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Salinity variations of the surface water at the southern coast of the Baltic Sea in years 1950–2010

Józef Piotr Girjatowicz, Małgorzata Świątek*

Hydrography and Water Management Unit, University of Szczecin, Ul. Mickiewicza 16, 70-383 Szczecin, Poland

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ABSTRACT

This work aims to examine trends in surface water salinity along the southern Baltic Sea coast over the period between 1950 and 2010. Major trends in hydrological and meteorological factors that potentially influenced variations in salinity, and their relationships with salinity are examined as well. The study is based on monthly surface water salinity values from Międzyzdroje, Władysławowo, Hel and Gdynia (1950–2010), monthly atmospheric precipitation totals from Świnoujście, Hel and Gdynia (1951–2010), annual values of the North Atlantic Oscillation (NAO) index (1951–2010), monthly number of days with particular atmospheric circulation types over Poland according to Lityński classification (1951–2005), and monthly discharge values for Vistula and Oder rivers (1951–2010). Pearson correlation analysis and linear regression analysis were applied in this study.

A decrease in surface water salinity along the southern Baltic Sea coast was observed over the study period, especially pronounced in the eastern part of the coast. Winter salinity trends at Władysławowo, Hel and Gdynia were considerably statistically significant even at $\alpha=0.001$ level. For the remaining seasons, salinity trends were weaker, but still significant, at least at $\alpha=0.05$ level. For Międzyzdroje, however, salinity trends are not significant.

Even though increasing tendency prevailed over the study period, no statistically significant trends were detected in atmospheric precipitation sums, nor in river discharge. This probably results from a high annual variability in these parameters. An increasing trend in Vistula river discharge was observed in the last decade of the 20th century, i.e. a period of pronounced salinity drop.

1. Introduction

The salinity of the Baltic Sea is of great importance for the marine ecosystem. Some species require certain level of salinity during their life stages. For example, cod eggs need minimum salinity of 11.5 psu for buoyancy (BACC Author Team, 2008). Currently most taxa in the Baltic Sea experience physical stress because the water is too fresh for marine species, and too salty for freshwater ones simultaneously (Meier et al., 2006; BACC Author Team, 2008; BACC II Author Team, 2015). Additionally, introduction of non-indigenous marine species could be expected due to salinity decrease, and the simultaneous increase in water temperature (Strömer, 2011). Profound changes in deep water environments of the Baltic Sea were observed during the 1980s, when there were only rather weak inflows of highly saline and well oxygenated water (Matthäus, 1995). Saline water supply to the Baltic Sea was weakened during the 1980s to 1990s (Meier and Kauker, 2003b). From February 1983 to January 1993 there were no strong inflows from the North Sea (BACC Author Team, 2008; Leppäranta and Myrberg, 2009). This resulted in decreased Baltic Sea salinity, especially in the eastern part of the Gotland Deep, and decreased water ventilation, which ultimately resulted in a decrease in oxygen levels (BACC Author Team, 2008).

Data on salinity variations along the southern Baltic Sea coast, and the associated causal mechanisms, can be found mostly in monographic treatments on hydrological and meteorological conditions of the Pomeranian Bay (Majewski, 1974), Gulf of Gdańsk (Młodzińska, 1974; Cyberska, 1990), and in other areas of the south part of Baltic (BACC Author Team, 2008, Leppäranta and Myrberg, 2009; Schernewski et al., 2011; BACC II Author Team, 2015). Other works on the southern Baltic Sea salinity also mention changes in salinity (Piechura, 1974; Girjatowicz, 2008; Rak and Wieczorek, 2012). Trends in salinity variations in the Baltic Sea waters over the second half of the 20th century were analyzed by Nehring and Matthäus (1991), Samuelsson (1996) and Matthäus et al. (2008). Meier and Kauker (2003a, 2003b) examined trends in salinity of the Baltic Sea over the course of the entire 20th century.

* Corresponding author.
E-mail address: malgorzata.swiatek@univ.szczecin.pl (M. Świątek).

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The source of the Baltic Sea water salinity is an oceanic water flowing in through the Danish Straits (Matthäus, 2006; BACC Author Team, 2008, Leppäranta and Myrberg, 2009). The understanding of the processes associated with the influx of saline water in the transitional zone between the Baltic and the North Sea, and within the Danish Straits, has been given a high importance (Stigebrandt, 1983; Gustafsson, 1997; Madsen and Højerslev, 2009). These processes are highly significant not only for the Baltic Sea salinity, but also for its oxygenation and nutrient enrichment, especially in deep waters. Dispersal of saline waters in the Arkona Basin, which directly influences not only the salinity along the southern Baltic coast, but also the whole Baltic Sea, has been examined in detail (Burchard et al., 2005; Lass et al., 2005).

Salinity in the Baltic Sea decreases with the increasing distance from the Danish Straits. As the water circulation patterns in the major Baltic Sea basins tend to be anticlockwise, therefore in the eastern parts of these basins the upper water layer salinity is usually higher than in the western ones (Leppäranta and Myrberg, 2009). A high net freshwater supply to the Baltic Sea leads to an outflow to the North Sea of large volumes of a low density brackish surface water, which constitutes about 60% of total freshwater supply to the North Sea. After leaving Kattegat, low salinity Baltic Sea waters flow along the Swedish and Norwegian coasts. On the other hand, more saline and dense (heavier) water from the North Sea enter the Baltic Sea as the bottom layer. During strong North Sea water inflows to the Baltic Sea, approximately one third of total water volume flows through Drogden Sill, and the rest through Darss Sill. It is possible, however, for these volumes to be equal, or even for the Drogden Sill inflow to be higher (Leppäranta and Myrberg, 2009). Waters entering the Baltic Sea during strong inflows flow into the central Baltic between Bornholm and the southern coast of Sweden (Matthäus, 2006). Also the outflow of fresh waters from the Baltic Sea takes place along the Swedish coast (BACC Author Team, 2008). Cases are known to occur, however, when saline waters flow along a different route, e.g., via Słupsk Channel recorded in January 2003 (Meier, 2007).

The Baltic Sea halocline depth is found usually between 40 and 80 m. In the northeastern Gotland Deep it occurs at 68 m, and within Gdańsk Deep even at 75 m (Meier, 2007). In the shallow southwestern basin it is located considerably shallower. Overall, the halocline depth depends on advection, wind strength and its direction, convectional mixing and sill depth (Leppäranta and Myrberg, 2009).

Some works aim to explain the Baltic Sea salinity changes as depended on atmospheric circulation (Matthäus and Schinke, 1999; Zorita and Laine, 2000) and other factors, e.g., variations in fresh- or saline water influx associated with the Danish Straits sea level (Stigebrandt and Gustafsson, 2003). Forecasts of future Baltic Sea salinity variations were also attempted (Kilkus et al., 2006; Meier et al., 2006; Neumann and Friedland, 2011).

Salinity forecasts for 2071–2100 propose various scenarios for salinity trends. One scenario that indicates the highest positive change is statistically insignificant, whereas a scenario forecasting the largest salinity drop points to profound changes, for instance a salinity within Bornholm Basin comparable to that of today's northern Bothnian Sea (Meier et al., 2006).

It is important to be aware, that an understanding of causes impacting to the salinity of the Baltic Sea is very limited and more detailed investigations are needed. The strongest impact on the Baltic Sea salinity is made by: rainfall influencing riverine discharge (Leppäranta and Myrberg, 2009; BACC II Author Team, 2015), as well as winds and atmospheric circulation (Meier and Kauker, 2003b) and inflows of strongly highly saline water (Matthäus, 2006; BACC Author Team, 2008, Leppäranta and Myrberg, 2009).

The aim of this paper is to present and explore the contemporary trends in the sea water salinity, and trends in selected hydrological and meteorological factors along the southern Baltic coast, using linear regression analysis, and the correlation of the observed changes, which could indicate mutual relationships between the observed trends. Interrelationships between salinity and hydrological and meteorological factors were also investigated, using the longest salinity time series available for the southern Baltic Sea (1950–2010).

2. Materials and methods

This work utilizes monthly, seasonal and annual surface water salinity values from four stations located along the southern Baltic Sea coast: Międzyzdroje, Władysławowo, Hel and Gdynia, with a 1950–2010 time span (Fig. 1). Salinity measurements were carried out on the coastal stations belonging to Institute of Meteorology and Water Management IMWM (Instytut Meteorologii i Gospodarki Wodnej IMGW). Water samples for salinity measurements were collected daily (every day) at 0600 UTC from permanent sampling spots: from Międzyzdroje pier approximately 20 m from the shoreline, and in Władysławowo, Hel and Gdynia – from the seaward side of the harbor wave breaker. These locations have not changed throughout the all period of measurement. The responsibility for the homogeneity of a data series and collecting it is the duty of the Polish Hydrological and Meteorological Service being part of IMWM, from which the data has been obtained.

Surface water salinity and precipitation totals are derived from Hydrographic Yearbooks of the Baltic Sea (1950–1970) and from other publications (Marine report on Hydrologic Conditions and Weather, 1961–1990; Environmental Conditions of the Polish Zone of the Baltic Sea, 1991–2010). Atmospheric precipitation data from Świnoujście, Hel and Gdynia (time span 1951–2000) were also used. Precipitation sums for Władysławowo were extrapolated from Hel. The North Atlantic Oscillation (NAO) index values used in this paper are derived from the online database available from University of East Anglia (time span 1951–2010), and atmospheric circulation types for Poland (time span 1951–2005) are taken from the circulation calendar by Pianko-Kluczyńska (2006) according to Lityński classification (1969).

In order to define a circulation pattern, Lityński (1969) used three numerical patterns of equal probability (zonal circulation index, meridional circulation index, and pressure index for Warsaw), and plotted their frequency curves. The first two indices describe the direction of air mass advection; they were calculated for an area between 40° and 65°N as well as between 0° and 35°E. Consequently, a total of 27 different circulation patterns were obtained: Nc, No, Na, NEc, NEo, NEa, Ec, Eo, Ea, SEc, SEo, SEa, Sc, So, Sa, SWc, SWo, SWa, Wc, Wo, Wa, NWc, NWo, NWa, 0c, 0o, and 0a. The N, E, S and W letters refer to main geographical coordinates, while a, c and o refers to pressure classes denoted as: c - cyclonic, o (zero) – close to normal, a – anticyclonic. Vistula and Oder rivers discharge data represents the period between 1951 and 2010 (Fal et al., 2000; Environmental protection, 1995–2010).

Regression method was used to determine and examine the statistical significance of trends in salinity. Trends were determined as a linear regression. Determination coefficients were calculated, and their statistical significance were tested using Fisher-Snedecor test. Our null hypothesis was that the regression coefficient equals zero, i.e., in a considered study period, one variable does not influence the other. In cases when this hypothesis could not be rejected, influence of variable X on variable Y could not be confirmed using statistical methods. A regression/trend is statistically significant only when the degree of freedom $V_1=1$ (one independent variable) and $V_2=n-2$, and for the assumed significance levels $\alpha=0.05$ (5%) or $\alpha=0.01$ (1%), the