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Long-term temperature and salinity records from the Baltic Sea transition zone

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The digitization of temperature and salinity data from lightships and coastal stations in the North Sea–Baltic Sea transition zone allows for multi-station and long-term studies of the oceanographic conditions of the last century. The salinity records, in combination with tide gauge records, are analyzed to demonstrate the development of a major inflow to the Baltic Sea, in terms of surface salinity, changes in stratification throughout the transition zone, and variations in the water level gradient in the zone. Also, temperature and salinity variations for years 1900–1998 are analyzed and show a 0.7 °C warming at the Drogden station towards the end of the 20th century, and no large change in salinity. The temperature change is largest in the winter and spring.

Introduction

The Baltic Sea is experiencing climate changes (The BACC Author Team 2008). To understand these changes, detailed measurements of previous hydrographic conditions are of high value. This study focuses on the temperature and salinity of the only open boundary to the Baltic Sea, the transition zone to the North Sea. Measurements of temperature and salinity have been conducted from a dense network of lightships and coastal stations since the year 1880 (Fig. 1). The data from individual stations have been investigated in numerous studies (e.g. Pettersson 1931, Svansson 1975, Stigebrandt 1984), while long-term multi-station studies have been limited, most likely by the amount of work required to analyze paper records of data. Many of these high quality data are available in digital form. This paper presents a set of available digital data and gives examples of how the data allow for description of the temporal and spatial details of salinity in a major inflow event to the Baltic Sea and analysis of the long-term variations in the transition zone. For a more general introduction to the transition zone, as well as information on other observations in the area, *see* e.g. Kullenberg (1983) and Rodhe (1998).

Study area and materials

The transition zone is the Baltic Sea's only open boundary to the world ocean and consists of Kattegat, the Great Belt, the Little Belt and the Sound. It is characterized by narrow straits and

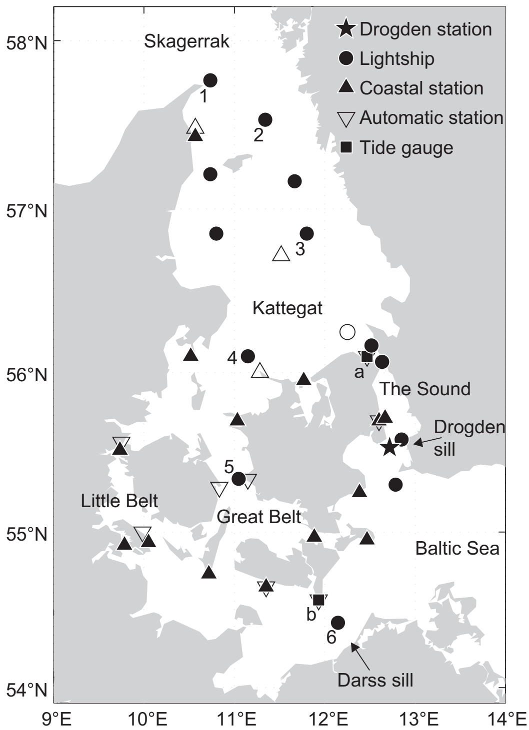

Fig. 1. The transition zone. Stations with data available during the 1951 inflow are marked with filled symbols, other stations with open symbols. The lightships are marked with numbers: (1) l/s *Skagens Rev*, (2) l/s *Læsø N*, (3) l/s *Anholt*, (4) l/s *Kattegat SW*, (5) l/s *Halsskov Rev*, (6) l/s *Gedser Rev*. The tide gauges are (a) Hornbæk and (b) Gedser. The Drogden station was a lightship until 1937, when it was replaced by a permanent station.

shallow sill depths (8 m at Drogden sill and 18 m at Darss sill, *see* Fig. 1), and the water exchange to the Baltic Sea is governed by fresh water forcing, sea level differences, and the topography in this zone. On average a two layer system is seen, stratified with brackish water from the Baltic Sea flowing out in the surface and a compensating, high salinity bottom current. The inflow of high saline water is limited by the topography, and only during special events will large amounts of high saline water cross the sills and flow into the Baltic Sea. The inflow event of 1951 was the largest observed in the 20th century. It lasted for 25 days, from 25 November to 19 December 1951, with a precursory period of 12 days, and was caused by a combination of preceding low sea levels in the Baltic Sea and three weeks of strong westerly winds (Wyrtki 1954, Matthäus and Franck 1992, Schinke and Matthäus 1998). Detailed salinity observations from this inflow event are presented in this paper.

On long time scales, the Baltic Sea is in balance with the world ocean and the atmospheric forcing. The time scale is about one year for heat, and thus temperature, and 30 times longer for salinity (Stigebrandt and Gustafsson 2003).

The study area is heavily loaded with ship traffic, and the systematic use of light towers for navigational purposes was initiated in 1560. From 1829, this system was supplemented by semi-stationary lightships in places where light towers could not be established, and most of these anchored ships have made oceanographic observations from 1875 onwards. The ships were withdrawn in the 1970s and 1980s (Hahn-Pedersen 2003).

The Danish lightship data (at the Danish Meteorological Institute (DMI)), have been digitized since the year 1931 (Sparre 1984), and are available for scientific use. Earlier data can be found in nautical-meteorological annuals of the Danish Meteorological Institute. The digital data include vertical profiles of temperature and salinity, waves, surface currents, and meteorological observations, all with daily resolution (measured at 7 or 8 a.m. local time). The data from Swedish ships are currently being digitized by the Swedish Meteorological and Hydrological Institute (SMHI) (J. Szaron (SMHI) pers. comm.), and vertical profiles of temperature and salinity, as well as currents at the surface and at one deep level, are available at variable temporal resolution (sub-daily to monthly), with some time series going back to 1924.

Besides the lightships, temperature and salinity have also been measured daily at Danish coastal stations, but only at one depth (surface). DMI has paper records of these data in the nautical-meteorological annuals back to 1873, and digitized data going back to 1931. Before 2000, the stations were regularly maintained and both temperature and salinity measurements are of high quality, hereafter the stations were replaced by automatic stations where only the temperature measurement is reliable.

The observation network is dense in the transition zone (Fig. 1), with much fewer stations in

Skagerrak and the surrounding seas. The number of observing lightships with digitized data was at its maximum (12–14) in the 1930s, 1950s and 1960s, whereas the number of coastal stations remained between 9 and 14 from 1931 to 1999 (Fig. 2). Note that the Drogden station started as a lightship, but was replaced by a permanent station in 1937. This record is digitized from 1900 to 1998, thus marking the longest digitally available high resolution sea temperature and salinity record in the area.

The measurements are generally expected to have accuracies of 0.2 °C and 0.1‰* for temperature and salinity, respectively (Andersen 1994). However, errors and complications are introduced, most importantly because of uncertainties in the depth determination for below-surface data (especially in case of strong currents), changes in instrumentation and personnel, and re-deployment of the lightships at new sites. Also, the coastal stations have mostly been placed in harbors. We have compared the monthly mean surface temperature and salinity records with the data from neighboring stations and with the data available from ICES (www.ices.dk/ocean), and found that the salinity values agreed very well, while some of the coastal data showed a larger seasonal cycle in temperature as compared with off-coast measurements.

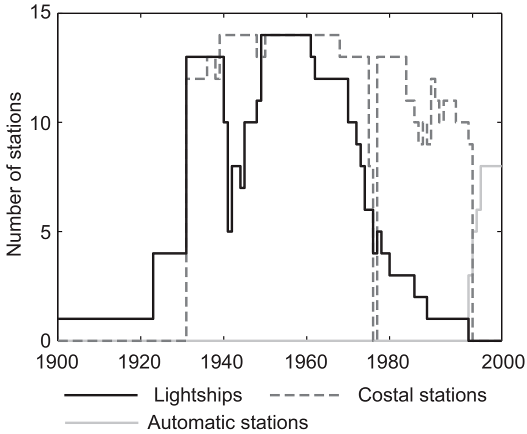

Fig. 2. Number of lightships, coastal stations, and automatic stations per year. Note that Drogden station is counted as a lightship.

Methods

To illustrate the possibilities for analyzing specific events offered by the digital data set, we focus on the daily salinity measurements at selected depths from 6 lightships for the period from 1 October 1951 to 1 March 1952 (Fig. 3), and on all available surface salinity measurements at three selected dates, chosen to show the buildup of the inflow (Fig. 4). A two-dimensional linear interpolation between available data has been calculated and is shown with contour curves.

The inflow is also reflected in the water level difference between the two tide gauges in Hornbæk and Gedser (Fig. 5). The two stations are selected to give the best possible estimate of the water level gradient of the narrow parts of the transition zone. Starting from hourly observations (Hansen 2007), we removed tidal effects by making a 25 hour running mean, and subtracted the 1900–2000 mean to remove differences in the reference level.

To investigate the long-term temperature and salinity development, we calculated the 10-year centered running mean surface temperature and salinity for the Drogden station (Fig. 6). The 10-year average length is chosen to filter out short-term variability while maintaining as narrow filtering window as possible; a 15-year filter has been tested with much the same results but less information at the ends of the time series. To support the analysis of the observations from the Drogden station, similar calculations were made for all other stations (Figs. 6a and b), and for air temperature measurements at the Landbohøjskolen station, Copenhagen, Denmark (55.6°N, 12.7°E, Fig. 6a).

The Drogden station measurements constitute one continuous series at a fixed position, the only major change being the shift from a lightship to a permanent station in 1937. Many of the other stations experienced movements of a few kilometers. To compensate for this effect, and allow for comparison between stations, we subtracted the climatological mean value (Janssen *et al*. 1999) from the salinity data, but not from the temperature data, where the spatial variation in this area is much smaller. Temperature data from coastal stations and the modern automatic stations were merged into one record when the stations were located close to each other.

*Since historic salinity observations were measured in a variety of units without defined conversion to psu, the salinities in this study are left dimensionless.

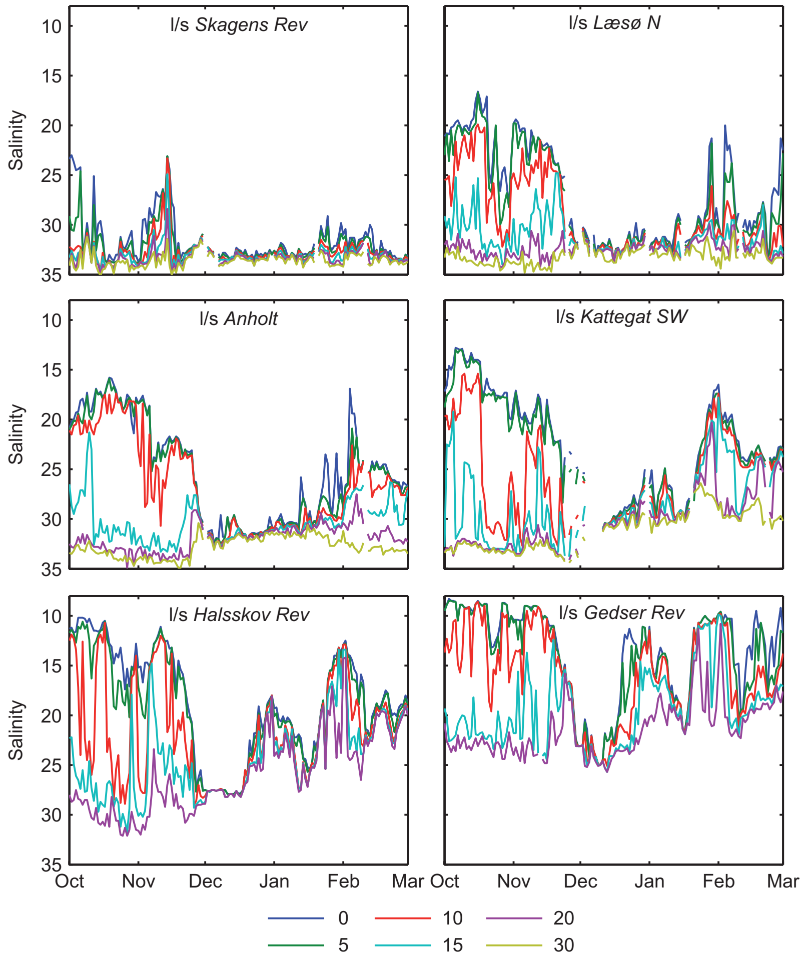

Fig. 3. The salinity at six lightships throughout the transition zone at selected depths and for the period from 1 October 1951 to 1 March 1952. Note that the *y*-axis is reversed.

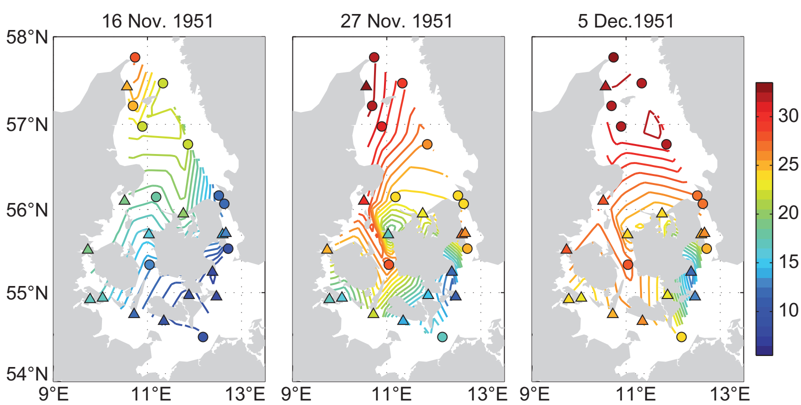

Fig. 4. Surface maps of the salinity on three selected dates during the precursory and inflow periods with contour curves of interpolated salinities (one salinity unit per curve).

In all calculations, 250 measurements per year or 60 measurements per season were required, and one missing year per 10 year mean was accepted.

Results and discussion

The daily salinity data show that the water in the transition zone was stratified before the 1951 inflow event (Fig. 3), with bottom salinities of 33‰ in Kattegat, falling to 23‰ at l/s *Gedser Re*v and surface salinities rising from 10‰ at l/s *Gedser Rev* to 22‰ at l/s *Læsø N*. The thickness of the surface layer was not constant, but was in most cases between 10 and 15 meters. At l/s *Skagens Rev*, the water was less stratified, and had a higher salinity.

The inflow event is clearly seen as a collapse of the stratification, with salinities above 30‰ in the whole water column in Kattegat, 27.5‰ at l/s *Halsskov Rev* and about 23‰ at l/s *Gedser Rev*. These numbers correspond well to the findings of Wyrtki (1954). The salinity at l/s *Gedser Rev* was approximately the same as that of the water that enters the Baltic Sea, as the station is close to the Darss Sill.

After the inflow, the water was again stratified at l/s *Gedser Rev*, while it remained mixed in Kattegat for another month. This made way for a smaller inflow in the middle of January 1952, and then the stratification was re-established all the way to l/s *Anholt*.

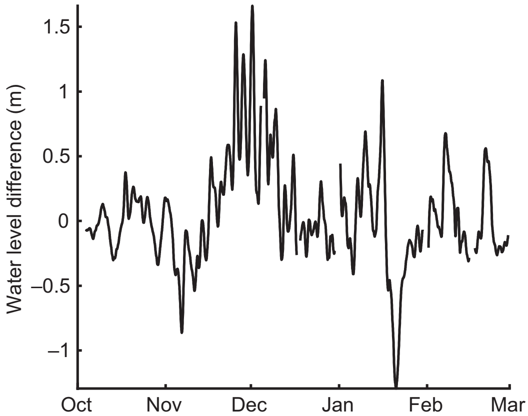

Fig. 5. The 25-hour running mean water level difference between the Hornbæk and Gedser tide gauges for the period from 1 October 1951 to 1 March 1952. Positive values indicate higher water level at Hornbæk than at Gedser, and thus possibilities for inflow.

This salinity pattern was supported by the surface maps (Fig. 4). On 16 November, in the

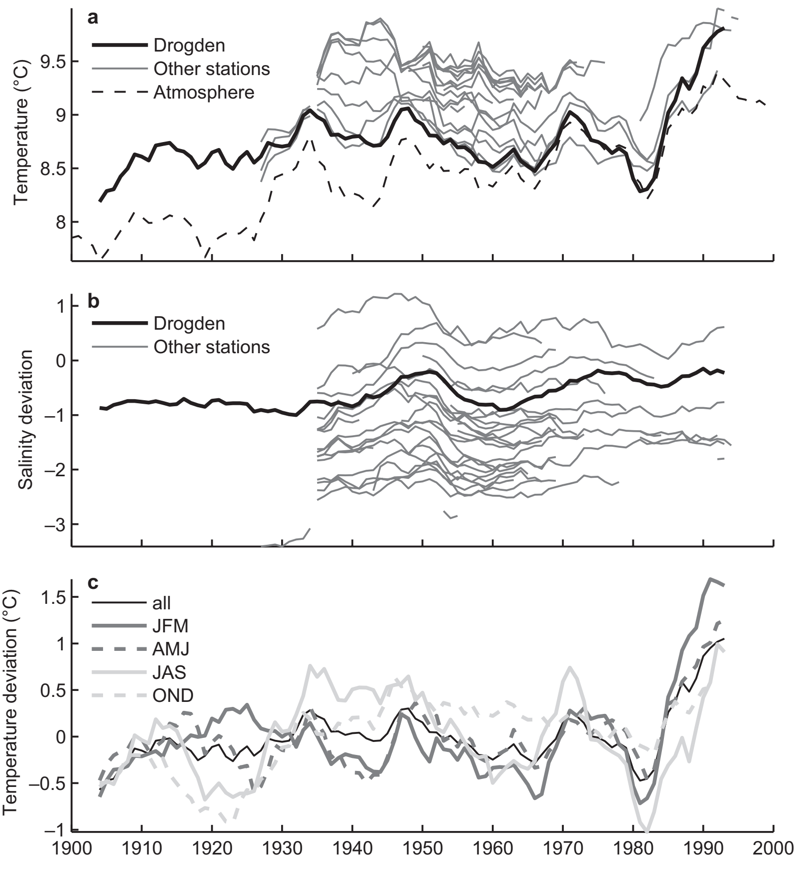

Fig. 6. 10 year running mean surface data. — **a**: temperature. — **b**: salinity deviations from climatology. — **c**: seasonal temperatures (January–March, April–June, July–September, and October–December), deviations from seasonal mean.

beginning of the precursory period, a normal situation with an increase in salinity from 10 at l/s *Gedser Rev* to 25 at l/s *Skagens Rev* was seen. On November 27, the inflow event was in its initial phase, and high salinity water was pressed through the Great Belt and the Sound. On 5 December, the inflow was fully developed, with high salinity water all the way to l/s *Gedser Rev*.

The inflow signal was also clearly seen in the water level measurements, with a water level up to 1.66 m higher at Hornbæk than at Gedser and a mean water level difference of 0.50 m during the 25-day inflow period. This is a large deviation as compared ith the 30-cm mean sea surface topography difference between the central Baltic Sea and Skagerrak (Ekman and Mäkinen 1996) and with the standard deviation of the year 1900–2000 time series of 0.34 m. A simple estimate of the resulting current velocities can be made based on the assumption of a one layer channel flow with friction (Stigebrandt 1980). According to this, the velocity is

$$u = \sqrt{\frac{2g}{1+\frac{2kL}{H}}\Delta\eta} \qquad (1)$$

where g is gravity acceleration, k is a drag coefficient, L and H are the channel length and depth, and $\Delta\eta$ is the water level difference between the ends of the channel. Stigebrandt uses $g = 9.8$ m s^{-2}, $k = 0.003$, $L = 40$ km, and $H = 20$ m, resembling the Great Belt system. With this, the mean and maximum inflow speeds in our case are estimated to be 0.9 m s^{-1} and 1.6 m s^{-1}, respectively.

The 1905–1985 running mean temperature at the Drogden station varied between 8.2 and 9.1 °C, rising to 9.8 °C in 1992 (Fig. 6a). This is generally supported by the data from the other stations when these data are available, and is thus assumed representative for the transition zone. The running mean air temperature shows a trend of 1.0 °C/century for the period 1904–1985, while only 0.1 °C/century for the Drogden station record. Despite of this, the correlation coefficient between the two records is 0.80, and the extra years of the air record, therefore, indicate that the high temperature towards the end of the century is persistent. Omstedt *et al*. (2004) noticed similar trends in records from Stockholm, and the BACC Author Team (2008) showed rising of the air temperature over the entire Baltic Sea.

The change in temperature towards the end of the century was largest in winter and spring, whereas the summer and autumn temperatures were only slightly higher than earlier in the century (Fig. 6c).

The Drogden station running mean salinity record varied within 0.85 throughout the century (Fig. 6b). The salinity was generally high around 1950 and from 1975 onwards, but with no large change towards the end of the period. Again, the data from the other stations support this. The relatively large variations in the mean value between the stations indicate that the climatology for the area possibly could be improved by including these data.

Concluding remarks

The North Sea–Baltic Sea transition zone water temperature and salinity were monitored on a daily basis by a network of lightships and coastal stations in the 20th century, and the major part of these unique time series is available in digital form.

The data allow for detailed studies of past events, here exemplified by the Baltic Sea inflow event of 1951. The horizontal and vertical details of the daily salinity observations enable us to follow the event during the precursory, inflow, and recovery periods, and we see the breakdown of stratification in the transition zone, salinities of up to 23‰ at the entrance to the Baltic Sea, and a water level gradient through the transition zone of up to 1.66 m.

The 10-year running mean surface temperature at the Drogden station showed no significant trend from 1904 to 1985, with running mean values ranging between 8.2 and 9.1 °C, but then a noticeable strong climatic signal at the end of the time series was seen: a 10-year mean value, centered in 1992, of 9.8 °C, 0.7 °C higher than earlier running mean values. Available data from the other stations generally support the observations from the Drogden station, and the signal was strongest in winter and spring. No similar change in salinity was seen.

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