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Winter upwelling in the Gulf of Finland, Baltic Sea

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Abstract Traditionally, upwelling-related studies in the Baltic Sea have been limited to the period from May to September. Based on wintertime in situ measurements at two nearshore locations in the Gulf of Finland, clear evidence of winter "warm" upwelling events was detected and analysed. The process was very common. At a 10 m deep location, upwelling caused water temperature (T) to switch from 0—1 to 4—5°C and salinity (S) to switch from 4.5 to 6 PSU; at 20 m depth it caused a switch in T between 1 and 2—4°C and in S between 5.5 and 6.8 PSU. Differently from summer upwelling, T and S variations were positively correlated to each other. Salinity variations remained roughly the same throughout the winter, whereas T differences were higher in winter onset, then decreased to ca. 1°C, and increased again after the process reversed to summer-type upwelling in April—May. Based on analysis of SatBaltyk (January to March) sea surface temperature and salinity product imagery, winter upwelling occurrence along the North Estonian coast was 21—28% over 2010—2021, and slightly less along the Finnish coast. Regarding S variations, winter upwelling occurred with roughly similar frequencies and impacts in the northern and southern parts of the gulf. However, the impacts on T and sea ice conditions were highly asymmetrical. Upwelling kept the Estonian coast ice-free longer and water temperatures slightly higher than at the Finnish coast. Winter upwelling as a phenomenon has long been ignored and therefore probably underestimated.
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1. Introduction

Upwelling is an oceanographic phenomenon that involves wind-driven motion of dense, usually cooler, and nutrient-rich water towards the sea surface, replacing the warmer surface water (e.g. Gill and Clarke, 1974). It can be recorded in many specific areas of the World Ocean, but also in its marginal seas and in larger lakes. In the Baltic

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Sea, on the northern hemisphere, coastal upwelling — the most common upwelling type — is a mesoscale spatially and temporarily variable process, which occurs when wind blows parallel to a coastline on its left (e.g. Alenius et al., 1998). Then, owing to the Coriolis effect of the Earth's rotation and frictional forces, a system of "three currents" (pure wind-current, "midwater" gradient current and bottom current) is generated according to Ekman (1905), where the flow is deflected off the coast, which in turn is balanced by upward flow from deep layers. However, if the coastal zone is very shallow (order of 10—20 m) and gently sloping, there is no room for such a circulation cell and an offshore wind is more effective than an alongshore wind in producing upwelling (also called *Leewirkung* in such a case; Myrberg and Andrejev, 2003). The effect of upwelling is best seen ca. 1—10 km off the coast, however, the upwelled water can later spread over much broader sea areas (e.g. Uiboupin et al., 2012).

Coastal upwellings have been extensively studied in the Baltic Sea since 1970s, firstly based on in situ measurements (Haapala, 1994; Hela, 1976; Lass et al., 1994; Svansson, 1975; Walin, 1972). Because the upwelled water is usually different in its physical and chemical properties from the surface waters, the occurrence of upwelling can be also inferred from satellite imagery, especially from sea surface temperature (SST) images (Bychkova and Viktorov, 1987; Gidhagen, 1987). Starting from around 1990s, rapid advancement in remote sensing techniques, as well as in eddy-resolving hydrodynamic modelling, have enabled achieving qualitatively new insights into the process. Upwelling-prone coastal areas have been detected in the Baltic Sea along with corresponding occurrence statistics, and impacts of upwelling have been analysed (e.g. Dabuleviciene et al., 2018; Delpeche-Ellmann et al., 2018; Kowalewski and Ostrowski, 2005; Krężel et al., 2005; Lehmann et al., 2012; Myrberg and Andrejev, 2003; Zhurbas et al., 2008).

Although upwelling may seem foremost as a prominent summertime event, for instance, when affecting holiday-makers with extremely low water temperatures and rapid variations in bathing conditions, it is not merely a summer process. Because the upwelling-favouring wind conditions do not disappear in autumn or winter, it is reasonable to assume that the process somehow continues, despite difficulties with perceiving it. Although wind-driven hydrodynamic modelling does not necessarily discriminate against winter conditions, such studies have typically covered a period from May to September—October only. In satellite imagery analyses and ecological studies, the winter events have been mostly ignored, too. While summertime upwelling and its impacts have been covered in hundreds of articles concerning the Baltic Sea, the occurrence of winter upwelling is mentioned in only a few.

In situ measurements made by Svansson (1975) between Västervik and Visby (Sweden) showed that upwelling can occur in winter. The studied example was not very clear, however, with up to 0.5°C (warming) effect in temperature (T) and <0.5 effect in salinity (S), but the evidence also included a nearshore rise in pycnoclines and in PO_4 concentrations. Based on in situ measurements, Suursaar (2010) reported that wintertime upwelling-related variations near Letipea Peninsula (North Estonia), 1—2 km off the coast, can include a 2—3°C increase in water temperature, and up to a 2 PSU increase in salinity. SST imprint of winter ("warm") upwelling in satellite imagery has been analysed in the southern Baltic Sea along the Polish coast by Kowalewska-Kalkowska and Kowalewski (2019). They also compared the statistics to those computed using a 3D hydrodynamic model and found the frequency to be between 28 and 43%. In fact, the effects of winter upwelling events have been occasionally analysed in some other seas, too (e.g. in Spain in oceanic conditions; Alvarez et al., 2003), but such studies are nevertheless very rare.

The current study focuses on the Gulf of Finland (Figure 1), which is a fjord-like, nearly 400 km long and 50—130 km wide sub-basin of the Baltic Sea. The brackish water (S between 1—7 PSU) basin is located on the relatively high latitudes (59.2—60.6°N), where dominant westerlies are related to the North Atlantic Oscillation (NAO) positive phases (NAO+) and sub-dominant easterlies are related to the NAO- episodes (Jaagus and Suursaar, 2013; Kont et al., 2007). The gulf has a surface area of 29 571 km^2, and an average depth of 37 m with maximum values reaching 120 m in its western part, enabling vertical stratification both in terms of T and S. Fresh water enters the gulf from the East, whereas salt is predominantly transported along the deep parts of the sea from the South-West (e.g. Alenius et al., 1998; Soomere et al., 2008). Owing to its elongated shape, an upwelling can occur along both coasts; westerly winds evoke upwelling along the Finnish coast, and easterly winds along the relatively straight, 350 km-long North Estonian coast (Suursaar and Aps, 2007; Kikas and Lips, 2016). Moreover, upwelling at one coast is usually paired with downwelling at the opposite coast (e.g. Zhurbas et al., 2008). However, downwelling seems to have hardly distinguishable imprint and a lesser impact on sea surface properties. Due to statistically prevailing westerlies (Soomere et al., 2008; Suursaar, 2013), the occurrence of upwelling is expectedly slightly higher on the northern shore, reaching ca. 20—25% (Lehmann et al., 2012; Myrberg and Andrejev, 2003). Yet the upwelling appearances along the Estonian coast seem to be more prominent than those on the Finnish side — probably due to different slopings at the opposing coasts of the gulf (e.g. Delpeche-Ellmann et al., 2018) and different climatological backgrounds of westerlies and easterlies (Jaagus and Suursaar, 2013). For instance, dramatic, up to 20°C water temperature variations and salinity variations between 3.6 and 6.2 PSU have been observed in the Letipea — Kunda coastal area in summer 2014 (Suursaar, 2020).

The aim of the study was to analyse in situ measurements performed in two different locations in the Gulf of Finland in 2009 and 2014, which included plenty of evidence of wintertime upwelling occurrence (Figure 2). The corresponding spatial patterns were characterized based on SST satellite imagery and surface salinity products from the SatBaltyk system. We also discuss the general implications of such "warm" upwelling events on upwelling detecting procedures, but also on thermohaline, ecological and sea ice conditions in the Gulf of Finland.

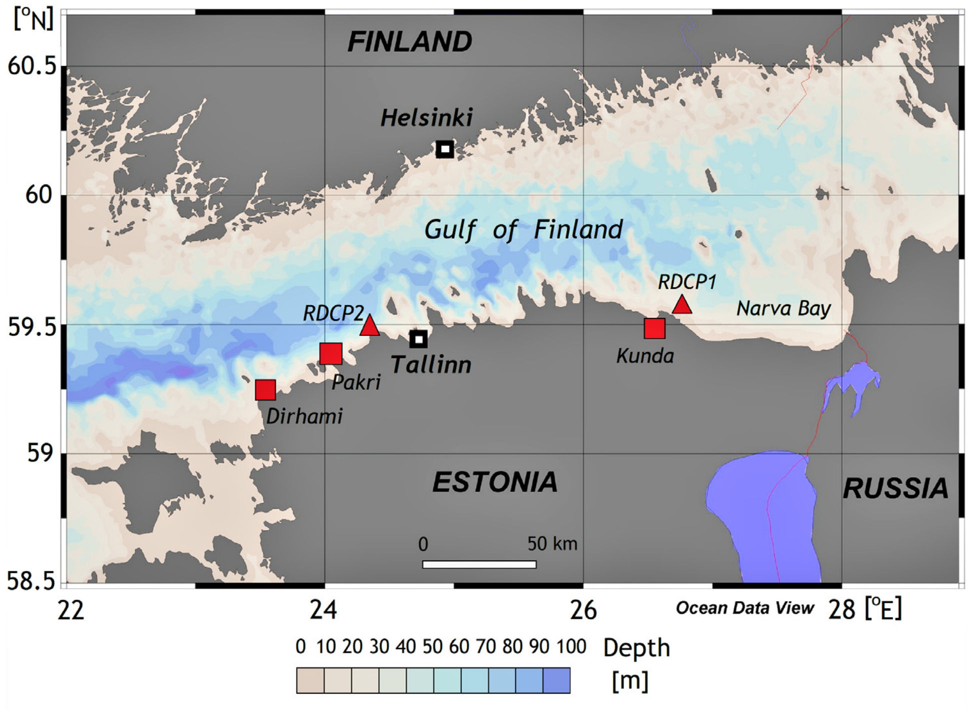

Figure 1 Bathymetric map of the Gulf of Finland (Schlitzer, 2020). Red rectangles mark weather stations by the Estonian Weather Service (EWS), the triangles mark the Recording Doppler Current Profiler mooring locations near Letipea Peninsula (RDCP1, in 2009) and at Suurupi (RDCP2, in 2014).

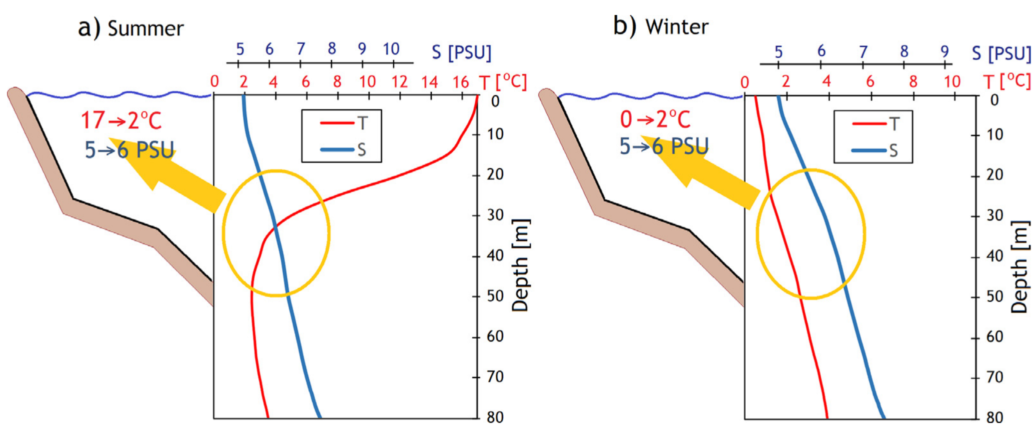

Figure 2 A sketch illustrating different impacts of summer (a) and winter (b) upwelling events on T and S. Water from 20—50 m depth layer flows up the coastal slope and replaces the previous surface water. (The profiles were generalized for the Gulf of Finland from the data by Haapala and Alenius (1994).)

2. Material and methods

2.1. In situ measurements

The study was based on measurements performed with a Recording Doppler Current Profiler (RDCP) Mark 600 manufactured by AADI Aanderaa (currently YSI, a Xylem brand). Such measurements have been performed in various locations in the Estonian coastal waters since 2003, a partial overview of which is given by Suursaar (2013). The two series, which came from upwelling-prone coastal areas, covered the entire winter.

At the Kunda—Letipea area (Figure 1, RDCP1; 59°33′30″N; 26°40′10″E), the upward-looking instrument was deployed on the seabed about 2 km off the coast by divers from a boat of the Estonian Marine Institute on 15 November 2008. The instrument was retrieved 206 days later on 9 June 2009. The depth of the instrument varied along with meteorologically forced sea-level variations between 10.8 and 12.0 m. The instrument recorded hourly contact values (i.e. at 10.3—11.5 m depth) of water temperature, salinity, but also variations in pressure (instrument depth), wave parameters and flow components (u, v, z) at 7 depth intervals above the instrument (see also: Suursaar, 2010).

Near Suurupi Peninsula (Figure 1, RDCP2; 59°29′10″N; 24°21′10″E), the instrument was deployed ca. 1.5 km off the coast on the seabed from R/V Salme (operated by the Marine Systems Institute, TalTech). The measurement period spanned 139 days from 10 December 2013 to 29 April 2014. Instrument depth varied between 19.6 and 20.9 m and the hourly recorded variables were the same as in 2009. This mooring was a part of a larger field-work campaign carried out in the entrance section of the Gulf of Finland in winter 2013/14 (Lips et al., 2017), thus providing some background information on the hydrodynamic situation in the gulf.

In this study, we do not present all the possible records retrieved from the RDCP moorings, but the ones illustrating wintertime upwelling conditions in T, S, depth and currents. Flow data at two depth intervals (from upper and lower parts of the vertical profile) was used. However, we occasionally review the results of other similar measurements made at Letipea using the RDCP. While the Letipea year 2009 measurements have already been partly reviewed by Suursaar (2010), the T and S winter measurements from the Suurupi year 2014 survey have never been analysed and presented before.

2.2. Meteorological data and web-based sources

Meteorological description of this study was based on data by the Estonian Weather Service (EWS). For the Suurupi location, hourly wind speed and direction data from the Dirhami station (59°12′41″N; 23°30′02″E; Figure 1) was used. Although being more distant to the RDCP mooring site (55 km) than the nearby Pakri station (20 km), Dirhami provides nearly non-disturbed marine wind measurements for the region, whereas Pakri wind data are distorted by the Baltic Klint (Keevallik et al., 2007). For the Letipea mooring, wind data from the Kunda station (59°31′17″N; 26°32′29″E; 8 km from the RDCP) was used. All these stations were equipped with MILOS-520 automated weather complexes. Meteorological background data (on air temperatures, weather patterns), as well as annual overviews and meteorological normal, were retrieved from the website of the EWS (EWS, 2021). For variations in sea ice conditions, some ice extent charts of the Baltic Sea were downloaded from the corresponding webpage of the Swedish Meteorological and Hydrological Institute (SMHI, 2021).

SST images retrieved from satellite-borne sensors are among the most widespread sources for upwelling studies. The first-hand data sources are the large agencies (e.g. NOAA, NASA, ESA, Copernicus) that operate the satellites and sensors. In this study, the processed imagery "products" were retrieved from the Polish SatBaltyk Operational Service (http://www.satbaltyk.pl/). Cloud-free images can be rare in the Baltic Sea area, especially for winter. Therefore, in SatBaltyk, a 3D eco-hydrodynamic model version called the Parallel Model 3D (PM3D) is used to assimilate the SST data from the AVHRR or MODIS radiometer and to produce four times daily output (see Kowalewska-Kalkowska and Kowalewski (2019) for the additional details and validation). We retrieved SST and surface salinity distributions (from 2012—2014, 2019, 2021) to illustrate the spatial patterns of winter-time upwelling events in the Gulf of Finland. We also browsed daily images zoomed into the Gulf of Finland from December to April over the period from 2010—2021,

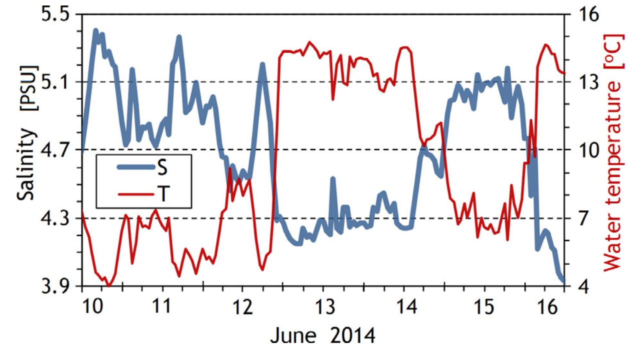

Figure 3 Upwelling-related negatively correlated variations in water temperature (T) and salinity (S) at 10 m depth near Letipea (Figure 1) in summer 2014 (see also: Suursaar, 2020).

and compiled a preliminary estimation for winter (January to March) upwelling occurrences (percentages of images with upwelling-like evidences) on either coast of the gulf (roughly between longitudes of Dirhami and Kunda stations; Figure 1). The spatial difference of 2°C within 30 km off the coast was chosen for SST, and 1 PSU for salinity. This was only a preliminary analysis and we suggest that more detailed studies should follow in the future.

3. Results and discussion

3.1. Winter 2014 case

From January to April 2014, evidence of several remarkable upwelling events was recorded at the Suurupi (RDCP2) location. While summer upwelling manifests in the stratified Baltic Sea (Figure 2) as negatively correlated T and S variations (i.e., decrease in T and increase in S; Figure 3), a unison increase both in T and S occurs in case of winter upwelling (Figure 4a). Although the temperature of the upwelled water can be merely 2—4.5°C, it is still relatively warm considering the 0—1°C water temperatures in adjacent sea areas (Figure 5), or in time series, the temperatures preceding or following the event on a spot (Figure 4a).

Following the stormy December 2013 with prevailing westerlies (in NAO+ intra-annual episodes), a cold anticyclonic weather pattern (NAO- phase) settled above the Gulf of Finland in the middle of January 2014 (Lips et al., 2017). Air temperatures dropped to −10°...−15°C in North Estonia and SST cooled down to 1—2°C in most of the Gulf of Finland. Associated with a blocking anticyclone above Russia, persistent and spatially rather uniform easterly winds correspondingly caused west-directed currents (i.e., the speed vector's negative u-component) along the North Estonian coast (Figure 4d), which in turn enabled the up-welling of deep waters. At the 20 m deep RDCP mooring spot, salinity rose from 6.1 to 6.6 PSU and water temperature rose from 1.4 to 4.3°C within a few days (Figure 4a). The relatively warm water probably originated from intermediate layers, which had not cooled down yet while the SST has dropped fast with winter onset. Salinity and SST distribution results from 25 and 29 January (Figure 5a,c) show that this warm water eventually surfaced, creating an area in the SW part of the Gulf of Finland where the water properties were strik-

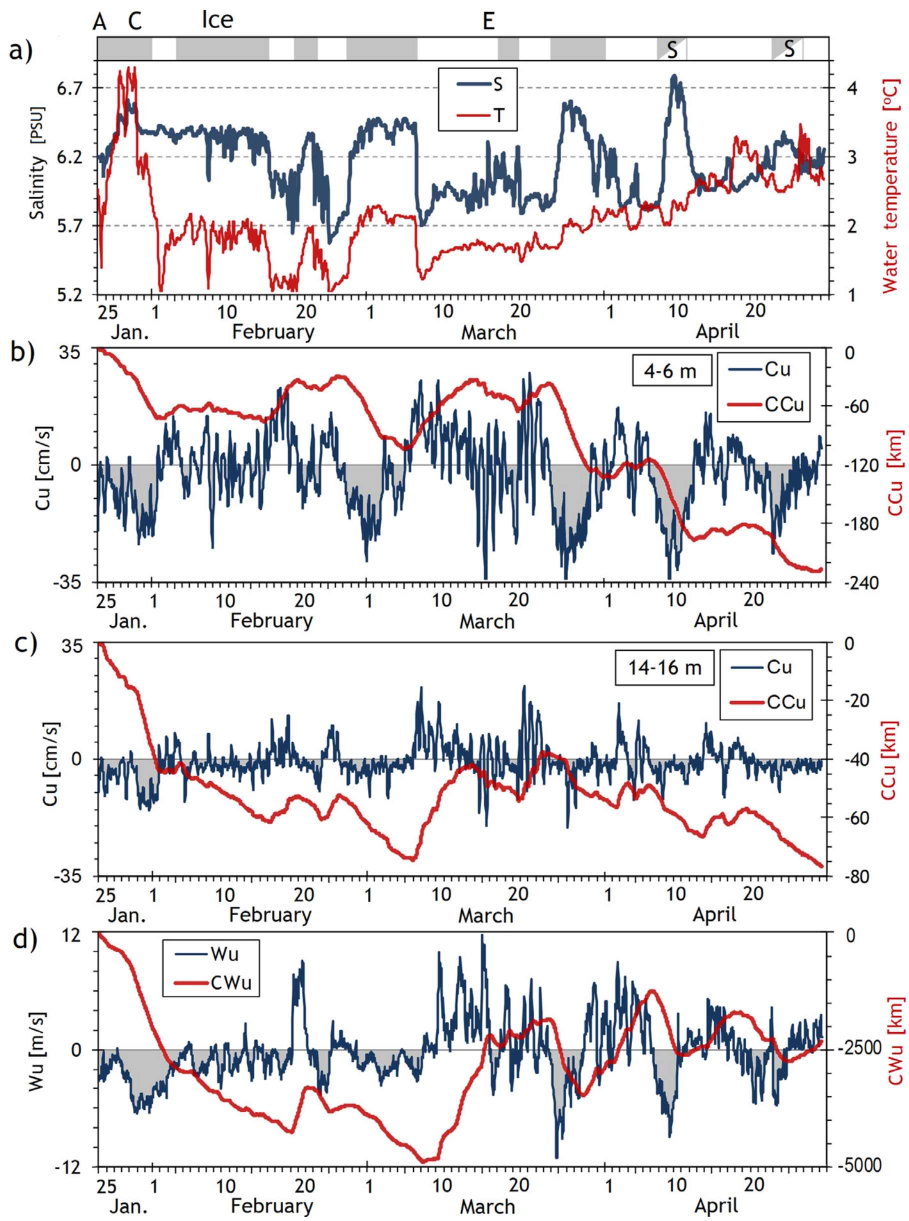

Figure 4 Variations in T and S recorded at Suurupi (Figure 1) at 20 m depth using a RDCP (a) over the period from 25 January to 29 April 2014 (excerpt from a longer record). Variations in hourly wind u-component (Wu) and cumulated u-component (CWu) at Dirhami (d). RDCP-measured flow u-component (Cu, CCu) at 4—5 m (b) and 14—16 m depth (c); u is positive for westward motion both for wind and current. Grey shade (on b—d) and on a bar (a) indicates upwelling conditions; winter to summer upwelling switch in April is marked with "S" (a). The dates for spatial distribution images (Figure 5a and b, c and d, e and f) and ice map (Figure 6) are marked with A, C, E, and "Ice" above (a).

ingly different from those in the N or E parts of the gulf. In the following days, the upwelling weakened, and the upwelled surface water spread to the centre of the gulf and cooled down to ca. 1—2°C.

When looking at SST and salinity images alone, one may question, whether there was horizontal advection from the Baltic Proper instead? Firstly, the warm (+4°C) water zone spread and strengthened along the Estonian coast over many days, as exemplified by Figure 5a and c. At the same time, air temperatures were very low, varying between −17 and −10°C between January 24 and 29. Additionally, and especially in SST images, the shape and detachment of the "clouds" from possible sources in the central Baltic Sea indicated the local (coastal) origin of such patterns. Finally, the entire meteorological situation (e.g. Figure 4d) showed prevailing alongshore (West-directed) airflow. This, in concurrence with the theory, evoked corresponding alongshore current (Figure 4b,c) in all depth layers (the velocity decreased by depth, though) and caused the matching S and T temporal variations (Figure 4a). The saltier and warmer water evidently originated from the intermediate deep layers of the Gulf of Finland, which, in turn, was fed by estuarine circulation and near-bottom up-slope advection from the Baltic Proper along the thalweg of the gulf (e.g. Lips, et al.,

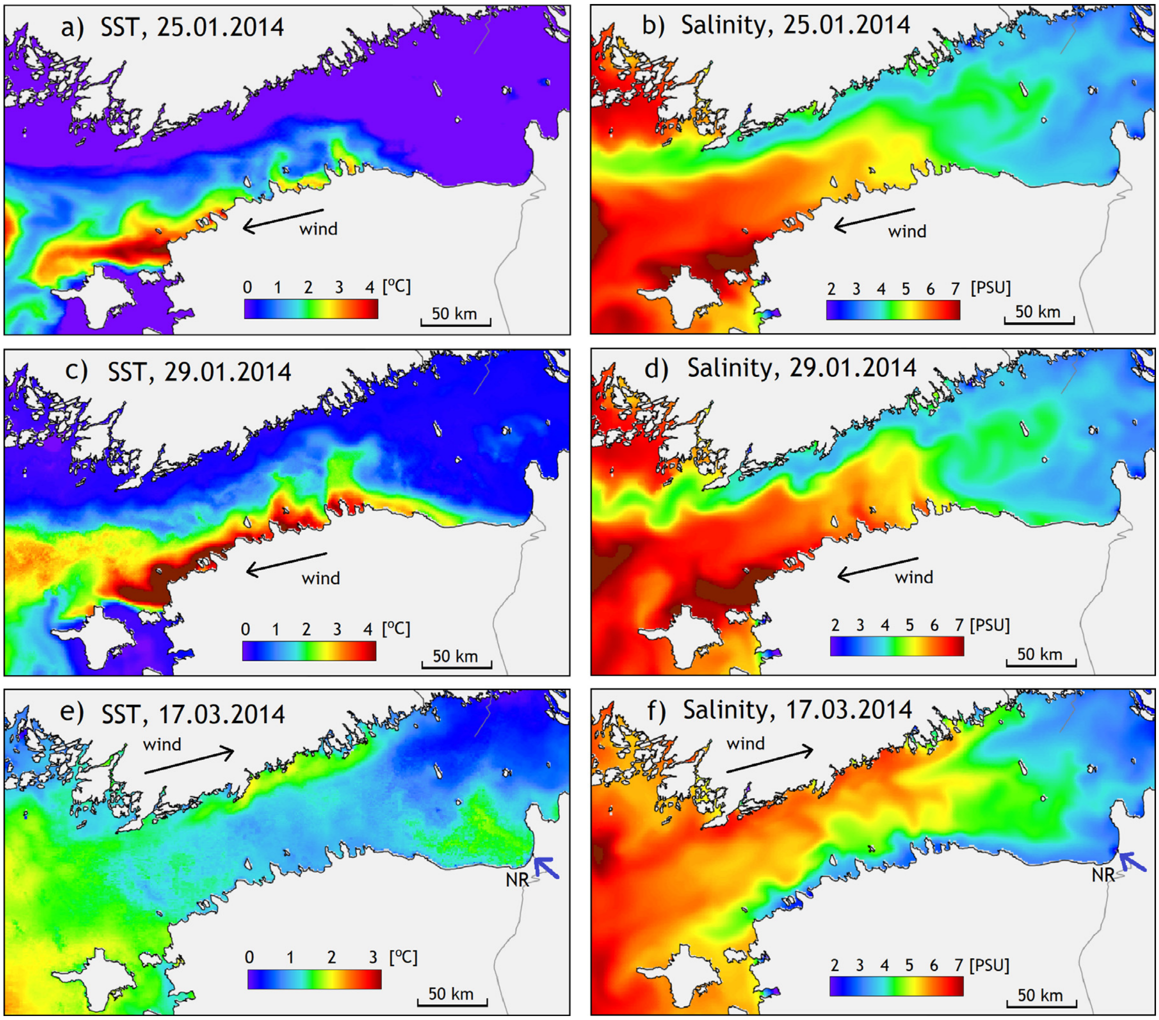

Figure 5 Spatial patterns of SST (a,c) and salinity (b,d) during winter upwelling along the Estonian coast in January 2014 and along the Finnish coast on 17 March 2014 (e,f); snapshots retrieved and edited from the SatBaltyk system. NR — Narva River inflow. Also see the corresponding dates on the time series in Figure 4a.

2017). It could not have originated from the eastern gulf either, where the surface water was much cooler and less saline (Figure 5a—d).

Over the next ca. 50 days (from about 4 February to 1 April; Figure 4), upwelling was marked with 1.8—2.2°C water temperatures and 6.4—6.6 PSU salinity, and upwelling-free periods with 1—1.6°C temperatures and 5.5—5.9 PSU salinity. Within this period, a short upwelling also occurred along the Finnish coast, as shown in the SST and salinity product images from 17 March 2014 (Figure 5e,f). However, the event was not as prominent as its Estonian coast counterpart, probably because of more uniform water column conditions in late winter. Also, on the Finnish side, advection from the Baltic Proper and upwelling — both evoked by westerlies — may cause similar patterns on the surface in winter.

In March, on the slightly varying uniform SST background, the influence of river inflows (such as the Narva River plume; Figure 5e,f) can be seen, as rivers start to bring warmer water to the sea in spring. Except for the coastal areas in the far NE and E ends of the gulf, ice cover did not fully develop on the Gulf of Finland that winter. According to the maximum ice extent chart (Figure 6), the ice did not cover more than 40% of the gulf's area in 2014 and the Suurupi site was completely devoid of any ice forms throughout the winter, which spatially corresponds to mild ice conditions in the Gulf of Finland (Schmelzer et al., 2008).

In April, SST gradually rose above 2.5—3°C and upwellings turned to "normal" (Figure 4). In that regime shift, the dependence (e.g. Caldwell, 1978) between the highest-density water temperature (T_D) and salinity (S) is important, which can be estimated using a simplified formula version (e.g. Sælen and Aas, 2012): $T_D = 3.98 - 0.215$ S.

It yields about 3°C at salinity 5 PSU and 2.5°C at salinity 7 PSU. Although the imprint in T was very small in the beginning of this transition period because of thermally near-homogeneous conditions, the presence of upwelling-favouring wind and current conditions and the negatively correlated salinity variations evidenced the beginning of summer upwellings in the end of April 2014. Over the time period shown on Figure 4, the upwelling-favouring wind conditions occurred 59% of the time, the upwelling evoking current patterns occurred 57% of the time (the corresponding cumulated curves were descending; Figure 4f,g), and salin-

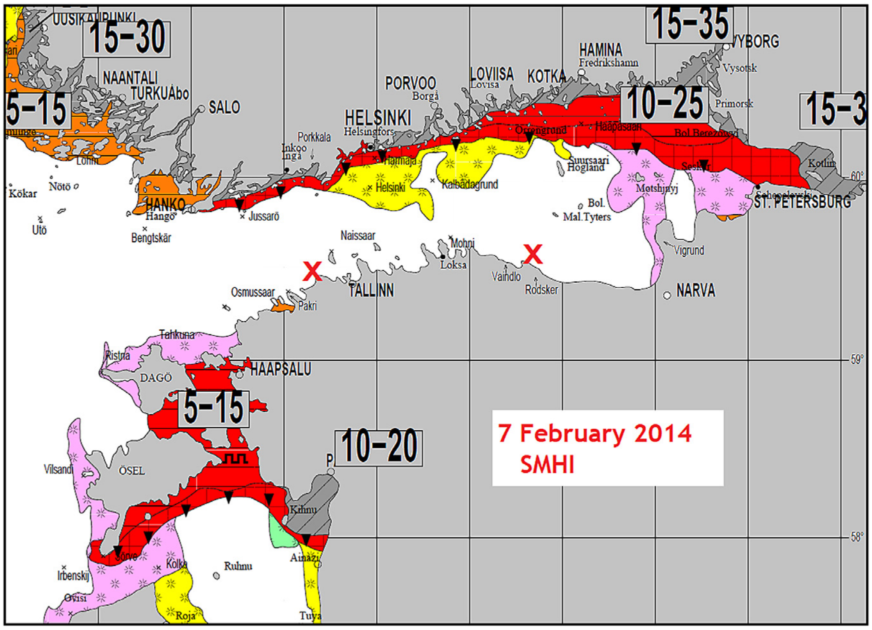

Figure 6 A fragment of the Baltic Sea ice chart (SMHI, 2021) showing the maximum ice extent in the Gulf of Finland area during upwelling on 7 February 2014. x — RDCP locations.

ity based upwelling cases (both "warm" and "cold") occurred 51% of the time.

3.2. Winter 2009 and other cases in 2010–2021

According to the Letipea measurements in 2009 (RDCP1; Figure 1), the onset of upwelling-favourable conditions occurred on around 15 January 2009, when a blocking anticyclonic weather pattern and westward air and nearshore water flow started to reign (negative u; Figure 7b,c,d). According to the EWS data, air temperatures varied between −5 and −10°C at Kunda, 2–10 m/s winds blew mainly from E or NE, and the cumulated wind u-component value steadily decreased from +3000 to −1000 km (Figure 7d). The corresponding West-directed current prevailed both the in upper and lower layers (Figure 7b,c), although the flow magnitude decreased with depth. Over the next 90–100 days, upwelling conditions were more frequent than non-upwelling conditions (ca. 70% vs 30%). Occasional, short recessions provided us the variability range, which was 1–1.5 PSU in S and up to 4°C in T (Figure 7a). At the mooring location, T varied between 0 and 4.5°C, and S varied between 4.3 and 6.3 PSU. Like in the previous case study, a regime shift occurred once the SST attained 2.5–3°C around 20 April (Figure 7a). The first summer-type of upwelling occurred on 1 May, when a S increase of 1.3 PSU was associated with a 2°C T decrease. While upwelling-related S variations remained roughly the same (1–2 PSU) throughout the winter, the T differences were higher (up to 4°C) in winter onset, then gradually decreased (to 1°C) by April, when seasonal warming started, and increased again after upwelling was reversed back to summer regime in May. Like in 2014, the upwelling frequency was 50–60% over the study period, showing that winter upwelling can indeed be frequent along the northern coast of Estonia.

Winter 2009, like 2014, was relatively mild (Table 1) and fast ice did not develop at the study site. However, some new and level ice events occurred at the RDCP1 site in a few days in February 2009. Ice-covered the NE and E sections of the gulf (SMHI, 2021).

There were no good SST satellite images available for winter 2009, and SatBaltyk data began with 2010. However, when browsing the SatBaltyk winter data on the Gulf of Finland, there is evidence of warm upwellings practically in every winter (Table 1). Figure 8 shows just a few examples. The SST images from winter 2012/13 and 2013 (Figure 8a,c) showed deflected patterns as a result of wind direction changes from E to SW. All the images (Figure 8) showed filaments occurring in the same areas and in similar shapes as they do in summer events (see e.g. Figure 3 in Delpeche-Ellmann et al., 2018; Figure 4 in Uiboupin et al., 2012), — except, in a reversed manner (cold in summer, relatively warm in winter).

The distribution maps of the latest, January 2021, event showed that across the Gulf of Finland, sea surface salinity varied between 2–4 PSU on the Finnish side and 4–6 PSU on the Estonian side, and SST varied between 0–2°C and 4–6°C, respectively (Figure 8g). This very prominent event lasted over a month. In Northern Estonia, it was followed by massive lake-effect (also, sea-effect; e.g. Hjelmefelt and Brahan, 1983) snowfalls in January and February 2021, as cold air masses from the North moved across expanses of upwelling-influenced warm and ice-free sea.

An analysis of the SatBaltyk imagery (2010–2021) indicated that warm upwellings can occur between December and April at either coast of the Gulf of Finland. However, both December and April were mixed or transition months and Table 1 provides an annual overview of the proper winter months: January, February and March. Indeed, December is climatologically a very variable month

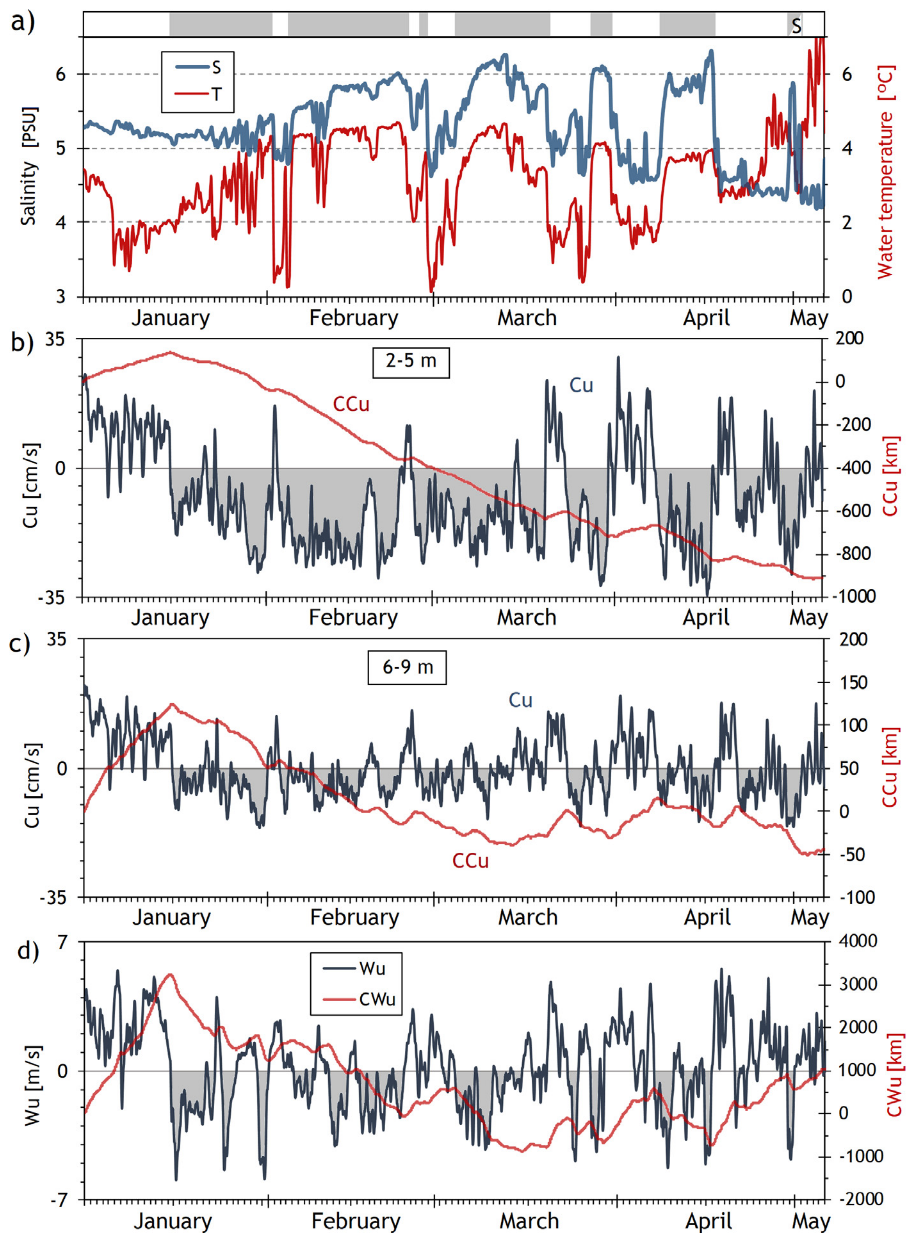

Figure 7 Variations in hourly T and S series (a; RDCP measurements at ca. 10 m depth at Letipea, excerpt from a longer record), and in current u-components (Cu; cumulated — CCu) integrated over the 2—5 m (b) and 6—9 (c) depth layers over the period from 1 January to 5 May 2009. Grey shade indicates upwelling conditions, winter-summer upwelling switch in April—May is marked with "S" on (a).

in Estonia (Jaagus and Suursaar, 2013), being sometimes very stormy and potentially upwelling-favourable for the Finnish coast. In such cases, the upper layers are still too warm or strongly mixed and upwelling can only manifest through salinity increase. In some cases, however, when the cold weather pattern has already settled in December (such as winters 2009/10, 2010/11, 2012/13), "warm" upwelling can develop along the Estonian coast in December (Figure 8c). In April, which is usually a rather calm month, upwellings are either rare or do not differentiate well from the background of seasonally warming surface water.

According to SST distribution maps (Table 1), upwelling along the North Estonian coast had a probability of 44% in January, and it decreased by February (25%) and March (16%). Also, T differences decreased from January to March (Figure 7a). The average occurrence (28% by SST and 21% by S) did not differ much from the previous estimations for upwelling occurrences for the Gulf of Finland in May to September (Lehmann et al., 2012; Myrberg and Andrejev, 2003). On the Finnish side of the gulf, the occurrence of upwelling-like patterns was 21% according to salinity and 7% according to SST (Table 1). However, we point out that this is a preliminary and not quite exact quantification. a) The preciseness of the method is low due to relatively small SST variations in winter; b) subjectivity in the choice of SST and S difference thresholds; c) an uneven number of covered days per month (4—31), especially

Table 1 A preliminary estimation of January (J), February (F), March (M), and J–M average (A) upwelling occurrences (%) along Estonian (E) and Finnish (F) coasts according to water temperature (SST) and salinity (S) pattern analysis (SatBaltyk) in 2010–2021. Ice – maximum ice coverage (0–10/10, 10 – entire gulf covered) according to SMHI (2021). Air – Jan.–March average atmospheric temperature (°C) anomalies from the norm at Kunda station (−3.1°C in 1980–2010; EWS, 2021). NAO – Jan.–March average NAO values (Gibraltar-Iceland index version; CRU, 2021, updated from Jones et al. (1997)).

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	A
SST, J–E	44	38	44	47	53	12	68	23	55	61	0	81	**44**
SST, F–E	0	6	19	11	68	7	10	0	61	39	6	71	**25**
SST, M–E	0	0	0	16	11	6	26	16	23	39	6	44	**16**
SST, A–E	15	15	21	25	43	9	35	13	46	47	4	65	**28**
SST, A–F	0	9	0	5	5	24	13	12	3	11	0	2	**7**
S, J–E	19	19	32	35	39	6	35	13	19	26	0	48	**25**
S, F–E	20	29	54	25	21	0	0	4	29	25	6	36	**21**
S, M–E	0	17	10	39	6	10	32	19	39	13	0	16	**17**
S, A–E	13	21	31	33	22	6	23	12	29	21	2	33	**21**
S, A–F	3	37	25	6	20	31	22	37	9	22	33	9	**21**
Ice	10	10	8	10	4	2	7	6	9	5	0	9	7
Air	−4.0	−2.3	−1.6	−1.6	2.8	3.5	0.8	2.0	−1.1	2.4	5.3	−0.0	0.5
NAO	−2.4	0.3	1.7	−1.0	1.5	2.1	1.0	0.9	0.2	1.3	2.7	−0.1	0.7

for SST in 2010–15; d) inertia: the once surfaced water causes upwelling "evidence" that lasts for many days after the physical impulse has ended; however, the dissipating cloud usually drifts away from the coast, then; e) occasional, very warm first halves of January and last halves of March; f) while on the Estonian coast, the upwelling-induced patterns are easy to detect (warm, saltier water directly against the coast; the patterns detached from other open-sea patterns), winter upwelling is sometimes hardly differentiable from Baltic Proper advections on the Finnish side, as westerly winds can bring warmer and saltier water from the Baltic Proper, and also evoke upwelling along the Finnish coast – both with rather similar imprints in winter.

Considering the above-said, the automated image detection can be problematic, especially on the Finnish side. It should be accompanied by a simultaneous case-by-case analysis of SST and S imprints together with consideration of wind forcing (or current) data.

In extremely mild winters (such as 2020 and probably also 2015), winter upwelling did not occur on the southern side of the gulf because of vastly dominating westerly airflow (NAO+ phase). In most of the winters, easterly and westerly circulation types (NAO+ and NAO-) varied within a winter (Jaagus and Suursaar, 2013), causing upwelling conditions that alternated along the opposite coasts. When (probably) upwelling-related salinity imprint occurred practically equally along both sides of the gulf, the water temperature evidence was more frequent and clearer on the southern side of the gulf (Figure 8). This was also confirmed by the ice extent statistics (Table 1). According to the maximum ice extent charts of the Baltic Sea in 1980–2021 (SMHI, 2021), the gulf's ice extent was 9/10 or more in ca. 50% of cases. When 3–8/10 of the gulf's area was covered, open water was predominantly located in the southern side in ca. 90% cases (see also the ice charts in Figures 6,8). Even if the entire gulf was covered by ice, the ice cover was usually thinner on its southern side.

3.3. Discussion on upwelling definition

The upward flow component appears once the alongshore wind generates offshore transport of mass which is balanced by an onshore and upslope flow in the deep layers (Ekman, 1905; Gill and Clarke, 1974). Hence and foremost, upwelling should mean an upward current component. However, in practice, we can talk about upwelling once we have captured some of its manifestations. The first problem here is that the (very small) upwelling-associated vertical currents are notoriously difficult to detect, even though some instruments (including the RDCP) provide data on the vertical velocity component (yet practically unusable; Suursaar, 2009). Rather, upwelling manifested in RDCP records in the distinctive vertical structure of horizontal currents and through thermohaline effects (Suursaar and Aps, 2007). In some previous studies, concepts like cumulative wind impulse or upwelling index were introduced, basically stating that it takes some time (worth of 4000–5000 kg/m/s or 2–3 days; e.g. Haapala, 1994), before upwelling becomes visible on the surface (Figure 2). If upwelling evidence surfaces, we can conveniently measure its SST imprint using satellite or aircraft-borne sensors. No surprise that analysis of SST imagery has become the easiest, and along with hydrodynamic modelling, the most widespread tool in upwelling studies. Consequently, these methods have largely dictated the detection limits for upwelling events, and thus, a kind of "practical" upwelling definition.

Based on the abovementioned, one can ask some provocative questions, testing the upwelling detection and perception principles: (1) how large and what kind of change defines an upwelling? In practice, certain thresholds have been usually defined on the basis of the model-derived vertical velocities (Myrberg and Andrejev, 2003), the above-mentioned wind impulse concept, or spatial differences in SST (e.g. set at a 2°C or incorporated into a certain index; Gidhagen, 1987; Kikas and Lips, 2016; Lehmann et al., 2012). Quite naturally, all such thresholds

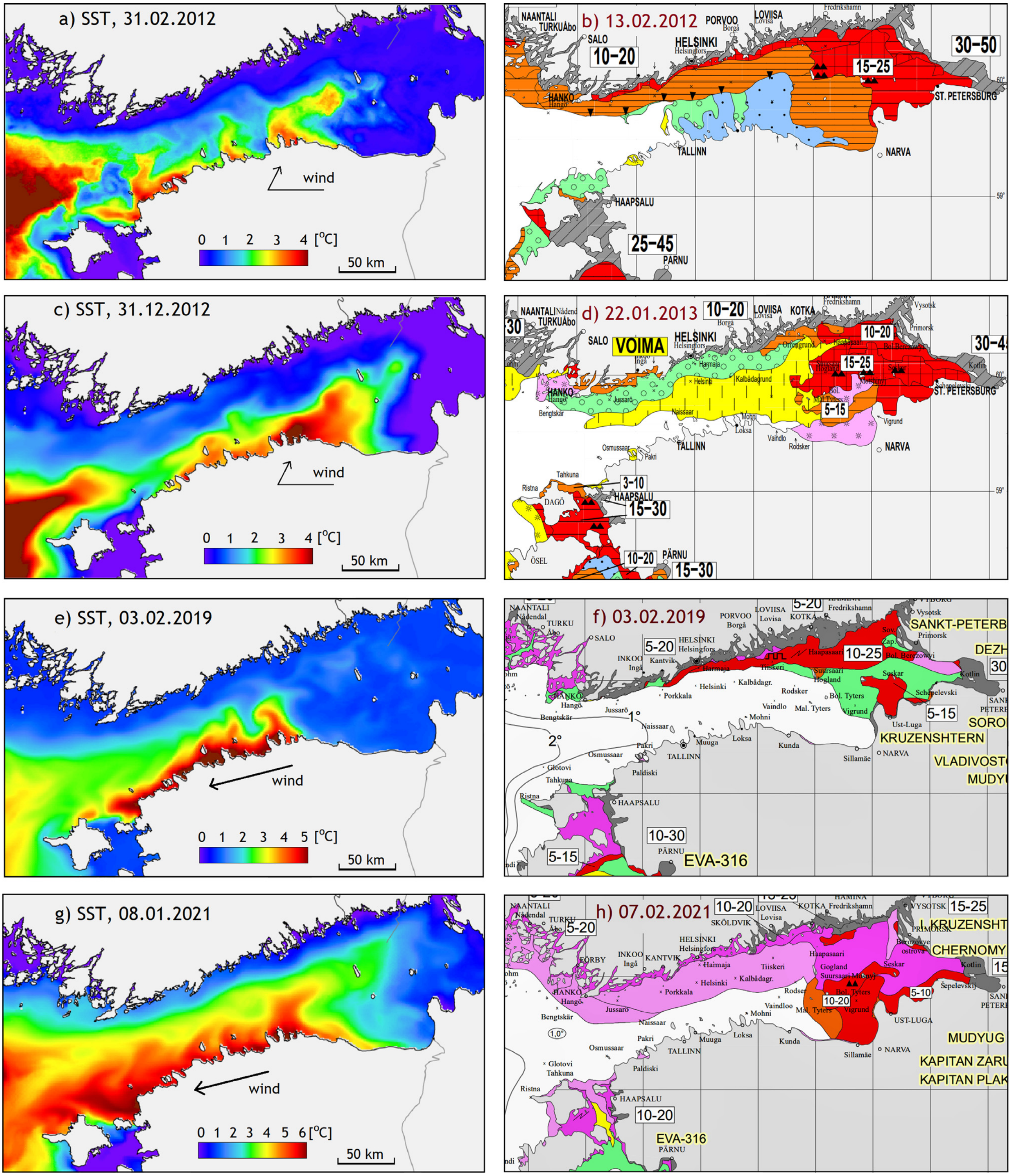

Figure 8 Examples of winter upwelling imprints in SST based on SatBaltyk and corresponding ice extent charts (SMHI, 2021). Seasonal maximum ice extent charts or charts from later dates were chosen because ice development takes time and sometimes there was no ice at all during maximum phases of upwelling events in the Gulf of Finland.

are more or less arbitrary and lead to somewhat different statistics (Kowalewska-Kalkowska and Kowalewski, 2019). They also did in this study (Table 1), and we have no good solution for that problem, yet. Establishing a threshold for a process that essentially begins simultaneously when the upwelling-generating impulse enters the water column may be technically necessary but theoretically restrictive. Imagine a definition of current stating that "a current is water movement which is faster than 1 cm/s". Or, "waves are *waves* that are higher than 10 cm". Whatever the thresh-

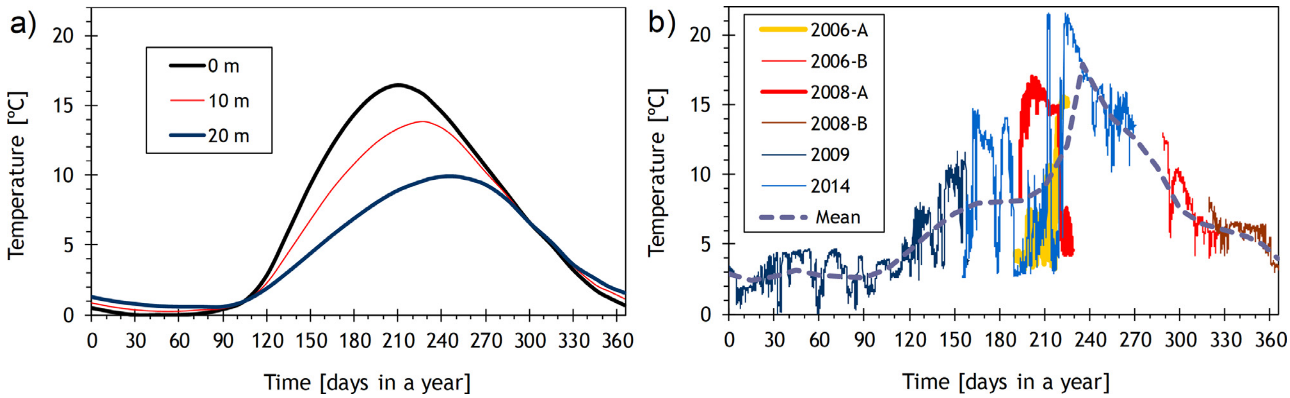

Figure 9 Typical seasonality in T in the open part of the Gulf of Finland (a; generalized and redrawn from Haapala and Alenius (1994)). Water temperature measurements at Letipea Ps. (see Figure 1) performed at 10 m depth in different RDCP moorings plotted against days in a year (see also: Suursaar, 2020) together with correspondingly estimated mean seasonal course at that spot (b).

old is chosen, it should be an integral part of the inferred statistics. (2) What if we have no SST imprint (e.g. in case of homothermia) but there is one in salinity? (3) What if neither T nor S signal had not surfaced yet, because the homogeneous layer was initially very thick? However, let us assume that we had sensors at 10 m depth and showing a truly remarkable event; the process could have significantly altered properties within the water column and probably would cause some kind of consequences also in the future. Was it upwelling then? (4) In contrast to the previous question, what if the upper warmed-up film is very thin and only a minuscule impulse is needed to show up the underlying waters? Indeed, such an event may prominently pop up from a SST image, but then it is probably quite short-lived and not so influential in the long run. (5) Finally, does a natural phenomenon occur, even if we are not able (or willing) to measure it? For instance, upwelling studies have been usually limited to the period from May to September in the Baltic Sea. *Inter alia*, winter upwelling can be thus viewed as a kind of "dark matter" of the upwelling process, which role should be ultimately established and quantified.

3.4. On "warm" upwelling impacts

Because the very existence of winter upwelling is rarely acknowledged, also its possible impacts have been probably underestimated. One of the reasons is the seemingly insignificant water temperature differences caused by it. The small differences hardly appear on SST images and data from coastal (contact) stations can include variations due to other nearshore phenomena that alter the winter upwelling evidence. The presence of warmer waters near the shore is not always caused by upwelling, but e.g. by river inflows or positive heat exchange episodes, mainly in the end of a winter (Kowalewska-Kalkowska and Kowalewski, 2019). Coastal stations are usually located (at least in Estonia) in very shallow water, where the imprint of upwelling can be rapidly erased, as water column properties in small volumes can be altered fast. At the same time, the main body of the upwelled water stays ca. 1–10 km off the coast relatively unchanged. Consequently, buoy stations e.g. 1–2 km off the coast (like in our study) should be more representative for upwelling detecting. However, most of the long-term records and statistics originate either from coastal contact stations or from deeper, central-basin stations, and rarely from the upwelling-prone zones between them.

It is possible that upwelling-related "distortions" in SST statistics are sometimes smoothed out or neglected on the grounds of some general idea how things should be. For instance, we are used to seminal, near-sinusoidal seasonality curves where water temperature amplitudes gradually decrease and lag orderly with depth (Figure 9a). While being valid for certain areas, such graphs are probably not representative of upwelling-prone areas. Figure 9b shows all our RDCP based T measurements at Letipea alongside with a resulting mean curve. Firstly, it is not possible that statistically mean water temperature falls to zero in winter, because the T essentially switches between zero and 3–4°C all the time. Similarly, we can imagine that instead of a smooth, near sinusoidal T increase in spring and summer, the average graph would be considerably crippled, as the T switches between 4 and 20°C (Figure 9b).

An uncredited role of warm upwellings can also be manifested in ice statistics. It is generally known that a close relationship between the Baltic Sea ice conditions and the NAO exists (e.g. Schmelzer et al., 2008). It is also known that the northern shore of the Gulf of Finland freezes over earlier, and ice is more frequent there, while the ports on the Estonian side are more ice-free and navigation is easier there (e.g. Figures 6,8). Is it because the northern shore is (80 km) farther North? One of the explanations is that the existence of numerous islets and peninsulas help to stabilize the ice sheet along the Finnish shore of the Gulf of Finland, while the sea on the Estonian side is deeper (Schmelzer et al., 2008; Soomere et al., 2008). That is true. However, we additionally suggest that as the North Estonian shore is upwelling-prone in winter (even ca 50% of the time), the excess 1–2°C from winter upwelling keeps the sea open for a longer time. Even the deepest central part of the gulf usually freezes over before the Estonian coast does (Figure 8).

On the Finnish side, although the upwelling-favouring conditions occur roughly with similar frequency in winter, they do not evoke, as shown before, equally impactful upwelling events. Upwelling along the North Estonian coast occurs during a persistent pattern of easterly winds, which in winter are accompanied by very low (−10...−20°C) air temperatures. This cools down the surface layers and a +4°C upwelling is easily detectable. However, upwelling along the Finnish coast is generated (in intra-annual NAO+ episodes) by westerlies, which are more variable in time, bring warm air, stronger mixing, and meddle with advection effects from the Baltic Proper. The water stays relatively warm anyway and ice does not develop easily neither on the Finnish nor Estonian coast. When proper winter conditions start to reign alongside with the onset of cold air masses from the East (NAO- episode), usually in mid-January, surface water rapidly cools down. Ice firstly develops along the Finnish coast, but due to easterly-generated upwelling along the Estonian shore, the warmer water keeps the sea ice-free there (Figure 8). In severe winters, the Estonian coast also and ultimately the entire Gulf of Finland freezes over and after that, wind-driven upwelling is no longer possible. However, the ice thickness statistics show the difference between the coasts.

Among the other important, well-known impacts of upwelling is the rise of nutrient-rich waters. However, it is reasonable to assume that the rise of nutrients is not limited to cyanobacterial blooms or other frequently studied illustrious summertime events (e.g. Uiboupin et al., 2012; Vahtera et al., 2005), but it proceeds quietly throughout the year. The statistical and ecological implications of winter upwellings deserve more thorough further studies.

4. Conclusions

(1) Coastal upwelling in the Baltic Sea is a rather frequent mesoscale process that occurs when the wind blows parallel to a coastline on its left. It involves an upward motion of deeper and more saline water, which usually is colder than the surface water. Traditionally, upwelling-related studies in the Baltic Sea have been limited to the period from May to September—October. As documented in this study, upwelling can also occur in winter with somewhat different implications. While proper "warm" upwellings can occur from January to March, December and April can be considered as transitory months.

(2) Based on wintertime RDCP measurements off the North Estonian coast, clear evidence of winter upwellings in 2009 and 2014 were detected and analysed. At a 10 m deep location off the Letipea Ps., upwelling caused the water temperature to switch from 0—1 to 4—5°C and salinity to switch from ca. 4.5 to 6 PSU. At the 20 m deep mooring near Suurupi Ps., it caused a T switch between 1 and 2—4°C and S switch between 5.5 and 6.8 PSU. Differently from summer upwelling, S and T variations were positively correlated to each other in winter events. While upwelling-caused S variations remained roughly the same (1—2 PSU) throughout the winter, the T differences were higher (up to 4°C) in winter onset, then gradually decreased to ca. 1°C.

(3) In the more closely studied winters (2009, 2014), upwelling occurred along the North Estonian coast ca. 50—60% of the time. Based on preliminary SatBaltyk SST and sea surface salinity distribution analysis, winter (January to March) upwelling evidence occurrence along the Estonian coast was 28% in SST and 21% in S in 2010—2021. On the Finnish side, the estimated occurrences — 7 and 21% respectively — did not correlate well with each other. Based on imagery analysis alone, it was sometimes difficult to differentiate upwelling patterns from advection on the Finnish side. The imagery analysis should be accompanied by case-by-case analysis of wind and flow conditions. The results also depend on pre-defined threshold values for SST and S differences for "upwelling".

(4) Winter upwelling as a phenomenon has long been ignored and therefore probably underestimated. Our analysis shows that it is more frequent and probably more influential than considered before. While probably not well captured on coastal stations and mid-gulf deep-water stations, upwelling can considerably distort T and S statistics in the zone ca. 1—10 km offshore. In terms of S variations, winter upwelling occurs roughly with similar frequencies and impacts in the northern and southern parts of the gulf. However, its impact on T and ice conditions is asymmetrical: it keeps the Estonian coast ice-free longer and the surface water slightly warmer than on the Finnish coast. Being upwelling-favouring for the Finnish side, the westerlies (during NAO+ episodes) are associated with higher air temperatures, stronger mixing and ice-free conditions (e.g. in early winter). If cold air masses onset from the East (during NAO- episodes), surface water cools down and ice firstly develops along the Finnish coast, whereas due to upwelling along the Estonian shore, the warmer water keeps the sea ice-free for longer. Like summer upwelling, winter upwelling contributes with nutrient transport up to the sea surface, too. Hence, the statistical and ecological implications of winter upwellings deserve more thorough further studies.

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