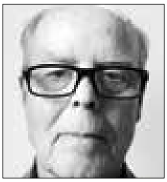
A Descriptive water mass analysis of T-S-Time relationships of hydrographic data from the Gullmarn Fjord

En tredimensionell temperatur-salthalt-tidsanalys av det hydrografiska tillståndet prövad på data från Gullmarsfjorden



Bertil Håkansson. Retired from the Swedish Agency for Marine and Water Management and earlier at SMHI.

Abstract

The Temperature-Salinity-Time analysis is for the first time tested in Swedish coastal waters. This three-dimensional method makes it possible to analyse the seasonal variability of hydrographic conditions in coastal waters strongly influenced by freshwater and heat fluxes. The method is implemented on data from the Gullmarn Fjord in western Sweden where one of the longest monitoring stations of daily hydrographic data was located. The time series covers the years between 1940 and 1985.

The rate of change of the hydrographic variability during an annual cycle is calculated. Decadal variability is related to changes in freshwater and heat fluxes. The near bottom layers hydrography is stable over time with salinities between 32-34 psu.

The method improves knowledge of external and internal processes influencing the hydrographic annual variability, by considering both temperature and salinity effects on density. Hence, neglecting temperature effects on density calculations leads to different results on dynamics and therefore estimates on currents. The method can also improve possibilities to test numerical models for their capabilities to map hydrographic conditions, support recipient control and intake of cooling waters.

Keywords: Temperature-Salinity-Time plots, Coastal Waters, Hydrographic Conditions, Monitoring data.

Sammanfattning

En ny metod har använts för första gången i svenska kustvatten för att i mer detalj än tidigare beskriva det hydrografiska tillståndet över tid. Data från Gullmarn har använts, som har haft dagliga observationer över lång tid (1933 tom 1985). Den månatliga förändringen per djup är statistiskt beräknad. Förändring över längre tidsperioden kan beräknas och kopplas till ändrade avrinningsförhållanden och förändrat klimat. Tillvägagångsättet kan användas för att testa numeriska modeller i mer detalj än tidigare. Samt ge information om storskaliga strömningsmönster. Analysmetoden kan ge underlag till recipientkontroll, bedömning av utlopp och intagande av kylvatten.

Introduction

In general, the traditional T-S analysis of ocean waters (cf. Tomczak (1999)) does not apply to coastal data due to non-stationary conditions in salinity and temperature distributions. However, by adding time as a third dimension to the classical analysis, the seasonal variability is considered, as demonstrated by Picard et.al (1977). The third dimension is shown by adding monthly average data of salinity and temperature at each depth at a single station. This requires time series over many years, which is difficult to achieve by short-time research projects, but is applicable to monitoring data, covering decades of information.

The methodology can support validating numerical models, adapt monitoring programmes to be more effective and support recipient control.

To test the methodology on coastal waters, the Bornö Station located in the Gullmarn fjord (Fig.1) was used. The fjord has a sill at the mouth of 30 meters depth while the fjord has a maximum depth of 118 m. Freshwater is added to the fjord at the inner part and from inflows at the fjord mouth. The fjord stretches from SW at the mouth and towards NE at the end, reaching a length of 35 km. Bornö Station is located ca 20 km from the mouth. More information on the fjord is available (Marin Mätteknik AB (2006), Bekkby and Rosenberg (2006) and Björk and Nordberg (2003)). The biography of Prof. Otto Pettersson written by Svansson (2006) give insight into the history of Bornö station.

Figure 1. Map of Gullmarn fjord with Bornö Station. Basemap from Google Maps, map data ©2026 Google

The fjord represents a hydrographic area typical of the Swedish west coast where the method is applicable. However, there are also sea bays, affected by river runoffs, in the Baltic Sea where the method can be applied.

Observations

Observations at Bornö Station was done from a suspension bridge about 10 meters from the rocky beach. The depth of observations covers a water column of 35 meters. The data series covers 52 years of daily observations. The station was manned year around and the observations were made by the same individual (Oscar Åkemo) during the years 1933 to 1985. The time series are almost homogenous with observations done 6 times a week. However, there are gaps due to ice conditions and vacations. The data used in this study covers the period 1940 to 1985.

Temperature measurements used the classical reversal thermometer technique and salinity measurements were made by analysing a water sample using a titration method developed by Knudsen (1901). The accuracy is about 2 % in salinity.

A monthly mean value covers theoretically 1080 data points at each depth (6 times a week x 4 weeks x 45 years), but ca 900 observations are used in this study. For each month and depth (5, 10, 15, 20, 25, 33 m) the standard deviations are calculated. The results are presented in Figure (2) and shows a variability between 1.5 to 2.5° C in temperature with a maximum at 10 to 15 meters depth. While salinity standard deviation varies between 2.5 to 3.8 psu in the upper part of the water column whereas in the lower part of the water column it varies between 0.6 to 1.0 psu.

Also included in the analysis is the monthly mean air temperature from the automatic station at Trubaduren located offshore Gullmar fjord. Monthly averages are based on data from 1971 to 2000. A

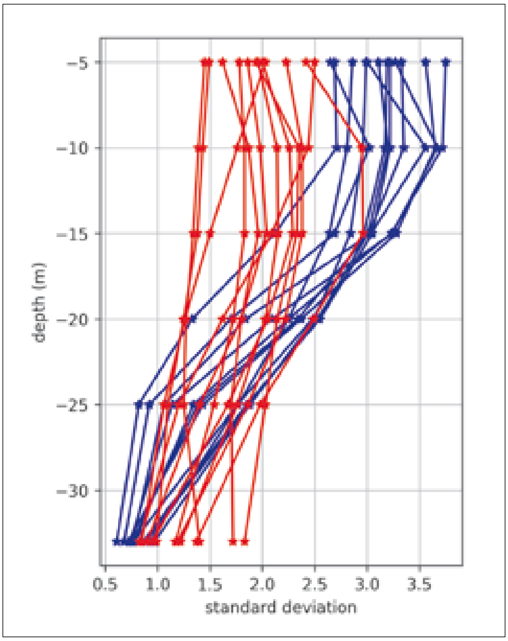


Figure 2. Standard Deviations of monthly mean salinity $\overline{S}(z_j, m_k)$ and temperature $\overline{T}(z_j, m_k)$. Blue-Salinity (psu) & Red-Temperature (°C)

second data source is the monthly mean runoff from the local river Örekilsälven, covering data from 1980 to 1985. In addition, the number of Major Outflows per month from the Baltic Sea through the Sound (Öresund Strait) is used (Håkansson (2022)) as a major outflow indicator of low saline waters, feeding the Baltic Stream. These data sets illustrate the influence of atmospheric and hydrological conditions on Gullmarn fjord hydrography.

Methodology

The analysis covers a semi three-dimensional set of salinity-temperature-month (S-T-Time) data for each monitoring station, sample depth and monthly mean:

$$\overline{S}(z_j, m_k) = \sum_{i=1}^{i=n} S(z_j, t_i)\,/n \qquad (1)$$

$$\overline{T}(z_j, m_k) = \sum_{i=1}^{i=p} T(z_j, t_i)\,/p \qquad (2)$$

$$L_H(z_j, m_k\text{-}m_{k+1}) = ((\overline{S}(z_j, m_k) - \overline{S}(z_j, m_{k+1}))^2 + (\overline{T}(z_j, m_k) - \overline{T}(z_j, m_{k+1}))^2)^{1/2} \qquad (3)$$

$$L_V(z_j\text{-}z_{j+1}, m_k) = ((\overline{S}(z_j, m_k) - \overline{S}(z_{j+1}, m_k))^2 + (\overline{T}(z_j, m_k) - \overline{T}(z_{j+1}, m_k))^2)^{1/2} \qquad (4)$$

Here ($\overline{S}$ & $\overline{T}$) represents the monthly mean salinity and temperature at the monitoring station. Where monthly mean is represented by (m_k) where k (= 1:12) the month of a standard year. The depth (z_j) represents monitoring depth where z = ([5, 10, 15, 20, 25, 33]m) and j = (1:6) respectively. Since there are different data gaps for salinity and temperature the monthly mean covers different time series lengths, i.e. n and p are numbers of salinity and temperature observations, respectively.

The present concept to analyse hydrographic data is using the terminology from the mathematical branch of graph theory.

General description of Salt-Temperature-Time plots

The basic results, presented in Figures (3 & 4), where salinity is placed on the y-axis as negative values, since in general salinity is increasing with depth. Temperature is on the x-axis. Density as sigma (σ) values (density-1000 kg/m^3) is presented with dotted lines.

L_H is the distance in $\overline{S}$ & $\overline{T}$ space of the sum of connecting months at a given depth (z_j), presented in Figure (3). In this figure the single months marked as dots, is the nodes and the lines connecting the nodes is the edges. These are circular graphs. In the Figure (3) December and January nodes is not visible with their edge to clarify where the annual rotation starts and ends. L_H rotates clockwise in surface layers and in the bottom layer, while in between, typical lemniscate (laying eight) forms takes place.

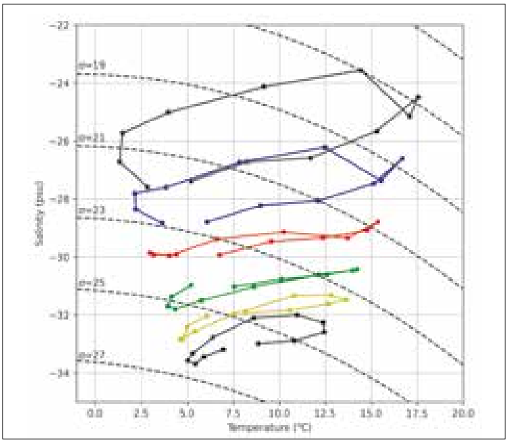


Figure 3. Bornö S-T-Time plot,1940-1980, for six depths (5, 10, 15, 20, 25, 33 m). Salinity-Temperature-Time Plot with nodes at each month connected with edges. Density as sigma (σ) values (density-1000 kg/m^3) is presented with dotted lines.

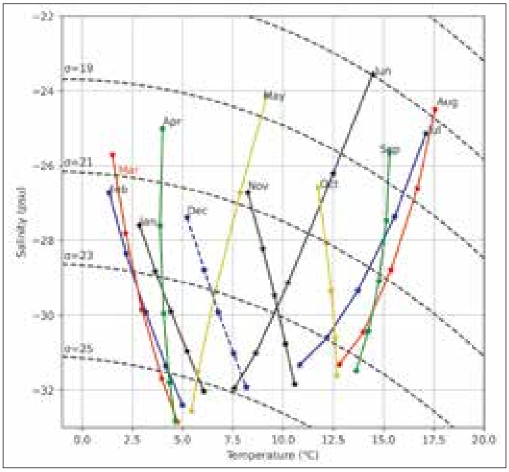


Figure 4. Bornö S-T-Time plot, 1940-1980, for six depths (5, 10, 15, 20, 25, 33 m). Salinity-Temperature-Time Plot, with nodes at each depth connected with vertical edges. Density as sigma (σ) values (density-1000 kg/m^3) is presented with dotted lines.

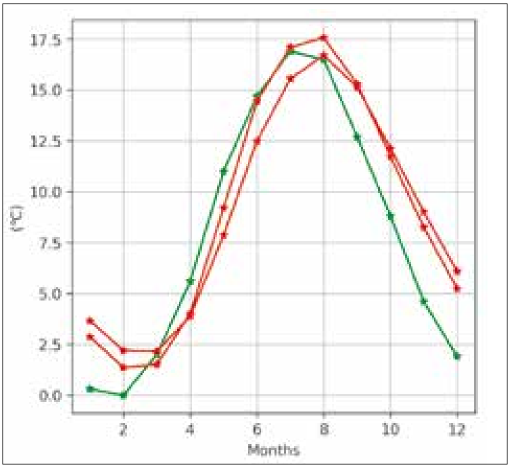


Figure 5. Air temperature from Hållö station and sea water temperatures at 5 and 10 metres depth at Bornö Station. Green-air temperature, Red- sea water temperature at 5 & 10 m.

The hydrographic circular graph direction depends on the forcing factors of heating and cooling and changes in freshwater input to the surface layer. Deep layers may have other characteristics influencing the rotation direction depending on the origin of the water mass.

L_V is the distance in $\overline{S}$ & $\overline{T}$ space connecting the sum of distances at a given month mk presented in Figure (4). In this figure the single depths is marked as dots, also called nodes and the lines connecting the nodes are called edges. These are non-circular graphs.

The non-circular graph (L_V) is synonymous with the classical water mass T-S diagram for ocean waters (Tomzcak (1999)) but in this case the analysis is based on mean monthly data. If the monthly non-circular graph (L_V) becomes a straight line, it indicates mixing between two water masses, i.e. surface and near bottom layer. The hydrographic distance represents the strength of stratification. A short distance indicates a weak density gradient, while a longer distance indicates a stronger density gradient.

Results

The hydrographic annual variability depends on the external forces air temperature and inflow of low saline waters (runoff). The air temperature is from observations at Hållö Weather Station and covers the period 1961 to 1970. The data are plotted in Figure (5) together with surface temperatures at 5 and 10 m depth. There is a strong correlation between air and surface water temperature.

In Figure (6) the net outflow (km^3/month) of Baltic low saline waters through the Sound (Öresund Strait) (Håkansson 2022) and the salinities at 5 and 10 m depth at Bornö Station, are presented. The salinities are low during high outflows in January to May

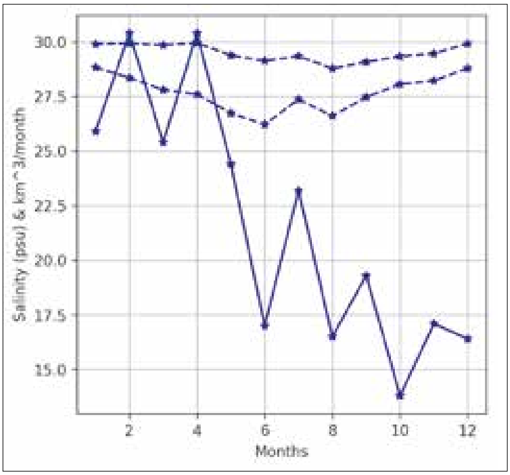


Figure 6. Salinity at 5 and 10 metres depth at Bornö Station and outflow per month of low saline Baltic waters through the Sound (Öresund Strait). Salinity, Dotted Blue-5 & 10 m, Straight Blue-Sound-Q.

and high during the rest of the year when outflows through the Sound is low. There are local sources of runoff to the Gullmarn Fjord but these are small and negligible in compared to the Baltic current.

To conclude, the surface layers (5 to 15 m depth) influenced by spring warming and high outflow of Baltic brackish water are the drivers of the clockwise rotation of hydrographic changes during spring. Vice versa during autumn when cooling and low outflows from the Baltic takes place, once again forcing the clockwise rotation of the hydrographic graph L_H. At mid-depth the rotation is weak, but at 33 m depth rotation is clockwise again.

The hydrographic distance (L_V) (Table 1) is longest in June, while shortest in October. When L_V is short the density difference between surface layer and bottom layer is small, while the opposite occurs when L_V is large. For the hydrographic distance (L_H), the fastest changes occur during spring and autumn while during summer and winter minor changes occur.

Table 1: Hydrographic length of Lv (Eq. 4)

Month	L_V	Month	L_V
Jan	20.85	Jul	35.72
Feb	25.87	Aug	33.05
Mar	29.94	Sep	23.95
Apr	30.98	Oct	19.76
May	36.21	Nov	21.49
Jun	42.92	Dec	20.99

Discussion

This method, dating back to the 1970s, has not been evaluated before for coastal waters around Sweden. It turns out to deliver more detailed information on the hydrographic state and its annual and decadal variability. Here only the monthly mean annual hydrographic variability is under investigation. The same analysis can be applied to decadal changes by dividing time series into two periods.

It is possible to test the method in other fjord areas along the Scandinavian west coast. In fact, it can be useful also in coastal areas of the Baltic, characterized by runoff conditions. The method can also be useful for other parameters, such as salinity and oxygen or salinity and nutrients. Perhaps more important to consider is that this analytical method can be applied to national and regional monitoring data, where observations cover decades of time.

For the Bornö Station data, there are still a few problems to explain, such as the mixing processes at mid-depths and the near bottom hydrographic clockwise rotation. The time series is indeed unique in Sweden due to its high sampling frequency and the fact that it has been continuously maintained for half a decade.

Acknowledgement

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