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Surface layer salinity gradients and flow patterns in the archipelago coast of SW Finland, northern Baltic Sea

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ABSTRACT

The highly fragmented Archipelago Sea in the northern Baltic Sea forms part of a sill area between two large sea basins. In addition to the water exchange between the basins, its waters are influenced by runoff, and thus the sea area has both sill and estuarine characteristics. We studied surface layer salinity gradients and their applicability in defining water exchange patterns through and within the region. A broad scale salinity pattern was detected during two sequential years. The spreading of fresh water in the spring was succeeded by a gradual increase in salinity during the summer. Long term data revealed a non-seasonal salinity fluctuation and diminished salinity stratification in the central and northern parts of the study area. We concluded that temporally unrepresentative mean values of salinity alone are inadequate for the purposes of coastal management in this region. In addition, both the range of variation and persistence of the conditions define the character of the transitional and coastal waters.

1. Introduction

The horizontal and vertical gradations of the water properties are characteristic features of the Baltic Sea. The basin has a positive water balance, whose major components are the in- and outflows through the Danish straits (Fig. 1), river runoffs and net precipitation (von Storch and Omsted, 2008). The occurrence and intensity of the water exchange through the straits control much of the physical, chemical and eventual biological processes in the Baltic Sea (HELCOM, 2009). Further, the sea basin is divided by sills into multiple large sub-basins, which complicates the distribution of the Atlantic waters, along with a weak anti-clockwise surface layer circulation (e.g. Alenius et al., 1998; Stigebrandt, 2001; Maslowski and Walczowski, 2002; Myrberg and Andrejev, 2006).

Surface water salinity in the Baltic Sea decreases from ~9‰ in the Arkona basin close to the entrance area to almost freshwater in the northern parts of the Gulf of Bothnia (Bock, 1971; Rodhe, 1998). In general, the less saline waters flow southwards in the surface layer, while the inflowing saline and dense water penetrates into the deeper layers. This results in a permanent stratification with the halocline at a depth of 60–80 m in the largest basin of the Baltic Sea, the Baltic Proper. The gradient of the surface salinity is rather even in the open sea, with the highest variations occurring in the sill areas between the sub-basins (Rodhe, 1998; Stigebrandt, 2001). The mean surface salinity fluctuations of the Baltic are related to the fresh water input and show ~1‰ variation over several decades with no long-term trends (Winsor et al., 2001; Fonselius and Valderrama, 2003). In the northern Baltic Sea salinity exhibits a seasonal cycle in near shore areas as in spring the snowmelt runoff diffuses from the mainland. In summer the water is temperature-stratified, while during spring, autumn and in mild winters the water column shows strong vertical circulation above the halocline.

In the coastal and estuarine regions of the northern Baltic Sea, the complex bathymetry associated with different geomorphic forms sets strong prerequisites upon coastal circulations, resulting in highly variable chemical and physical properties of seawater over space and time (e.g. Kirkkala et al., 1998; Hänninen et al., 2000; Weckström et al., 2002; Erkkilä and Kalliola, 2004). These kinds of transitional changes are ecologically significant with manifold implications for the living environment, fisheries and environmental planning (Anon., 2003; Schernewski and Wielgat, 2004; Nordic Council of Ministers, 2006). One of the most fragmented coastal areas is the Archipelago Sea between mainland Finland and the island of Åland, forming the eastern part of the sill between the Baltic Proper and the Gulf of Bothnia (Fig. 1). The

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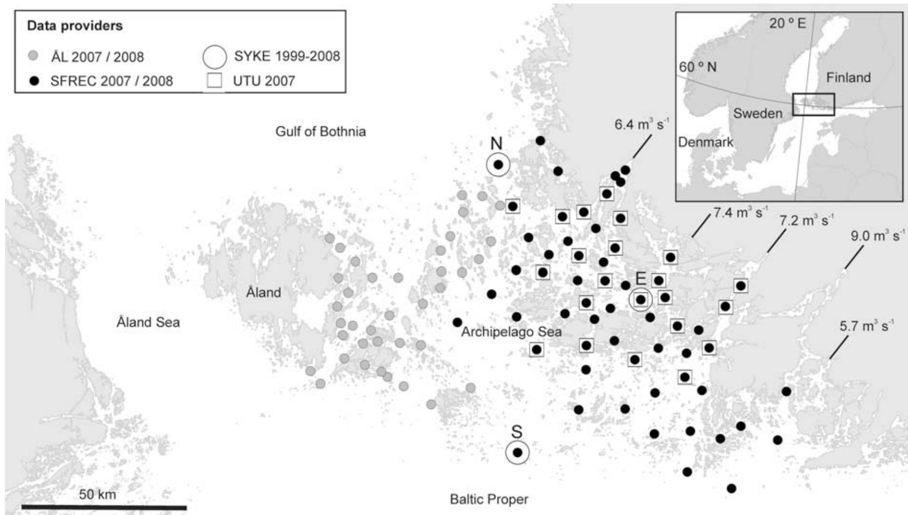

Fig. 1. Location of the study area and the observation stations. For the abbreviations of the data provider, see Table 1. The intensive monitoring stations KORP 200, NAU 2361 and BRÄNDÖ 100 are indicated with the letters S, E and N, respectively. The major rivers of the study area are indicated with their average discharge.

western side of this sill, formed by the Åland Sea between Åland and Sweden, is relatively deep and wide, whereas the Archipelago Sea is a unique coastal area with a mosaic of islands.

The net water exchange through the Archipelago Sea is estimated to be low compared to the Åland Sea (Kullenberg, 1981; Omsted et al., 2004). The baroclinic flows combined with river runoffs and net precipitation are of major importance considering the water exchange between the Baltic Proper and the large gulfs as a whole (Omsted and Axell, 2003). Water exchange through and within the Archipelago Sea is further mixed by estuarine circulation with wind–driven surface currents. Islands and underwater sills form numerous local sea basins at various scales, resulting in a complex transitional system where the fresh water runoff mixes with the brackish sea water of the adjacent main basins.

The intermediate osmotic pressure of the brackish water of the Baltic Sea does not correspond to either a purely marine or limnic environment, with many of the aquatic organisms occurring at the edge of their ecological amplitude. Thus, the horizontal and vertical salinity gradients of the Baltic Sea strongly influence the species composition and abundance of flora and fauna (e.g. Remane and Schlieper, 1972; Bäck et al., 1992; Lappalainen et al., 2000; Hänninen et al., 2003; Gasiūnaitė et al., 2005).

The aim of this paper is to provide detailed quantitative information about the surface salinity gradients and their temporal fluctuations in the Archipelago Sea – phenomena that create relevant dynamic ecological thresholds in the area. Further, we introduce an interpolation method modified for the archipelagian environment and discuss the applicability of salinity monitoring data in determining long term flow properties through the sill area of the Archipelago Sea.

We identified three main issues concerning the surface layer salinity: gradients, persistence and the magnitude of fluctuations. These issues were studied through three approaches. First, the general surface salinity patterns between the mainland and Åland Island were outlined using salinity data from different sources. The four contoured salinity raster maps show the salinity gradients in July–August in 2007 and 2008. Second, the succession of the salinity gradients was followed from late spring to early autumn to study the intra-annual persistence of salinity in greater detail in the north eastern Archipelago Sea. Third, to attain an inter-annual perspective, salinity time series data from three intensively monitored stations representing the southern, eastern and northern Archipelago Sea were used.

2. Materials and methods

2.1. Physical geography of the study area

Archipelago coasts are typical in the northern Baltic Sea (Frisén et al., 2005). The Archipelago Sea in SW Finland consists of 25 000 islands larger than 500 m^2 and 14 400 km of shoreline in an area of ~10 000 km^2 (Granö et al., 1999) (Fig. 1). The area is structured by fragmented bedrock that has a relative elevation range of about 200 m. The bedrock base is partially covered with till, glaciofluvial deposits and marine sediments. The deepest basins in bedrock faults provide channels for water currents through and within the area. The mean depth of the Archipelago Sea is estimated to be only 23 m. The depth is typically ranging from 0 to 50 m, but some deeps and fault lines exceed 100 m. The Åland Sea in the west is an ~40 km wide strait between the Archipelago of Stockholm and the island of Åland. Its maximum depth is 301 m, but there is a sill at a depth of 70 m at the southern end of the channel. In the Archipelago Sea, the highest surface-layer water temperatures (~20 °C) occur near the mainland in August, while the mean annual period of permanent ice cover extends to 100 days (Seinä and Peltola, 1991). According to the meteorological data from the island of Utö (close to the observation station S in Fig. 1), December is the windiest month with an average wind speed of 8.6 m s^{-1}, while May, June and July show the lowest average wind speeds (Drebs et al., 2002).

2.2. Description of the salinity data

2.2.1. The Archipelago Sea in July–August in 2007 and 2008

The Southwest Finland Regional Environment Centre (SFREC) collects annual water quality data from 61 stations in the eastern part of the Archipelago Sea (see Fig. 1 and Table 1), comprising three sampling visits in the period between July and August. At most stations only the surface layer is sampled, and salinity is rarely measured, since the analyses are focused on indications of eutrophication. However, extended surface-layer (1 m) conductivity sampling was carried out from 27 and 56 stations respectively, in 2007 and 2008. Conductivity was analysed by the laboratory of the Water Protection Association of Southwest Finland, according to the standard SFS-EN 27888. The conductivity values were compensated to 25 °C and the laboratory results were given in mS m^{-1}