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Increased frequency of wintertime stratification collapse events in the Gulf of Finland since the 1990s

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ABSTRACT

Since the 1990s, an increased frequency of stratification collapse events in the Gulf of Finland has been noticed, when the density difference between near-bottom and surface waters fell below 0.5 kg m^{-3}. Such stratification crashes occur in the winter months, from October–November to March–April, when saline and thermal stratification decrease compared to the summer period according to the well-known seasonal cycle. The stratification decay process is forced primarily by (1) the westerly-southwesterly wind stress, which causes anti-estuarine straining, and (2) direct wind mixing proportional to the wind speed cubed. The potential energy anomaly (PEA) is occasionally reduced from the average winter level of 70 J m^{-3} (per unit volume; 4.9 kJ m^{-2} per unit area of 70-m water column) to nearly zero, manifesting the stratification collapse, when the current-straining work and wind-mixing work significantly exceed their average levels. Increased collapse frequency is caused by the shift of wind forcing. Namely, the average bimonthly cumulative westerly-southwesterly wind stress in December and January has increased from 1.7 N m^{-2} d during 1962–1988 to 3.7 N m^{-2} d during 1989–2007, yielding a reduction in PEA during these two winter months of about 4.4 kJ m^{-2} between the periods. The other component of the reduction in PEA, wind mixing work per unit surface area, has also increased by 4.6 kJ m^{-2} since 1999 for these two months.

1. Introduction

Kullenberg (1981), among others, has noted that the Gulf of Finland (Fig. 1) is a "true estuarine embayment" of the Baltic Sea multi-basin brackish water system. With its dimensions (length of about 400 km and width from 48 to 135 km over most of the length), low salinity at the entrance (from 6–7 g kg^{-1}/on the reference-composition salinity scale, IOC et al., 2010/at the surface to 8–11 g kg^{-1} in the bottom layers below 80–100 m), and almost absent tides, the gulf is, however, quite unique among the world estuaries (Hansen and Rattray, 1966; see also the reviews by Alenius et al., 1998; MacCready and Geyer, 2010). In the west, the gulf has a free connection, 60 km wide and about 90 m deep, to the Baltic Proper, the central basin of a system that undergoes in its northern part large variations of the stratification (e.g. Elken et al., 2006; Matthäus, 1984). River discharge is concentrated in the eastern part of the gulf, where at the estuary head the Neva River drains an average of 2400 m^3 s^{-1} of freshwater, about two thirds of all of the freshwater imported to the gulf. Despite the large dimensions, compared to the internal Rossby radius (typical scales from 2 to 4 km, Alenius et al., 2003) and variable cyclonic circulation with a number of loops, eddies, fronts, and upwelling events (Andrejev et al., 2004; Elken et al., 2011; Lehmann et al., 2002; Lips et al., 2009; Pavelson et al., 1997, Zhurbas et al., 2008), the along-basin salinity and density gradients are still very profound, especially when studied on the basis of temporally mean values over the seasons.

Salinity and stratification of the Gulf of Finland undergo strong seasonal variations (Haapala and Alenius, 1994). In the period of highest thermal stratification in summer, after the spring maximum of freshwater discharge, the surface salinity is decreased from the winter values of about 6.5 g kg^{-1} down to about 5.5 g kg^{-1} in the central part of the gulf. At the same time, the deep salinity at around 90 m depth is increased from about 7.5 g kg^{-1} to about 10 g kg^{-1}, forming a kind of salt wedge. While a decrease of surface salinity during and after the period of high river discharge is a common feature of most of the estuaries (e.g. Hong et al., 2010; Kimbro et al., 2009; van Aken, 2008), a simultaneous increase of deep salinity is quite unique. The latter can be partly explained by the seasonal conditions of the adjacent larger sea basin, the Baltic Proper, where halocline goes deeper during the winter due to convection and entrainment from the layers above (e.g. Reissmann et al., 2009); in the Northern Baltic Proper deep salinity decrease in winter may exceed 1 g kg^{-1} below the halocline down to the bottom (e.g. Matthäus, 1984).

Interannual changes of the oceanographic conditions of the Gulf of Finland reflect the variations in the large-scale forcing factors. Regarding direct climate forcing, stronger zonal (westerly) winds have been identified in the 1990s and 2000s compared to the 1970s and 1980s. A number of climatic indices, including those at the regional level like the Baltic Sea Index (BSI, Lehmann et al., 2002, 2011) and the Baltic Winter Index (WIBIX, Hagen and Feistel, 2005) also reveal

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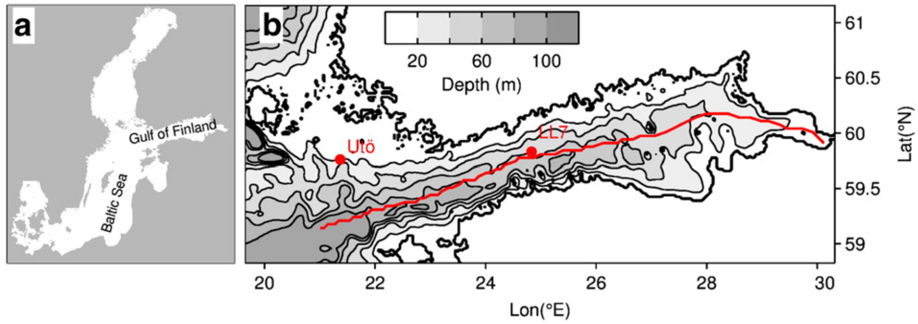

Fig. 1. A map of the Baltic Sea (a) and close-up of the Gulf of Finland (b). Locations of the HELCOM monitoring station LL7 (BMP F3), the Utö weather station, and the main axis of the Gulf (red line) are shown. The depth contours are drawn from the gridded topography (Seifert et al., 2001) in metres.

such a change. Combined with the changes in heat flux, net precipitation, freshwater discharge, and human impact, marine ecosystems have responded with variable regimes (e.g. Dippner et al., 2012, Voss et al., 2011).

A specific feature of the Baltic Sea is the intermittent nature of the large inflows of highly saline water from the North Sea (MBIs, Major Baltic Inflows, after Matthäus and Frank, 1992). With a stronger and shallower halocline in the Baltic Proper, more saline water can be transported to the Gulf of Finland, increasing the strength of stratification. The opposite occurs during the stagnation periods when MBIs are missing for many years. While deep layers of the Baltic Proper are supplied with oxygen only during MBIs by lateral advection, those of the Gulf of Finland are also ventilated during the stagnation periods when stratification is weaker (e.g. Conley et al., 2009, Kahru et al., 2000). As an example, on the basis of monitoring data for 1965–2000, Laine et al. (2007) have shown a decrease in salinity and density stratification until the early 1990s and a slight increase afterwards, while opposite changes in the oxygen content took place. Vermaat and Bouwer (2009) have proposed that a reduced ice extent during the recent period has favoured vertical mixing, causing a reduction of the extent of hypoxic bottoms.

Among the complex ventilation processes (Meier et al., 2006), convection due to surface cooling, turbulent erosion from surface towards deeper layers, and turbulent shear mixing are usually considered as most important in the Gulf of Finland. In summer, a significant decay of observed stratification has been explained by persistent south-westerly winds, creating a temporary estuarine circulation reversal (Elken et al., 2003). With reference to other estuaries, Blumberg and Goodrich (1990) showed for the Chesapeake Bay that wind-induced current shear is more effective in destratification than surface-generated turbulence. In the framework of estuarine dynamic concepts, Scully et al. (2005) presented a conceptual model for the exchange processes during up-estuary and down-estuary winds and pointed to the role of wind-induced current straining interacting with along-basin density gradients.

Observational data are quite rare for winter, during the period of the weakest stratification in the Gulf of Finland. Still, events of complete stratification collapse (reaching the well-mixed state) can be frequently observed during recent winters. These situations, when the bottom-to-surface density difference (and consequently, the potential energy anomaly) decreases drastically to almost zero, cannot persist over longer time periods since longitudinal gradients of mean density restore the stratification.

The aim of the paper is to study the stratification collapse events in the Gulf of Finland using observational data and to find the governing wind forcing mechanisms for such events. Further on, the purpose is to assess whether it is likely that the collapse events have also occurred during non-sampled times and whether there is a change of frequency of complete destratification related to the changing climate factors.

Our hypothesis is that purely vertical mixing processes in the Gulf of Finland are not always strong enough to cause complete destratification as observed, and wind-induced current straining is important. To evaluate the role of the different mechanisms, we use the balance for the potential energy anomaly (PEA), that is, the vertical integral of the potential energy density in reference to a well-mixed state (Burchard and Hofmeister, 2008; Simpson et al., 1990; Wang et al., 2011). The "normal" wintertime PEA values are determined from the hydrographic observations and they manifest the stratification under average forcing conditions. We further study changes in PEA due to straining by wind-induced currents and direct wind mixing using the data from long-term wind observations. The straining effect is estimated from the established correlation between the specific wind stress component and the time-dependent amplitude of the "strain" EOF mode of along-basin currents. The wind-to-EOF dependency is found from a numerical model. The effect of direct wind mixing is evaluated from the cubic relation to the wind speed. Changes in PEA are calculated for the ice-free periods of each winter. The paper ends with a discussion of the relation of PEA changes to the climatic forcing data.

2. Data and methods

2.1. Observational data

The basic data set describes stratification conditions in the Gulf of Finland. We used long-term data of hydrographic observations for the period 1900–2008 extracted from the ICES (International Council for the Exploration of the Sea) international database. The data are mainly from the standard depths (e.g. Haapala and Alenius, 1994; Janssen et al., 1999). Deeper layers have less data coverage than the surface, especially in the first half of the period. We focused on the data around HELCOM monitoring station BMP F3 (historically known also as LL7, $\varphi = 59.8465°$ N, $\lambda = 24.8378°$ E). This station is located in the deepest part of the central area of the gulf near the transect Tallinn-Helsinki, with a depth range of 80–110 m. For inclusion of the data we adopted a search radius of 15 km, well below the dimensions of the gulf. The ICES data were complemented with 38 profiles from the national CTD data set, observed since 1984. They were also converted to the standard depths to maintain homogeneity with historical data.

The main aim of the analysis was to characterize the strength of stratification over time, especially during the winter period. The basic approach is to investigate the near-bottom ρ_b to surface ρ_s density difference $\rho_b - \rho_s$, as can be found in many studies (e.g. Laine et al., 2007). For the deep values, we used the closest depth to 70 m below