Report

The physical oceanographic conditions in a range of fjords and coastal areas in Denmark

Date:	20 December 2022
Author(s):	Morten Holtegaard Nielsen
Prepared for:	SEGES Innovation P/S
Client's rep.:	Flemming Gertz
Client's project no.:	8623
Client's project:	Vejen til god økologisk tilstand i kystvande
Version:	Final
Status:	Open

Marine Science & Consulting ApS
Peder Lykkes Vej 8, 4. th.
DK-2300 Copenhagen S
Denmark

P: +45 5369 0888
E: info@msandc.dk
W: http://www.msandc.dk
CVR/VAT no.: DK39987082

Abstract. The physical oceanographic conditions in an estuary play a decisive role when trying to understand how the estuary is impacted by environmental problems, but also how these problems are best alleviated. In this report the physical oceanographic conditions in a range of Danish estuaries are discussed, based entirely on observations, and the circulation within these estuaries are quantified by way of the exchange and the residence time. The estuaries, termed fjords and coastal areas for the sake of their place names, are generally characterized by a relatively large exchange with the adjacent sea and, consequently, a relatively short residence time, typically a few weeks or less. However, the fjords and coastal areas are also very different, caused by differences in the mixing within the areas, the geometry of the areas, the freshwater run-off from land, the connection with the adjacent sea and the conditions in the adjacent sea. The latter plays a particular role in the Danish waters, which are subject to highly dynamic oceanographic conditions and strongly stratified water masses. Also, the connection with the adjacent sea is very important. In a few fjords the connection is so deep and wide that the area in question should probably not be considered an entity of its own. The differences that characterize the fjords and coastal areas in question are discussed, aiming at providing not only a better understanding of the systems, but also a foundation on which to improve the environmental conditions in these fjords and coastal areas.

1. Introduction

In many parts of the world estuaries, i.e. topographically constrained areas that receive run-off of freshwater from land and which are connected with an adjacent sea with which exchange of water masses is taking place, are suffering from environmental problems, including eutrophication, oxygen depletion, low biodiversity, pollution and more. Denmark is no exception to this, being a densely populated country and extensively exploiting its farmland. Compared to its area, Denmark has an exceptionally long coastline, which hosts a large number of estuaries, all of which are suffering from environmental problems at varying degree.

In this document the Danish estuaries will be referred to as fjords and coastal areas. This is so since the term 'fjord' is very often a part of the place name of the area in question. Strictly speaking, however, many of these areas are probably not fjords from a geomorphological point of view.

The fjords and coastal areas of Denmark include a multitude of shapes, areas and volumes and are influenced very differently by both run-off from land, exchange with the open sea and mixing due to winds and/or tides. These things must be taken into consideration when trying to understand how a given system works and how improvements of the environmental conditions in the system may be achieved. Complicating the matter, the hydrographic conditions in a given fjord or coastal area may be subject to considerable temporal and spatial variations, induced by the variability of the external forcing.

In this report recent advances of the knowledge of the physical oceanographic conditions in a range of fjords and coastal areas in Denmark are discussed. This knowledge has been obtained through a number of studies that have looked at different fjords and coastal areas in turn and which have been based entirely on observations of salinity, temperature, run-off of freshwater and so on. Focus is on the physical conditions since these are a prerequisite for understanding all others aspects of a given system, including, e.g., the transport and the turnover of nutrients. It should be noted that a review of the existing literature is outside the scope of this report. However, reference to some existing scientific papers is made, through which essential literature may be identified.

In carrying out these studies it has been imperative to employ observations. An observational material may be large and confusing on the one hand and limited in time and space on the other hand, implying that the analysis of a given system can be both slow and difficult. Despite this, observations offer the indispensable advantage that they reflect the reality, measurement errors or inaccuracies aside. In comparison, the results of numerical models are highly dependent on the parameterization of processes such as friction and mixing, which play critical roles in the study of the circulation of a fjord or a coastal area. These processes, however, are just a few of the crucial aspects of a numerical model that are necessary to describe correctly. Due to the complexity and oftentimes the lack of transparency, it may be very difficult, if not impossible, to figure out if a given numerical model is reliable at all.

The fjords and coastal areas on which the present document is based are shown in Figure 1. English summaries of the studies of the fjords and coastal areas are provided as appendices and included in the present document, cf. the following list. These summaries refer to a number of reports, referenced within each summary.

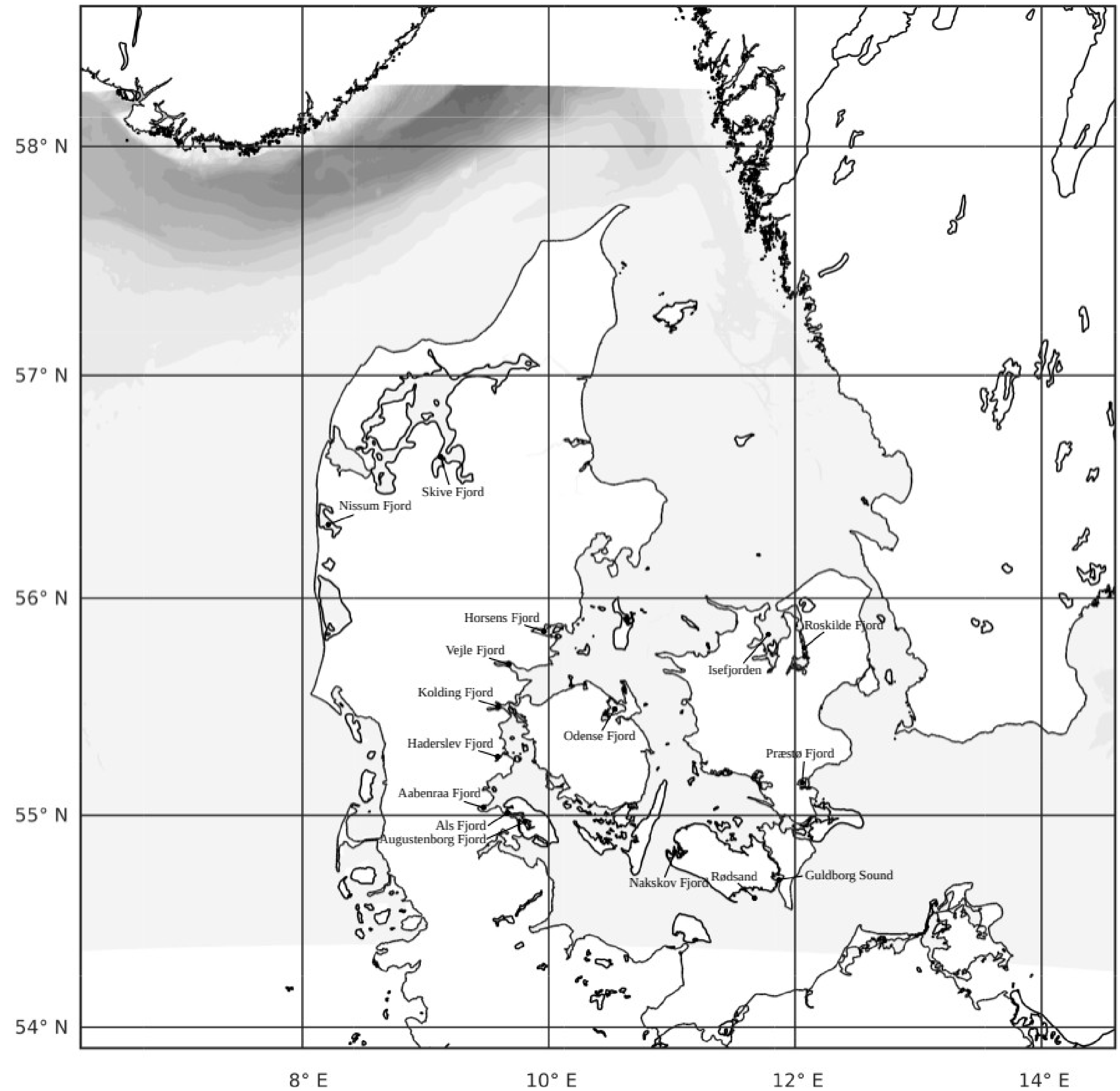

Figure 1: Map of the Danish waters and names and locations of the fjords and coastal areas that are discussed in the present document. The map also shows the bathymetric data that were used as part of the studies presented here.

Table 1: Appendix numbers and place names of the fjords or coastal areas that have been studied. The appendices are included in the present document.

No.	Fjord or coastal area	No.	Fjord or coastal area
1	Odense Fjord	8	Nissum Fjord
2	Vejle Fjord	9	Skive Fjord
3	Horsens Fjord	10	Isefjorden and Roskilde Fjord
4	Kolding Fjord	11	Præstø Fjord
5	Haderslev Fjord	12	Rødsand and southern Guldborg Sound
6	Aabenraa Fjord	13	Nakskov Fjord
7	Als Fjord and Augustenborg Fjord		

2. General aspects of the physical oceanography of the Danish waters

Forming the transition between the brackish Baltic Sea and the saline North Sea, large parts of the Danish waters are subject to stratification and highly dynamic oceanographic conditions. These dynamic conditions are caused by both barotropic and baroclinic forcings occurring on a number of timescales. The most narrow parts of the Danish waters, consisting of the three straits the Great Belt, the Little Belt and Øresund, are where the gradients in terms of water level and/or salinity are often at their maxima, giving rise to strong currents and prominent phenomena related to stratification of the water masses (e.g, Nielsen et al., 2017). Away from the most narrow parts, strong stratification is almost permanently present, e.g. in the Kattegat (Nielsen, 2005).

The atmospheric conditions over Scandinavia drive regional-scale wind fields, which again drive water level variations in the North Sea, the Skagerrak and the Kattegat on the one hand and the Baltic Sea on the other hand. Usually the wind conditions are so that a setup in the North Sea, the Skagerrak and the Kattegat are associated with a setdown in the western part of the Baltic Sea, and vice versa. Thus, the wind conditions are often quickly leading to strong barotropic currents going either into or out of the Baltic Sea. In addition, in almost all fjords and coastal areas in the Danish waters a large variability of the water level lead to quick exchange of considerable volumes of water. In fjords and coastal areas that are shallow this implies that a relative large fraction of the total volume may be exchanged. Tidal waves, which act similarly, play a role primarily in the North Sea, the Skagerrak and the Kattegat.

If the wind conditions are leading to inflow to the Baltic Sea and are lasting for more than a few days, relatively high-saline water masses of the Kattegat will be advected through the three straits. Such incidents are knowns as Major Baltic Inflows (Mohrholz, 2018). Conversely, outflow from the Baltic Sea lasting for more than a few days will lead to the advection of relatively low-saline water masses through the three straits. When considering fjords and coastal areas bordering any of the three straits it is clear that these interchanging flows will lead to substantial changes in the conditions in the adjacent sea. Dependent on the connection with the adjacent sea, such changes of salinity and thus density could drive an exchange of the fjord or the coastal area in question.

In connection with the studies of Aabenraa Fjord, Als Fjord and Augustenborg Fjord, an effort was made to elucidate the exchange of the water masses in the open part of the southern Little Belt. This effort showed how prolonged flows either into or out the Baltic Sea account for the most of the dynamics in this area. During prolonged inflows to the Baltic the observations have shown how relative high-saline water masses from the Kattegat are entering the deep basins and are replacing the existing deep water masses. During prolonged outflows the observations have shown how relative low-saline water masses from the Baltic Sea are entering and replacing the existing water masses in the upper part of the water column. In periods during which no significant flow is taking place through the Danish straits, the observations have shown these two things: the water masses in the upper part of the water column are subject to a slow increase in the salinity, due to wind-driven entrainment from the deep part of the water column. This is not surprising. The water masses in the deep basins, on the other hand, are subject to very little change in terms of both salinity and temperature, i.e. these water masses retain their identity for long periods of time. In fact, the observations have shown examples of residence times of the deep water masses of as long as four months. During such long periods other observations, which are not included in this study, have shown how oxygen depletion may develop in the deep water masses. The dynamics of the open parts of the Danish waters, such as the southern Little Belt, may play an important role for the exchange of the fjords and the coastal areas bordering these open parts.

In many studies related to the conditions and the water masses in the Danish waters, reference is often made to some average situation, i.e. low-saline water masses flowing out of the Baltic, high-saline water masses entering from the North Sea, and mixing taking place between them. However, in the view of the highly dynamic oceanographic conditions discussed above, the conditions at any given point in time or place may be much different from the average situation. This is important to realize since the circulation in many of the fjords and the coastal areas in question is highly influenced by the adjacent sea, including the highly dynamic oceanographic conditions. This is discussed in detail below and in the appendices, treating the fjords and the coastal areas in turn.

3. Data

The studies of the fjords and the coastal areas presented in the appendices, cf. the table above, and discussed below are based entirely on observations. Above all, CTD profiles of salinity and temperature made more or less regularly on a very large number of stations have been used. These observations have been retrieved from 'Overfladevandsdatabasen', a common database of the Danish Ministry of Environment and the Danish Centre for Environment and Energy (DCE) at Aarhus University. The observations that have been retrieved were made in the period between 1990 and roughly 2018. Especially the period between about 1995 and 2007 was characterized by a good coverage both temporally and spatially. Practical Salinity Units are assumed throughout. The CTD profiles contained in the database include the density of seawater, which in places are seemingly inaccurate or even incorrect. These data were certainly calculated somehow, but it is not known how. Instead, the density was calculated from the direct observations of salinity and temperature based on UNESCO (1981).

Data for the run-off of freshwater from land, specific to each fjord or coastal area in question, were provided as monthly averages for the period between 1990 and roughly 2020. These data were provided by DCE. The data consist of both observed and modelled data. Bathymetric data, at a horizontal resolution of roughly 50 by 50 m, were also provided by DCE.

4. Methods

When the origin, the transport and the mixing of water masses are investigated, much can be learned by carefully considering the salinity and the temperature of the water masses. Salt is a conservative matter and is not going to appear or disappear under normal conditions in nature. The temperature of a given body of water, on the other hand, may change because of exchange of heat with the atmosphere or a neighboring body of water. However, over a relatively short period of time, dependent on the volume of the body of water and the depth of the area in question, one may often assume that the temperature is roughly constant.

Thus, the studies presented here have been based on analyses of a very large number of CTD profiles. These CTD profiles have been selected from the database focusing on each of the fjords and coastal areas in question. The selection of the CTD profiles was done in order to obtain the best possible coverage with respect to both time, i.e. observations being repeated often for a long period of time, and space, i.e. observations being made on several stations both within the area in question and in the adjacent sea. Dependent on the observational programmes in the Danish waters, which have been carried out by the environmental authorities for more than three decades, the coverage has been somewhat variable, i.e. very good in some places during some periods or less good in other places during other periods.

In order to retain as much information as possible, each of the observed CTD profiles that have been used have been plotted separately. These plots consist of a vertical profile of the density as well as a plot showing concurrent observations of salinity and temperature. The latter makes it relatively easy to identify distinct water masses and the mixing between them, distributed over time and space in the fjord or the coastal area in question as well as in the adjacent sea.

In some cases the fjord or the coastal area in question fulfill a number of conditions that allow for a simple estimation of the exchange and the residence time of the area. This method is known as Knudsen's Theorem, named after the Danish oceanographer Martin Knudsen (1899), and is based on the conservation of volume and salt in the area in question. Knudsen's Theorem requires that the run-off of freshwater is well-known and that the salinities of both the water masses leaving the area and the water masses entering the area are also well-known. The latter usually implies that the connection between the area in question and the adjacent sea is well-defined and is clearly limiting the exchange. If the system in question can be considered steady or quasi-steady, the equations of conservation of volume and salt can easily be solved with respect to the rates of exchange at the connection to the adjacent sea and the residence time, a suitable defintion of which is the total volume divided by the total inflow of water masses.

Knudsen's Theorem provides a rough, but reliable estimate of the properties of the system in question. However, Knudsen's Theorem is not able to account for local variations, temporal or spatial, such as locally near a source of run-off of freshwater.

Since Knudsen's Theorem is based entirely on the conservation of volume and salt, it does not require any information about the physical processes determining the exchange or the residence time of the area in question. However, as long as the assumptions are fulfilled and the system is considered on a suitable time scale, Knudsen's Theorem does reflect how the system responds to changes in the driving forces, including the freshwater run-off, the mixing within the area and the conditions in the adjacent sea. This is in contrast to estimates based on a numerical model, which needs correct descriptions and paramterizations of the governing processes in order to deliver a reliable estimate.

If the system cannot be considered steady or quasi-steady, Knudsen's principles may still be used. This may happen if the conditions in the adjacent sea vary a lot, which may be the case for many fjords and coastal areas in the Danish waters. In these cases it is necessary to take into account the time-derivative of the total amount of salt in the area.

Using Knudsen's Theorem to estimate the exchange and the residence time of a fjord or a coastal area is associated with some uncertainty. This uncertainty is estimated using the method described by Muste et al. (2012), employing uncertainties associated with the salinities, the run-off of freshwater, the volume of the area in question and so on.

5. Results and discussion

The studies have shown that in many of the Danish fjords and coastal areas there is a large exchange with the adjacent sea. Also, the studies have shown that the run-off of freshwater from the catchment area often plays a small role for the circulation. This implies that the salinity found in the fjord or the coastal area is often close to that found in the adjacent sea. Another implication of this is that the residence time is often relatively short, typically a few weeks or shorter for most of the fjords and coastal areas in question. However, it must be noted that the mixing, primarily due to the wind, may be strongly variable, implying that also the residence time may be variable.

Despite these general remarks, it must be stressed that the physical conditions in the fjords and the coastal areas in question are very different in so many respects that trying to provide a unifying description may be misleading and oftentimes even impossible. In the following, different aspects of relevance to the circulation of a coastal area are discussed with reference to the fjords and the coastal areas in question. Although these aspects are discussed separately, it is important to understand that in all fjords and coastal areas these aspects all play roles at any given time, albeit at varying degree. It is hoped that this discussion will clearly show the diversity and the complexity of the fjords and the coastal areas in questions, but also lay the foundation for a better understanding and for ways to improve the environmental conditions in these fjords and coastal areas.

Mixing

Due to shallowness of many of the Danish fjords and coastal areas, the wind usually plays a very important role in terms of both mixing the water masses vertically and transporting the water masses horizontally. This means that very often there is a large degree of homogeneity in the fjords and coastal areas. In some cases, i.e. Odense Fjord, Nissum Fjord, Horsens Fjord, and, to some extent, Isefjorden, this allows for a simplified description and a quantification of the exchange and the residence time based on Knudsen's Theorem. A few exceptions, which are deep and do not follow these rules, are Vejle Fjord, Aabenraa Fjord, Als Fjord and Augustenborg Fjord. Although the latter is relatively shallow and is clearly influenced by wind mixing, these four fjords stand out for a much different reason, namely the connection with the adjacent sea, discussed below.

Another outstanding area with respect to mixing is Roskilde Fjord. Much of Roskilde Fjord is indeed shallow and subject to intense mixing due to the wind, particularly the inner part, which exhibits properties equal to the main basins of some other fjords and coastal areas. However, the outer part of Roskilde Fjord, which is both long and narrow, is subject to considerable mixing driven by tidal waves, which enter from the adjacent sea and propagate all the way along the fjord. This mixing strongly increases the circulation and drives a dispersive transport of water masses, characteristic of a well-mixed estuary (Fischer et al., 1979). Due to the complexity of the physical processes governing this circulation, it is hard to estimate the residence time in such a system. However, making assumptions about the water masses going into or out of the fjord the residence times were estimated at about three weeks for the inner part of Roskilde Fjord and about four weeks for Roskilde Fjord as a whole. Although not accurate, these estimates are reliable and correct to an order of magnitude.

Freshwater

In many fjords and coastal areas the run-off of freshwater is limited and does not contribute significantly to the circulation. However, in a few places the run-off is of a considerable magnitude and is strongly influencing the circulation. These places include Nissum Fjord, Odense Fjord and Roskilde Fjord. At certain times and in certain parts of these fjords, the contribution of the run-off is so big that the water masses in the adjacent sea play a small role. Moreover, in all three fjords the geometry of the system is important, allowing for an increased influence of the freshwater run-off. This is discussed in the following.

Geometry
The fjords and coastal areas in question vary strongly in terms of their geometry. As mentioned above, the depth plays a role for the wind and its ability to mix and transport the water masses. However, the shape of the area in question, including the length, the width, the location of the freshwater input and the location of the connection with the adjacent sea, also plays an important part. In addition, a fjord or a coastal area may even be shaped in a way that a description involving more parts or basins is appropriate. In this respect, Odense Fjord and Nissum Fjord are both remarkable, consisting of two and three separate basins, respectively.

Skive Fjord and its neighboring areas would seem to consist of two or three basins of their own, forming a substantial part of Limfjorden. However, since the wind is very often playing a dominant role and is breaking down the horizontal gradients in much of Limfjorden, which is mostly shallow, it does not make much sense to assume any geometric constraints here. This implies that the circulation is so strong that it is difficult to talk about any residence time at all. On the other hand, in the northern part of Skive Fjord and in the southern part of Risgaarde Broad, the neighboring area to the north, a deep basin is found. As it turns out, during periods of weak winds, the water masses of Limfjorden are subject to restratification, causing the deep basin to fill up with relatively dense water masses. Observations have shown that the residence time of the deep layer is typically a few weeks, which may lead to oxygen depletion and the release of considerable amounts of inorganic nutrients from the sediment.

From a geometric point of view, Roskilde Fjord must also be mentioned here, having a long and narrrow outer part through which tidal waves are propagating and are driving a strong mixing and dispersion, discussed above. Another long fjord is Haderslev Fjord, subject to a deep and narrow channel in the middle and wide and shallow areas on either side. However, due the absence of tidal mixing, Haderslev Fjord is dynamically much different, having the characteristics of a saltwater wedge. Als Fjord and Augustenborg Fjord together also constitute a long and relatively narrow system. However, the conditions in these two fjords are much influenced by their wide opening to the adjacent sea, discussed below.

Finally, Rødsand and the southern part of Guldborg Sound deserve attention. Located partly between two islands, this area may be subject to exchange of the water masses from two sides, although the proximity of and the wide opening toward the Fehmarn Belt, discussed further below, is the more important here.

Connection with the adjacent sea
Some of the fjords in question are characterized by a relatively narrow connection with the adjacent sea, limiting the exchange of the water masses. These fjords are Odense Fjord, Horsens Fjord, Isefjorden and Præstø Fjord. Due in part to the narrow connection with the adjacent sea the conditions in these fjords are all subject to relatively slow variations, making it possible to describe them by way of Knudsen's Theorem. Thus, for Horsens Fjord a residence time between about 5 and 18 days was estimated, reflecting the variability in the run-off of freshwater. However, at times Horsens Fjord may also be subject to a quick exchange driven by the changes in the conditions in the adjacent sea, discussed below.

Odense Fjord may be described as consisting of two separate basins, for both of which Knudsen's Theorem may applied. Thus, a residence time between a few days and about one week was estimated for the inner, smaller part of Odense Fjord. For the outer, bigger part of Odense Fjord a residence time between 1 – 2 weeks and 6 – 8 weeks was estimated. These ranges reflect, primarily, the variation of the freshwater run-off, which is strongly seasonal. For both Isefjorden and Præstø Fjord, however, the conditions in the adjacent sea are such that Knudsen's Theorem requires some modification. This is discussed below.

In other cases, i.e. Vejle Fjord, Kolding Fjord, Aabenraa Fjord, and partly Als Fjord and Augustenborg Fjord, the connection with the adjacent sea is so wide and deep that it is not meaningful to consider these systems as having properties and a circulation of their own. Instead, these areas are so openly connected with their adjacent seas that they are merely parts of the adjacent seas. A good example is Vejle Fjord in which observations have shown that the water masses in the fjord are almost identical to the water masses found in the northern part of the Little Belt, the adjacent sea, and that there is very little evidence of the local run-off of freshwater. Moreover, the observations have shown how the water masses in Vejle Fjord are quickly replaced when the water masses in the northern Little Belt are subject to changes, due to the general flows in the Danish waters going either into or out of the Baltic Sea. Accordingly, trying to estimate a residence time is not meaningful either.

An exception from this is Als Fjord and Augustenborg Fjord. Together they form a long and narrow system, in which it takes some time, estimated at less than one week, to replace the water masses. In addition, due to the shallow depths in much of Augustenborg Fjord mixing and transport due to the wind contributes considerably to the exchange of the water masses. This is discussed above.

Nakskov Fjord and Rødsand and the southern Guldborg Sound are also characterized by wide connections with the adjacent seas, although in both cases the depths are also rather shallow. This implies that the wind is the primary driver of the exchange, leading to short residence times of a few days in both bases due also to the small volumes. During periods of weak winds slightly longer residence times are expected.

Finally, Nissum Fjord is in a class of its own, the connection with the adjacent sea being controlled by a sluice. Thus, the conditions in the fjord are to a large extent influenced by the operation of this sluice. However, Nissum Fjord also stands out because of the presence of a number of bassins separated by geometric features as well as a very large run-off of freshwater. Using Kundsen's Theorem the residence time of Nissum Fjord as a whole was estimated at 20 – 40 days in general. During periods of either a very large or a very small run-off of freshwater, one can expect a shorter or a longer residence time, respectively.

Conditions in the adjacent sea

The fjords and coastal areas located along or near the Great Belt, the Little Belt or Øresund are subject to highly dynamic conditions in their adjacent seas. These fjords and coastal areas include, primarily, Vejle Fjord, Kolding Fjord, Horsens Fjord and Haderslev Fjord, all in or near the narrow part of the Little Belt, Nakskov Fjord in the Langelands Belt, and Rødsand and Guldborg Sound in the Fehmarn Belt. Dependent on the connection with the adjacent sea as well the geometry, the dynamic conditions in the adjacent sea influence the fjord or the coastal area differently.

In both Vejle Fjord and Kolding Fjord, which have wide and deep connections the exchange is almost fully driven by the conditions in the adjacent sea, making it meaningless to consider these entities of their own. Horsens Fjord has a relatively narrow connection, and when changes in the adjacent sea occur, these changes result in the replacement of the water masses in the fjord in less than 1 – 2 weeks. In Haderslev Fjord, which is very long and narrow, the dynamics in the adjacent sea plays an insignificant role.

In Nakskov Fjord as well as Rødsand and Guldborg Sound the dynamic conditions in the adjacent sea play small roles compared with mixing and transport by the wind. However, in these places changes in the properties of the water masses in the adjacent may be used to observe the exchange and to estimate the residence time. Præstø Fjord can also be characterized in this way since the connection with the adjacent sea is narrow, but deep and much of the fjord is very shallow. In Præstø Fjord the dynamics in the adjacent sea is due to upwelling of the deep water masses in the Baltic Sea or inflow of saline water masses from the Kattegat through Øresund.

Aabenraa Fjord, Als Fjord and Augustenborg Fjord are subject to some dynamics in the adjacent sea, although on a different time scale due to replacement of the water masses in the southern Little Belt in connection with prolonged flows either into or out of the Baltic Sea. However, upwelling of the deep water masses due to wind forcing, which may occur on a relatively short timescale, may also drive some variability, which may propagate into Aabenraa Fjord, Als Fjord and Augustenborg Fjord. Fjords and coastal areas that are little influenced by the dynamics of the adjacent sea are Nissum Fjord, which are connected to the sea by way of a sluice, Skive Fjord and neighboring areas and, some times, Horsens Fjord.

Isefjorden is in a particular way influenced by the dynamics in the adjacent sea, i.e. the southern Kattegat, which is subject to both some variability due to the stratification in the Kattegat and intermittent, prolonged outflows from the Baltic, which may lead to rather low salinities. In addition, Isefjorden has a very large volume and a wide, but shallow connection with the adjacent sea, both of which are conducive to a slow exchange and a long residence time. In fact, for periods of time the salinity in the southern Kattegat may be so low that a reverse estuarine circulation is established, i.e. relatively low-saline water masses entering from the adjacent sea and relatively high-saline water masses leaving the fjord.

Since the conditions in Isefjorden are otherwise suitable for the use of Knudsen's Theorem, the exchange may be estimated by taking into account the nonsteady conditions, i.e. by including the time-derivate of the total amount of salt in the fjord. The calculations resulted in typical residence times of less than two months during the wintertime and between two and four months during the summertime.

6. Conclusions

The studies reported here have shown that, in general, the exchange of the water masses in the Danish fjords and coastal areas in question are relatively large and that the corresponding residence times are relatively short, usually a few weeks or shorter. In some cases the residence time was calculated by way of Knudsen's Theorem. In other cases the residence time was observed directly as the water masses in the area were replaced. However, very large differences are found, the residence time in some places being a few days only and in other places some months. These differences are due to aspects of the mixing within the fjords and coastal areas in question, determined mostly by the wind and, in one case, by tidal waves, the geometry, the run-off of freshwater, the connection with the adjacent sea and the conditions in the adjacent sea. These aspects have been discussed in order to provide insight into the complicated dynamics that are very often found in estuaries.

When it comes to the Danish waters the dynamical conditions in the adjacent sea, including both barotropic and baroclinic forcing of a considerable magnitude, often have a strong influence on the exchange and the residence time of a fjord or a coastal area. Many areas are rather shallow, allowing the wind to mix and transport of the water masses. A third thing of particular interest is that some fjords and coastal areas have connections with the adjacent sea that are very wide and deep. This implies that the exchange is so large and quick that the areas in question should probably not be considered entities of their own.

A few cases stand out, one being Roskilde Fjord in which the exchange through the outer, long and narrow part is almost entirely dispersive, determined by the propagation of tidal waves. Another extraordinary case is Isefjorden, which is characterized by a large volume and highly dynamic conditions in the adjacent sea, implying that the fjord is sometimes subject to a reverse estuarine circulation. Finally, Nissum Fjord is connected with adjacent sea by way of a sluice and is strongly influenced by the operation of this sluice.

References

Fischer, H. B., E. J. List, R. C. Y. Koh, J. Imberger, N. H. Brooks (1979) Mixing in coastal and inland waters. Academic Press, London, 499 pp.

Knudsen, M. (1899) De hydrografiske forhold i de danske farvande inden for Skagen i 1894–1898. Komm. Vidensk. Unders. Dan. Farv. 2 (2), 19 – 79 (in Danish).

Mohrholz, V. (2018) Major Baltic Inflow Statistics – Revised. Front. Mar. Sci. 5:384. doi: 10.3389/fmars.2018.00384

Muste, M., L. Kyutae, J.-L. Bertrand-Krajewski (2012) Standardized uncertainty analysis for hydrometry: a review of relevant approaches and implementation examples. Hydrological Sciences Journal, vol. 57 (4), pp. 643-667.

Nielsen, M. H. (2005) The baroclinic surface currents in the Kattegat, J. Mar. Syst., 55, 97–121

Nielsen, M. H., Vang, T., and Lund-Hansen, L. C. (2017) Internal hydraulic control in the Little Belt, Denmark – observations of flow configurations and water mass formation. Ocean Science, 13, 1061–1075.

UNESCO (1981) International oceanographic tables, Vol. 3. UNESCO Technical Papers in Marine Science, 39. UNESCO, Paris.

Appendix 1. Odense Fjord

The summary provided here is based on the report “Exchange of water masses and residence times in Odense Fjord” (in Danish), 20 December 2020 (with a few corrections and an addition as of 16 November 2022).

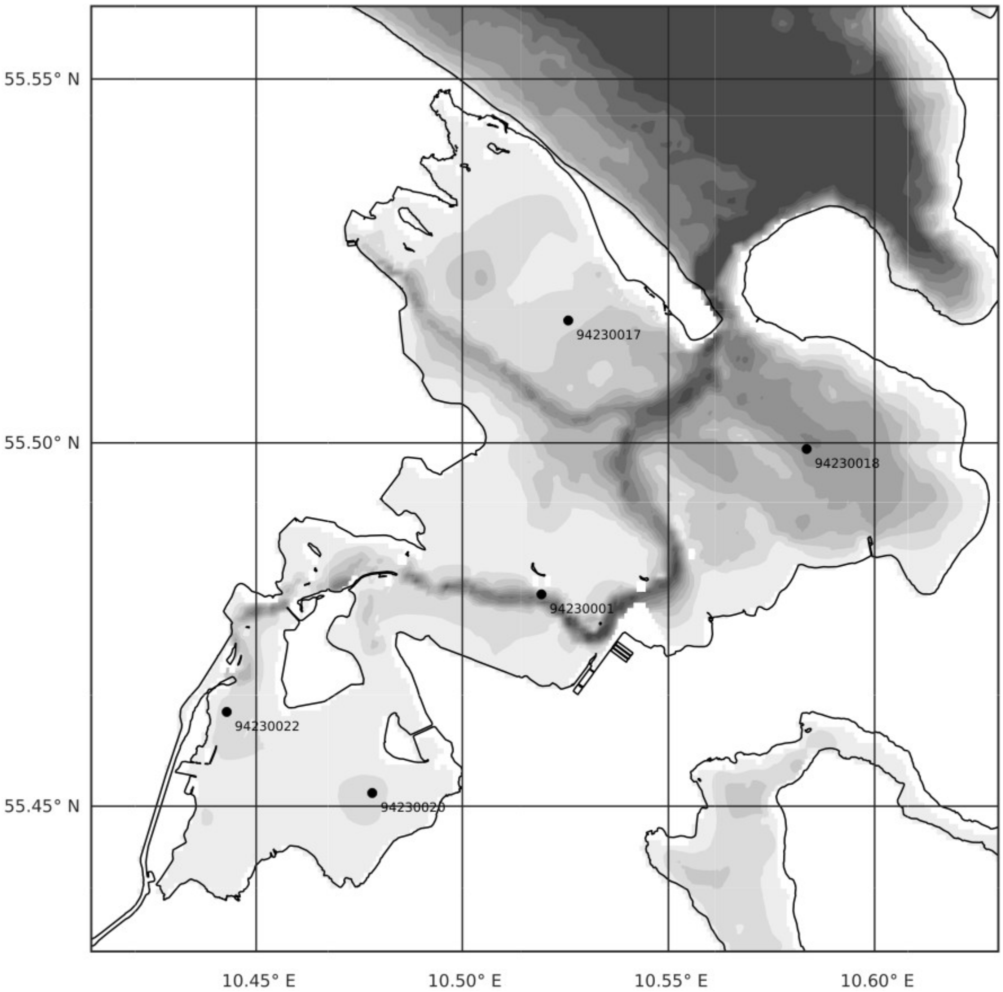

Figure 1: Map showing Odense Fjord, including the bathymetry (shaded areas) at a vertical resolution of 1 m. The locations of the CTD stations and their numbering are shown. To the north, outside the boundaries of the map the CTD station 94220007 is located.

Odense Fjord is located at roughly 55.5 °N, 10.5 °E, cf. Figure 1. Odense Fjord can be divided into two parts naturally, i.e. an inner part which is relatively small and very shallow (an average depth of ca. 0.7 m) and which receives almost all of the freshwater run-off from land, and an outer part which is somewhat bigger and deeper (an average depth of ca. 2.3 m) and which is connected to the adjacent sea. A relatively deep area is found in the outer part of the fjord, including a channel of depths of around 11 m, which is maintained for navigation purposes. The connection between the outer part of the fjord and the adjacent sea is equally deep and relatively narrow. A second, rather narrow navigation channel continues toward and through the inner part of the fjord. This channel, maintained at a depth of 7.5 m, is leading to the port of Odense. The connection between the two parts of Odense Fjord is thus partly relatively deep and narrow, partly wide and very shallow. In addition, the two parts of the fjord are separated by an island. The two parts are both characterized by width-to-length ratios of roughly one, suggesting that along-estuary density gradients in either of the two basins are relatively small. As large parts of the two basins are quite shallow, transport and mixing due to the wind can be expected to play a predominant role.

Odense Fjord is receiving freshwater run-off from a comparatively large catchment area. This run-off has a substantial seasonal variation, amounting to typically 20 – 30 m^3 s^{-1} during the winter half of the year and 5 – 10 m^3 s^{-1} during the summer half of the year, based on monthly estimates.

Located in the northern part of the island of Funen, Odense Fjord is connected to the northern Belt Sea, which is strongly influenced by the oceanographic conditions in the northern Great Belt and the southern part of the Kattegat. These include saline water masses and a strong stratification, generally found in the Kattegat, the salinities ranging from 20 – 25 in the upper part of water column to typically 30 or higher in the lower part of the water column. Occasionally, less saline water masses, of salinities down to 15 or less, may appear in connection with prolonged outflow from the Baltic.

The CTD profiles on which the present analysis was based include six stations, i.e. 94230020, 94230022, 94230001, 94230018, 94230017, and 94220007. The locations of five of these stations are shown in Figure 1. The analysis was based on observations collected in 1999, during which three of the stations were visited about once per week. During the second half of 1999 the other three stations were also visited about once per week. This is apparent from the attached plots of all the CTD profiles.

In general, Odense Fjord is characterised by a substantial, horizontal salinity gradient, moving from the innermost part of the fjord toward the opening to the adjacent sea. The seasonal pattern in the freshwater run-off and certainly also the mixing conditions (data not shown) is quite apparent, implying much larger salinity gradients during the wintertime than during the summertime. During the wintertime the salinity difference between the two parts of the fjord is relatively large and may exceed 10, whereas in the summertime the salinity difference is oftentimes less than 5. Throughout the year the salinity difference between the outer part of the fjord and the adjacent sea is less than 5, although with notable exceptions in connection with prolonged outflow from the Baltic Sea.

The water masses in much of either of the two parts of the fjord can often be characterized as roughly homogeneous. However, the observations show that deep, saline water masses in the adjacent sea may protrude into the deep channel and may be found at the deepest station in the inner part of the fjord. This may lead to both vertical and horizontal gradients in the water masses. These gradients may drive considerable density-driven currents and exchange of water masses within either of the two basins, which becomes apparent particularly during periods of weak wind mixing.

Insight into the circulation of Odense Fjord can be obtained by estimating the exchange and the residence times in the two parts of the fjord. This is done by way of Knudsen's Theorem, i.e. considering stationarity and conservation of volume and salt. This approach is based on the assumption that the water masses in either of the two parts of the fjord are roughly homogeneous and that their properties are varying slowly. Using the CTD profiles to determine the monthly salinities in both the two parts of the fjord as well as in the adjacent sea, the exchange and the residence times are calculated during the course of 1999, taking into account the temporal variation of the freshwater run-off.

These assumptions, however, are not always fulfilled. First, considering the system on a monthly basis does not allow one to capture all the details of the circulation. Second, within either of the two parts of the fjord there may be gradients in the water masses, which a bulk approach is unable to take into consideration. These deficiencies may be accounted for by also estimating the uncertainties associated with the exchange and the residence times.

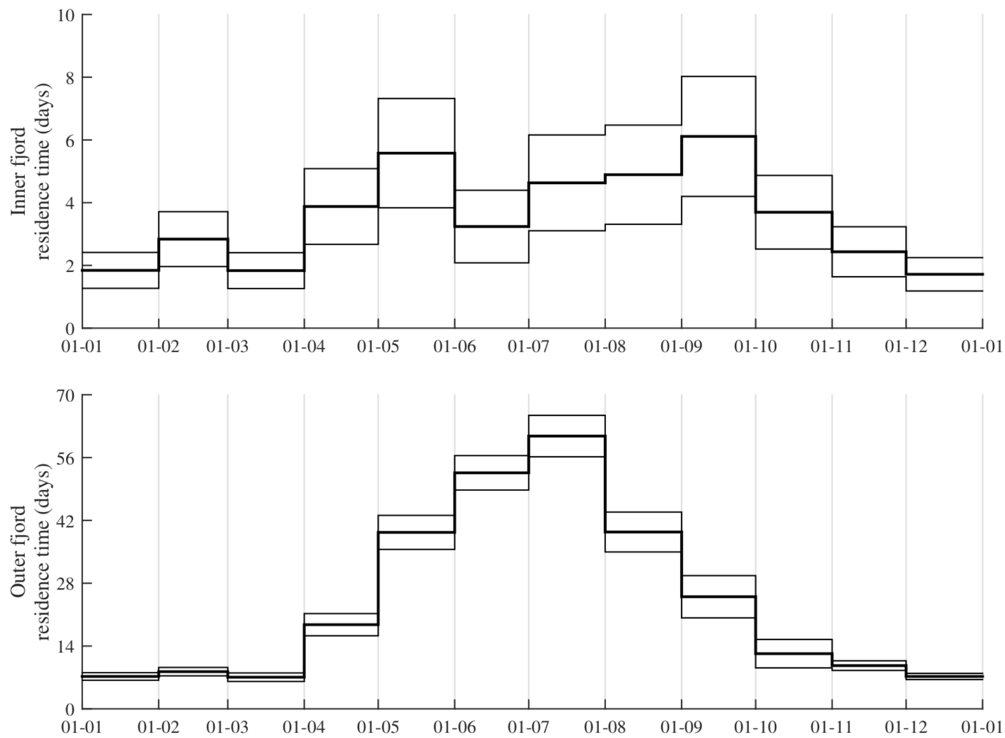

Figure 2: Calculated residence times (thick lines) and their uncertainties (thin lines), in terms of a 95% confidence interval, in the two parts of Odense Fjord for 1999.

In Figure 2 the estimated residence times of the two parts of Odense Fjord during the course of 1999 are shown. Also shown are the estimated uncertainties, in terms of a 95% confidence interval, of the residence times. During the wintertime as the freshwater run-off is large, the exchange in Odense Fjord is also large, resulting in residence times at 2 – 3 days and 1 – 2 weeks in the inner part and the outer part of the fjord respectively. During the summertime as the freshwater run-off is small, the exchange is also small, corresponding to residence times at about one week in the inner part and 6 – 8 weeks in the outer part. The uncertainties show that these estimates are fairly good, unless perhaps in the inner part of the fjord during the summertime. Here, however, the residence time is short regardless.

It is important to note that on short occasions less saline water masses may appear in the adjacent sea. This happens in connection with prolonged outflow from the Baltic. The CTD profiles show that the salinity in the adjacent sea on these occasions may even fall below the salinity found in the outer part of Odense Fjord. Under such conditions a reverse estuarine circulation will take place, i.e. the more saline water from the fjord flowing out and the less saline water from the sea flowing in. This short-term variability, which would reduce the residence times below the results shown in Figure 2, could be examined by considering the system on a shorter time scale than one month and by adapting Knudsen's Theorem to account for the derivative with time of the total amount of salt in the two parts of the fjord. Likewise, one could expect that short incidents of large freshwater run-off, which are not captured by the monthly run-off data, result in an increased exchange and an decreased residence time.

On the following pages all the CTD profiles used in the present analysis are plotted and presented. The CTD profiles are plotted separately and grouped in short periods of time as indicated by the red lines on the page preceeding the plots. This page shows the temporal coverage of all CTD stations in the area of interest contained in the database. In the plot of a given CTD profile the vertical distribution of the density is shown to the left. To the right the CTD profile is shown in a salinity-temperature diagram, with which different water masses in the system can be identified.

Appendix 2. Vejle Fjord

The summary provided here is based on the report “The oceanographic conditions in Vejle Fjord” (in Danish), 31 January 2021.

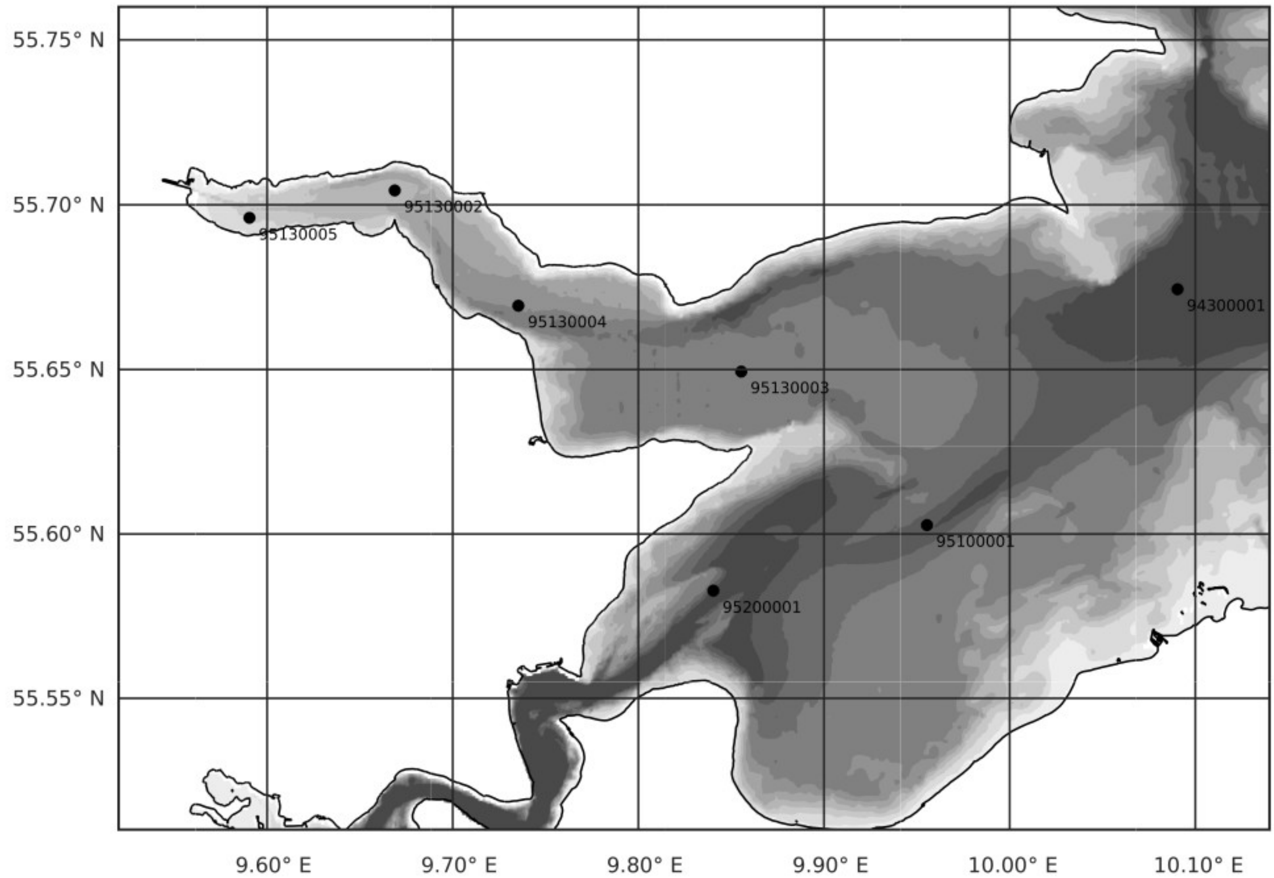

Figure 1: Map showing Vejle Fjord, including the bathymetry (shaded areas) at a vertical resolution of 2 m. The locations of the CTD stations and their numbering are shown.

Vejle Fjord is located at roughly 55.7 °N, 9.7 °E, cf. Figure 1. Vejle Fjord is relatively long compared to its width, but most importantly the estuary is characterized by a constantly increasing depth, ranging from a shallow, innermost part of a few metres or less to a deep, outer part of roughly 15 m. In addition, the outer part of Vejle Fjord is wide, so the exchange between the fjord and the adjacent sea is not really limited by the geometry.

Vejle Fjord is connected to the northern Belt Sea and is located only a short distance to the north of the narrowest part of the Little Belt. Thus, Vejle Fjord is influenced by both the conditions found in the Kattegat, i.e. saline water masses and a strong stratification, and the conditions found in the Little Belt, i.e. strong flows and quick advection of the water masses. During periods of north-going flows in the Little Belt, water masses of low salinity, down to 15 or less, usually appear after a couple days. On the average Vejle Fjord is receiving some 5 – 10 $m^3 s^{-1}$ of freshwater run-off from land, of which roughly 50% is entering the innermost part of the fjord.

The CTD profiles on which the present analysis was based include seven stations, i.e. 95130005, 95130002, 95130004, 95130003, located along the main axis of the fjord, and 94300001, 95200001, and 95100001, located in the Belt Sea and in the northern Little Belt, outside the opening of the fjord. The locations of these stations are shown in Figure 1. The analysis was based on observations collected in 1995, during which some of the stations were visited relatively often, about once per week or more often, and other stations were visited less frequently. This is apparent from the attached plots of all the CTD profiles.

Analyzing the CTD profiles, the freshwater run-off from land is sometimes visible at the innermost stations in Vejle Fjord. Apart from this, though, there is very little evidence of the presence of freshwater in the fjord running off locally. Accordingly, the fjord is not subject to an estuarine circulation as such. This is most certainly due to the wide and deep opening, which does not in any way reduce the exchange with the adjacent sea. Thus, the observations show that the water masses found in Vejle Fjord are almost always identical to the water masses found in the adjacent sea.

This implies that it is not meaningful to consider Vejle Fjord a semi-enclosed area with a circulation of its own. It is not meaningful either to talk about a residence time of the fjord. The close correspondence between the conditions inside and outside the fjord as shown by the observations, suggests that Vejle Fjord is directly connected to and is merely a part of adjacent sea. The physical oceanographic conditions in Vejle Fjord must be understood and analyzed in the light of this.

In connection with flows into or out of the Baltic of a duration of more than a couple of days, the water masses in the adjacent sea will be replaced relatively quickly by new water masses of either higher or lower salinity. This will imply a strong density gradient between Vejle Fjord and the adjacent sea, driving an exchange of the water masses in the fjord. The observations show clearly how the water masses in Vejle Fjord are replaced at the same time. In fact, the observations show that during 1995 the water masses in Vejle Fjord were replaced completely at least 18 times, which occured roughly evenly throughout all seasons. Since observing such events is dependent on the availability of CTD profiles, a complete replacement of the water masses in Vejle Fjord has certainly taken place more often.

On the following pages all the CTD profiles used in the present analysis are plotted and presented. The CTD profiles are plotted separately and grouped in short periods of time as indicated by the red lines on the page preceeding the plots, which shows the temporal coverage of the CTD profiles. In the plot of a given CTD profile the vertical distribution of the density is shown to the left. To the right the CTD profile is shown in a salinity-temperature diagram, with which different water masses in the system can be identified.

Appendix 3. Horsens Fjord

The summary provided here is based on the report "The oceanographic conditions in Horsens Fjord" (in Danish), 3 March 2021.

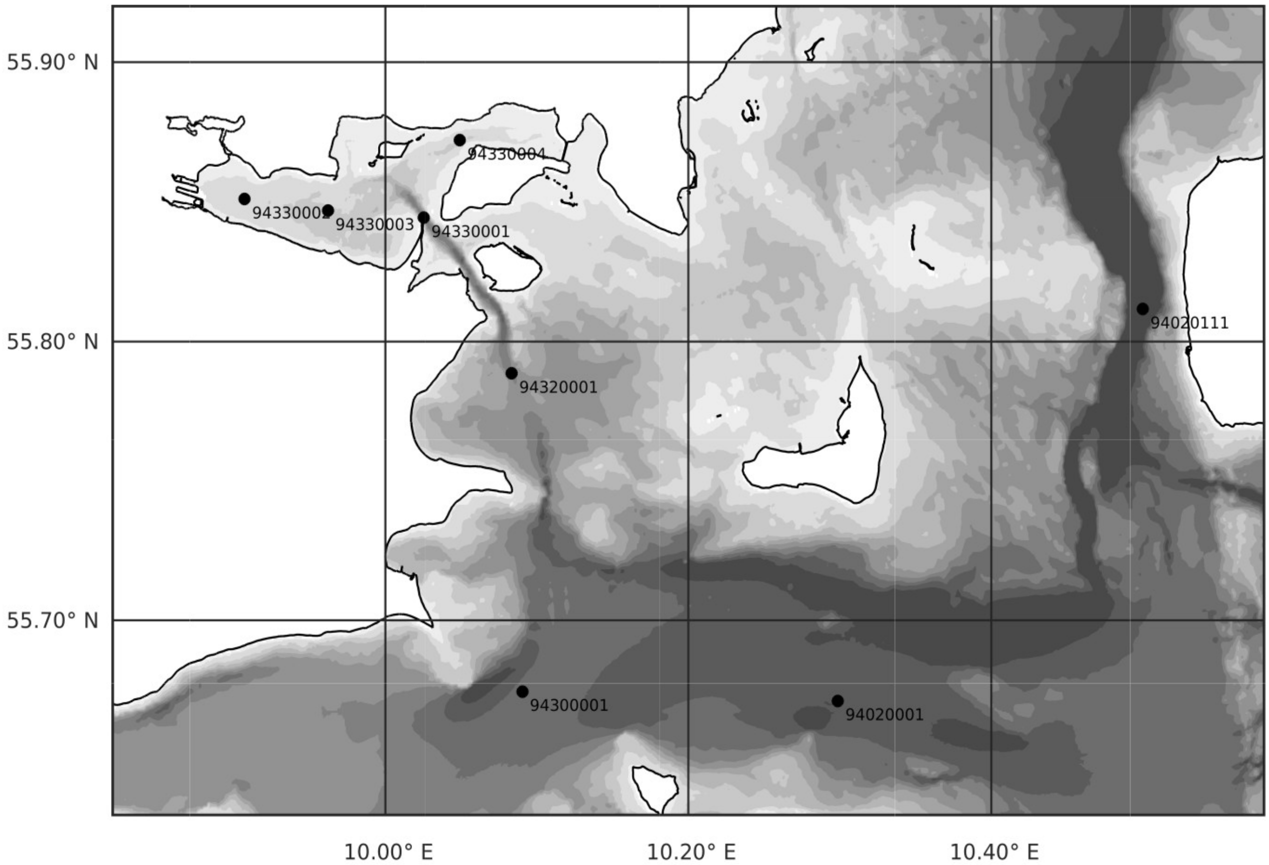

Figure 1: Map showing Horsens Fjord, the northern part of the Little Belt and a part of the northern Belt Sea, including the bathymetry (shaded areas) at a vertical resolution of 2 m. The locations of the CTD stations and their numbering are shown.

Horsens Fjord is located at roughly 55.85 °N, 10.0 °E, cf. Figure 1. Horsens Fjord is characterized by both relatively shallow depths in general, typically less than 5 m, and a relatively deep channel, of depths up to about 20 m, which connects the fjord with the adjacent sea, i.e. the northern Belt Sea. In the outer part of the fjord two islands and a headland are found, which limit the exchange between the fjord and the adjacent sea. The average depth in the fjord is 3.0 m.

Horsens Fjord is receiving freshwater run-off from a relatively small catchment area. In the wintertime the run-off is typically 7 – 13 m^3/s, whereas in the summertime the run-off decreases to typically 2 – 4 m^3/s.

The CTD profiles on which the present analysis was based include eight stations, i.e. 94330002, 94330003, 94330001, and 94330004, located in Horsens Fjord, 94300001, located in the northern Little Belt, and 94320001, 94020111, and 94020001, located in the northern Belt Sea. The locations of these stations are shown in Figure 1. The observations shown in the attached plots were collected in 2002 and 2006, during which four of the stations were visited about once per week, two of the stations were visited less frequently, and two stations were not visited at all.

The shallow depth in general implies that the wind plays an important role in mixing the water masses in the fjord. In addition, due to the deep, but narrow connection in the outer part of the fjord a considerable exchange may take place with the adjacent sea. Such an exchange, however, is much dependent on both the differences in the water masses between the fjord and the adjacent sea and the variations of the water level, due to tides or wind-generated surges, which may quickly drive large volumes of water in or out of the fjord.

The observations show that there is often a relatively high salinity in the fjord, showing that a substantial exchange with the adjacent sea takes place. This exchange is particularly prominent at times when the water masses in the northern Belt Sea are replaced, which takes place in connection with prolonged flows into or out of the Baltic. Under such circumstances it is clearly observed how the water masses in Horsens Fjord may be replaced almost fully in less than 1 – 2 weeks, the period of the CTD profiles. Going through all the CTD profiles it is found that such incidents of almost complete replacement of the water masses in Horsens Fjord took place about nine times in 2002 and about six times in 2006. These estimates are somewhat subjective though since the differences in the water mass properties are not always marked.

In connection with periods during which the water masses in the adjacent sea are subject to little change the combination of wind mixing in the fjord and exchange through the deep, but narrow channel results in an estuarine circulation. This circulation and the associated exchange and residence time of the fjord can be examined using Knudsen's Theorem, provided that periods of somewhat constant conditions can be identified. Based on the observations, two such periods, both of a duration of about one month, have been found. These two periods, one in the winter of 2002 and one in the fall of 2006, are characterized by much different run-off of freshwater. Using the observations to determine the salinities during these two periods, the residence times are estimated at 5.1 ± 0.9 days and 18.1 ± 2.8 days, respectively.

The examples of the exchange of Horsens Fjord discussed here are based on situations in which one or the other physical mechanism is dominant. Generally, however, both of these physical mechanisms will be contributing to the exchange of the fjord concurrently. This results in a little shorter residence time in general that what has been calculated above.

On the following pages all the CTD profiles used in the present analysis are plotted and presented. The CTD profiles are plotted separately and grouped in short periods of time as indicated by the red lines on the pages preceeding the plots. These pages, one for 2002 and one for 2006, show the temporal coverage of the eight CTD stations in the database. In the plot of a given CTD profile the vertical distribution of the density is shown to the left. To the right the CTD profile is shown in a salinity-temperature diagram, with which different water masses in the system can be identified.

Appendix 4. Kolding Fjord

The summary provided here is based on the report “The oceanographic conditions in Kolding Fjord” (in Danish), 14 April 2021.

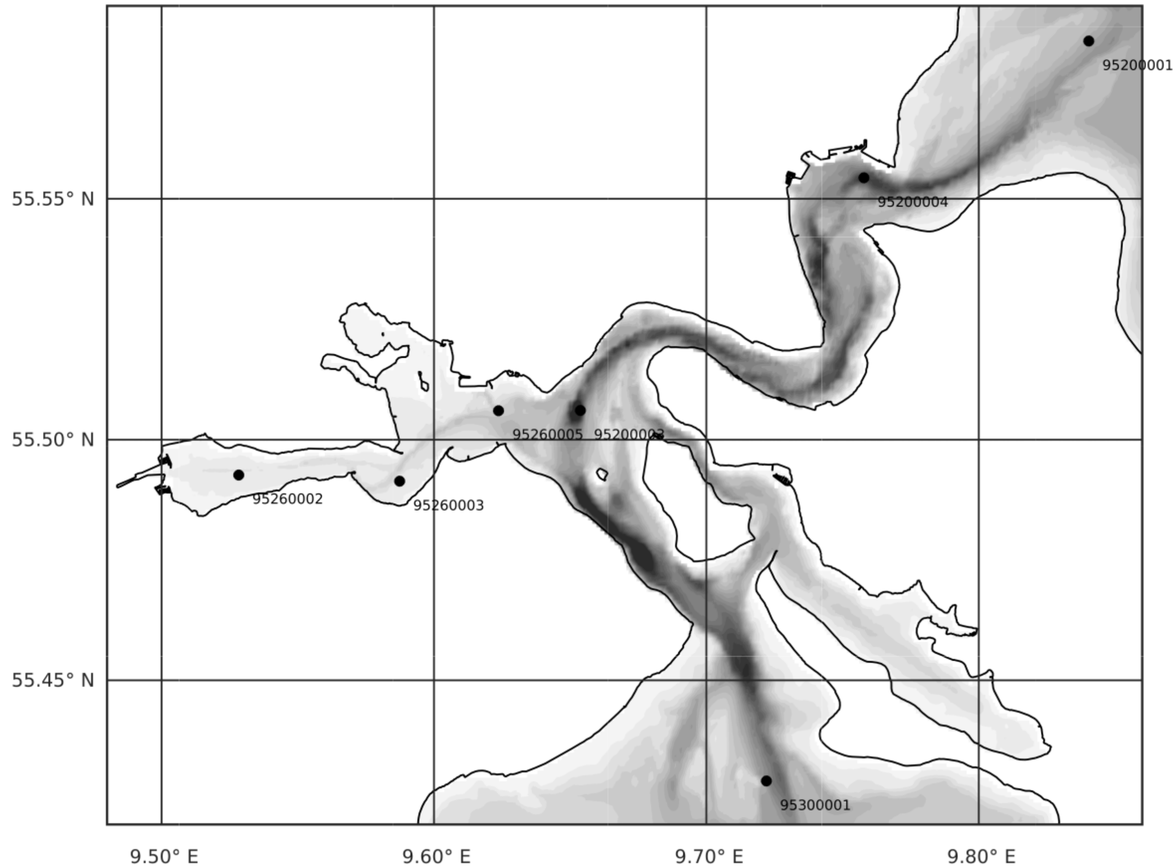

Figure 1: Map showing Kolding Fjord and the central, narrow part of the Little Belt, including the bathymetry (shaded areas) shown at a vertical resolution of 2 m. The locations of the CTD stations and their numbering are shown. One CTD station, 95100001, is located to the north-east, a bit outside the boundaries of map.

Kolding Fjord is located at roughly 55.5 °N, 9.6 °E, cf. Figure 1. Kolding Fjord is mostly relatively shallow with depths less than 5 m. The outer part of Kolding Fjord, however, is both wide and deep, the depths reaching about 15 m. In addition, Kolding Fjord is characterized by the presence of a channel of depths between 7 and 10 m, stretching along the fjord until the harbour of Kolding, located in the innermost part of the fjord. A part of this channel is maintained for the purpose of navigation. The average depth of the fjord is slightly less than 4 m.

The catchment area of the fjord and the average run-off of freshwater are both relatively small, the latter amounting to 2 – 4 $m^3\ s^{-1}$. However, during periods of strong precipitation the run-off may reach 10 – 15 $m^3\ s^{-1}$ on a monthly average.

Importantly, the deep and wide outer part of Kolding Fjord is directly connected with the narrow part of the Little Belt. The Little Belt, the narrow part of it in particular, is much influenced by the prevailing conditions in the inner part of the Danish waters. I.e., during periods of prolonged outflow from the Baltic, which occurs in connection with easterly winds, low-saline water masses of the Baltic are advected through the straits, including the Little Belt. During periods of prolonged inflow to the Baltic, which occurs in connection with westerly winds, high-saline waters of the Kattegat are advected through the straits. In addition, the narrow part of the Little Belt is influenced by tidal currents of a velocity amplitude of up to 1 $m\ s^{-1}$. This means that the water masses at the opening of Kolding Fjord may be replaced within a few days.

The CTD profiles on which the present analysis was based include eight stations, i.e. 95260002, 95260003, and 95260005, located in Kolding Fjord, 95200003, located in the narrow part of the Little Belt just outside the opening of Kolding Fjord, 95200004, 95200001, and 95100001 located to the north in the Little Belt and in the northern part of the Belt Sea, and 95300001, located to the south in the Little Belt. The locations of these stations are shown in Figure 1, except for one of the stations located to the north outside the boundaries of the map.

The observations shown in the attached plots were collected during two separate periods. During the first period, the entire year of 1995, two of the stations in Kolding Fjord were visited at a period of roughly 2 – 4 weeks, whereas the stations outside the fjord were visited more often. During the second period, the summer and fall of 2000, two of the stations in Kolding Fjord were visited irregularly, but oftentimes at a period of 1 – 2 weeks, whereas the stations outside the fjord were visited regularly every 1 – 2 weeks. The availability of the observations is thus insufficient to provide a picture of the full dynamics of the physical oceanographic conditions in Kolding Fjord. In addition, oftentimes the observations were not made concurrently in Kolding Fjord and outside.

Despite the limited coverage, the observations clearly show that the exchange between Kolding Fjord and the narrow part of the Little Belt is both large and quick. This is primarily a consequence of the wide and deep outer part of Kolding Fjord. In addition, the observations show that the water masses in the narrow part of the Little Belt is often subject to large changes, due to outflow from and inflow to the Baltic occuring interchangeably. This implies that the exchange of the water masses in Kolding Fjord takes place more often than what the limited coverage of the observations indicates, i.e. of a period of less than 1 – 2 weeks. The exchange of the water masses in Kolding Fjord is also driven by both the strong tide in the narrow part of the Little Belt and the wind, which causes mixing and currents in the inner, shallow part of Kolding Fjord. This means that even during periods that are not associated with distinct changes of the water masses in the narrow part of the Little Belt, a large exchange of the water masses in Kolding Fjord may still be taking place.

The wide and deep outer part implies that the conditions in Kolding Fjord is driven almost entirely by the conditions prevailing in the narrow part of the Little Belt and that Kolding Fjord does not really have an estuarine circulation of its own. Accordingly the local run-off of freshwater is rarely seen to have an influence on the water masses observed in the fjord.

On the following pages all the CTD profiles used in the present analysis are plotted and presented. The CTD profiles are plotted separately and grouped in short periods of time as indicated by the red lines on the pages preceeding the plots. These pages, one for 1995 and one for a part of 2000, show the temporal coverage of the eight CTD stations in the database. In the plot of a given CTD profile the vertical distribution of the density is shown to the left. To the right the CTD profile is shown in a salinity-temperature diagram, with which different water masses in the system can be identified.

Appendix 5. Haderslev Fjord

The summary provided here is based on the report “The oceanographic conditions in Haderslev Fjord” (in Danish), draft, 5 May 2021.

Figure 1: Map showing Haderslev Fjord and adjacent sea around the island Årø in the southern part of the Little Belt. The locations of eight CTD stations and their numbering are shown. The chart has been adapted from krak.dk.

Haderslev Fjord is located near 55.3 °N, 9.6 °E, cf. Figure 1. Haderslev Fjord has a length of about 13 km and is rather narrow, the width amounting to a few hundred meters. In by far most of the fjord the depth is less than 2 m. However, for the entire length of the fjord a narrow channel of depths of 5 – 6 m is found, which is used for navigation to the port of Haderslev and so is maintained. Haderslev Fjord has a relatively small catchment area and receives a limited run-off of freshwater of about 1 – 2 $m^3 s^{-1}$ on the average. During periods of large precipitation the run-off of freshwater to the fjord may increase to 3 – 6 $m^3 s^{-1}$ on a monthly average.

The adjacent sea, i.e. the southern part of the Little Belt, is much influenced by the prevailing conditions in the inner part of the Danish waters. I.e., during periods of prolonged outflow from the Baltic, which occurs in connection with easterly winds, low-saline water masses of the Baltic are advected through the straits, including the Little Belt. During periods of prolonged inflow to the Baltic, which occurs in connection with westerly winds, high-saline waters of the Kattegat are advected through the straits. This implies that the water masses occuring at the outer end of Haderslev Fjord are subject to some variability, which may influence conditions in the fjord.

The CTD profiles on which the present analysis was based include 13 stations of which eight are shown in Figure 1, i.e. 95440002, 95440003, 95440004, 95440005, 95440006, 95440001, and 95440007, located in the channel along the entire length of Haderslev Fjord, and 95400009, located in the Little Belt near the opening of Haderslev Fjord. The five remaining stations include one station, 95440017, located in the inner part of Haderslev Fjord, and four stations located in the Little Belt both to the north and to the south of the opening of Haderslev Fjord. The stations are 95300001, 95500001, 95500006, and 9560001. These five stations are not shown in any map in the present document.

The observational material from Haderslev Fjord is generally rather poor. However, on three separate occasions, in 1993, 1995, and 1996, the eight stations shown in Figure 1 were visited almost simultaneous, providing very important information on the dynamics of the system. The three transects all show that Haderslev Fjord can be accurately described as a saltwater wedge. This means that along the entire length of the fjord a two-layer system exists in which the relatively saline water masses of the adjacent sea is found in the deep layer, which is limited to the deep channel, and and in which the shallow layer consists of the freshwater run-off and is subject to dilution by entrainment of the saline water from below. Thus, the properties of the deep layer are roughly the same throughout the fjord, whereas the salinity of the upper layer is increasing gradually between the innermost part and the outermost part of the fjord. This implies that the upward entrainment is balanced by an continuous inflow of relatively saline water masses from the adjacent sea. The mixing of the water masses is primarily due to the wind, which causes upward entrainment of the deep layer and substantial exchange in the shallow parts along either side of the fjord. This implies that the circulation and the residence time of the system may be easily estimated under the assumption of roughly stationary conditions.

Taking typical numbers of the freshwater run-off and the cross-sectional area of the upper layer, a residence time of the outflowing freshwater was found at roughly two weeks. In addition, at the time of one of the three transects the dilution of the outflowing freshwater with the inflowing saline water was found at a ratio of 1:4 at the outer part of Haderslev Fjord. I.e. within the fjord one part of the freshwater was mixed with four parts of the saline water before exiting the fjord. This example shows accurately that a large amount of water masses from the adjacent sea is entering the fjord and is taking part in the circulation. A more accurate estimate of the circulation and the residence time under different conditions could be made by way of a non-steady, two-layer modelling approach.

Other observations, having been made for long periods of time, but only on one station in Haderslev Fjord and some stations in the Little Belt, show how the conditions in the Little Belt are influencing Haderslev Fjord. Thus, on several occasions it is clearly seen how new water masses in the Little Belt, which appear in connection with prolonged flow from or to the Baltic, are propagating into Haderslev Fjord and are replacing the water masses in the deep layer. As the water masses in the Little Belt are almost always more saline than the upper, freshwater-influenced layer in Haderslev Fjord, the replacement of the deep layer is not expected to have any significant, dynamic impact on the upper layer and thus the circulation and the residence time of Haderslev Fjord.

On the following pages all the CTD profiles used in the present analysis are plotted and presented. The CTD profiles are plotted separately and grouped in short periods of time as indicated by the red lines on the page preceeding the plots, which shows the temporal coverage of five of the CTD stations available in the database. On the last three pages, the CTD profiles observed at the stations located along the fjord as shown in Figure 1 and observed on three separate occasions are shown along with CTD profiles at up to three stations in the Little Belt. In the plot of a given CTD profile the vertical distribution of the density is shown to the left. To the right the CTD profile is shown in a salinity-temperature diagram, with which different water masses in the system can be identified.

Appendix 6. Aabenraa Fjord

The summary provided here is based on the report “The oceanographic conditions in Aabenraa Fjord” (in Danish), 17 February 2022.

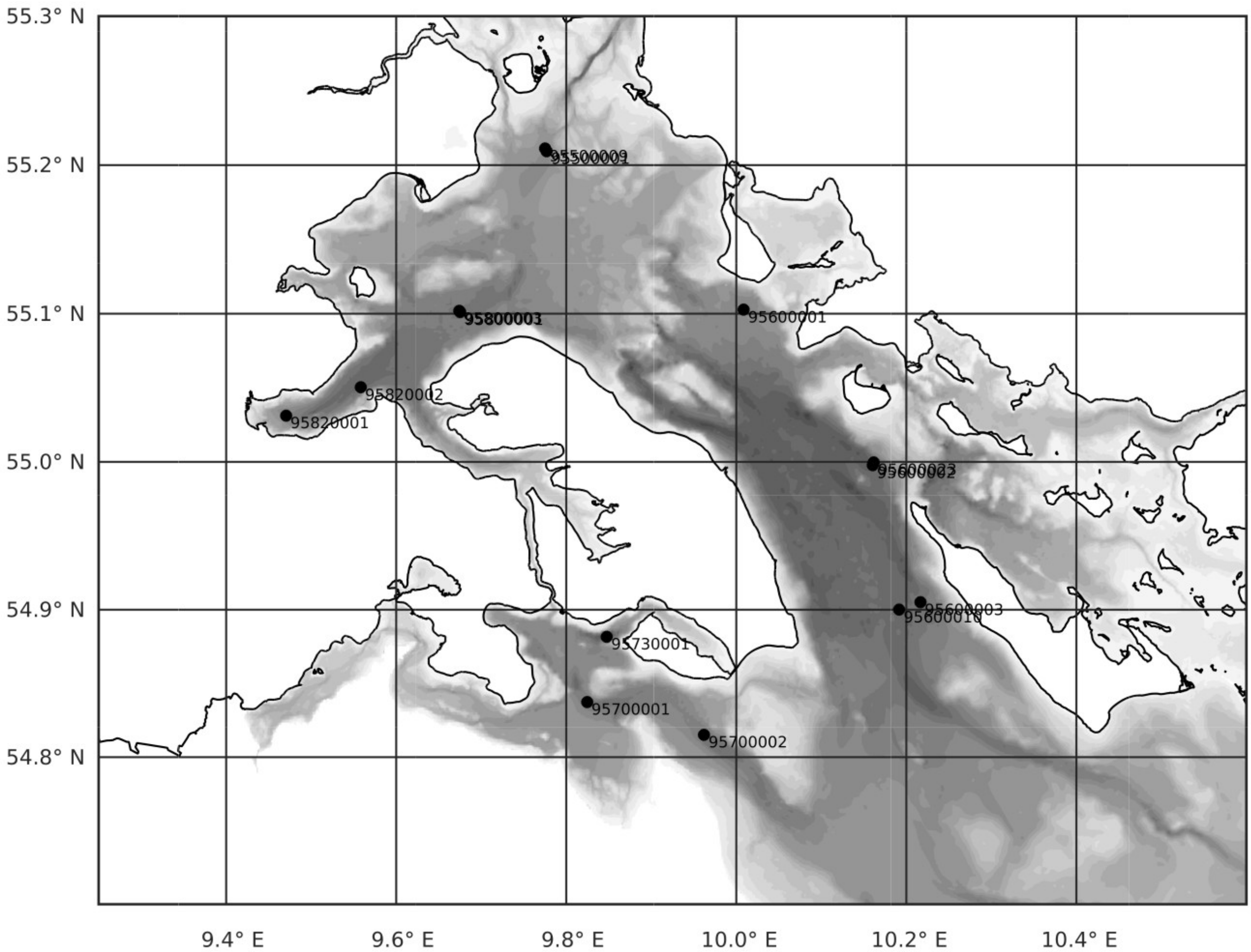

Figure 1: Map showing the southern Little Belt and the western part of the Baltic, including Aabenraa Fjord. The bathymetry (shaded areas) at a vertical resolution of 2 m and the locations of 14 CTD stations and their numbering are shown.

Aabenraa Fjord is located at 55.05 °N, 9.50 °E, cf. Figure 1. Aabenraa Fjord is the innermost half of an elongated, relatively deep basin that is connected with the southern part of the Little Belt, a mostly open area comprised of some large, deep basins, which are separated by sills and narrow channels. Aabenraa Fjord has depths reaching down to about 35 m, whereas the outer part of the basin has varying depths between roughly 10 and 25 m. Apart from the less deep, outer part of the basin, there are no geometric features that restrict the exchange between Aabenraa Fjord and the southern part of the Little Belt.

The catchment area of Aabenraa Fjord is relatively small, and so is the run-off of freshwater to the fjord, being less than 2 m^3 s^{-1} on the average. During periods of large precipitation the run-off to the fjord may increase to about 5 m^3 s^{-1} on a monthly average. In addition, Aabenraa Fjord may be influenced by the run-off to other coastal areas nereby, i.e. Als Fjord, Als Sound, and Augustenborg Fjord. In total these areas receive about 2 m^3 s^{-1} on the average, and during periods of large precipitation the monthly run-off may increase to about 10 m^3 s^{-1}.

The adjacent sea, i.e. the southern part of the Little Belt, is much influenced by the prevailing conditions in the inner part of the Danish waters. I.e., during periods of prolonged outflow from the Baltic, which occurs in connection with easterly winds, low-saline water masses of the Baltic are advected through the straits, including the Little Belt. During periods of prolonged inflow to the Baltic, which occurs in connection with westerly winds, high-saline waters of the Kattegat are advected through the straits.

Due to the almost unrestricted connection the conditions in the southern Little Belt play a very important role for Aabenraa Fjord. On the other hand, any significant exchange of water masses between Aabenraa Fjord and Sønderborg Bight can safely be ruled out due to Als Sound being long and narrow.

The CTD profiles on which the present analysis was based include 14 stations, shown in Figure 1. In Aabenraa Fjord and in the outer part of the fjord the stations 95820001, 95820002, 95800001, and 95800003 are found, the two latter having almost exactly the same location. In the central part of the southern Little Belt the following stations are found. 95500001 and 95500009, having almost exactly the same location, 95600001, 95600023 and 95600002, having almost exactly the same location, and 95600010 and 95600003, being located a short distance from each other. In the area south of the island of Als, known as Sønderborg Bight, the stations 95730001, 95700001, and 95700002 are found. Focus in the analysis was put on 1999 and 2000 during which many of the stations were visited every 1 – 2 weeks.

The observations show that the water masses found in Aabenraa Fjord very often are equal to those found in the southern part of the Little Belt. This shows that the exchange is so large and so quick, due to the wide and deep connection with the southern Little Belt, that it does not make any sense to consider Aabenraa Fjord a semi-enclosed area with a circulation and a residence time of its own. Adding to this picture, the observations show almost no signs of any local run-off of freshwater. The only exception to the close agreement with the southern part of the Little Belt occurs if the deep water mass in Aabenra Fjord is deeply located, and if an inflow of saline water masses from the Kattegat is not big enough to replenish the deep water mass. Still, under such circumstances the water masses in the upper part of the water column in Aabenraa Fjord and in the southern Little Belt are essentially the same.

During the summer and the fall the deep water masses in the southern Little Belt are often subject to oxygen depletion, owing in part to the residence times of up to several months. Oftentimes, when oxygen depletion is observed in the fjords and coastal waters around the southern Little Belt it is due to the highly dynamic nature and the movements of the stratified water masses in the southern Little Belt. On special occasions oxygen depletion may occur locally in Aabenraa Fjord if the deep water mass is disconnected from the southern Little Belt.

On the following pages all the CTD profiles used in the present analysis are plotted and presented. The CTD profiles are plotted separately and grouped in short periods of time as indicated by the red lines on the pages preceeding the plots, which shows the temporal coverage of all the CTD stations available in the database. On the first set of pages CTD profiles observed at all 14 stations during 2000 are shown. On the second set of pages CTD profiles observed at five stations along Abenraa Fjord and in the central part of the southern Little Belt during 1999 are shown. In the plot of a given CTD profile the vertical distribution of the density is shown to the left. To the right the CTD profile is shown in a salinity-temperature diagram, with which different water masses in the system can be identified.

Appendix 7. Als Fjord and Augustenborg Fjord

The summary provided here is based on the report “The oceanographic conditions in Als Fjord and Augustenborg Fjord” (in Danish), revised draft, 17 February 2022.

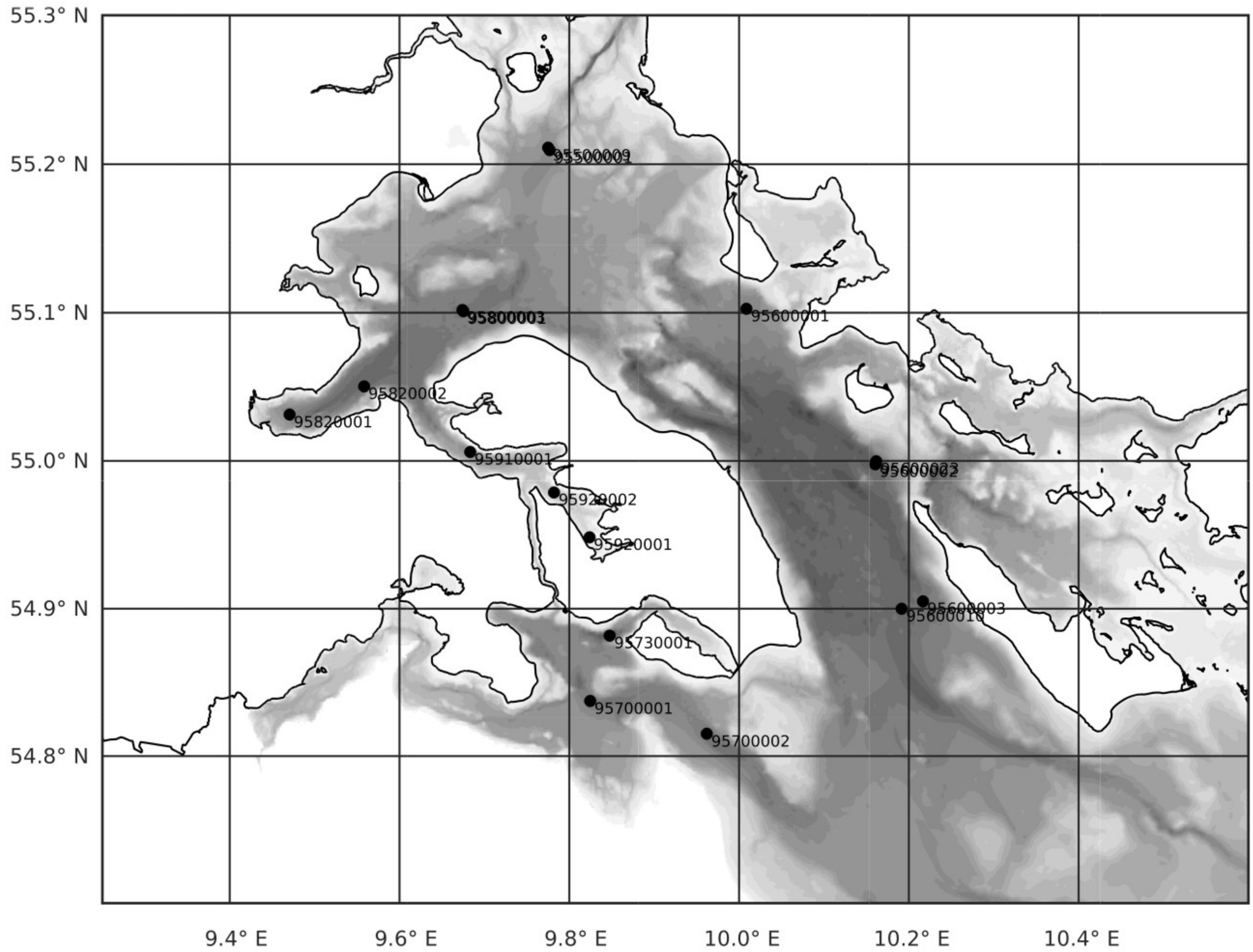

Figure 1: Map showing the southern Little Belt and the western part of the Baltic, including Als Fjord and Augustenborg Fjord. The bathymetry (shaded areas) at a vertical resolution of 2 m and the locations of 17 CTD stations and their numbering are shown.

Als Fjord and Augustenborg Fjord are located at roughly 55.00 °N, 9.70 °E and 54.98 °N, 9.80 °E, respectively, cf. Figure 1. The two fjords are tightly connected and constitute a roughly 22 km long and elongated system. Much of the innermost part of Augustenborg Fjord is shallow, less than 4 m, but moving outwards the depth increases steadily and reaches roughly 30 m in the outer part of Als Fjord, about the same as is found in the adjacent sea, i.e. the outer part of Aabenraa Fjord. There are no geometric constraints that limit the exchange between either part of the system or between Als Fjord and the adjacent sea.

Als Fjord is connected with Sønderborg Bight, located to the south of the island of Als, by way of the rather narrow and roughly 10 km long Als Sound. The currents in Als Sound are often weak and north-going and can be assumed to play only a minor role for the exchange of the water masses in Als Fjord and Augustenborg Fjord. Exceptions occur in connection with strong winds, which cause significant water level differences and considerable currents in Als Sound.

Als Fjord and Augustenborg Fjord have a relatively small catchment area and receive a freshwater run-off of about 2 $m^3 s^{-1}$ on the average. During periods of large precipitation the monthly run-off may increase to about 10 $m^3 s^{-1}$.

The adjacent sea, i.e. the outer part of Aabenraa Fjord, is wide and deep and has an open and almost unrestricted connection with the southern part of the Little Belt. Thus, Aabenraa Fjord is subject to the same dynamics as is found in the southern Little Belt, which is much influenced by the prevailing conditions in the inner part of the Danish waters. I.e., during periods of prolonged outflow from the Baltic, which occurs in connection with easterly winds, low-saline water masses of the Baltic are advected through the straits, including the Little Belt. During periods of prolonged inflow to the Baltic, which occurs in connection with westerly winds, high-saline waters of the Kattegat are advected through the straits. Due to the wide and deep outer part, Als Fjord and Augustenborg Fjord are much and relatively quickly influenced by the conditions in Aabenraa Fjord.

The CTD profiles on which the present analysis was based include 17 stations, shown in Figure 1. Als Fjord and Augustenborg Fjord are covered by three stations, i.e. 95910001, 95920002, and 95920001. In Aabenraa Fjord and in the outer part of Aabenraa Fjord the stations 95820001, 95820002, 95800001, and 95800003 are found, the two latter having almost exactly the same location. In the central part of the southern Little Belt the following stations are found. 95500001 and 95500009, having almost exactly the same location, 95600001, 95600023 and 95600002, having almost exactly the same location, and 95600010 and 95600003, being located a short distance from each other. In the area south of the island of Als, known as Sønderborg Bight, the stations 95730001, 95700001, and 95700002 are found. Focus in the analysis was put on 1999 and 2000 during which many of the stations were visited every 1 – 2 weeks and the stations in Als Fjord and Augustenborg Fjord were visited roughly every 2 weeks.

The observations show that the water masses found in Als Fjord and Augustenborg Fjord are almost always very similar to the water masses found in Aabenraa Fjord. In addition, the observations show that there is hardly no trace of the local run-off of freshwater. That means that the circulation of Als Fjord and Augustenborg is relatively quick and that the conditions in the two fjords are mostly determined by the conditions in the southern part of the Little Belt. The lack of observations made more frequently than every two weeks makes it difficult to observe the exchange of the water masses directly. But a conservative estimate of the residence time is less than one week. This also includes periods during which only small or no changes of the properties of the water masses are apparent. Such periods are often associated with relatively strong winds, which drive significant flows and strong mixing in, above all, the inner part of the system.

The observations also show nice examples of how a deep water mass in Aabenraa Fjord and in the southern part of the Little Belt is able to propagate far into Als Fjord and Augustenborg Fjord. If such a deep water mass is subject to oxygen depletion, this condition is able to hit Als Fjord and Augustenborg Fjord as well. The lack of a geometric constraint and the quick correspondence with Aabenraa Fjord implies that incidents of oxygen depletion in Als Fjord and Augustenborg Fjord most likely always are a result of the conditions in the southern part of the Little Belt.

On the following pages all the CTD profiles used in the present analysis are plotted and presented. The CTD profiles are plotted separately and grouped in short periods of time as indicated by the red lines on the pages preceeding the plots, which shows the temporal coverage of all the CTD stations available in the database. On the first set of pages CTD profiles observed at all 17 stations during 2000 are shown. On the second set of pages CTD profiles observed at four stations comprising a transect from Augustenborg Fjord through Als Fjord to Abenraa Fjord during 1999 are shown. In the plot of a given CTD profile the vertical distribution of the density is shown to the left. To the right the CTD profile is shown in a salinity-temperature diagram, with which different water masses in the system can be identified.

Appendix 8. Nissum Fjord

The summary provided here is based on the report "The oceanographic conditions in Nissum Fjord" (in Danish), draft, 12 June 2022.

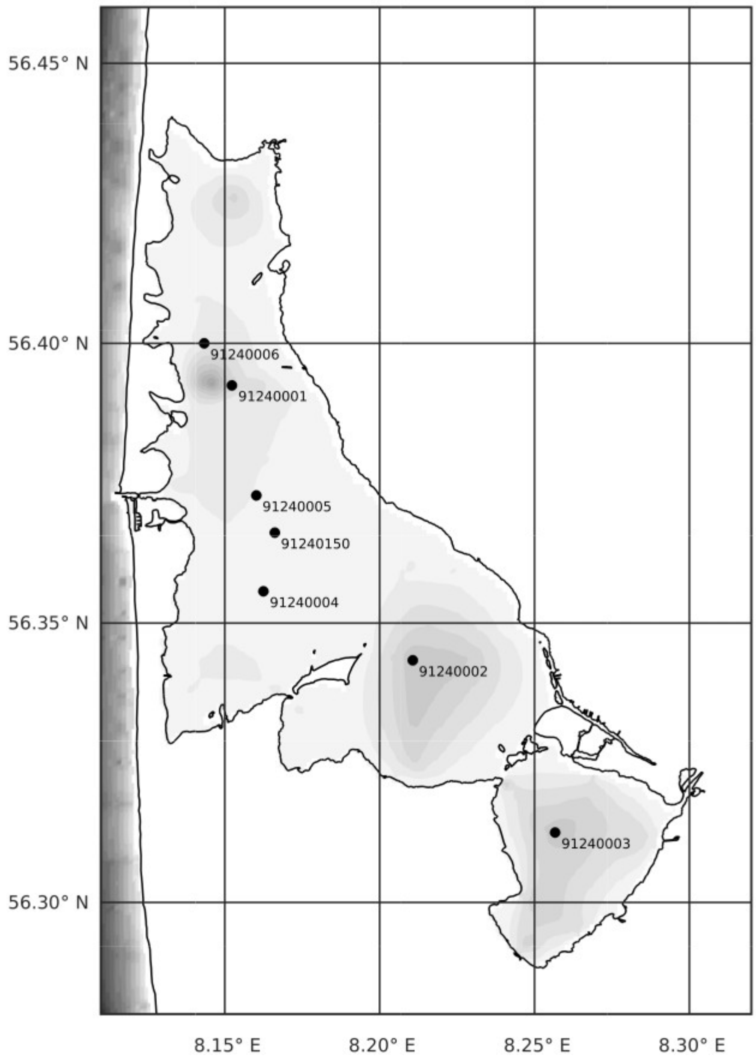

Figure 1: Map showing Nissum Fjord and a small part of the adjacent sea, i.e. the North Sea. The bathymetry (shaded areas) is shown at a vertical resolution of 0.5 m. The locations of seven CTD stations and their numbering are shown. In the North Sea outside the boundaries of the map two additional CTD stations are located. It should be noted that the bathymetry shown in the figure might be inaccurate.

Nissum Fjord is located at roughly 56.35 °N, 8.20 °E, cf. Figure 1. Nissum Fjord is rather shallow of depths less than about 2.5 m everywhere. Nissum Fjord is comprised of three basins, separated by islands and very shallow areas of depths less than 0.5 m except for narrow channels of depths of probably around 1 m connecting the basins. Importantly, the connection to the adjacent sea, i.e. the North Sea, consists of a man-made canal and a sluice, located at Thorsminde. The sluice is generally operated so as to avoid tidal waves and storm surges from entering the fjord, but also to avoid a rising water level in the fjord due to the run-off of freshwater from land.

Nissum Fjord has a large catchment area and is receiving a considerable amount of run-off from land. On the average the run-off amounts to about 25 $m^3\ s^{-1}$. However, during periods of large precipitation the monthly run-off may increase to as much as 70 m^3 s^{-1}, which occurs primarily during the wintertime. About 80% of the run-off is entering the innermost basin of the fjord.

Since the exchange with the adjacent sea is fully controlled by sluice, the properties of the North Sea of relevance are the water level, which is influenced by both tides and surges, and the salinity, which is often high.

The CTD profiles on which the present analysis was based include nine stations, of which seven are shown in Figure 1. Five of the seven stations in Nissum Fjord are located in the outer basin (91240006, 91240001, 91240005, 91240150, 91240004), one is located in the middle basin (91240002), and one is located in the inner basin (91240003). Two stations are located in the North Sea to the south and to the north of Thorsminde at a distance of 5 – 10 km from the coast (91300001, 91200001 respectively). These two stations are not visible in the map. Focus in the analysis was put on the years of 1997 and 2008. During 1997 four of the stations in Nissum Fjord, all three basins included, were visited at an interval of 2 – 4 weeks for most of the year, and the two stations in the North Sea were visited a little less frequently. During 2008 four of the stations in Nissum Fjord, all three basins included, were visited at an interval of about 2 weeks, whereas the stations in the North Sea were not visited at all.

The observations show that Nissum Fjord is strongly influenced by both the run-off of freshwater from land and the exchange with the North Sea through the sluice. Because of the large temporal variability of the run-off and difficulties letting water out of the fjord during periods of westerly winds and thus high water level in the North Sea, a considerable variability of the salinities in the fjord are found. The observations also show that the water masses in either of the three basins are very often homogeneous, which is due to a combination of the shallow depth and wind mixing. Because of the simplicity of the properties of the system, it is possible to estimate the exchange and the residence time of the fjord by way of Knudsen's Teorem. Since the salinities in the three basins are not constant, the changes in the total amount of salt in the fjord must be taken into account in this calculation. The calculation is carried out on a monthly basis for the period between 2003 and 2009. Generally the residence time is calculated at 20 – 40 days. However, during the wintertime the residence time may be shorter, and during the summertime it may be longer. In connection with inflows from the adjacent sea, both vertical and horizontal stratification may develop in the outer basin for short periods of time. This stratification as well as an inaccurate total volume for varying water levels lead to some uncertainties regarding the estimated residence time. These uncertainties may become relatively large when the run-off of freshwater is small.

On the following pages all the CTD profiles used in the present analysis are plotted and presented. The CTD profiles are plotted separately and grouped in short periods of time as indicated by the red lines on the pages preceeding the plots, one for 1997 and one for 2000. In the plot of a given CTD profile the vertical distribution of the density is shown to the left. To the right the CTD profile is shown in a salinity-temperature diagram, with which different water masses in the system can be identified.

Appendix 9. Skive Fjord and neighboring areas

The summary provided here is based on the report “The oceanographic and chemical conditions in Skive Fjord and neighboring areas” (in Danish), 19 August 2020, which makes reference to an earlier status report of the same title, but dated 19 December 2019.

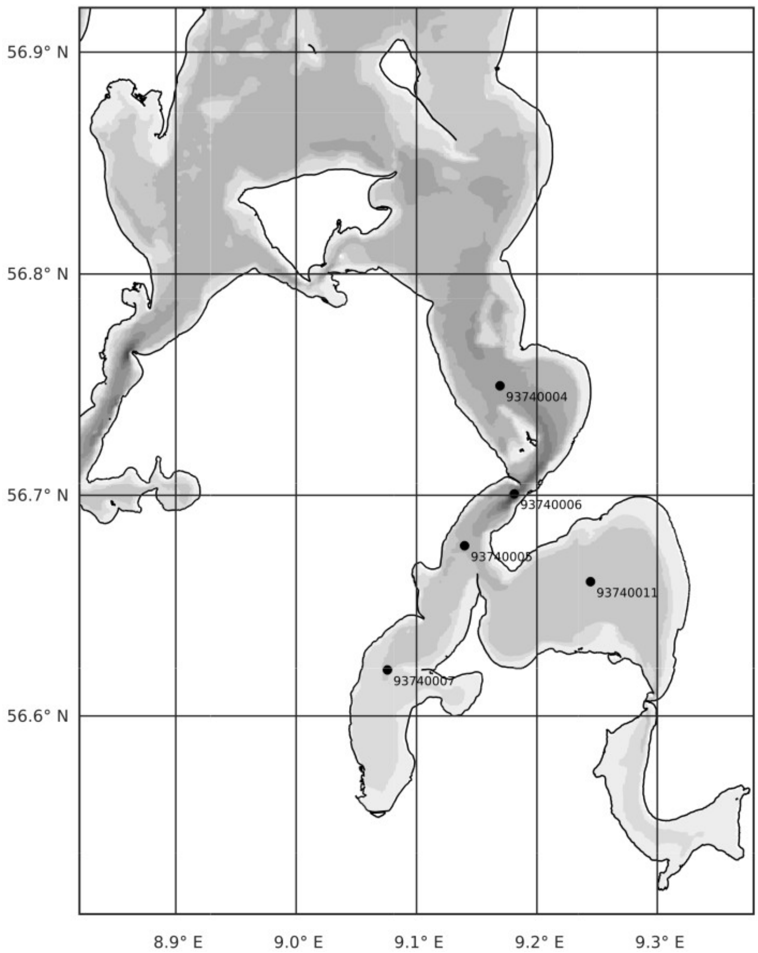

Figure 1: Map showing Skive Fjord and neighboring areas, including Lovns Broad, Risgaarde Broad and Bjørnsholm Bay, and the central part of Limfjorden. The bathymetry (shaded areas) is shown at a vertical resolution of 2.5 m. The locations of five CTD stations and their numbering are shown.

Skive Fjord is located at roughly 56.6 °N, 9.1 °E, cf. Figure 1. The neighboring areas include Lovns Broad, located to the east of Skive Fjord, and, moving to the north, Risgaarde Broad and Bjørnsholm Bay. Much of both the area in focus and the central part of Limfjorden is shallow of depths less than 8 m. In the northern part of Skive Fjord and in Risgaarde Broad an area of increasing depths up to around 25 m is found.

Limfjorden is connected with and is receiving salty water masses from both the North Sea to the west and the Kattegat to the east. Tidal waves propagate into Limfjorden through these connections, but in the central part of Limfjorden and in Skive Fjord and neighboring areas very little tidal energy is left.

Skive Fjord and neighboring areas have a large catchment area and are receiving a considerable amount of run-off from land. On the average the run-off amounts to about 30 $m^3\ s^{-1}$. However, during periods of large precipitation the monthly run-off may increase to more than 60 $m^3 s^{-1}$. Much of the run-off is entering the innermost part of Skive Fjord.

The CTD profiles on which the present analysis was based include primarily five stations, shown in Figure 1. Three of these stations are located along the main axis of Skive Fjord (93740007, 93740005, 93740006), one station is located in Lovns Broad (93740011), and one station is located in Risgaarde Broad (93740004). The reports on which this summary is based make use of CTD profiles from additional stations, located in the central part of Limfjorden. Focus in the analysis was put on the years of 1998 – 2000 and 2003. During these periods most of the stations were visited at an interval of 4 – 8 days. Some of the stations were visited less frequently during the wintertime, and one station was only visited between May and October. Except for one station, the observations included not only vertical profiles of salinity and temperature, but also water chemistry, i.e. nutrients, chlorophyll aso., observed using water samples taken near the surface and near the bottom.

Due to the large surface area and the generally small depths the wind plays a very important role in terms of both mixing and transporting the water masses. The CTD profiles show that very often the water column is vertically homogeneous everywhere, but that horizontal gradients exist, the salinity increasing slowly from the innermost part of Skive Fjord through Risgaarde Broad and Bjørnsholm Bay toward the central part of Limfjorden. This is known as a well-mixed estuary and is characterized by a strong vertical mixing and a considerable horizontal transport. The CTD profiles observed in the innermost part of Skive Fjord show that relative large salinities are very often found and that signs of the local run-off of freshwater are rarely found, both owing to the nature of a well-mixed estuary. These things imply that Skive Fjord and neighboring areas are so tightly connected with the central part of Limfjorden that it does not make much sense to talk about them having a circulation and a residence time of their own.

Since the vertical mixing and the horizontal transport is due primarily to the wind, not tidal waves, periodes of weak winds may lead to vertical stratification of the water masses, the more salty water masses from the central part of Limfjorden flowing southward and the less salty water masses from Skive Fjord flowing northward. This clearly seen in the observations, which show that the stratification in much of the area persists until the wind picks up again. As the vertical stratification is never strong, it does not take much wind to break it down.

Importantly, however, the observations also show that in the deep basin found in the northern part of Skive Fjord and in the southern part of Risgaarde Broad, the vertical stratification may exist for weeks until the stratification is eroded away or the deep water mass has been replenished. During such periods of stagnancy the oxygen concentration may drop, leading to oxygen depletion and the release of considerable amounts of nutrients from the sediment.

On the following pages all the CTD profiles used in the present analysis are plotted and presented. The CTD profiles are plotted separately and grouped in short periods of time. The plot of a given CTD profile, contained in a row, contains the vertical distributions of density (left), oxygen (second from the left), fluorescence and chlorophyll (third from the left), particulate concentrations of N and P (third from the right), concentrations of dissolved inorganic N, P and Si (second from the right) and the CTD profile shown in a salinity-temperature diagram (right), with which different water masses in the system can be identified.

Appendix 10. Isefjord and Roskilde Fjord

The summary provided here is based on the report "The oceanographic conditions in Isefjorden and Roskilde Fjord" (in Danish), 11 April 2022.

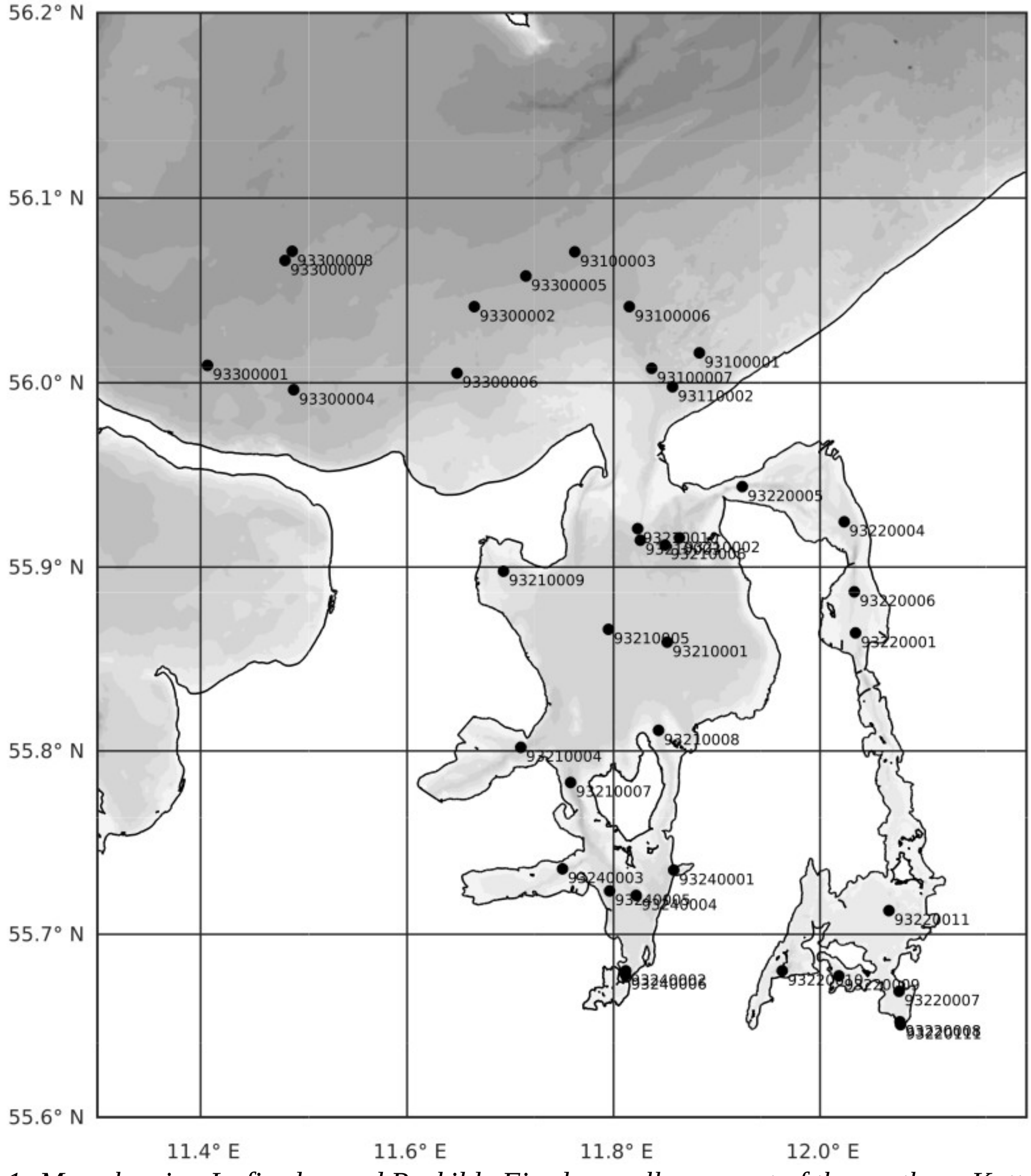

Figure 1: Map showing Isefjorden and Roskilde Fjord as well as a part of the southern Kattegat, the adjacent sea to the north. The bathymetry (shaded areas) at a vertical resolution of 2.5 m is shown. Also shown are the locations and the numbering of a total of 38 CTD stations of which 26 have been used.

Isefjorden and Roskilde Fjord cover a relatively large area located roughly between latitudes of 55.65 °N and 55.95 °N and longitudes of 11.60 °E and 12.10 °E, cf. Figure 1. The two fjords are both discussed in the present document as they are tightly connected and share the connection with the adjacent sea, i.e. the southern part of the Kattegat. However, it is important to note that Isefjorden and Roskilde Fjord are dynamically very different.

Isefjorden consists roughly of two separate parts, i.e. an outer, large part of depths mostly between 8 and 10 m and an inner, much smaller part of depths mostly between 6 and 8 m. The two parts are separated by an island and two narrow channels on either side of this island. In both parts of Isefjorden there are substantial areas of depths less than 4 m, implying that the wind plays an important role in mixing and transporting the water masses. The run-off of freshwater to Isefjorden, which takes place from a relatively large catchment area, is about 5 m^3 s^{-1} on the average, but may increase to more than 22 m^3 s^{-1} on a monthly basis during periods of strong precipitation.

Roskilde Fjord can also be considered as consisting of two parts, the inner part being relatively large and wide and the outer part, a north-south going stretch of about 30 km, being long and narrow. The outer part of Roskilde Fjord connects with the outer part of Isefjorden, not far from the opening to the southern Kattegat. The inner part of Roskilde Fjord has depths less than 6 m apart from a few exceptions, primarily a small basin of depths up to 30 m. This implies that in the inner part the wind plays an important role in mixing and transporting the water masses. The outer part of Roskilde Fjord is also characterized by depths mostly less than 6 m. However, large areas have depths less than 2 m, and at the northern end, approaching Isefjorden, a narrow channel of depths up to around 10 m is found. In two places, dams have been constructed partway across the outer part of Roskilde Fjord, providing the foundations of a road and a (now disused and disassembled) railway. The catchment area of Roskilde Fjord is relatively large. On the average the total run-off of freshwater to Roskilde Fjord is a little less than 7 m^3 s^{-1}, but during periods of strong precipitation the run-off may increase to about 26 m^3 s^{-1} on a monthly basis. A considerable part of the total run-off of freshwater takes place into the long and narrow outer part. The run-off to the inner part is 2.5 m^3 s^{-1} on the average and about 11 m^3 s^{-1} on a monthly basis during periods of strong precipitation.

The connection between Isefjorden and the southern Kattegat is wide and mostly shallow of depths less than 4 m, but consists also of two channels of depths typically between 6 and 8 m. The southern Kattegat is characterized by roughly a two-layer structure and somewhat stable salinities, which range from 33 in the lower part of the water column to 15 – 25 in the upper part of the water column, the latter being a mixture of saline North Sea water and outflowing, brackish Baltic water. The depth of the interface between the two layers is variable, but is often found at around 15 m. In connection with prolonged outflow from the Baltic, the salinity in the upper part of the water column in the southern Kattegat may decrease to about 12. This typically happens a few times per year.

The southern Kattegat is also characterized by tidal waves, which propagate into both Isefjorden and Roskilde Fjord. At the connection between Isefjorden and the southern Kattegat the tidal wave height is 15 – 25 cm. Measured at the town of Holbæk, located in the inner part of Isefjorden, the tidal wave is arriving with only a short delay, and the wave height has been amplified slightly, possibly due to decreasing depths and/or a gradually contracting width. At the city of Roskilde, on the other hand, located at the innermost part of Roskilde Fjord, the tidal wave is arriving at a delay of nearly 6 hours, and the wave height has decreased to less than 10 cm. This shows that much of the tidal energy is lost, certainly due to substantial tidal flows and friction in the long and narrow part of Roskilde Fjord. The water level variations due to tides in Isefjorden and Roskilde Fjord are relatively small compared to water level variations due to wind-generated surges in the Kattegat and in the western Baltic, which also propagate into Isefjorden and Roskilde Fjord. However, the tides are taking place constantly and so play an important role for the mixing and the transport of the water masses in, primarily, Roskilde Fjord.

The CTD profiles on which the present analysis was based include 26 stations, cf. Figure 1. 14 of these stations are located in Isefjorden (93210001, 93210002, 93210003, 93210004, 93210005, 93210006, 93210007, 93210008, 93210009, 93240001, 93240002, 93240003, 93240004, 93240006), nine of the stations are located in Roskilde Fjord (93220001, 93220005, 93220004, 93220006, 93220008, 93220007, 93220011, 93220009, 93220010), and three of the stations are located in the southern Kattegat (93300001, 93100001, 93110002). The stations were visited at much varying intervals, ranging from about one week for some stations and some periods to 4 – 6 weeks for other stations. The analysis was carried out using observations from 1992, 1994 and 1995, with which it was possible to obtain a reasonable temporal and spatial resolution of, respectively, the system as a whole, Isefjorden and Roskilde Fjord.

Focusing first at the conditions in the southern Kattegat, the observations show that it is primarily the water masses in the upper part of the water column that is subject to exchange with Isefjorden and that high-saline water masses are rarely found outside the opening of Isefjorden. The salinities found in the upper part of the water column vary between 15 and 25 and may decrease to as little as 12 in connection with prolonged outflow from the Baltic. Remarkably, the observations show that the water masses outside the opening of Isefjorden may relatively quickly change. In fact, it is possible that the observational material is not sufficient to display the dynamics of the water masses in the southern Kattegat fully.

When it comes to Isefjorden, the observations show a number of important properties. First, the salinities are relatively high and close to what is observed in the southern Kattegat, showing that Isefjorden is strongly influenced by the inflow of water masses from the southern Kattegat. Second, at almost any given point in time the salinities in the two parts of Isefjorden are roughly equal, both horizontally and vertically, showing that mixing and transport within Isefjorden is of a considerable magnitude. Owing to this, there are hardly no signs of the local run-off of freshwater. Third, changes of the water masses in the southern part of Kattegat propagate slowly into Isefjorden, owing probably to both the shallow connection, but also the large volume of Isefjorden. This implies that in connection with the occurence of low-saline water masses in the southern Kattegat, a reverse estuarine circulation is established, i.e. relatively high saline water masses flowing out Isefjorden and relatively low saline water masses flowing in.

The quality of the observational material and the properties of Isefjorden imply that a calculation of the exchange and the residence time is possible based on Knudsen's Theorem. However, due to the variability of both the conditions in the southern Kattegat and the direction of the exchange, an assumption of steadiness or even quasi-steadiness is not applicable. The variability is accounted for by expanding Knudsen's Theorem to include the rate of change of the total amount of salt in Isefjorden, neglecting Roskilde Fjord since the volume of this is relatively small. Based on the available observations for 1994 and 1995 it was attempted to carry out the calculation of the exchange and the residence time of Isefjorden at a temporal resolution of one month, the time step of the run-off data. This was generally successful except for some short periods for which it was not possible to reliably determine the salinities in, primarily, the southern Kattegat. The calculations show that the system is subject of a large variability. In some periods, primarily during the wintertime, the exchange is large and the residence time is short, often less than two months. In other periods, primarily during the summertime, the exchange is small, and the residence time is long, typically 2 – 4 months. At times the exchange is so slow that it corresponds to a residence time of one year or more. However, it must be noted that such periods of small exchange are both short-lived and associated with large uncertainties. The variability of the exchange and the residence time of Isefjorden reflects variations in the physical processes driving the exchange, i.e. the run-off of freshwater, mixing due to winds, inflows and outflows driven by both tides and wind-generated surges, and the conditions in the southern Kattegat.

The CTD profiles show that the inner part of Roskilde Fjord always has a salinity of 10 – 12. This is much lower than what is found in the outer part of Isefjorden, which connects with the long and narrow part of Roskilde Fjord, even considering the variability in Isefjorden discussed above. The observations also show that the inner part of Roskilde Fjord is very often homogeneous both vertically and horizontally and that changes in the inner part take place slowly. These things imply that the exchange of the water masses in Roskilde Fjord takes place relatively slowly and that the run-off of freshwater to the inner part plays a considerable role. Importantly, the observations made along the long and narrow outer part show some very characteristic properties, namely a horizontal salinity gradient that is roughly constant and that the water column is almost vertically homogeneous everywhere. This is known as a well-mixed estuary in which the exchange is a result of the complicated interplay between the horizontal density gradient, the excursion and the velocity profile of propagating tidal waves, the bottom friction, the geometry of the channel and the (weak) vertical density gradient. These processes, collectively termed dispersion, are very hard to quantify in general. Typically, a given system is therefore often described quantitatively in terms of a diffusion process in which the coefficient of diffusion must be determined using observations. In the case of Roskilde Fjord such a quantification is complicated by the facts that along the narrow part the run-off of freshwater is taking place continuously and the tidal amplitude is increasing.

However, considering the limiting situation at the innermost point of the long and narrow part of Roskilde Fjord, i.e. at the transition to the wide, inner part, some calculations may be made. Taking the average run-off and typical numbers for the horizontal salinity gradient and the cross-sectional flow area, a dispersion coefficient of about 40 m^2 s^{-1} was found, in agreement with other estuaries of a similar nature. In order to assess the exchange and the residence time of the wide, inner part, Knudsen's Theorem was used. In doing so the salinity difference between the water masses transported into and out of the inner part was estimated as the product of the tidal excursion and the horizontal salinity gradient. This resulted in a residence time of the wide, inner part of roughly three weeks. It must be noted that this method assumes that the water masses going out of the inner part are not the same as the water masses going in. In other words, it is assumed that the water masses lose their identity as they are transported out of the area in question. Due to the considerable amount of mixing in the long, narrow part this cannot be said with certainty. However, although this calculation is associated with some considerable uncertainties, it does provide a realistic order-of-magnitude estimate of the exchange.

Carrying out the similar calculation at the outermost part of the long, narrow part of Roskilde Fjord, i.e. at the connection with the outer part of Isefjorden, it is easier to follow the assumption that the water masses are losing their identity. Assuming a salinity difference of 1 between the water masses being transported into or out of the long, narrow part, a residence time of some four weeks was found. Again, although this calculation is associated with considerable uncertainties, it does provide a realistic order-of-magnitude estimate of the exchange of Roskilde Fjord as a whole.

On the following pages all the CTD profiles used in the present analysis are plotted and presented. The CTD profiles are plotted separately and grouped in short periods of time as indicated by the red lines on the pages preceeding the plots. On the first set of pages CTD profiles observed at 14 stations during 1992 are shown, covering broadly Isefjorden, Roskilde Fjord and the southern part of Kattegat. On the second set of pages CTD profiles observed at 12 stations during 1994 are shown, covering Isefjorden and the southern part of Kattegat in as much detail as possible. On the third set of pages CTD profiles observed at ten stations during 1995 are shown, covering Roskilde Fjord, the outer part of Isefjorden and the southern Kattegat in as much detail as possible. In the plot of a given CTD profile the vertical distribution of the density is shown to the left. To the right the CTD profile is shown in a salinity-temperature diagram, with which different water masses in the system can be identified.

Appendix 11. Præstø Fjord

The summary provided here is based on the report “The oceanographic conditions in Præstø Fjord” (in Danish), 13 June 2022.

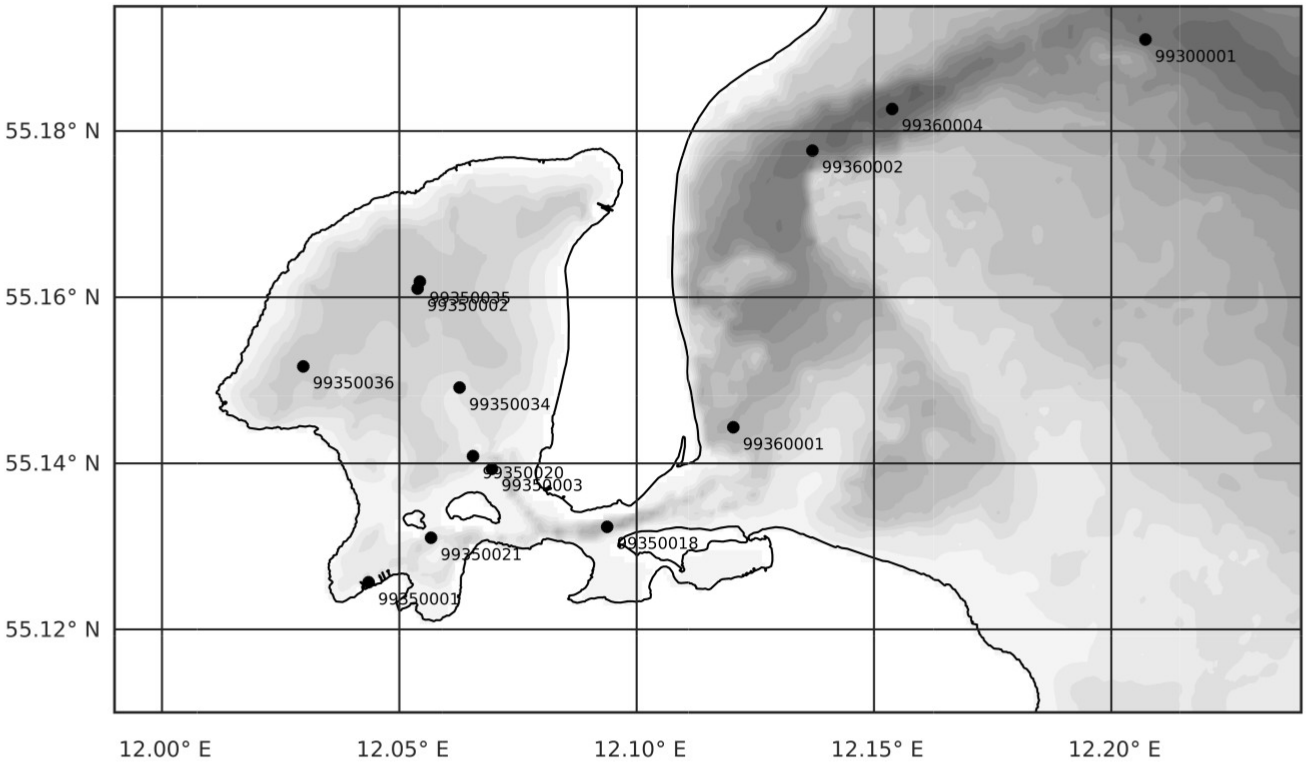

Figure 1: Map showing Præstø Fjord and a part of the western Baltic, the adjacent sea to the east. The bathymetry (shaded areas) at a vertical resolution of 1 m is shown. Also shown are the locations and the numbering of 13 CTD stations from which observations have been used. Two additional CTD stations are located in the Baltic outside the boundaries of the map.

Præstø Fjord is located at about 55.15 °N and 12.05 °E, cf. Figure 1. Præstø Fjord consists roughly of two parts, i.e. a northern, relatively deep part of depths around 4 – 5 m and a southern, rather shallow part much of which has depths less than 1 m. The shallow depths implies that the wind plays a prominent role with respect to both mixing and transport of the water masses. The connection with the adjacent sea, i.e. the western part of the Baltic, consists of a relatively long, narrow and relatively deep channel of depths mostly between 4 and 6 m, which stretches into the fjord and splits in two. At the side of the adjacent sea, the narrow channel stretches to the north into a wide area of increasing depths, which is directly connected with the open part of the Baltic. Apart from that much of the area immediately to the east of the opening of Præstø Fjord is rather shallow.

The catchment area of Præstø Fjord is relatively small, and so is the run-off of freshwater, amounting to about 1.2 $m^3 s^{-1}$ on the average. During periods of strong precipitation the run-off may increase to about 6 $m^3 s^{-1}$ on a monthly basis.

The open part of the Baltic is characterized mostly by brackish water masses of a salinity of around 8. More saline water masses, of salinities up to about 17, are found deep in the water column. These water masses may be subject to up-welling and movement towards the coastlines of the western Baltic. When salinities above some 17 are observed in the western Baltic, this is primarily due to intermittently inflows of saline waters through Øresund. Water level variations in the Baltic are primarily due to wind-generated surges, which may be relatively large. Tides, on the other hand, are almost absent.

The CTD profiles on which the present analysis was based include a total of 15 stations, cf. Figure 1. Nine of these stations are located in Præstø Fjord (99350018, 99350021, 99350001, 99350003, 99350020, 99350034, 99350036, 99350002, 99350035), and six stations are located in the western Baltic (99300002, 99300003, 99300001, 99360004, 99360002, 99360001), the latter of which is close to the opening of Præstø Fjord. However, several of the stations in the fjord were visited not so often. Focus in the analysis was put on the two years 1997 and 2009 throughout which there was a good temporal coverage, oftentimes at an interval af about one week, at one station in Præstø Fjord and at one or two stations the western part of the Baltic. In addition, occasionally (at an interval of roughly four weeks) there was a good spatial coverage of Præstø Fjord, including observations at three stations made almost concurrently.

The observations show that the salinities found in Præstø Fjord are very often close to those found in the western Baltic. This means that Præstø Fjord is almost completely influenced by the conditions in the adjacent sea and that the local run-off of freshwater plays a very small role. When changes are taking place in the western Baltic, i.e. in connection with upwelling of the deep-lying water masses or inflow of saline water masses through Øresund, the exchange of the water masses in Præstø Fjord may be observed directly as these changes are propagating into the fjord. Following these changes, the observations show that the residence time of Præstø Fjord is 2 – 4 weeks in general.

This density-driven exchange is certainly much influenced by the channel being both long and narrow and is probably not able to account for the exchange of the fjord fully. Instead, the wind plays a double and much more important role. First, even small variations of the water level due to wind-generated surges will cause substantial parts of the entire volume to move into or out of the fjord. Second, due to the shallow depths the wind is able to quickly mix the water masses in the fjord. Thus, during periods of strong winds the residence time is probably shorter than mentioned above, and during periods of weak winds the residence time may be longer.

On the following pages all the CTD profiles used in the present analysis are plotted and presented. The CTD profiles are plotted separately and grouped in short periods of time as indicated by the red lines on the pages preceeding the plots, one page for 1997 and one page for 2009. In the plot of a given CTD profile the vertical distribution of the density is shown to the left. To the right the CTD profile is shown in a salinity-temperature diagram, with which different water masses in the system can be identified.

Appendix 12. Rødsand and the southern Guldborg Sound

The summary provided here is based on the report “The oceanographic conditions at Rødsand and in the southern part of Guldborg Sound” (in Danish), draft, 22 May 2022.

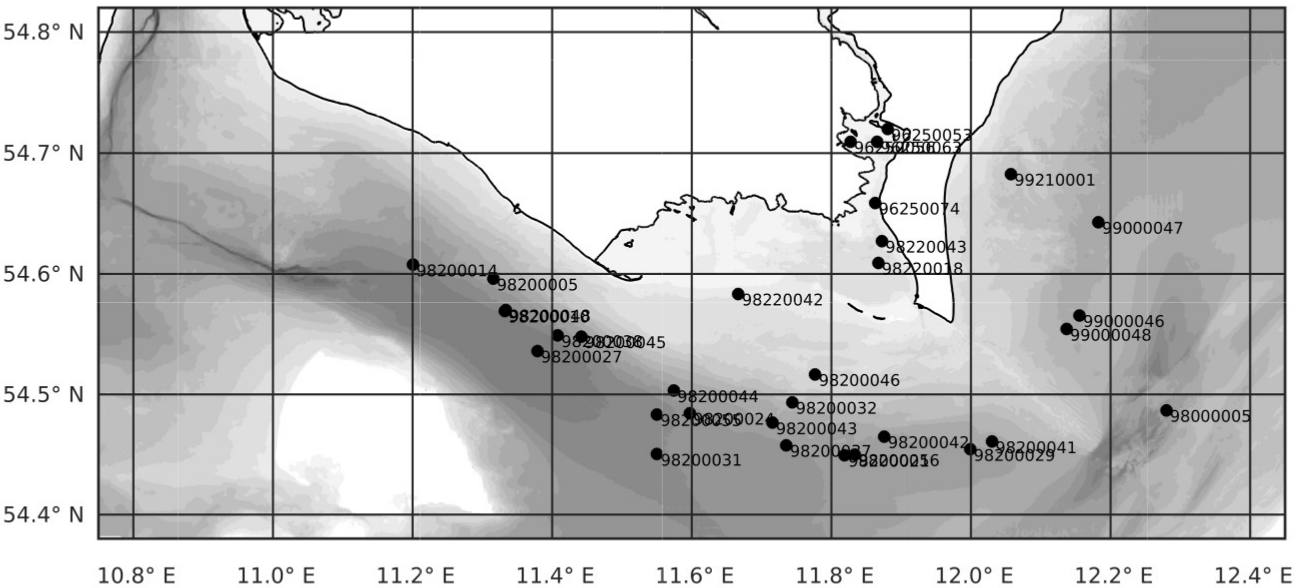

Figure 1: Map showing Rødsand and the southern Guldborg Sound, including the Broad, and the adjacent areas, i.e. Fehmarn Belt and the Darss Sill. The bathymetry (shaded areas) at a vertical resolution of 2.5 m is shown. Also shown are the locations and the numbering of a total of 32 CTD stations of which five stations have been used. One additional CTD station is located to the north outside the boundaries of the map. Note that the coastline of the island Fehmarn is missing, due to an error in the map data.

Rødsand is located at about 54.6 °N and 11.7 °E, and Guldborg Sound is stretching northward from Rødsand toward 54.8 °N and 11.8 °E, cf. Figure 1. Rødsand is a shallow area bounded by the island of Lolland to the north and to the west and by a long, shallow bank to the south. The bank, which in places reaches above the surface of the sea, is probably the result of the governing sedimentary processes. One may assume that this bank is growing, resulting from an on-going deposition of sediment, and is going to develop into a barrier island, turning Rødsand into a lagune. In the eastern part of Rødsand, where the depths are increasing a bit, the southern part of Guldborg Sound is found. Guldborg Sound is a long and mostly narrow strait between the islands of Lolland and Falster, connecting Fehmarn Belt to the south with an open part of the inner Danish waters located to the north. Guldborg Sound is mostly shallow, of depths less than 2 m, although to the north a narrow, but relatively deep channel is found. In the southern part, a stretch of Guldborg Sound is wide, an area known as the Broad and of depths around 3 m.

The catchment area of Rødsand and Guldborg Sound is relatively small, and so is the run-off of freshwater. On the average the run-off amounts to about 2 $m^3 s^{-1}$, but during periods of strong precipitation the run-off may increase to about 10 $m^3 s^{-1}$ on a monthly basis.

Due to the shallow depths in much of both Rødsand and the southern Guldborg Sound the wind plays a dominant role in mixing and transporting the water masses. The exchange of the water masses with the adjacent areas may take place both to the south and to the north. The exchange with Fehmarn Belt to the south, which must be assumed to be the dominating one, takes place thorugh both a very narrow, but relatively deep channel, found close to the southern tip of the island of

Falster, and a very wide, but relatively shallow opening in the long bank. Through the latter, one can expect a considerable wind-driven transport. However, the exchange and the currents through Guldborg Sound is probably mostly determined by the water level difference between either end, which can be expected to follow the general flows into or out of the inner Danish waters.

Despite the large number of stations shown in Figure 1, only a few stations are located within the area of interest. In general, the available data material for the purpose of the study is very limited. In fact, no observations have been made in the shallow area at Rødsand, the nearest station being located in the relatively deep part to the east. Focus have been put on the years of 1994 and 2007, during which the best spatial and temporal coverage is available. During these periods, observations have been made on three stations in the southern part of Guldborg Sound, including the Broad (96250056, 96250053, 98220018), two stations in Fehmarn Belt and on the Darss Sill (98200048, 98000005) and one station in the open area north of Guldborg Sound (96250088). At its best, the observations were made at an interval of 2 – 4 weeks, and oftentimes the observations at the six station were made a few days apart.

Due to the limited observational material it has not been possible to fully observe the exchange and the dynamical properties of Rødsand and the southern Guldborg Sound. However, the observations have clearly shown how the water masses in Fehmarn Bælt are often of a salinity close to that of the western Baltic, but that in connection with prolonged inflow to the Baltic, water masses from the Kattegat of relatively high salinities appear. The changes of the water masses in Fehmarn Belt propagate into Rødsand and the southern Guldborg Sound. Due to both the wide opening in the bank to the south and the role played by the wind in terms of mixing and transport, the residence time of Rødsand and the southernmost part of Guldborg Sound is estimated at a few days and less than a week. Since the mixing and the transport due to the wind are so dominant, the same residence time can be expected even if no changes of the water masses are taking place. The large exchange between Rødsand and the southern Guldborg Sound on the one hand and Fehmarn Belt on the other hand implies that the local run-off of freshwater plays a very small role in general. In the Broad the exchange of the water masses takes place at a slower rate than at Rødsand and in the southernmost part of Guldborg Sound. Thus, the residence time can be expected to be slighter longer in general, presumably 1 – 2 weeks.

During periods of both weak winds and no changes of the water masses in Fehmarn Belt, one may expect a lesser exchange and a longer residence time, at Rødsand and in the southern part of Guldborg Sound probably more than a week. However, periods of such conditions are not long-lived and are often quickly interrupted by passing low-pressure weather systems and the associated winds.

On the following pages all the CTD profiles used in the present analysis are plotted and presented. The CTD profiles are plotted separately and grouped in short periods of time as indicated by the red lines on the pages preceeding the plots, one page for 1994 and one page for 2007. In the plot of a given CTD profile the vertical distribution of the density is shown to the left. To the right the CTD profile is shown in a salinity-temperature diagram, with which different water masses in the system can be identified.

Appendix 13. Nakskov Fjord

The summary provided here is based on the report “The oceanographic conditions in Nakskov Fjord” (in Danish), draft, 27 May 2022.

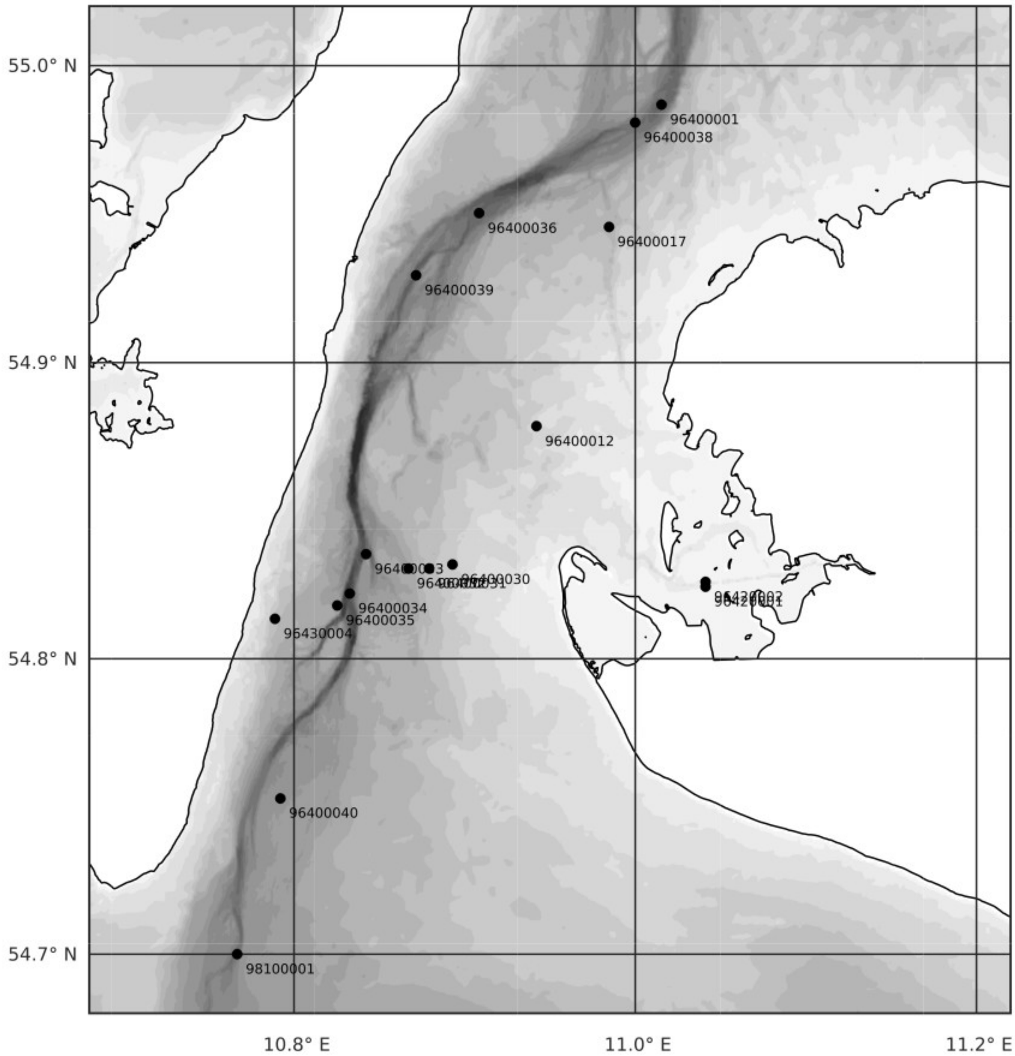

Figure 1: Map showing Nakskov Fjord and the adjacent area in the Langelands Belt. The bathymetry (shaded areas) at a vertical resolution of 2.5 m is shown. Also shown are the locations and the numbering of a total of 18 CTD stations at which observations have been made. Two additional CTD stations are located outside the boundaries of the map. Only three stations, located in the central part and in the opening of Nakskov Fjord and in the Langelands Belt have been used.

Nakskov Fjord is located at roughly 54.85 °N and 11.05 °E. Nakskov Fjord is generally very shallow, of depths less than 2 m, and has a wide opening toward the adjacent area. Nakskov Fjord is traversed by a narrow and relatively deep channel, which is used for the purpose of navigation to the port of Nakskov. The channel follows a natural and meandering course of depths mostly around 7 m. However, in the central part of Nakskov Fjord a designated, straight navigation channel has been excavated and is maintained at a depth of around 9 m. In the outer part of Nakskov Fjord, a relatively big island is found, limiting the exchange of the inner part of the fjord. The outer part of the fjord is characterized by depths between 2 and 6 m, deepening further toward the adjacent area.

The catchment area of Nakskov Fjord is relatively big, but the run-off of freshwater is small, amounting to about 1.4 m^3 s^{-1} on the average. However, during periods of strong precipitation the run-off may increase to about 8 m^3 s^{-1} on a monthly basis.

The wind plays an important role for the exchange of Nakskov Fjord for two reasons. First, since the fjord is mostly very shallow, wind-driven mixing and transport of the water masses are often of a considerable magnitude. Second, water level variations, which are mostly due to regional wind conditions, may contribute substantially to the exchange by quickly letting large volumes of water into or out of Nakskov Fjord. Tides, on the other hand, play a small role.

The conditions in the adjacent area, i.e. the Langelands Belt, also play a substantial role for Nakskov Fjord. Langelands Belt is connected with the Great Belt to the north and the Fehmarn Belt to the south-east and is thus a part of the primary route of exchange between the brackish Baltic and the saline Kattegat. When prolonged flow takes place in either direction the properties of the water masses in the Langelands Belt change and contribute to the exchange of Nakskov Fjord. Although this exchange is certainly less important and much less frequent than exchange driven by wind, changes of the properties of the water masses allow a direct observation of the exchange and the residence time of Nakskov Fjord.

Unfortunately, only a small number of observations have been made with which the physical oceanographic conditions in Nakskov Fjord can be studied, cf. Figure 1. Focus was put on the year 1990 during which three stations, located in the central part of the fjord (96420001), in the navigation channel outside the opening of the fjord (96400012) and in the Langelands Belt (98100001), were visited at an interval of roughly 4 weeks. Also, observations from the year 2017 were analyzed during which the station in the central part of the fjord were visited at an interval of 1 – 2 weeks mostly, but where data from the station outside the opening of the fjord are lacking completely and data from the Langelands Belt are few.

Despite the limited amount of observations, it is clearly seen how changes of the properties of the water masses in the Langelands Belt, which are tightly connected with the general flows either into or out of the Baltic Sea, are propagating into and are replacing the water masses in Nakskov Fjord. This exchange, which is relatively quick, is partly due to the wide opening of the fjord. The shallow depths in much of the area imply that the wind is contributing considerably to the exchange of Nakskov Fjord. This means that the exchange of Nakskov Fjord is relatively quick even when changes of the properties of the water masses cannot be observed directly. The residence time of Nakskov Fjord is estimated at a few days in general. During periods of weak winds and constant properties of the water masses in the Langelands Belt, one can imagine a slightly longer residence time.

On the following pages all the CTD profiles used in the present analysis are plotted and presented. The CTD profiles are plotted separately and grouped in short periods of time as indicated by the red lines on the pages preceeding the plots, one page for 1990 and one page for 2017. In the plot of a given CTD profile the vertical distribution of the density is shown to the left. To the right the CTD profile is shown in a salinity-temperature diagram, with which different water masses in the system can be identified.