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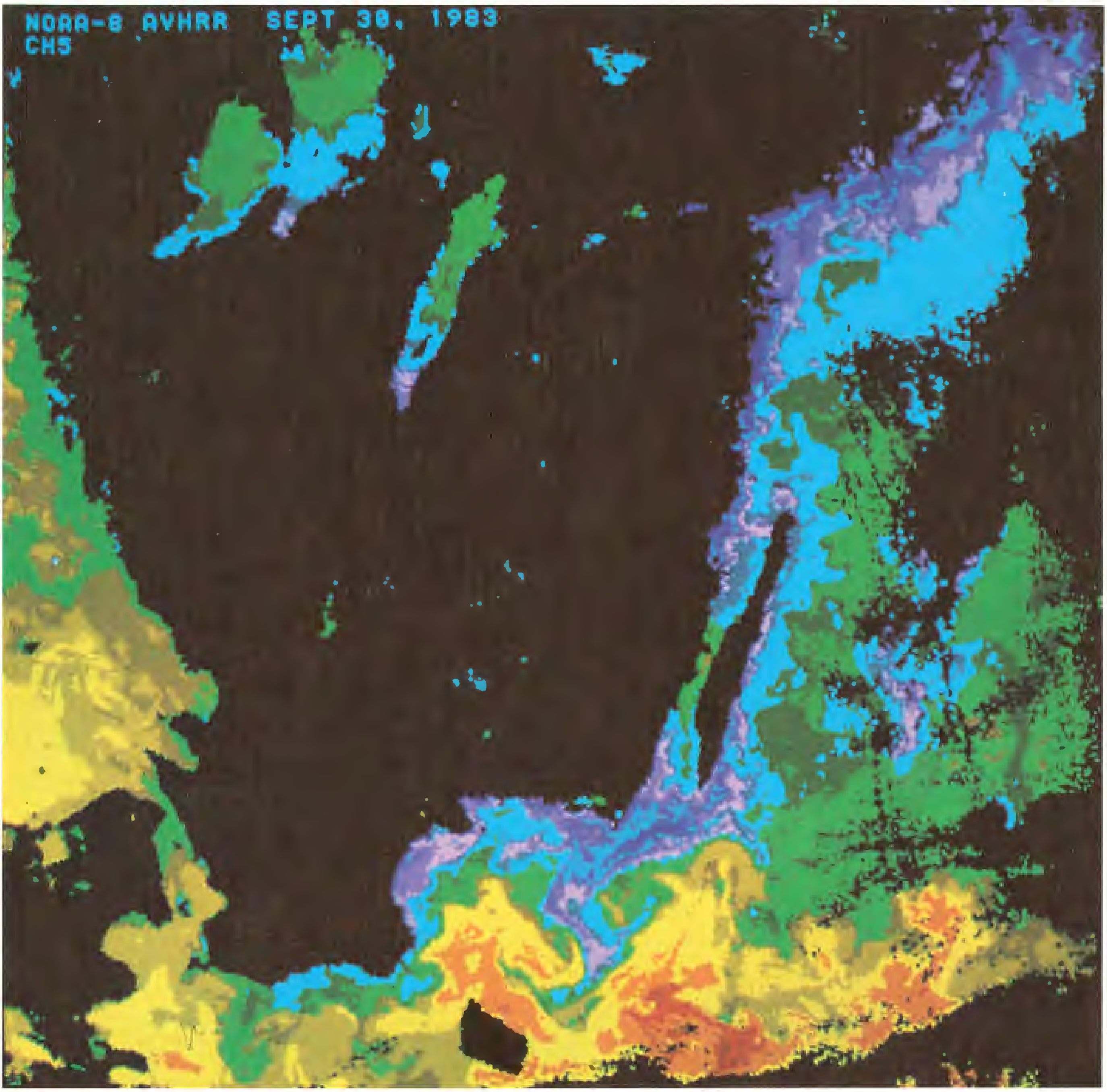

# COASTAL UPWELLING IN THE BALTIC

## - a presentation of satellite and in situ measurements of sea surface temperatures indicating coastal upwelling

by Lars Gidhagen

## Part I

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# COASTAL UPWELLING IN THE BALTIC

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Part I: Text Part II: Appendices

Abstract

Satellite data (AVHRR) and in situ data of sea surface temperatures have been used to describe wind-induced upwelling along the Swedish coast of the Baltic.

The satellite data, transformed to isotherm charts, points out three sections of the coast where the upwelling is especially intense. The cold upwelled water, normally found within 10 - 20 kilometres from the coast, sometimes spreads out in finger-like filaments. There are indications of propagation of upwelling fronts and centers, which may be associated with coastal-trapped waves.

Ten years of in situ measurements of sea surface temperature have been used for a statistical compilation of upwelling events. The statistics reveal that upwelling is a common feature along certain sections of the coast, occuring for about one fourth to one third of the time. Some information of time-scales and temperature anomalies associated with the upwelling events are also given. A wind analysis shows a correlation between upwelling and winds parallell to the shoreline, in accordance with the Ekman theory of upwelling generation.

Key words

Baltic, upwelling, sea surface temperature, satellite data.

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# COASTAL UPWELLING IN THE BALTIC

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ABSTRACT

# 1. INTRODUCTION

The large-scale upwelling of cold and nutritious water taking place at the eastern side of the oceans has been studied for a long time owing to its strong ecological and climatological consequences. The fundamental mechanism which gives rise to the upwelling - the Ekman transport away from the coast created by persistent winds towards the equator - is both theoretically well-known and documented in many field experiments.

Less is known about the wind-induced upwelling on a smaller scale, which occurs in a semi-enclosed sea like the Baltic. There the forcing consists of sudden storms or strong wind-events from different directions, with typical time-scales ranging from a couple of days up to a week.

There is sound agreeement among Baltic oceanographers that the circulation in the coastal zone (extending some 10 kilometers out from the shoreline) is somewhat different from the more open, inner parts of the Baltic basins. Some processes - like coastal jets, intense upwelling and coastal trapped waves - are linked to the coastal zone.

Of course, upwelling means a strong renewal of the waters in the part of the coastal zone where it takes place. But there are good reasons to believe that the coastal upwelling is also an effective mechanism to enhance the mixing between denser deeper water and less dense surface water in the Baltic as a whole.

As can be seen from the next section, there are several examples of documented upwellings in the Baltic. This work is meant to give more information concerning the existence and distribution of upwelling along the Swedish coast of the Baltic. Some questions raised are:

- how common is upwelling?
- where are intense upwelling centers located?
- what are the horizontal dimensions and forms of upwellings?
- how do they develop in time (spreading out, propagation)?
- what wind conditions generate upwelling?

The method used - studying sea surface temperature patterns alone during the summer months with a strong temperature stratification - makes it difficult to do a more detailed analysis of the dynamics of an upwelling. For that purpose, knowledge of temperature, salinity and currents beneath the surface is indispensable. The use of sea surface temperatures also implies that the concept upwelling will be restricted to the upwelling of cold water.

Although this study only describes the surface "foot prints" produced by upwelling, it is hoped that the upwelling events documented by the rather novel technique of satellite data processing as well as the statistical compilation of upwellings found in the routine maps of sea surface temperatures, are of a general interest.

This work has been supported by the National Swedish Environment Protection Board. The author wishes to thank the following persons for their contribution: Mats Rosengren at the Swedish Space Corporation for collaborating in the satellite data processing, Lotta Andersson and Bo Juhlin for the help with the statistical compilation, Eva-Lena Ljungqvist for drawing the figures and Vera Kuylenstierna for typing.

## 2. A SHORT REVIEW OF EARLIER WORK

Before looking at the upwelling situations, it may be appropriate to recapitulate some earlier findings on the subject of coastal upwelling and its causes.

The upwelling presented in the following sections is due to windforcing, although not necessarily to the local wind. The theory (Ekman, 1905) predicts that a wind parallel to the coast, with the sea to the right (on the northern hemisphere), creates a net transport of surface water - the Ekman transport - to the right of the wind direction, i.e. out from the coast. The withdrawn surface water is replaced by upwelling water from below.

For homogeneous and deep water conditions, the Ekman transport is confined to a depth $D_E = \pi \sqrt{\frac{2\nu}{f}}$, $\nu$ being the kinematic viscosity and f the Coriolis' parameter. Empirically this depth is found to be $D_E = 0.25 * \frac{U_*}{f}$, with $U_* = \sqrt{\frac{\tau}{\rho}}$. For a windspeed of 10 $ms^{-1}$, the stress $\tau$ will be 0.17 $Nm^{-2}$, hence $D_E \approx 25$ meters in the Baltic for that windspeed.

Ekman also calculated the effect of finite but constant depth. When the actual bottom depth is less than $D_E$, the Ekman transport turns more towards the direction of the wind.

The influence of a pycnocline on the Ekman depth is another complicating factor (see for example Csanady, 1982). Due to the small momentum transfer through the pycnocline, the upper layer slides more or less frictionless over the underlying layer. When the pycnocline depth is less than $D_E$, the well-mixed layer depth substitutes the Ekman depth. The Ekman transport in the well-mixed layer is to the right of the wind. A thin well-mixed layer means uniform velocity profile within the layer, the velocity being everywhere nearly perpendicular to the wind.

During the summer, the thermocline in the Baltic has a typical depth of 15 - 30 meters. Hence it can imply a limitation to the depth of the Ekman transport.

The time scale for the Ekman transport to force the cold water below the pycnocline to rise to the sea surface is of great interest. One estimation formula by Csanady (1981) will be cited:

Consider a two-layered sea with a well-mixed upper layer and no mixing across the pycnocline. Then, for a constant wind stress, the time for lifting the pycnocline to the surface is

$$t = \frac{h_1 \cdot (h_1 + h_2) \cdot C_i \cdot \rho}{h_2 \cdot \tau}$$

With the values relevant to the Baltic summer stratification $h_1 = 20$ m, $h_2 = 40$ m, $C_i$ = internal wave speed = $0.35 \text{ ms}^{-1}$, $\rho = 10^3 \text{ kgm}^{-3}$, $\tau = 0.1 \text{ Nm}^{-2}$ (windspeed $7 \text{ ms}^{-1}$) the time scale will be 29 hours. A typical time scale for an upwelling to be established should then be one day of favourable winds.

The upwelling may propagate along the coast - with the coast to the right - as an internal Kelvin wave. Walin (1972) measured upwelling in the southern part of the Hanö Bight, when the local wind was perpendicular to the coast, while the wind at another part of the bight was parallel to the shoreline. If travelling with the speed of an internal wave, the upwelling should arrive to the measuring section about two days after generation. This result was compatible with the measurements.

Upwelling is a three-dimensional feature, and field measurements show locally intensified upwelling centers. There are also examples where the upwelled water leaves the coast and protrudes out into the basin in fingerlike bands, sometimes called upwelling filaments (Brink, 1983).

The influence of an irregular coastline curvature and/or bottom topography on upwelling is an intricate matter. Peffley and O'Brien (1979) used a numerical model to calculate the effects of a cape with and without an irregular bottom topography. They found no influence of the cape, when the bottom was plane, the upwelling going symmetrically around the cape. However, with a realistic bottom topography where the shelf was narrower outside the cape, the upwelling was increased locally at the cape. A canyon oriented perpendicular to a straight shoreline also implied intensification of the upwelling. This result gives more importance to the bottom topography than to the coastline configuration itself.

Satellite-derived isotherm maps of the Gulf of Lion (Millot et al., 1981) show that the upwelling centers repeatedly are found along certain straight coastal segments. Sometimes the upwelled water also spreads out into the gulf in the form of filaments.

Hua et al. (1983) tried to explain the fixed locations as a result of the coastline curvature alone. With the aid of a two-layer numerical model, they found that the coastline can be divided into bays and capes of two types, depending on the direction of the wind (see Figure 1). Type B permits strong upwelling in the corner and propagation of the Kelvin wave, while type A arrests the upwelling.

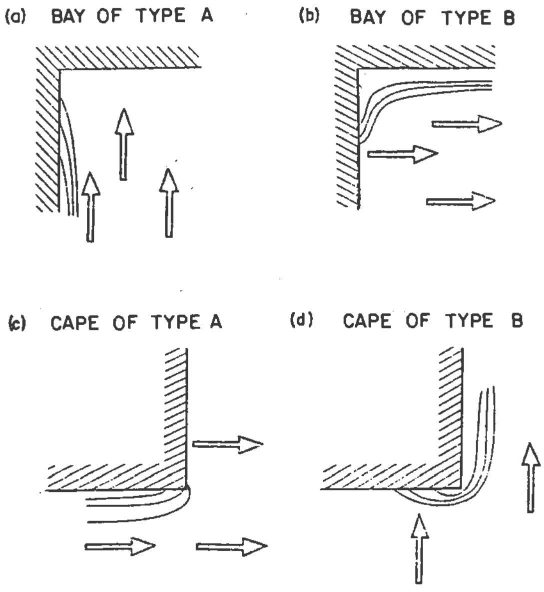


Figure 1. Analogous cases for bays and capes(from Hua et al.,1983).

They also made calculations involving mixing between the two layers. The decreased density difference slowed down the Kelvin wave, leading to more stationary upwelling centers, which also spread out farther from the shore.

Some earlier examples of upwellings in the Baltic are found in Svansson (1975) and Shaffer (1979). Svansson showed upwelling in the western Hanö Bight, and summer as well as winter upwelling outside Västervik. Shaffer documented temperature, salinity and currents from an upwelling event outside the steep west coast of Gotland.

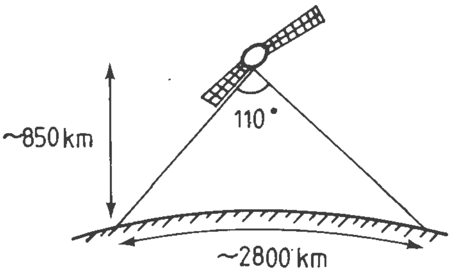
## 3. SATELLITE DATA

### 3.1 The satellite and the AVHRR instrument

The satellite data come from the AVHRR (Advanced Very High Resolution Radiometer) on board the polar orbiting weather satellites in the NOAA series.

Time of passing over Scandinavia:
- NOAA-6: ~ 07 GMT
- NOAA-7: ~ 13 GMT
- NOAA-8: ~ 07 GMT

AVHRR wavelenghts (μm):
- ch 1: 0.58-0.68
- ch 2: 0.725-1.1
- ch 3: 3.55-3.93
- ch 4: 10.3-11.3
- ch 5: 11.5-12.5 (only NOAA-7)



Ground resolution in nadir: 1.1 km

Relative resolution in temperature (NEΔT): 0.12 K

Figure 2. Specifications for NOAA satellites and the AVHRR.

The AVHRR is a passive receiver of electromagnetic radiation in 4 or 5 wavelength intervals, concentrated in the atmospheric windows: Channel 1 is in the visible region, channel 2 is in the near infrared, and channel 3 and channels 4 - 5 are in two distinct atmospheric windows of the infrared region (see Figure 2).

## 3.2 Data processing and visualization

Twenty-four different scenes from the summers of 1981 - 1983 (see Appendix 1) were chosen after a check that cloud-free conditions over the Swedish coast were to be expected at the same time as there were indications for upwelling to occur. The indications were observed from prevailing wind conditions and in situ measurements.

The digitalized data were taken from Tromsö receiving station in Northern Norway, and then processed in an interactive computer, allowing the data to be visualized on a colour TV monitor. One part of the work was done on the IAS (Image Analysis System, developed by MDA, Canada), situated at the Swedish Space Corporation, and the other on a simpler EBBA (Simple Image Processing System), built by the Swedish Space Corporation. The IAS images consist of 512 x 512 pixels and the EBBA images of 256 x 256 pixels in full resolution.

The images - projected on the TV monitor as grey-scale images or false colour images - were documented by colour slides taken with an ordinary camera (for the false colour scale, see Appendix 2).

The IAS computer also reads the calibration data supplied by the satellite, from which it is possible to translate the digital data of channels 4 and 5 into temperatures. These temperatures - corresponding to the infrared radiation reaching the satellite - are called brightness temperatures, and they are generally a couple of degrees lower than the actual sea surface temperature.

For comparison purposes, most of the infrared images have been transferred into isotherm maps. The geometrical distortion was then compensated for by projection on an inclined table.

### 3.3 Interpretation of the satellite data

In the wavelength region of channel 4 and 5, the emissivity of sea water is very close to unity; hence the measured infrared radiation may be interpreted as the temperature of the sea. However, when translating the brightness temperatures to bulk sea surface temperatures (SST), some important processes must be considered:

1) cloud contamination
2) atmospheric absorption and emission
3) diurnal thermocline in the uppermost metre of the sea
4) skin effects in the uppermost millimetres of the sea

The first two processes refer to changes in the emitted radiation from the sea surface, and the other two are consequences of the definition of what is the sea surface temperature, i.e. the bulk sea surface temperature that can be measured at a depth of about one metre.

These four processes are briefly discussed, and then an interpretation example is given. Observe that all the analyses refer to daytime satellite data.

1) When dealing with SST, the need for accuracy in separating cloud contaminated areas is very high. Liljas (1984) has developed an automatic cloud classification method for weather forecasting purposes, using the AVHRR channels 1, 3, and 4. The findings of Liljas have been used qualitatively in a manual cloud separation.

Clouds, especially high clouds such as cirrus, are seen as cold areas on the infrared channel. Since clouds have a high albedo, it is normally easy to unveil cloud-contaminated areas by looking at the channel 1 image.

Fog over water gives a rather high albedo in channel 1, combined with high temperatures in channel 3. The same is valid for sunglints, the latter fortunately strictly related to the angle of the sun. The increased temperatures in channel 3 are due to reflection of infrared radiation from the sun in the water particles of the fog, or - in the sunglint case - in the sea surface. For the SST mapping, fog is of importance, but sunglints are not.

2) The infrared radiation emitted by the sea surface is partially absorbed by the atmosphere, mainly by water vapour absorption, and then the atmosphere reemits at longer wavelengths. There are several methods for correcting the atmospheric attenuation, some of them using in situ data of SST and/or the vapour content of the atmosphere, others using the satellite data alone.

Since this study deals with rather small areas, where the relative temperatures are of more interest than the absolute values, and since in situ measurements of SST are taken on a routine basis, a very simple correction method has been chosen.

A few in situ measurements at cloud-free locations near the upwelling areas are used as true bulk SST. The mean brightness temperatures of nine pixels ($\sim 10$ km$^2$) large areas at these locations are then used to find the atmospheric attenuation. All brightness temperatures are then corrected with the same number.

This method could only be justified if the atmospheric conditions in the area are thought to be similar, and if the angle at which the satellite looks at the area does not vary too much. The small dimensions of the studied scenes - the Baltic basins (~ 300 kilometres wide) are covered by an angle of just 12° - mean that these assumptions are not too hazardous.

With the above outlined method, 24 individual corrections gave a mean of 2.5 °C. The maximum correction was 4.3 °C, the minimum was 1.1 °C. As this correction method uses ship measurements taken at or below a depth of one metre, the diurnal thermocline and skin effect discussed below are also included in the correction.

3) In a review, Robinson (Robinson et al., 1983) estimates that the diurnal thermocline in the top metre of the sea can create differences between 0.1 to 1.5 °K. The highest value would probably be in the afternoon after a sunny day without winds.

   In the Baltic, some "hot spots" have been found, for instance in the centre of a high pressure, where the incoming radiation was high and calm conditions prevailed.
   In these "hot spots", the uppermost metre or metres can warm up well above the limits given by Robinson. A ferry passing through the area of one of these spots reported temperatures between 14 and 15 °C at a depth of 4 metres, while the satellite derived SST raised up to 19 °C (the satellite data were calibrated at places outside the "hot spot").

   The "hot spots" have only been found on a few occasions in this study.

4) The radiometer registers the radiation emitted by the uppermost 0.1 millimetres of the sea. The vertical heat flux is normally directed from the sea to the atmosphere,

leading to a temperature in the uppermost skin that is 0.1 to 0.5 $^{O}K$ colder than at a few centimetres depth (Robinson et al., 1983).

To illustrate the interpretation technique, an example is chosen from the area between Gotland and Latvia (see Appendix 3).

On the channel 1 image, clouds can be seen over Gotland, between Gotland and the Latvian coast, and also over land. The outstanding feature of this image is the albedo variation on the sea surface. There is one patch of lower albedo (difference ~ 2 %) south of Gotland and some smaller patches near the coast.

The channel 2 image is used to find the coastline geometry. On this image, the coastline of southern Gotland can be seen through the clouds that hide the contour in the channel 1 image. Observe that in the channel 2 image, the greyscale is inverted, with white corresonding to low albedo.

Channel 3, although disturbed by noise during this period, shows lower temperatures in the earlier mentioned patches. Taken together, the images of channel 1 and 3 indicate that the patches correspond to areas of no wind action, which make the surface free of waves and mirrorlike. The angle of the unidirectional reflection of the sunlight differs from the satellite viewing angle.

As could be seen in the channel 4 image, the area of calm conditions south of Gotland creates a "hot spot" in the afternoon. At the Latvian coast, upwelling of cold water occurs. This leads to more stable stratification in the atmosphere layer near to the sea surface and, consequently, less wave generation.

The channel 4 image could be overlayed with a landmask and a cloudmask, and also be coupled to a false colour scale marking the isotherms (Appendix 4).

## 4. IN SITU DATA

The in situ measurements of SST have served the purpose of correcting the satellite data for atmospheric attenuation, and they were also used alone in the statistical compilation described in Chapter 7.

The sea surface temperature in the Baltic and outside the Swedish westcoast is plotted every second day at SMHI. This routine has been going on since 1973.

Data come from approximately 40 coastal stations and from about 25 ships. From the plotted maps, it is possible to decide the day but not the hour of every individual measurement. At the coastal stations, the measurement depth is 0.5 metres, but the ship measurements can be taken from depths varying between 0.5 and 4 metres. For more details, see Thompson et al. (1974).

The locations for the vertical soundings referred to in Chapter 6 are found in Appendices 57 and 58. These vertical soundings are taken in a routine program without connection to the upwelling study.

## 5. METEOROLOGICAL DATA

The wind data are taken from coastal meteorological stations in the neighbourhood of the upwelling areas. The data are plotted as time series of wind vectors, with the vector pointing in the same direction as the wind blows. The wind is measured every third hour.

Observe that the height at which the wind is measured could vary, and that some stations demonstrate lee effects for wind from certain directions. Information about this as well as the geographical localization of the stations is to be found in Appendices 57 and 58.

In the text, the following classification of the wind speed is used:

| | $ms^{-1}$ |
|---|---|
| Calm | 0 |
| Weak | 1 - 2 |
| Moderate | 3 - 7 |
| Fresh | 8 - 13 |
| Strong | $\geq$ 14 |

## 6. UPWELLINGS SEEN FROM THE SATELLITE

All satellite images are transformed to isotherm maps. A few examples of the false colour images are given, as well as black and white images illustrating circulation patterns and upwelling front behaviour.

Together with the isotherm maps, synoptic wind measurements are presented as time series. The rather few examples of vertical soundings of temperature in the neighbourhood of the upwellings are found in tables.

### 6.1 Bothnian Bay

Three upwelling events from this area are shown in Appendices 5 to 8.

#### The 1981 event

There are two satellite images from this upwelling situation: September 30 and October 6. The temperature decrease due to the upwelling is rather modest, about 3 °C. However, looking at the vertical soundings of temperature taken before this event, it is seen that water of a temperature less than 7 °C has its normal position at depths below 20 metres.

On September 30, the upwelling extends from the cape of Bjuröklubb some 30 - 35 kilometres to the south, forming a band of maximum 10 kilometres width. A week later, the upwelling center outside Bjuröklubb has widened and turned around the cape in the direction towards Skellefteå. A band of cold water east of Skellefteå almost joins the Bjuröklubb upwelling. To the south, the upwelling front is rather stationary, it has just advanced around 10 kilometres towards Umeå.

The coldest patches in the upwelling are found 5 to 10 kilometres out from the coast.

A week of moderate to fresh winds from south to south-west precedes September 30, although with a short period of winds from south-south-east on September 28. After September 30, the wind is fresh from south-south-west until October 4, when it first turns to south and later, on October 5, to south-east.

### The 1982 event

In July, this region is characterized by a thin layer of warmed surface water. Cold water of a temperature around 4 - 5 °C can then rather easily be drawn to the surface. On the July 16 image, the cold center outside Bjuröklubb shows temperatures as low as 4 °C, while a temperature of 10 °C is to be found only 18 kilometres away. Locally, the gradients are even sharper.

The extension of the very cold water ($\leq 6\ ^{o}C$) forms a band almost along the whole straight coast of the southern Bothnian Bay, about 70 kilometres long and extending around 10 kilometres out from the coast. Even outside this band, there is a lowering of the temperature. The coldest patches are found 3 - 4 kilometres from the coast. A smaller upwelling is also seen east of Holmön. The upwelling seen on July 16 was preceded by two days of fresh winds from south to south-south-west.

The vertical sounding of July 17 is inside the upwelling center. Around July 19 the upwelling outside Bjuröklubb ceased, giving room to more normal summer temperatures such as those seen on the sounding on July 21.

## The 1983 event

Once again a band of cold water is found along the straight coast of the southern Bothnian Bay, but contrary to the earlier examples, the cape of Bjuröklubb does not form a center of the upwelling. Tendencies of lowered surface temperatures are also found east of Holmön and north of Skellefteå.

From the vertical sounding at the open sea station F 9, it can be seen that water of $7\ ^{o}C$ was to be found at rather modest depths - between 10 to 20 metres - on the day before the satellite image.

According to in situ measurements, an upwelling was formed along the same coastal section - without affecting the cape of Bjuröklubb - on August 12, after some days of fresh winds from south-west to west-south-west. There are further measurements indicating that the upwelling along the coast between Bjuröklubb and Umeå persisted through some periods of strong northwesterlies, but the main wind direction was between south to south-west during the period preceding the image. On the day foregoing the satellite image, the wind was fresh from west-north-west to north-west.

### Discussion

Upwelling seems to develop along the straight coast south of the cape of Bjuröklubb after a wind impulse from south to south-south-west. The upwelling extends like a band some 10 to 15 kilometres out from the coast. An upwelling center is likely to be found east of the cape of Bjuröklubb.

One example (October 6, 1981) shows upwelling spreading around the cape towards north-west, which is contrary to the theory cited earlier (the cape of Bjuröklubb being of type A). The probable explanation is the change of wind direction, that took place on the preceding day. The wind impulse from south-east implied upwelling also along the coastal section between Bjuröklubb and Skellefteå.

The 1983 event does not show an upwelling center outside the cape of Bjuröklubb, although the strong wind from south to south-south-west two days earlier would make it probable. On the day preceding the satellite image, the wind at Bjuröklubb was from west-north-west, a direction which, according to the Ekman theory, would not favour strong upwelling. A propagation of the upwelling center from the vicinity of the cape some 25 kilometres in one or two days towards the south - where it was found on the satellite image - cannot be excluded.

## 3.2 Bothnian Sea

Three upwelling events from this area are shown in Appendices 9 to 22.

## The 1981 event

Four satellite images exist from this longlived upwelling, centered east of Hudiksvall. During the last part of the period, it is necessary to take autumn cooling into account. The whole period is characterized by winds with a strong component from the south.

In situ measurements show a drop in the sea surface temperature at the north-eastern tip of Hornslandet (the peninsula east of Hudiksvall) on September 18. The first satellite image, September 23, shows slightly colder water north and east of Hornslandet and warmer water to the south. The wind was moderate to fresh from the south to the south-east on September 18 to 21, then on September 22 it turns more to the south-west and ceases.

On September 24-25, there is a fresh wind from the south to south-west, followed by a period of weaker winds. The satellite image from September 30 still shows colder water north and, more pronounced, east of Hornslandet, but the upwelling is very limited in strength and dimension.

Two hits of winds from south to south-south-west on October 1 - 2 and 4 - 5 lead to strong upwelling on the satellite image of October 6. The horizontal extensions of this upwelling could be approximated by the 8 $^{o}$C (or 9 $^{o}$C) isotherm, which gives a length along the shore of 100 (or 180) kilometres and a width of 10 to 20 kilometres. The upwelling centers (temperatures less than 6 $^{o}$C) are found east and north of Hornslandet, pressed to the coast between Hornslandet and Brämön, the island outside Lörudden (see amplifications of the false colour image and corresponding isotherm map in Appendices 13 and 14).

On October 10 there is a fresh wind from the south-east, which turns to south-west on October 11. The following days show weak and changing winds. Nevertheless, the upwelling can be seen on the satellite image of October 16. However, at this date autumn cooling starts in shallow coastal waters, and this could be an explanation of the cold band outside Gävle.

Some vertical temperature soundings from Storjungfrun and Söderhamn - both places outside the upwelling area - are listed in Appendix 11. Water with a temperature of 6 °C or less is found at depths of about 40 metres.

### The 1982 event

This sequence - July 13, 14, and 16 - shows very cold but small scale upwelling in the Bothnian Sea. The period is characterized by high sun radiation due to a high pressure area over Scandinavia, leading to a sharp and shallow thermocline in the Bothnian Sea (see vertical soundings at Brämön).

Fresh winds from south-south-west on July 10 to 11 create cold, upwelled water to the north of Hornslandet. In situ measurements give 8.4 °C north of the peninsula and 16.4 °C on the southern side on July 12. However, on the same day, July 12, the wind changes to north-west and to north, which leads to a ceasing of the upwelling. The satellite image of July 13 shows the quick response to this change in wind direction: there are hardly any signs of cold, upwelled water at the surface.

On July 13 the wind turns back to south to south-south-west, giving an abrupt change in the isotherm pattern on the image of July 14. The cold upwelling spots are rather small - typically a few tens of kilometres on their longest axis - but very intense in horizontal gradients, with differences of 7 °C over 2 kilometres.

Two days later, on July 16, the northernmost cold spot has disappeared and a new one has formed more to the south.

In situ measurements indicate that this upwelling event ended around July 19, i.e. it had a total duration of one week.

### The 1983 event

The first sign of this upwelling occurs outside Örnsköldsvik on July 20, when a surface temperature of 5.2 °C was registered in an in situ measurement. The driving force was a strong wind - well over 10 $ms^{-1}$ - from west-south-west to west-north-west, starting the day before. Vertical soundings before and during the upwelling reveal that this cold water originated from a rather moderate depth, between 10 and 20 metres.

On the July 22 image, three upwelling centers are found: outside the peninsula Åstholmsudde, east of Hemsön, and east of Ulvöarna. The maximum temperature anomaly is about 6-7 °C.

A look at the wind vector series makes it likely that the upwelling generation ended on July 21, as the wind got a strong component from the north.

After July 22 the wind was from north-west, and it dropped to less than 10 m/s. At noon on July 24, the wind became weak or nonexistent. On the satellite image of July 25, the cold water has disappeared from the surface; just leaving some smaller areas with a temperature a few degrees lower. The northwesterlies (perpendicular to the coastline and directed seawards) were incapable of retaining the upwelling from July 22; and/or the calm conditions during 24 hours before the satellite pass on July 25 lasted long enough to reestablish more normal surface temperatures.

### Discussions

It is quite clear that the coastal section between Hornslandet and Lörudden is a place where upwelling readily occurs after a wind impulse from the south to south-south-west. The northern and eastern sides of the cape of Hornslandet seem to be the places with the coldest water.

The varying "normal" depth of the thermocline in July compared to September is reflected in the difference between the 1981 and 1982 events. In the first case, the upwelling is on a fairly large, horizontal scale (~ 100 kilometres), the cold water forming a band attached to the coast. The coldest water originates from depths of around 40 metres, and the upwelling is persistent for several weeks. The second case is from a period with a sharp thermocline near the surface, hence even a weak upwelling leads to surfacing of the cold, underlying water. The very cold areas are patchlike and rather small (~ 10 - 20 kilometres). They also seem to disappear quickly.

The difference between the 1981 and 1982 upwellings also demonstrates the shortcomings of using the sea surface gradients alone as an indicator of the intensity of the upwelling.

The 1983 event shows that when the wind has stronger west components, the upwelling occurs more to the north, along the deep coast between Sundsvall and Örnsköldsvik.

## 6.3 Baltic Proper

In Appendices 23 to 25 are illustrated three upwelling events from the northern and central parts of Baltic Proper. Two are from the westcoast of Gotland and one from the archipelago area between Norrköping and Stockholm with its center outside Oxelösund.

Three events from the late summers of 1981, 1982, and 1983 are discussed in Appendices 26 to 32, showing upwelling outside the southern parts of Sweden. A couple of these images also cover upwelling areas more to the north, including an upwelling east of the southern tip of Gotland.

## The July 1982 event: Gotland

At midnight between July 12 and 13, a fresh wind from northeast to east-north-east starts to blow over Gotland and Öland. The July 14 image shows a lobate upwelling, with filaments extending some 25 kilometres from the shore. One upwelling center is found north of Visby and another in the bay outside Klintehamn.

There are also satellite images from July 13 and 16. In spite of a turning to moderate winds from the south-east on July 15, the upwelling remains on the July 16 image. The contours of the sharpest gradients on the three images are drawn in Appendix 23. The sequence indicates a certain slow (~ 10 kilometres in two days) movement of the front. The direction of propagation is in accordance with that of a Kelvin wave.

The same slow movement could be seen outside northwestern Öland. Apart from being a result of wave propagation, the movement could also be a response to the change in the wind direction.

These satellite images can also be seen as greyscale images in Appendices 32 to 35.

## The July 1983 event: Gotland

In Appendix 22, the isotherms of the July 25 upwelling are drawn. The northern half (towards the wind) of the upwelling front is straight and shore-parallel at a distance of about 3 kilometres from the coast. The southern half of the upwelling spreads some 20 kilometres out into the sea. There the coldest water separates from the coast, following the bottom depth contours. The horizontal temperature gradient in the front towards the wind is 4 °C over one kilometre.

The fresh wind around north-west turned to north at noon on July 22, then it continued to turn towards north-east and ceased on July 23 - 24. On July 24, cold water (11 °C) was observed outside Klintehamn in an in situ measurement.

There is another satellite image of July 26. The position of the upwelling front on that day is marked on the same figure as that of July 25 in order to show the frontal movement.

The wind during the time lapse between the two images was from north to north-north-east and of moderate strength. The movement of the front is slow but evident, 12 kilometres i 24 hours, giving a propagation velocity of 0.14 $ms^{-1}$. The direction is the same as that of a Kelvin wave. Unfortunately no vertical soundings are known to be taken in this area and from this period.

### The July 1983 event: Oxelösund

On the July 22 image, slightly colder water extends from Västervik northwards up to the archipelago south of Stockholm. One principal cold patch is seen outside Oxelösund and two less pronounced patches outside Västervik and Landsort.

In situ measurements reveal the beginning of an upwelling outside Västervik on July 19, while the cold water outside Oxelösund was drawn to the surface some days later.

The wind was fresh from the south on July 18, thus lifting colder water outside the coast at Västervik. On July 19 it turned to west-south-west, on July 20 - 21 to north-west, but still with windspeeds around 10 $ms^{-1}$. This turning of the wind to become more westerly then led to the upwelling outside Oxelösund.

The vertical soundings (Grässkären) from the area indicate that the upwelling did not have to be intense in order to produce surface temperatures around 12 °C.

## The 1981 event: Southern Baltic Proper

The upwelling on August 3 could be divided into three regions: east of Öland, Karlskrona to Åhus, and Ystad to Trelleborg. The last coastal section is unfortunately affected by clouds.

The upwelling east of Öland is pressed to the shore with a width of a few kilometres. However, off the southern tip of Öland, the colder water protrudes south-eastwards some 30 kilometres.

The coldest water (11 °C) is found east of Karlskrona, but the upwelling goes around the corner and continues westward outside the Karlskrona archipelago. A tendency towards colder water could also be seen outside Åhus.

Furthermore, there are indications of colder water outside Ystad and, more pronounced, outside Trelleborg.

The wind over the area had a strong westerly component during the five days preceding the satellite image, being closer to west-south-west over Öland and west-north-west over the Trelleborg area. The windspeed was well over 10 $ms^{-1}$ during a great deal of this five day period.

Although the wind-forcing was strong and cold water was found at a rather modest depth (see vertical soundings at Hanöbukten and Karlskrona), the lowest temperature found at the surface was as high as 11 °C. Apparently the upwelling was not very effective in lifting deep water.

## The 1982 event: Southern Baltic Proper

The first half of September was dominated by fresh to strong winds from the south-west. In situ measurements reveal intense upwelling in the western Hanö Bight and south of Karlskrona to south-east of Öland on September 6.

The same pattern is to be found on the satellite image of September 15. The upwelling center is located in a band from east of Öland to south of the Karlskrona archipelago. Cold water is also found in the western Hanö Bight.

Along the eastern side of Öland, the upwelling is pressed to the coast. Outside the southern tip of the island, the cold water spreads out towards the south-east some 40 kilometres. South-east of Karlskrona, the cold water protrudes southward, extending like a filament some 50 kilometres out from the coast. The horizontal gradients are considerable in this area - 7 °C over 9 kilometres.

In September, water with a temperature of less than 7 °C has its normal position at depths of around or below 30 metres (see vertical soundings from Hanöbukten), indicating that intense upwelling was taking place.

## The 1983 event: Southern Baltic Proper

This sequence of three satellite images within a week demonstrates changes in an already established upwelling. Besides the isotherm images, the false colour images of the first two occasions are reproduced in Appendix 26, the last being reproduced on the cover of part I.

The first image, from September 23, shows upwelling outside Oskarshamn and Västervik, along the eastern coast of southern Gotland, east and south of Öland, and east and south of Karlskrona. In situ measurements show the existence of cold water ($<7$ °C) east of Öland on September 22.

This time the upwelling front east of Öland is not pressed to the coast, a tongue of colder water extends some 30 kilometres eastward. South of the island, another tongue is spreading southward.

As can be seen from the wind vector plotting, there was a ten days' period with fresh winds - often with wind speeds exceeding 10 $ms^{-1}$ - from south-west preceding the first satellite image. On September 22 the wind turned to west-north-west.

The vertical soundings (Ölands södra udde and Karlskrona) indicate that water with a temperature of 7 - 8 $^{o}C$ was drawn from a depth of at least 20 metres, or more probable, around 30 metres.

The wind direction over the south-eastern parts of Sweden then varied in the sector from south-west to north-west, stabilizing on September 26. One and a half days of wind speeds exceeding 10 $ms^{-1}$ from west-south-west immediately preceded the satellite image of September 28.

This second image shows how the upwellings outside Öland and outside Karlskrona have merged into one big upwelling, protruding some 80 - 90 kilometres southward in a tongue-like filament. The upwelling is also spread westward along the whole coastline of the Hanö-Bight.

Two days later - on September 30 - the upwelling east of Öland has weakened. The big upwelling center south-east of Karlskrona remains, as well as the cold water in the western Hanö Bight. The long tongue of cold water extending southward has not advanced, but it has been bent and twisted. There is also another filament stretching out south-eastwards from Öland.

Over the southern part of Sweden, the wind was of moderate strength and of varying directions during the two days' elapse between the September 28 and September 30 images. More to the north, the wind was fresh from north-west.

## Discussion

Winds between north and north-east give upwelling along the steep west coast of Gotland. In fact, the coastal section outside Visby is one of the steepest and straightest to be found in the Baltic (see bathymetric chart, Appendix 59). Such a coast would theoretically be suitable for letting a thermocline lifting propagate as a Kelvin wave without too rapid a dissipation of energy.

The satellite images of July 25 and 26 indicate that a movement of the upwelling front takes place. The velocity of the frontal movement (0.14 $ms^{-1}$) can be compared with the propagation velocity of a perturbation on the thermocline, about 0.35 $ms^{-1}$ ($\Delta\rho$ = 0.9 $kgm^{-3}$, $h_1$ = 20 m, $h_2$ = 40 m). An explanation of the slower movement seen on the images can be mixing which leads to diminishing density differences.

On the July 25 image, it can also be observed how the position of the coldest water of the upwelling seems to be governed more by the 25 and 50 depthlines rather than by the coastline itself.

The two independent events - 1982 and 1983 - from the southern Baltic Proper indicate that the area south of Karlskrona to east of Öland is a frequent place for intense upwelling to occur. The wind direction should then be south-west to west-south-west.

The time series September 23,28 and 30 1983 document a movement of the coldest spot (the upwelling center), from east of Öland to south-east of Karlskrona. This movement corresponds to a propagation velocity of 15 kilometres per day, or 0.17

$ms^{-1}$, between each of the images.

The most striking feature of the upwellings in this area (both the 1982 and 1983 event) is the spreading of a cold filament out into the Bornholm Basin. The cold water spreads out like a plume, with mixing taking place on the sides behind the front. If the front seen on September 23 was advected to the position seen on September 28, that would imply an average current velocity of about 0.20 $ms^{-1}$. Apparently the horizontal shear was strong on the sides of the advancing cold filament.

It is unclear if the spreading out is due to the upwelling itself (gravitational spreading), or if the cold water is drawn as a tracer into an already existing basin circulation.

So far, this study has dealt with describing the locations of the upwellings, their dimensions and, occasionally, the existence of filaments extending out from the upwelling center. For this purpose, the false colour images give adequate information. If more detailed information about the circulation pattern is desired, it is possible to use the full resolution of the satellite radiometer. With a grey-scale illustrating the different temperatures, one may detect variations of about 0.1 $^{o}C$ and, hence, much more of the fine structure appears.

Two time series of upwelling events discussed earlier are shown in Appendices 33 to 38.

Sometimes cyclonal eddies are observed on the upwelling front, as in Appendix 39, where the upwelling outside the cape of Bjuröklubb is reproduced. Another example can be seen outside the south-eastern tip of Skåne( Appendix 38). The wavy form of the front is also seen on Appendix 40.

The question then arises, of whether the eddies are consequences of the density discontinuity or if they exist there and are visible just when temperature gradients are drawn into the eddies. The image showing eddies outside the capes of the Karlskrona archipelago and Öland (Appendix 39, bottom) indicates that at least some eddies are present in the coastal zone, even when there is no visible upwelling front seen at the sea surface.

## 7. UPWELLING STATISTICS FROM THE IN SITU DATA

### 7.1 How the statistics were produced

At SMHI, the sea surface temperature of the Baltic has been plotted every second day since 1973. Comparisons between this routine mapping and the temperature pattern achieved from satellite data, indicate that the major upwelling areas are covered in the in situ measurement network. Three examples of comparisons are shown in Appendices 41 to 46.

The sea surface temperature from in situ data is better analysed - owing to more data information - in the Baltic Proper than in the Bothnian Sea or the Bothnian Bay. Small scale upwellings like those on July 16, 1982 (Appendices 43 and 44) are not registered by the in situ measurements.

The experience of the different horizontal scales of upwelling drawn from the satellite images together with a look at the bathymetric chart for the Baltic, suggested a rather fine division of the Swedish coastline into 55 coastal sections, each with a typical length of 20 to 40 kilometres (Appendix 47). The sections are chosen so that they, as far as possible, are uniform in length direction, bottom topography, type of coast etc. The upwelling statistics were produced only for those coastal sections where frequent in situ measurements were available.

In situ data from July, August and September during the ten year period 1973 to 1982 were studied. A minor part of these data has earlier been used at SMHI in a similar approach to quantify upwelling (Johansson, 1977).

In order to demonstrate the reliability of the statistics, the frequency of days with measurements, taken within a distance of 10 kilometres from the coast, was calculated for each coastal section.

Upwelling was proved if an in situ measurement showed an abnormal temperature drop of at least $2^{o}C$, compared to earlier and surrounding measurements. The days of the beginning and ending of the upwelling event were documented.

The maximum lowering of the temperature during the upwelling can be interpreted as a measure of the strength of the upwelling. As the lowering depends on the actual depth of the thermocline, it is called "relative strength", and should be used with caution when compared from month to month and section to section.

The requirements for a certain coastal section to enter the statistics were:
- At least 9 days per month when in situ measurements were taken.
- At least 8 years during which the earlier requirement was accomplished.

These requirements were fulfilled at 15 to 17 (depending on the month) coastal sections, which means that the statistics cover about 30% of the Swedish coastline.

## 7.2 Result of the upwelling statistics

The main information from each coastal section is found in Appendices 49 to 54.

## How common is upwelling?

In Appendix 48 the sections are listed in the order of how frequent upwelling occurs. The same sections, which in Chapter 6 were characterized as places of frequent intense upwelling - Bjuröklubb to Ratan, Kuggören and Kalmarsund to Karlshamn -are also found in top of this list. Upwelling is also very common along the Trelleborg and Ystad section during July and August.

In the other end of the list there are two sections with no upwelling at all. Svenska Högarna is a section outside a rather sparse but extensive archipelago, which can store a lot of warm surface water. It is unclear why upwelling is so rare along the eastern side of the northernmost tip of Gotland.

September, with its stronger winds, is a month of increased upwelling. Almost all coastal sections show an increased rate of upwelling during that month, with the exception of Trelleborg and Ystad. It is likely that the increasing depth of the thermocline in late summer makes it more difficult, even for stronger winds, to draw cold water to the surface at the rather shallow coast outside Trelleborg and Ystad. The vertical circulation imposed by the upwelling is then confined to the upper well-mixed layer, and is not seen as a temperature drop at the surface.

There is a strong year-to-year variation in the rate of upwellings. There are some examples where there was no upwelling at all during an entire summer period, even among the coastal sections at the top of the frequency list.

## How long do upwellings persist?

There are some examples of upwelling events that lasted for more than a month. The average length during July and August is a week, in September a week and a half. The increased rate of upwelling in September is not due to a higher number of upwellings, but rather to a longer duration.

How strong is the temperature drop due to the upwelling?

The relative strength of the upwelling is found in the range between 2 to 10°C. A typical drop is 4 - 5°C, although the coastal sections outside extensive archipelagos - Landsort NE and Almagrundet - give typical temperature drops of 3-4°C. There seems to be no significant difference in the magnitude of the temperature drop from month to month.

## 7.3 Wind correlations

Appendices 55 and 56 illustrate an approach to document how the wind correlates to upwelling frequency. The diagrams show the statistics of three hourly wind measurements from one day before the beginning to one day before the end of each upwelling event.

The top diagram of Appendix 55 shows a strong peak for winds parallel to the shoreline, coming from west to west-north-west. This is in accordance with the Ekman theory of shore parallel wind for upwelling generation.

To be sure that this peak has to do with the upwelling, the distribution of the wind during the complementary period of no upwelling is drawn in the bottom diagram. There the wind is more homogeneously distributed over all directions, even if west and west-north-west also here are highly represented. It has already been said that upwelling of cold water outside Trelleborg seems difficult during September, even with favourable winds from west to west-north-west.

Appendix 56 shows a strong peak for winds from south-south-west. During the complementary period of no upwelling, this peak is absent. Hence winds from south-south-west seem essential in the upwelling generation along the Ratan section. Winds from the south are almost equally represented in the two diagrams. This can be interpreted as if the limit where the wind starts to generate upwelling lies within that wind sector.

## 8. CONCLUSIONS

Coastal upwelling - in the meaning of upwelling of cold water during summer conditions - is a common phenomenon along the Swedish coastline of the Baltic. For some coastal sections, upwelling occurs during one fourth to one third of the time.

Satellite data reveal three regions of especially intense upwelling: South of the Karlskrona archipelago to southeast of Öland (Baltic Proper), north of the peninsula Hornslandet (Bothnian Sea) and from Ratan to Bjuröklubb (Bothnian Bay).

Intense upwelling means that water from a depth of 20 to 40 metres - i.e. between the seasonal thermocline and the main halocline - is lifted to the surface.

In situ data also reveal these places as the most frequent places of upwelling, together with the Trelleborg-Ystad coastline.

The satellite data indicate that the horizontal scales of coastal upwelling are in the order of a hundred kilometres alongshore and some ten to twenty kilometres in the direction out from the coast. When the thermocline is situated near to the surface, shortlived upwellings with strong temperature gradients can occur on a smaller scale, a few tens of kilometres in dimension.

Sometimes the upwelled water is spread out several tens of kilometres out into the basin, forming filaments of cold water.

Some of the satellite images show a certain movement (of the order of 10 to 15 kilometres per day) of the upwelling front and the upwelling center. These movements may be associated with the propagation of coastal-trapped waves.

A very simple wind analysis of the upwelling events documented in the in situ data, confirms the importance of shore parallel winds for coastal upwelling generation.

For the future work on coastal upwelling, the remote sensing of the sea surface temperature from satellites together with a traditional field program can be a very fruitful combination.

The satellite data in real time can be used to tell the exact position of the upwelling fronts and centers before the initiation of intensive field measurements. This implies that at least a part of the measuring program has to be open for day-to-day changes called for by the satellite information.

The satellite data will of course also give valuable information concerning the sea surface temperature for the analysis and interpretation of in situ data.

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