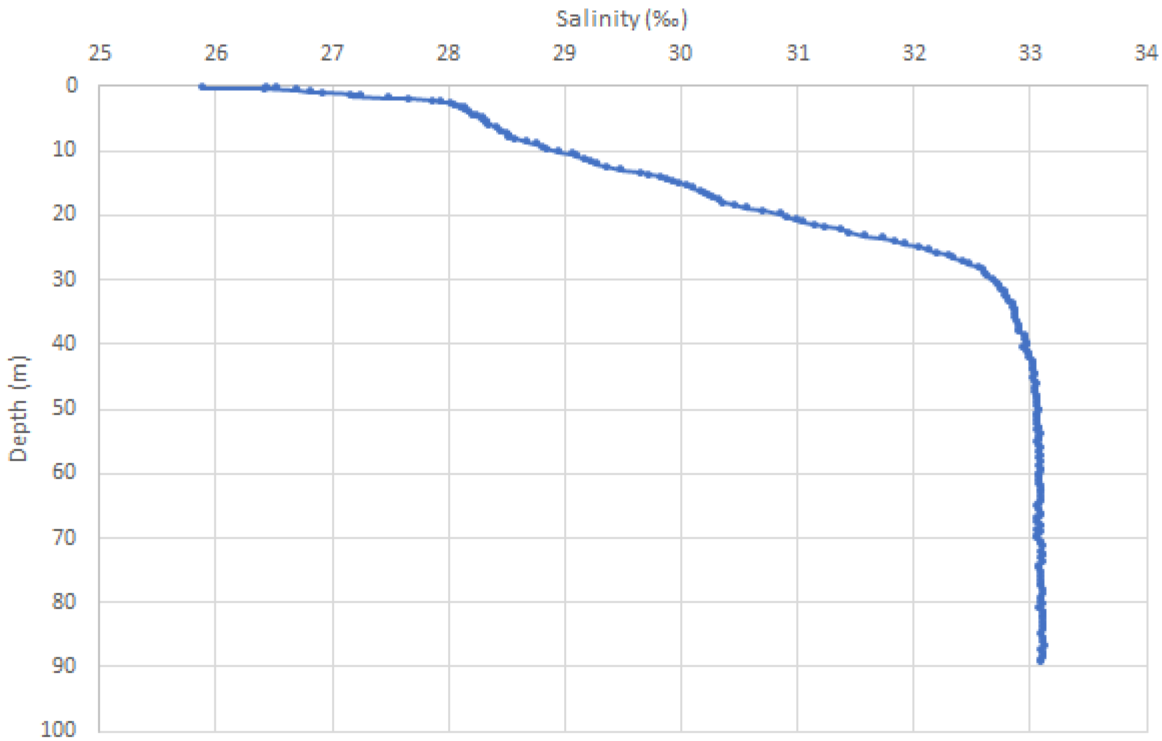


Figure 53: Salinity (‰) throughout the water column of the Finnabotn on 2020-12-09

Regarding the temperature depth profile (figure 54) the thermocline appears to follow a unique shape, initially increasing then suddenly sharply decreasing as it approaches a depth of 20 m. The hypolimnion appears to begin at a depth of 40-50 m. The temperature remains relatively constant at around 6.5 ºC from that depth on to the bottom of the basin.

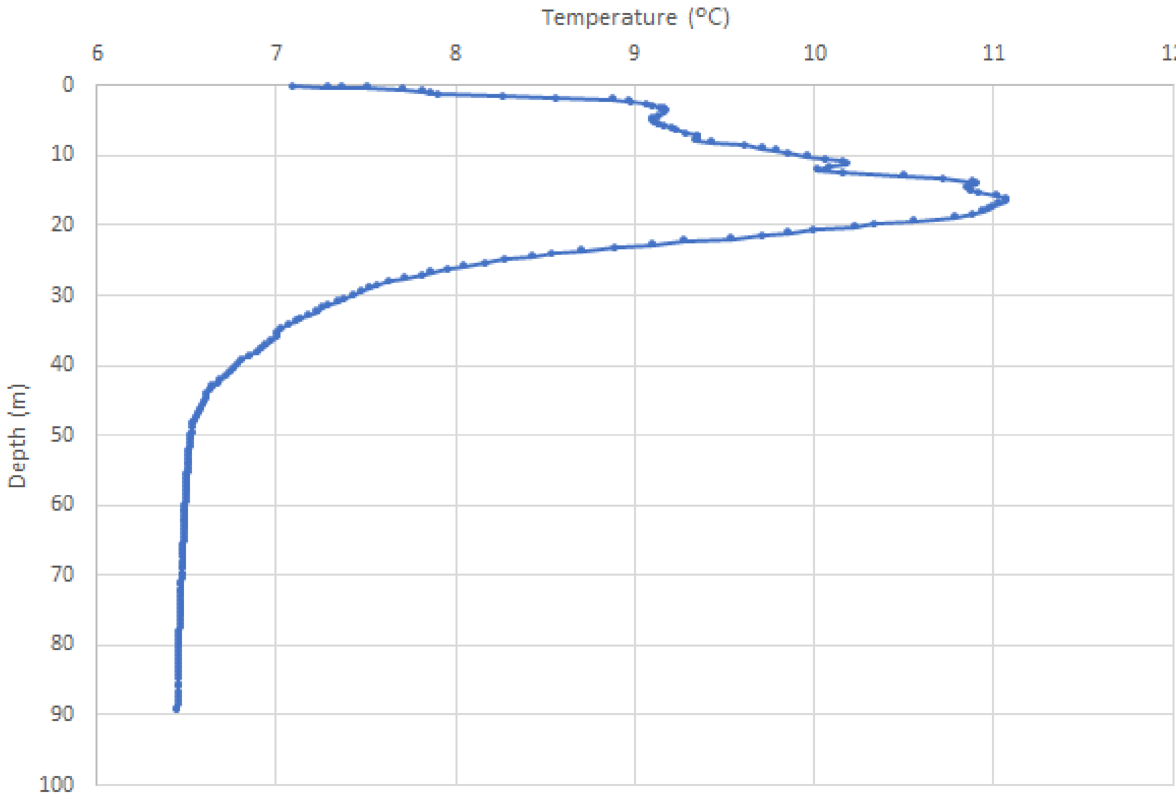


Figure 54: Temperature (ºC) throughout the water column of the Finnabotn on 2020-12-09

In terms of the oxygen concentration in the Finnabotn (figure 55) the anoxia in this fjord appears to begin at approximately 35 m. The sudden increase in oxygen at 85 m could actually be an indication of a large increase in hydrogen sulfide at this time, which the measuring instrument sometimes confuses with oxygen. The highest oxygen values are located in the top 2 m of the water column. A large range in oxygen concentration throughout the water column is present, with values ranging from 0 mg/L to 9.5 mg/L.

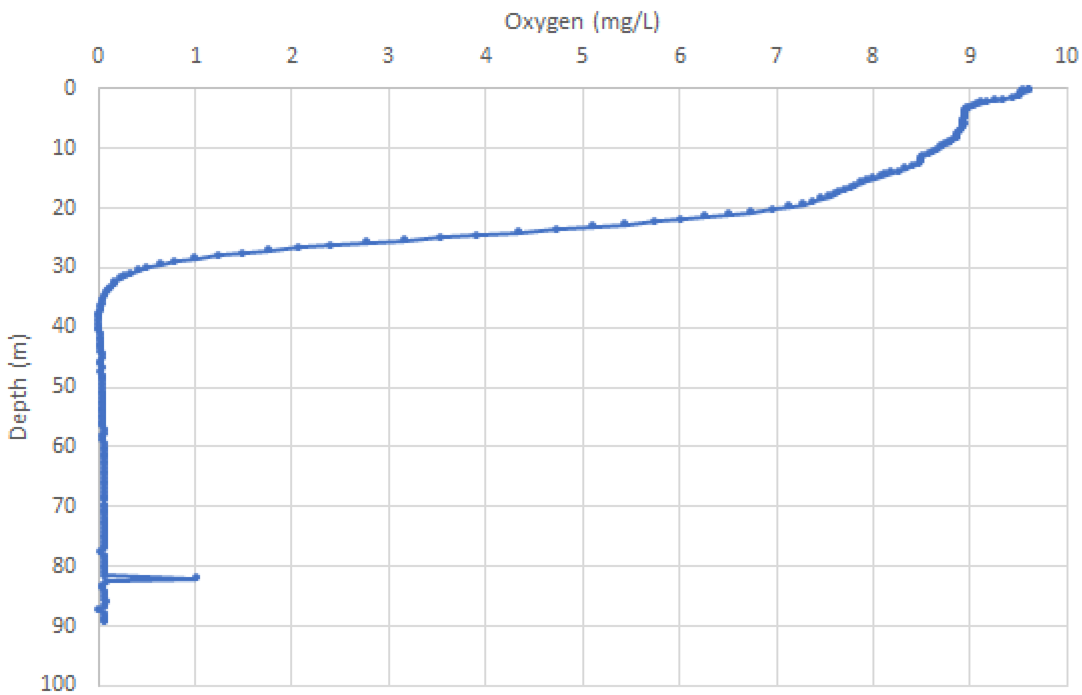


Figure 55: Oxygen concentration (mg/L) throughout the water column of the Finnabotn on 2020-12-09

3.8 Oxygen Consumption Rates Within the 7 Basins

Theoretical oxygen consumption rates for each basin were calculated using the equations presented by Aure and Stigebrandt (1989), and actual oxygen consumption rates at a shallow basin depth & deep basin depth were calculated for each fjord with sufficient data to produce a reasonably accurate rate (table 3).

	Theoretical Oxygen Consumption Rate (mg/L/month)	Actual Oxygen Consumption Rate; Shallower Basin Depth (mg/L/month)	Actual Oxygen Consumption Rate; Deeper Basin Depth (mg/L/month)
Barsnesfjorden	0.210	0.364 (60 m)	0.291 (75 m)
Sogndalsfjorden	0.0638	0.117 (150 m)	0.0878 (200 m)
Nærøyfjorden	0.194	-	-
Ikjefjorden	0.123	0.129 (75 m)	0.179 (100 m)
Østerbøvatn	0.181	-	-
Fuglsetfjorden	0.343	0.279 (30 m)	0.137 (45 m)
Finnabotn	0.110	-	-

Table 3: Theoretical and Actual Oxygen Consumption Rates for the 7 Basins

The Sogndalsfjorden had the lowest theoretical consumption rate with a value that was 0.0462 mg/L/month lower than that of the Finnabotn, which had the second lowest theoretical consumption rate. The Fuglsetfjorden had the highest theoretical consumption rate with a value that was 0.133 mg/L/month higher than that of the Barsnesfjorden, which had the second highest theoretical consumption rate.

The actual consumption rates differed from the theoretical rates. The Barsnesfjorden had the highest actual consumption rates of all the basins studied in this thesis. Its actual rates were higher than its theoretical rate by 0.154 mg/L/month at 60 m and 0.081 mg/L/month at 75 m. The Sogndalsfjorden also had actual consumption rates that were higher than the theoretical rate. The rate at 150 m was higher than the theoretical rate by 0.0532 mg/L/month and the rate at 200 m was higher by 0.024 mg/L/month. Despite the actual consumption rates being higher than the theoretical rate, they were the lowest consumption rates found in any of the basins. The theoretical consumption rate in the Ikjefjorden was very close to the actual consumption rate at 75 m with a difference of only 0.006 mg/L/month between the two rates. The consumption rate at 100 m was also close to what was theorized with an overall difference of just 0.05 mg/L/month. Although the Fuglsetfjorden has the highest theorized consumption rate, the same cannot be said of the actual consumption rates. A rate of 0.279 mg/L/month was found at a depth of 30 m and a rate of 0.137 mg/L/month was found at 45 m. The consumption rate at 45 m was found to be lower than the theorized consumption rate by 0.206 mg/L/month. This is the largest difference between a theoretical rate and an actual rate found in this thesis.

4.0 Discussion

4.1 Comparison of Hydrographical Conditions Within the 7 Basins

The results of this thesis yielded illuminating information regarding the water chemistry over time in the Outer Barsnesfjorden, Sogndalsfjorden, Inner Nærøyfjorden, Ikjefjorden, Østerbøvatn, Inner Fuglsetfjorden and Finnabotn. These results painted a clear picture of the situation within each water column. A summary of said results for each fjord can be found in table 4 below.

	Depth of comparison (m)	Minimum Temp (ºC)	Maximum Temp (ºC)	Average Temp (ºC)	Minimum Salinity (‰)	Maximum Salinity (‰)	Average Salinity (‰)	Minimum Oxygen (mg/L)	Maximum Oxygen (mg/L)	Average Oxygen (mg/L)
Outer Barsnesfjorden	75	4.92 (1916)	8.33 (2019)	6.04 (n=49)	32.04 (2011)	34.03 (1922)	33.35 (n=54)	0 (1991)	5.86 (1931)	2.79 (n=42)
Sogndalsfjorden	200	5.56 (1948)	9.217 (2011)	6.63 (n=52)	33.69 (1932)	35.2 (1984)	34.09 (n=49)	2.56 (2008)	9.89 (1933)	6.50 (n=36)
Inner Nærøyfjorden	75	5.79 (1920)	8.61 (1993)	7.63 (n=10)	33.48 (2020)	33.87 (2015)	33.71 (n=7)	0 (1987, 2006, 2020)	7.2 (1996)	1.96 (n=9)
Ikjefjorden	120	7.261 (2017)	7.967 (2019)	7.44 (n=6)	33.66 (2020)	34.09 (2019)	33.84 (n=6)	0 (2017, 2020)	1.21 (2019)	0.304 (n=6)
Østerbøvatn	50	5.042 (2020)	6 (2006)	5.51 (n=4)	29 (2005)	29.23 (2020)	29.07 (n=4)	0.08 (2020)	2.3 (2006)	0.890 (n=4)
Inner Fuglsetfjorden	50	6.86 (2020)	7.229 (2018)	7.08 (n=5)	33.06 (2020)	33.47 (2018)	33.35 (n=5)	0.07 (2020)	2 (2019)	0.618 (n=5)
Finnabotn	~90	-	-	6.451 (n=1)	-	-	33.1 (n=1)	-	-	0.06 (n=1)

Table 4: Depth Profile Ranges at Basin Depths

As indicated by table 4 above, the largest ranges and highest averages can be found in the Barsnesfjorden, Sogndalsfjorden and the Nærøyfjorden. Conversely, the lowest ranges and lowest averages can be found in the Ikjefjorden, Østerbøvatn, Fuglsetfjorden and Finnabotn. This difference in ranges can likely be attributed to the fact that the Barsnesfjorden, Sogndalsfjorden and Nærøyfjorden have the largest pool of data containing ~10-55 observations in their respective depth profiles, allowing the existence of larger ranges simply because there is more data available. Conversely, the Ikjefjorden, Østerbøvatn, Fuglsetfjorden and Finnabotn depth profiles only contain 1-6 observations. Analogously, the former 3 fjords have the highest averages amongst them for all parameters while the latter 4 fjords have the lowest averages. The Ikjefjorden, Østerbøvatn and Fuglsetfjorden all consist of more recent data so the averages are reflective of modern conditions. It makes sense that the lowest salinity and oxygen averages can be found in these fjords as this reflects what was hypothesized.

It has been deemed that the "critical" level for oxygen concentration is 2 mg/l (EPA, 2012). After this point, organisms begin to die. At concentrations of 0-1 mg/L, organisms are most certainly already dead. It can be definitively stated that the Nærøyfjorden, Ikjefjorden, Østerbøvatn, Fuglsetfjorden and Finnabotn have average oxygen concentrations in their basins that are insufficient to sustain macroscopic life. Thus, these fjords can be considered anoxic. The Sogndalsfjorden oxygen appears to be at a sufficient level within the basin (as indicated by the average), but getting more anoxic over time as seen in figure 25. The Barsnesfjorden oxygen average is very close to a level that would be insufficient to sustain organisms, and the modern data indicates that the Barsnesfjorden is tending towards oxygen levels that are quite concerning as seen in figure 17.

In terms of the salinity averages, the Barsnesfjorden, Sogndalsfjorden, Nærøyfjorden, Ikjefjorden, Fuglsetfjorden, and Finnabotn basin water can all be classified as "euhaline" as their averages fall between 30-40 ‰. The Østerbøvatn basin water can be classified as "polyhaline" because its average falls between 18-30 ‰.

4.1.1 Hydrographical Conditions in the Barsnesfjorden

The Barsnesfjorden has a relatively shallow sill depth and is known to receive its inflows in the winter time (Kaufmann, 2014). The Barsnesfjorden has the greatest ranges in salinity and temperature. The increase in hydropower activity in the Sognefjorden along with climate change could be playing a role in these high ranges. These large ranges may also be attributed to an increase in the speed of the water in the Barsnesfjorden over time due to constriction from the multiple bridges constructed at its entrance. This increased speed is expected to have resulted in more vertical turbulence and vertical mixing which speeds up the diffusion of higher density water, allowing more room for outliers in the data (thus resulting in higher ranges). However, the high salinity range is not synonymous with a high variance. A one way analysis of variance test did not find a statistically significant difference in the salinity depth profile $[F(53, 395)=0.098, p=1]$.

The high range in the Barsnesfjorden temperature data can be directly attributed to climate change as indicated by the fact that temperature in the Barsnesfjorden is increasing over time. The fact that the minimum occurred in 1916 and the maximum occurred in 2019 only proves this further.

Furthermore, analysis of the Barsnesfjorden oxygen depth profile (figure 14) clearly shows that anoxia in the Barsnesfjorden is tending to occur at shallower depths in the water column than previously seen.

4.1.2 Hydrographical Conditions in the Sogndalsfjorden

The Sogndalsfjorden has the deepest sill at 25 m of all basins included in this thesis. This deep sill allows for easier ventilation of basin water, and is likely why the Sogndalsfjorden has the highest average salinity and oxygen out of all the basins. Additionally, it is located directly adjacent to the main fjord which reasonably increases the potential for water exchange (figure 3). These constituents all play a role in why the Sogndalsfjorden also has the greatest oxygen ranges. The Sogndalsfjorden is known to receive its inflows in the summer time (Hovgaard, 1985; Dale and Hovgaard, 1993).

Despite the high oxygen values along the water column, there are some indicators that conditions in the Sogndalsfjorden are not always ideal. A study conducted by Myrseth et al. (2000) compared benthic biological samples from 1999 with samples from 1993. It was noted that species numbers were approximately the same, but numbers of specimens (particularly molluscs) had declined. This is a definitive sign of negative development. However, an improvement in basin water was seen from 1999 to 2006 when the total number of species and the number of molluscs was determined to have increased (Johansen et al., 2007).

4.1.3 Hydrographical Conditions in the Nærøyfjorden

The Nærøyfjorden has the highest average temperature. Although the Nærøyfjorden has data going back to 1920, nine of the ten observations occurred in the past 30 years. This is likely a factor in the high average temperature seeing as most of the data is recent and there are indicators that temperature has been increasing over time.

The Nærøyfjorden anoxia appears to be extending to shallower depths as time progresses (figure 29). The 2020 oxygen time series is the lowest ever recorded below the threshold in this fjord with the anoxia beginning at 50 m. There are no constrictions on the flow of water to the Nærøyfjorden at its entrance, so there is likely a low water speed associated with low vertical turbulence and vertical mixing. This may be a constituent in the frequent anoxia that can be found in the Nærøyfjorden.

Additionally, it is worth noting that although the Nærøyfjorden does not have any hydropower activities influencing it directly, hydropower in the nearby Aurlandsfjorden has resulted in freshwater injection to the surface layers of the fjord that has been occurring since the 1980s (Berg et al., 2017). This has resulted in a reduction in surface salinity of the water supplying the Nærøyfjorden.

There have been observations of hydrogen sulfide in the Nærøyfjorden basin over the years, including one recorded in 1987 at 75 m and another at 75 m in 1993. A study by Rustad (1980) noted that on a visit to the fjord on August 7th, 1942 there was rich bottom fauna at the sill, but when they returned in June 1943 there were only a few living organisms left in this location. This implies the occurrence of an inflow between these dates that caused an uplifting of an anoxic water mass containing hydrogen sulfide, killing these organisms. A publication by Vassenden et al. (2007) implied the presence of hydrogen sulfide by stating that only a few living organisms were found in the basin. This study also found low nitrate values and high phosphate values demonstrating denitrification and increased solubility of phosphates at 75 m. These processes are commonplace in anoxic waters.

4.1.4 Hydrographical Conditions in the Østerbøvatn

The lowest average temperature can be found in the Østerbøvatn. However, it is worth noting that the Østerbøvatn temperature data only consists of 4 observations and was deemed not statistically significant from the results of a one way analysis of variance test *[F(3, 228)=0.53, p=0.663]*. With that being said, a study conducted by Aasen (1953) described an observed temperature below 5ºC along the Østerbøvatn hypolimnion. The average temperature in the Østerbøvatn basin in this study was determined to be 5.51ºC.

The Østerbøvatn has the shallowest sill at 2 m (table 2), implying the occurrence of winter inflows. This theory is supported by the low average temperature seen in this basin. Of the fjords in this study, the Østerbøvatn has the lowest average salinity and the lowest salinity range. This low salinity and low average temperature can be directly attributed to the shallow sill. However, it must be noted that the results of a one way analysis of variance test found differences in Østerbøvatn salinity to not be statistically significant *[F(3, 228)=1.60, p=0.190]*. Thus, more data would be required in order to draw conclusive conclusions around changes in Østerbøvatn salinity.

The Østerbøvatn oxygen depth profile shows anoxia that appears to be extending to shallower depths over time. The Østerbøvatn has a smolt production operation that has been proven to be releasing large amounts of organic matter (Lode et al., 2013), which may be connected to increased oxygen consumption rates in this basin. Additionally, it has been noted in the literature that the Østerbøvatn receives much of its inflows through a shallow and narrow inlet, restricting water exchange and causing anoxic conditions in its basin (Lode et al., 2013).

The presence of hydrogen sulfide has been recorded in the basin at various times. A report authored by Johnsen and Kålås (2007) found high levels of hydrogen sulfide at 25 m, 30 m and 60 m on December 12th, 2006 and high levels of hydrogen sulfide at 60 m on January 13th, 2006, February 16th, 2006 and May 21st, 2006. This information is important because in the oxygen depth profile (figure 43) the most anoxic measurement occurred in 2020 with the anoxia beginning at 35 m. The observation of hydrogen sulfide present at 25 m in the fjord on December 12th, 2006 shows that this is not the first time that the Østerbøvatn has been subject to highly anoxic conditions.

4.1.5 Hydrographical Conditions in the Ikjefjorden

The Ikjefjorden has a moderate sill depth and maximum depth of 16 m and 120 m respectively (table 2). It also has the lowest oxygen range and the 2nd lowest average oxygen concentration. The low oxygen ranges and concentrations may be attributed to the construction of a bridge at the entrance to the sound in 1977 (Koek and Van Doorn, 2018; Van Rossum, 2018). The successful construction of this bridge required a reduction of the deepest sill point by approximately 5 m, a decrease that would be sufficient to have restricted the basin water renewal and caused oxygen concentrations to decrease more rapidly (Koek and Van Doorn, 2018). The Ikjefjorden oxygen depth profile (figure 36) exhibits anoxic conditions that begin at shallower depths as time goes on. Notably, the Ikjefjorden has the 2nd lowest temperature range and the 2nd highest average temperature. Additionally, it is worth noting that the Ikjefjorden lost 50% of its natural freshwater supply in the 1970s due to hydropower activities, which has likely had an impact on salinity in this fjord.

4.1.6 Hydrographical Conditions in the Fuglsetfjorden

The Fuglsetfjorden has a low sill depth of 6 m and the lowest maximum depth at 50 m (table 2). It also has the lowest temperature range and the 2nd lowest oxygen range. When deducing why the Fuglsetfjorden has such a low temperature range, it is important to consider the fact that this fjord only has data covering the duration of 2018-2020 which likely played a large role in this low range.

Regardless of the fact that the data is limited, there is a trend of diminishing salinity with the minimum value for salinity occurring in 2020 and the maximum occurring in 2018. Furthermore, the oxygen concentration appears to be decreasing in the period shown with the exception of a 2019 inflow (figure 49). Despite the inflow visible in 2019, the 2020 data is fully anoxic with anoxia beginning at 25 m. This is the only fully anoxic series that is presented in this depth profile.

4.1.7 Hydrographical Conditions in the Finnabotn

The Finnabotn has a sill depth of 2.5 m, a basin depth of 90 m and is surrounded on three sides by 1000 m high cliffs which almost completely isolate it from the main fjord (Swanberg and Bjørklund, 1987). It also has the lowest "average" oxygen concentration out of all the fjords in this study, although its oxygen data consists of only a single time series from 2020-12-09. It has been noted previously in the literature that the Finnabotn was found to be totally anoxic below 50 m and low in oxygen below 25 m (Swanberg and Bjørklund, 1987). The data in this study saw the Finnabotn anoxia beginning at a depth of 35 m. The Finnabotn entrance has been altered in such a way that has likely changed how oxygen is transported along the water column. The entrance was deepened by approximately 1.5 m in the 1950s/60s. Before deepening, the inflowing/outflowing water was described as being similar to a river. After deepening the water velocity was reduced, which may have decreased oxygenation of the basin water. Swanberg and Bjørklund (1987) also found the Finnabotn to be colder and less saline than the main fjord. The Finnabotn does have an average temperature and salinity that is comparatively lower than those of the other fjords in this thesis. This phenomenon along with the low sill depth of the Finnabotn suggests that it may be the recipient of winter inflows.

4.2 Long-term Variation in Hydrography of 7 Basins

The timelines produced for these fjords illustrate the following general trends: oxygen is decreasing over time in all fjords with data representative enough to allow conclusive conclusions to be drawn, there is a strong correlation between increasing temperatures and decreasing oxygen concentrations, and salinity is decreasing over time in most fjords (although there are some varied results regarding salinity). This analysis supports the theory that the basin water in the side fjords of the Sognefjorden are becoming more anoxic over time.

All parameters profiled in this study (oxygen concentration, temperature and salinity) are interconnected, and some degree of codependency is visible in the corresponding figures for each fjord. Due to this relationship, it can be assumed that when outside factors influence these parameters (i.e climate change increasing temperature or hydropower decreasing salinity), it will likely affect the other parameters in some way as well.

In terms of deducing long-term trends from the timelines, it must be noted that only the Outer Barsnesfjorden, Sogndalsfjorden and Inner Nærøyfjorden contain sufficient data for this.

4.2.1 Salinity trends in the 7 Basins

Salinity appears to be decreasing over time in most fjords, although there are some varied results. Salinity appeared to be decreasing on a long-term basis at all depths in the Nærøyfjorden. A decrease was seen in the limited data available for the Ikjefjorden and Fuglsetfjorden as well, although long-term salinity trends cannot be deduced in these fjords. A statistically significant difference in the Barsnesfjorden salinity data was only found at depths of 60 m and 75 m, however salinity was decreasing over time at both these depths. No trends were visible in the Østerbøvatn salinity data, and it was not found to be statistically significant (likely owing to the fact that the dataset only extended to 2005 and contained few observations). The only fjord that did not see a decrease in salinity over time was the Sogndalsfjorden, where salinity was steadily increasing over time at all depths.

Salinity was decreasing at the fastest rate in the Barsnesfjorden, which had a trendline slope of -0.0042 for the 60 m dataset and a trendline slope of -0.0046 for the 75 m dataset. Conversely, the slowest decrease over time could be seen in the Nærøyfjorden which had a maximum trendline slope of only 0.00003. The Sogndalsfjorden displayed the only increase over time with representative trendline slopes between 0.0020 and 0.0042.

When considering factors influencing salinity within the basins, one must consider the changes in sources feeding the basins. Salinity values mainly depend on salinities at threshold depth in the basin immediately outside the one being studied at the time of inflows, with coastal water ultimately feeding all the basins (Strøm, 1936; Johansen et al., 2018). The oceanic source water in the Nordic Seas has undergone a pronounced change in density over the past 40 years with the catalyst for this change being an initial drop in salinity in the 1980s (Aksnes et al., 2019). This phenomenon was labelled the “Great Salinity Anomaly”, and caused a decrease in density in the source water (Aksnes et al., 2019; Kaufmann, 2014). In 1990 the salinity average returned to previous levels and remained high, but density did not return to its previous level (Aksnes et al., 2019).

Leading up to the Great Salinity anomaly was an initial increase in salinity from 1940-1970 (Aksnes et al., 2019). Analogously, an increase in salinity can be seen from 1916-1965 in the Sogndalsfjorden data as well as from 1940-1956 in the Barsnesfjorden data (figure 23; figure 15). However, during the peak of the Great Salinity Anomaly during the 1970s there is a gap in both datasets so it is impossible to say for certain what effect this phenomenon had in the basins, if any. Effects of the Great Salinity Anomaly have been seen in other fjords in Western Norway. An example of this is the Masfjorden, which is 489 m deep with a 70 m sill (Aksnes et al., 2019). Aksnes et al. (2019) saw an increase in salinity in this basin from 1940-1970, a large drop in the 1980s and a slow increase from the 1990s on. It was noted in this study that similar effects could likely be seen in other Western Norwegian fjords. The Barsnesfjorden and Nærøyfjorden salinity levels dropped from the 1990s on while the Sogndalsfjorden salinity levels continued to increase.

Furthermore, it has been observed that a salinity decrease in surface water could be tied to increasing precipitation caused by climate change (Caroletti and Barstad, 2010) or positive North Atlantic Oscillation winter trends. The North Atlantic Oscillation has been deemed the leading cause of weather and climate variability over the Northern Hemisphere (Olsen et al., 2012; Visbeck et al., 2001; Hurrel and Deser, 2009). When it is in positive periods, warm and wet winters tend to occur along the coast of Norway (Kaufmann, 2014; Hurrel and Deser, 2009; Visbeck et al., 2001). Salinity has been known to be strongly influenced by this as the North Atlantic Oscillation governs precipitation and sea ice cover (Hurrel and Deser, 2009). There was a positive trend that occurred from 1900-1930 (Hurrell, 1995), another that occurred from 1965-2009 (Kaufmann, 2014), and one seen again from 2011-2012. Visbeck et al. (2001) has suggested that climate change could be associated with an increased frequency in positive North Atlantic Oscillation periods, which could be expected to influence the salinity of oceanic waters feeding the basins. However, due to anthropogenic influence, a negative North Atlantic Oscillation event does not necessarily result in decreased salinity everywhere. During these periods, Norway is cold and dry. Citizens consume more electricity than normal, causing hydropower plants to release more freshwater than usual in order to meet the increased demand (Cherry et al., 2005).

Hydropower production is an important constituent influencing salinity in Norwegian fjords. The first hydropower station in Europe was constructed in Norway in 1882 (Øystein et al.,

2010) and a steep rise in hydropower production in Norway has occurred from the 1970s on (Manzetti and Stenersen, 2010). It is estimated that 248% more freshwater is entering the Sognefjorden in the winter than would occur if the fjord was not regulated (Berg et al., 2017). However, the effects of this are varied and inconsistent in side fjords as hydropower activities are known to decrease surface salinity in some areas that are receiving more freshwater and increase surface salinity in other areas that experienced a removal of freshwater supply from their watershed. A study conducted by Berg et al. (2017) found the largest freshwater increase in the Sognefjorden to be 1833% in February in Fortunvassdraget, which is located in the inner part. Hydropower plants in Norway have been known to release more freshwater in winter to meet higher demands for electricity, which leads to elevated surface salinity at this time. Side fjords with shallow sills tend to receive inflows in the winter months (Gade and Edwards, 1980), so fjords with shallow sills have experienced the greatest reduction in salinity. This is why the shallow-silled Barsnesfjorden has seen a reduction in salinity over time while the deep-silled Sogndalsfjorden (which receives its inflows in the summer) has seen an increase in salinity over time.

4.2.2 Temperature trends in the 7 Basins

Temperature was found to be increasing over time in all fjords included in this thesis that had sufficiently representative data. In the Barsnesfjorden, Sogndalsfjorden and Nærøyfjorden the temperature was steadily increasing over time at all depths. The Østerbøvatn temperature data appeared to be somewhat sporadic, but was deemed to not be statistically significant. Although not indicative of long-term trends, an increase can be seen at basin depths in the Ikjefjorden and at surface depths in the Fuglsetfjorden. Not only was a temperature increase seen in the basins in this thesis, but similar trends have been observed in basins across Western Norway (Aksnes et al., 2019; Johansen et al., 2018).

The slowest increase over time was seen in the Nærøyfjorden which was associated with trendline slopes ranging from 0.00007 to 0.00009. The Sogndalsfjorden saw the greatest increases over time with trendline slopes ranging from 0.0266 to 0.0315. The Barsnesfjorden did have a similar increase over time as the Sogndalsfjorden, with trendline slopes ranging from 0.0264 to 0.0271 when the 0 m dataset is omitted.

Analogously to the salinity changes, the key to the temperature changes lies in how the coastal water has changed over time. Recent climatic trends show there has been a warming trend in the world oceans since 1960, with this trend being particularly pronounced in the Nordic Seas (Husa et al., 2008). The Great Salinity anomaly is known to have played a role in this increase. Although the coastal salinity returned to a high level in 1990 after the anomaly, the density did not rebound along with it (Aksnes et al., 2019). This is because there was a rise in temperature at this time that prevented an increase in density along with the salinity increase. Aksnes et al. (2019) saw an overall 1ºC increase in temperature in the coastal water result in a temperature increase in the Masfjorden, and suggests that similar correlations can likely be found in basins across Western Norway. Since the Great Salinity Anomaly, water temperatures have only continued to rise. Husa et al. (2008) found that during 1997, 2002, and 2006 the average sea temperatures along the Western Coast of Norway in August were between 3ºC and 4ºC higher than normal. As climate change progresses, these occurrences can only be expected to happen with greater frequency.

The North Atlantic Oscillation is a constituent in these temperature increases, with positive trends resulting in a warmer and stronger flow of Atlantic Water northwards to the Barents Sea and Arctic Ocean (Dickson and Østerhus, 2007). Such occurrences have been observed since the 1960s.

Hydropower has also presumably had some impacts on temperatures seen in the fjord, although these mechanisms have not been studied in depth. One theory proposed by Torbjørn Dale (2021, *personal communication*) involves hydropower inducing changes in winter convection. Hydropower production has the major effect of adding freshwater to the surface layers in wintertime, thus resulting in a reduced density. This density reduction at the surface has presumably prevented winter convection currents from penetrating the water column as deep as they used to before the influx of hydropower in Norway. This means that less of the water column experiences a mixing resulting in a temperature reduction, so a larger volume of water is retaining heat than would previously occur due to shallower convection.

Additionally, the production of hydropower has been linked to lower water temperatures occurring in summer and higher water temperatures occurring in winter (Jensen, 1987). The implication of this is that shallow-silled fjords which receive winter inflows (such as the

Barsnesfjorden) may experience a reduced frequency in dense inflows that possess the ability to penetrate all depths of the water column, thus contributing to prolonged anoxia at basin depths.

4.2.3 Oxygen Trends in the 7 Basins

As was hypothesized, oxygen is decreasing over time in all basins. It is highly likely that hydrogen sulfide is being produced in the depths of many of the basins, particularly in cases such as the Barsnesfjorden where anoxic events at 75 m have been occurring at increasingly frequent intervals. Strøm (1936) noted that sometimes quantities of ventilated waters carried in are too small to affect hydrogen sulfide content for any more than a short time. This could be playing a role in the consistently more frequent anoxic conditions seen in these basins.

The fastest decrease in oxygen concentration over time was seen in the Sogndalsfjorden, which was associated with trendline slopes ranging from -0.04 to -0.0499. The slowest decrease over time was seen in the Nærøyfjorden which displayed a range of -0.0001 to -0.0003 in its trendline slopes. The Nærøyfjorden also had the slowest increase over time for temperature and the slowest decrease over time for salinity, which may have played a role in the slow decrease over time seen in oxygen concentration as well. The Barsnesfjorden had the second fastest decrease in oxygen over time with trendline slopes ranging from -0.0236 to -0.0319.

The foraminifera data available for the Barsnesfjorden, Sogndalsfjorden, Nærøyfjorden, and Ikjefjorden are useful in corroborating the findings of the oxygen timelines. The Barsnesfjorden had foraminifera records available for both the inner and outer basin. The inner basin (figure 18) displayed a trend of the number of individuals increasing with depth of the core. This indicates that the basin has steadily become more anoxic over time, sustaining less individuals as time goes on. Conversely, there does not appear to be any distinctly evident trend in the Outer Barsnesfjorden foraminifera data (figure 19). The contrasting data in the different cores is illuminating in terms of oxygen conditions in the Barsnesfjorden. First, this shows that the inner basin is in a worse state than the outer basin. The outer core has a range of 22-350 individuals over its entire depth. The inner core does not exceed 31 individuals at any depth in the core. Second, the state of anoxia in the Inner Barsnesfjorden is becoming worse at a faster rate than the Outer Barsnesfjorden.

The Sogndalsfjorden foraminifera data (figure 26) does not appear to have very distinct trends regarding the number of individuals at varying depths in the sediment cores. This implies that although oxygen is declining over time, it has not yet declined to a concentration that is threatening foraminifera abundance. However, this situation could change if the decreasing trends seen in oxygen continue as they are.

Regarding the Nærøyfjorden foraminifera data, there does appear to be an increase in the number of individuals as depth increases (figure 33). The Nærøyfjorden core corroborates the findings of the oxygen timeline (figure 32), confirming that conditions in the fjord are deteriorating over time.

Seeing as the Ikjefjorden oxygen data only goes back to 2015, it was not possible to draw definitive conclusions regarding how oxygen concentrations in the Ikjefjorden have changed over time. The foraminifera data (figure 40) details what the oxygen timeline could not. The number of individuals in the sediment were found to be increasing with increasing depth in the core, implying that conditions in the Ikjefjorden are getting more anoxic over time.

Oxygen concentration is not only deteriorating over time in the basins detailed in this thesis, but also in basins across Western Norway. Although there is a lack of long-term studies analyzing water chemistry in fjord basins, some examples where decreasing oxygen was found included the Masfjorden (Aksnes et al., 2019), the Raunefjorden (Johansen et al., 2018), the Byfjorden (Johansen et al., 2018), the Sørfjorden (Johansen et al., 2018), the Lysefjorden (Aure et al., 2001) and the Ofotfjorden (Dommasnes et al., 1994). Norway also has its fair share of permanently anoxic fjords including the Framvaren (Yao and Millero, 1995), the Kyllaren (Golmen and Lundmark-Daae, 2011; Golmen and Staalstrøm, 2012) and the Sælenvatn (Johnsen et al., 2020), to name a few. Strøm (1939) remarked that most Norwegian fjords did originate as well-ventilated areas.

The most important driving factor in decreasing oxygen concentrations appears to be temperature. This is because increasing temperatures have a multitude of effects that all push fjords to more anoxic states. First, water with higher temperatures does not contain as much dissolved oxygen as cold water does (Johansen et al., 2018). Since there has been a pronounced warming of the coastal water supplying the basins (Aksnes et al., 2019; Husa et al., 2008) this means there is also an associated oxygen decrease in this coastal water. The implication of this is that the basins are not receiving water that is as ventilated as it was before warming trends in the source water, so even if basin oxygen consumption rates remain the same then oxygen will run out quicker than previously seen.

Second, warmer water is associated with a lower density, which influences stratification along the water column and has been proven to extend the residence time of bottom water, leading to longer stagnation periods (Pakhomova et al., 2014). Salinity decreases resulting in lower density also have this effect. Thus, production of lower density water through either increased temperature or decreased salinity results in reduced inflow frequencies. Such effects have been seen in the Barsnesfjorden. Kaufmann (2014) looked at inflow events in the Barsnesfjorden and found that in earlier years the inflow frequency was 1 inflow every year and a half. In recent years she found this to be 1 inflow every 3 years. Aksnes et al. (2019) also attributed the decreasing oxygen in the Masfjorden to a reduced density in the oceanic source water resulting in reduced ventilation.

Third, increased water temperatures are associated with increased oxygen consumption rates. This is especially concerning in fjords that also receive influxes of organic matter, as organic matter input can also increase oxygen consumption rates. Sill fjords are especially susceptible to organic matter inputs because the matter becomes trapped below the depth of the sill and is not readily flushed out (Meyer et al., 2020). Both temperature and salinity are decreasing very slowly in the Nærøyfjorden over time. However, a pronounced decrease in oxygen concentration is also seen. Vassenden et al. (2007) implies that the low oxygen levels seen in this basin could be connected to sewage release and rock-material input resulting in increased oxygen consumption. It is expected that other fjords in this thesis (and in Western Norway in general) could have elevated oxygen consumption rates associated with organic matter input as well.

4.3 Management Suggestions Regarding the 7 Basins

The table below (table 5) includes the EU Water Framework Directive classification for each of the 7 basins included in this study as well as the LENKA classification for each basin. The EU Water Framework classifications were obtained from www.vann-nett.no for all fjords except the Inner Fuglsetfjorden, which was not in this database. Rankings were assigned to the

Inner Fuglsetfjorden based on the results of this thesis. The LENKA classification for each fjord was determined based on published LENKA guidelines (Pedersen et al., 1988).

	Water Type	Ecological Classification	Chemical Classification	LENKA Classification
Barsnesfjorden	Oxygen Depleted	Moderate	Undefined	C
Sogndalsfjorden	Oxygen Depleted	Moderate	Undefined	B3
Inner Nærøyfjorden	Oxygen Depleted	Bad	Undefined	C
Ikjefjorden	Oxygen Depleted	Moderate	Bad	C
Østerbøvatn	Freshwater Influenced, Protected	Very good	Undefined	C
Inner Fuglsetfjorden	Oxygen Depleted	Moderate	Undefined	C
Finnabotn	Freshwater Influenced, Protected	Good	Undefined	C

Table 5: EU Water Framework Directive and LENKA Classifications for each of the 7 basins

The EU Water Framework Directive was put into effect on October 23rd, 2000. This directive aimed to protect water resources within the European Union and specified that water is not a commercial product, but “a heritage which must be protected, defended and treated as such” (EU Water Framework Directive, 2000). It also set out a timeline for shifting all waters within the EU into “good” condition. The directive specified guidelines for classifying various types of water bodies and determining their ecological conditions. Under the EU Water Framework Directive, most basins in this study would be considerate to be in “moderate” condition.

LENKA is a Norwegian fjord classification system that was started in 1987. This program aimed to classify coastal water bodies based on their capacity to handle organic matter from aquaculture activities (Pedersen et al., 1988). Although the main focus of LENKA is aquaculture, these classifications could also be useful for the regulation of sewage. The regulation of sewage in Norway is currently based on population size, not on the capacity of the outlet's ability to handle it (Torbjørn Dale, 2021, *personal communication)*. This system should be revised to consider hydrography of the fjord and the ongoing progression of climate change before the dumping of sewage is allowed.

The rankings included A1, A2, A3, B1, B2, B3 and C. A-ranked coastal zones were best able to handle organic loads and C-zones were deemed less capable. Higher numbers were better equipped than lower numbers. Thus, A1 was the best ranking and C was the worst. Through the specifications of this classification system, the Sogndalsfjorden is described as a B3 fjord. All other fjords would receive a "C" classification. The implication of this is that all fjords in this study are not well equipped to be the recipients of large amounts of organic matter.

Based on the results of this thesis, it is suggested that the EU Water Framework classifications for these fjords should be revisited. The Østerbøvatn and Finnabotn water type should be changed from "Freshwater Influenced, Protected" to "Oxygen Depleted Fjord". Additionally, the ecological classifications should be reconsidered for all fjords due to how the changing climate and anthropogenic impacts have affected fjord processes.

In terms of the LENKA classifications, it seems that there should be a reduction in the amount of sewage being introduced to the Sogndalsfjorden in light of the increasing temperatures and decreasing oxygen levels seen in this fjord. This data suggests that the fjord is not able to handle the amount being released currently and if this is extrapolated into the future then the Sogndalsfjorden may become an anoxic zone. The current LENKA classification does not take increasing temperatures resulting in increased oxygen consumption rates into account, which could produce some misleading classifications. Seeing as the Sogndalsfjorden is currently classified as a B3 fjord, it must be considered that other B3 fjords could be suffering and the government should consider all other B3 fjords being sensitive to temperature increases.

5.0 Conclusions

It can be concluded that the basin water of the Barsnesfjorden, Sogndalsfjorden, Nærøyfjorden and Ikjefjorden is getting more anoxic over time. The data available for the Østerbøvatn, Fuglsetfjorden and Finnabotn is not comprehensive enough to draw firm conclusions regarding trends over time, however the baseline conditions of these three basins can all be classified as "anoxic". These fjords should continue to be monitored.

Oxygen depletion in these fjords can be definitively tied to increasing temperatures, which has a multitude of impacts on oxygen concentration. These include warmer water containing less oxygen than cooler water, warmer temperatures decreasing water density which reduces inflow frequencies, and increased temperatures resulting in increased oxygen consumption rates.

Additionally, the influx of hydropower impacting surface salinities appeared to have a profound effect on shallow-silled fjords that tend to receive winter inflows. Reduced salinity tied to positive North Atlantic Oscillation periods also has an effect as the reduced density associated with lower salinity results in reduced inflow frequencies. Seeing as it has been suggested in the literature that positive North Atlantic Oscillation periods are occurring more frequently due to climate change, it is to be expected that salinity in coastal source water will continue to decrease.

It is suggested based on these results that the EU Water Framework Directive classifications for these fjords including their ecological classifications should be revisited due to how the changing climate and anthropogenic impacts have affected fjord processes. Additionally, there should be a reduction in the amount of sewage being introduced to the Sogndalsfjorden in light of these findings. To conclude, the effects seen in these fjords are likely analogous to those occurring in other Western Norwegian fjords. Future studies should be conducted to monitor changing oxygen levels across coastal waters and fjords in Western Norway. Additionally, classification systems for these fjords such as LENKA need to take climate change and anthropogenic impacts into account, and should be revised.

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Appendix A: Sampling Methods for Historical Datasets of each Basin

Date	Reference	Water Sampler	Oxygen	Salinity	Temperature
1916-1956	Geophysical Institute. University of Bergen. Unpublished	Nansen Bottle	Winkler	Mohr Titration	Reversing Thermometer
1978	Grønning, 1983	Nansen Bottle	Winkler	Mohr Titration or Induction Salinometer	Reversing Thermometer
1984-1985	Hovgaard, 1985	Nansen or Ruttner Bottle	Electrode, YSI mod 57	Electrode, Salinoterm MC 5	Electrode, Salinoterm MC 5
1991-1993	Dale and Hovgaard, 1993	Ruttner Bottle	Winkler	Densimeter	Low Quality Thermometer
1996	Mikalsen et al., 1999	CTD, SAIV 204	Electrode	Electrode	Electrode
1999	Myrseth et al., 2000	Niskin Bottle, CTD (ME-Meerestechnik Electronik)	Winkler	Electrode	Electrode
2001-2019	Dale, T. Unpublished	CTD, SAIV 204	Electrode	Electrode	Electrode

Table 6: Sampling Methods For the Barsnesfjorden

Date	Reference	Water Sampler	Oxygen	Salinity	Temperature
1916-1956	Geophysical Institute. University of Bergen. Unpublished	Nansen Bottle	Winkler	Mohr Titration	Reversing Thermometer
1978	Grønning, 1983	Nansen Bottle	Winkler	Mohr Titration or Induction Salinometer	Reversing Thermometer
1982	Swanberg and Bjørklund, 1987	Nansen Bottle	Winkler	Electrode, Induction Salinometer	Reversing Thermometer
1984-1985	Hovgaard, 1985	Nansen Bottler or Ruttner Bottle	Electrode, YSI mod 57	Electrode, Salinoterm MC 5	Electrode, Salinoterm MC 5
1991-1993	Dale and Hovgaard, 1993	Ruttner Bottle	Winkler and Electrode, YSI mod 57	Densimeter	Low Quality Thermometer
1996	Mikalsen et al., 1999	CTD (SD 204 or OTS-probe)	Electrode	Electrode	Electrode
1999	Myrseth et al., 2000	Niskin Bottle CTD (ME-Meerestechnik Electronik)	Winkler	Electrode	Electrode
2013	Brekke et al., 2014	CTD, SAIV 204	Electrode	Electrode	Electrode
2001-2019	Dale, T.	CTD, SAIV 204	Electrode	Electrode	Electrode

	Unpublished				

Table 7: Sampling Methods for the Sogndalsfjorden

Date	Reference	Water Sampler	Oxygen	Salinity	Temperature
1920	Helland-Hansen and Lie, 1944	Nansen Bottle		Mohr Titration	Reversing Thermometer
1987	Johannesen and Lønning, 1988	Nansen Bottle	Winkler	Electrode, Autolab MK III	Reversing Thermometer
1993	Tvedten et al., 1994	Nansen Bottle	Winkler	Electrode, Autolab MK III	Reversing Thermometer
1994	Dale et al., 1994	Rutner Sampler	Electrode, YSI mod 57	Densimeter	Low Quality Thermometer
March 1996	Dale, T. Unpublished	Rutner Sampler	Electrode, Oxy guard	Densimeter	Low Quality Thermometer
June 1996	Dale, T. Unpublished	Rutner Sampler	Electrode, Oxy guard	Densimeter	Low Quality Thermometer
2006	Vassenden et al., 2007	Nansen Bottle	Winkler	Electrode, Autolab MK III	Reversing Thermometer
2015	Dale, T. Unpublished	CTD, SAIV 204	Electrode	Electrode	Electrode
2019	Dale, T. Unpublished	CTD, SAIV 204	Electrode	Electrode	Electrode
2020	Dale, T. Unpublished	CTD, SAIV 204	Electrode	Electrode	Electrode

Table 8: Sampling Methods for the Nærøyfjorden

Date	Reference	Water Sampler	Oxygen	Salinity	Temperature
1982-1983	Swanberg and Bjørklund, 1987	Nansen Bottle	Winkler	Electrode (Induction Salinometer)	Reversing Thermometer
1996	Mikalsen et al., 1999	CTD, SAIV 204	Electrode	Electrode	Electrode
2015	Dale, T. Unpublished	CTD, SAIV 204	Electrode	Electrode	Electrode
2017	Dale, T. Unpublished	CTD, SAIV 204	Electrode	Electrode	Electrode
2019	Dale, T. Unpublished	CTD, SAIV 204	Electrode	Electrode	Electrode
2020	Dale, T. Unpublished	CTD, SAIV 204	Electrode	Electrode	Electrode

Table 9: Sampling Methods for the Ikjefjorden

Date	Reference	Water Sampler	Oxygen	Salinity	Temperature
1952	Aasen, 1953	Nansen Bottle			Reversing Thermometer
Nov 2005	Johnsen and Kålås, 2007	Self Logging YSI	Electrode	Electrode	Electrode
May 2006	Johnsen and Kålås, 2007	Self Logging YSI	Electrode	Electrode	Electrode
2013	Lode et al., 2013	CTD, SAIV 204	Electrode	Electrode	Electrode
2020	Dale, T. Unpublished	CTD, SAIV 204	Electrode	Electrode	Electrode

Table 10: Sampling Methods for the Østerbøvatn

Date	Reference	Water Sampler	Oxygen	Salinity	Temperature
2018	Dale, T. Unpublished	CTD, SAIV 204	Electrode	Electrode	Electrode
2019	Dale, T. Unpublished	CTD, SAIV 204	Electrode	Electrode	Electrode
2020	Dale, T. Unpublished	CTD, SAIV 204	Electrode	Electrode	Electrode

Table 11: Sampling Methods for the Fuglsetfjorden

Date	Reference	Water Sampler	Oxygen	Salinity	Temperature
1982-1983	Swanberg and Bjørklund, 1987	Nansen Bottle	Winkler	Electrode (Induction Salinometer)	Reversing Thermometer
2020	Dale, T. Unpublished	CTD, SAIV 204	Electrode	Electrode	Electrode

Table 12: Sampling Methods for the Finnabotn

Appendix B: One Way Analysis of Variance Results for each Basin

Parameter	*Source of Variation*	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Salinity	Between Groups	745.7159	53	14.07011	0.097885	1	1.372987
	Within Groups	56777.53	395	143.7406			
	Total	57523.24	448				
Temperature	Between Groups	1457.118	115	12.67059	1.747835	9.54E-06	1.247212
	Within Groups	5850.19	807	7.249307			
	Total	7307.308	922				
Oxygen	Between Groups	1645.679	119	13.82924	1.465156	0.002054	1.247379
	Within Groups	6399.469	678	9.438744			
	Total	8045.148	797				

Table 13: Barsnesfjorden ANOVA results for salinity, temperature and oxygen

Parameter	*Source of Variation*	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Salinity	Between Groups	44.82021	147	0.304899	4.445077	4.59E-31	1.247856
	Within Groups	25.0363	365	0.068593			
	Total	69.8565	512				
Temperature	Between Groups	502.7163	153	3.285727	38.38302	2.3E-183	1.237067
	Within Groups	36.98079	432	0.085604			
	Total	539.6971	585				
Oxygen	Between Groups	1339.546	127	10.54761	10.94861	6.58E-73	1.26087
	Within Groups	356.4483	370	0.963374			
	Total	1695.994	497				

Table 14: Sogndalsfjorden ANOVA results for salinity, temperature and oxygen

Parameter	*Source of Variation*	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Salinity	**Between Groups**	**886.4652**	**6**	**147.7442**	**6.888164**	**4.51E-07**	**2.114668**
	Within Groups	**12075.78**	**563**	**21.449**			
	Total	**12962.25**	**569**				
Temperature	**Between Groups**	**453.4127**	**9**	**50.37919**	**19.35704**	**1.86E-28**	**1.895983**
	Within Groups	**1512.127**	**581**	**2.602629**			
	Total	**1965.54**	**590**				
Oxygen	**Between Groups**	**527.1168**	**8**	**65.8896**	**6.265111**	**8.7E-08**	**1.954634**
	Within Groups	**5994.638**	**570**	**10.51691**			
	Total	**6521.754**	**578**				

Table 15: Nærøyfjorden ANOVA results for salinity, temperature and oxygen

Parameter	*Source of Variation*	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Salinity	**Between Groups**	**1228.498**	**5**	**245.6996**	**28.42235**	**2.34E-27**	**2.221276**
	Within Groups	**10779.81**	**1247**	**8.644592**			
	Total	**12008.3**	**1252**				
Temperature	**Between Groups**	**2130.783**	**5**	**426.1565**	**72.98309**	**3.99E-67**	**2.221276**
	Within Groups	**7281.374**	**1247**	**5.839113**			
	Total	**9412.156**	**1252**				
Oxygen	**Between Groups**	**745.7277**	**5**	**149.1455**	**13.30238**	**1.19E-12**	**2.221276**
	Within Groups	**13981.29**	**1247**	**11.21194**			
	Total	**14727.02**	**1252**				

Table 16: Ikjefjorden ANOVA results for salinity, temperature and oxygen

Parameter	*Source of*	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*

	Variation						
Salinity	**Between Groups**	**69.15584**	**3**	**23.05195**	**1.599029**	**0.190425**	**2.644194**
	Within Groups	**3286.897**	**228**	**14.41622**			
	Total	**3356.053**	**231**				
Temperature	**Between Groups**	**9.25688**	**3**	**3.085627**	**0.528299**	**0.663281**	**2.644194**
	Within Groups	**1331.676**	**228**	**5.840686**			
	Total	**1340.933**	**231**				
Oxygen	**Between Groups**	**344.3788**	**3**	**114.7929**	**8.2521**	**3.1E-05**	**2.644194**
	Within Groups	**3171.652**	**228**	**13.91075**			
	Total	**3516.031**	**231**				

Table 17: Østerbøvatn ANOVA results for salinity, temperature and oxygen

Parameter	Source of Variation	SS	df	MS	F	P-value	F crit
Salinity	**Between Groups**	**335.8751**	**4**	**83.968774**	**6.610334**	**3.35E-05**	**2.387993**
	Within Groups	**7049.9716**	**555**	**12.702651**			
	Total	**7385.8467**	**559**				
Temperature	**Between Groups**	**1519.5239**	**4**	**379.88098**	**55.56802**	**2.05E-39**	**2.387993**
	Within Groups	**3794.1596**	**555**	**6.8363236**			
	Total	**5313.6835**	**559**				
Oxygen	**Between Groups**	**733.7244**	**4**	**183.4311**	**12.98521**	**4.09E-10**	**2.387993**
	Within Groups	**7840.017**	**555**	**14.12616**			
	Total	**8573.742**	**559**				

Table 18: Fuglsetfjorden ANOVA results for salinity, temperature and oxygen

Appendix C: Independent Samples t-test Results for Relevant Basins

	0 m 1978-2019	0 m 1916-1956	20 m 1978-2019	20 m 1916-1956	40 m 1978-2019	40 m 1916-1956	60 m 1978-2019	60 m 1916-1956	75 m 1978-2019	75 m 1916-1956
Mean	4.97	6.33	32.93	33.0	33.17	33.33	33.28	33.44	33.05	33.48
Standard Deviation	7.48	9.40	0.70	0.39	0.66	0.34	0.63	0.21	0.57	0.21
Observations	40	80	37	81	36	82	36	79	15	81
df	118		116		116		113		94	
t Stat	-0.80		-0.72		-1.75		-2.01		-5.27	
P(T<=t) two-tail	0.43		0.47		0.084		0.047		8.64E-07	
t Critical two-tail	1.98		1.98		1.98		1.98		1.99	

Table 19: Barsnesfjorden salinity t-test results

	0 m 1978-2019	0 m 1916-1956	20 m 1978-2019	20 m 1916-1956	40 m 1978-2019	40 m 1916-1956	60 m 1978-2019	60 m 1916-1956	75 m 1978-2019	75 m 1916-1956
Mean	10.17	9.42	8.10	6.50	7.73	6.07	7.62	5.90	7.81	5.86
Standard Deviation	4.77	4.88	0.83	0.85	0.71	0.52	0.62	0.38	0.56	0.35
Observations	31	80	49	82	46	82	43	79	24	81
df	109		129		126		120		103	
t Stat	0.73		10.50		15.18		19.04		20.86	
P(T<=t) two-tail	0.47		5.18E-19		3.13E-30		4.59E-38		9.29E-39	
t Critical two-tail	1.98		1.98		1.98		1.98		1.98	

Table 20: Barsnesfjorden temperature t-test results

	0 m 1978-2019	0 m 1916-1956	20 m 1978-2019	20 m 1916-1956	40 m 1978-2019	40 m 1916-1956	60 m 1978-2019	60 m 1916-1956	75 m 1978-2019	75 m 1916-1956
Mean	11.06	12.00	6.42	7.83	4.35	6.01	3.58	4.65	1.34	3.22
Standard Deviation	1.81	1.43	1.26	1.13	1.99	1.56	2.39	2.05	1.71	2.15

Observations	36	4	46	67	45	67	42	66	22	67
df	38		111		110		106		87	
t Stat	-1.00		-6.23		-4.92		-2.50		-3.73	
P(T<=t) two-tail	0.32		8.66E-09		3.11E-06		0.014		0.00034	
t Critical two-tail	2.02		1.98		1.98		1.98		1.99	

Table 21: Barsnesfjorden oxygen t-test results

	50 m 1978-2019	50 m 1916-1965	100 m 1978- 2019	100 m 1916- 1965	150 m 1978- 2019	150 m 1916- 1965	200 m 1978- 2019	200 m 1916- 1965
Mean	33.86	33.61	34.03	33.92	34.15	33.98	34.17	34.02
Standard Deviation	0.43	0.26	0.60	0.19	0.66	0.18	0.64	0.21
Observations	34	99	29	100	27	99	26	99
df	131		127		124		123	
t Stat	4.06		1.51		2.27		2.03	
P(T<=t) two-tail	8.34E-05		0.13		0.025		0.045	
t Critical two-tail	1.98		1.98		1.98		1.98	

Table 22: Sogndalsfjorden salinity t-test results

	50 m 1978-2019	50 m 1916-1965	100 m 1978- 2019	100 m 1916- 1965	150 m 1978- 2019	150 m 1916- 1965	200 m 1978- 2019	200 m 1916- 1965
Mean	8.22	6.20	8.0	6.19	8.05	6.24	8.01	6.27
Standard Deviation	0.56	0.67	0.39	0.38	0.37	0.39	0.41	0.38
Observations	47	104	44	105	39	104	40	103
df	149		147		141		141	
t Stat	18.07		26.11		24.86		24.05	
P(T<=t) two-tail	2.18E-39		4.52E-57		2.20E-53		9.40E-52	
t Critical two-tail	1.98		1.98		1.98		1.98	

Table 23: Sogndalsfjorden temperature t-test results

	50 m 1978-2019	50 m 1916-1965	100 m 1978- 2019	100 m 1916- 1965	150 m 1978- 2019	150 m 1916- 1965	200 m 1978- 2019	200 m 1916- 1965
Mean	5.88	8.08	4.88	7.23	4.39	6.98	4.23	6.80
Standard Deviation	1.42	1.16	0.88	1.31	0.90	1.44	1.24	1.59
Observations	45	82	41	83	37	82	34	81
df	125		122		117		113	
t Stat	-9.48		-10.35		-10.07		-8.40	
P(T<=t) two-tail	2.18E-16		2.15E-18		1.50E-17		1.51E-13	
t Critical two-tail	1.98		1.98		1.98		1.98	

Table 24: Sogndalsfjorden oxygen t-test results