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CONTENTS

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ABSTRACT

64 years of observations of 13 Finnish tide gauges were adjusted together to obtain precise relative land uplift values. The observations were prepared in the form of complete monthly averages, to avoid biases possibly introduced by interpolating missing data.

The results obtained were compared with those of determinations by three earlier authors, finding good agreement. Agreement improved when our data set was limited to the same span of years, and on one occasion improved still upon treating the exact same data (yearly means) by our technique.

Including air pressure corrections ("inverse barometer effect") led to slight improvement.

An earlier study by Sjöberg and Fan (1986) on the Fourier spectrum of tide gauge time series could for the most part be replicated.

Key words: Tide gauge, adjustment, land uplift, Baltic Sea, Fourier analysis

TABLE OF CONTENTS

1. INTRODUCTION

This is a joint report by the Finnish Institute of Marine Research and the Finnish Geodetic Institute on a study of the land uplift on the coast of Finland as determined by tide gauge measurements.

The Finnish Institute of Marine Research has been responsible for the tide gauge registrations being made continuously and nowadays automatically in currently 13 stations all along the Finnish coast, which are of a high quality and cover a period of up to a century.

The Finnish Geodetic Institute (FGI) has been involved in the study of land uplift mostly by other means (precise levelling, *KAKKURI AND VERMEER (1985)*, *KÄÄRIÄINEN (1966)*, *SUUTARINEN (1983)*) but also by the use of tide gauge data. The FGI's contributions are in the field of high precision analyses by adjustment techniques.

The purpose of this study has been twofold:

1. Perform an accurate analysis of the *relative* motions of the 13 tide gauges w.r.t. each other, to unearth possible geophysical motions between them, at the same time deriving a new set of land uplift values for them;

2. Get a better insight into the dominant components of sea level variability, which enters the above determination as "noise", and try to remove some of them by appropriate modelling. In this context we replicated a study by *SJÖBERG AND FAN (1986)* on the Fourier spectrum of Baltic tide gauge time series.

2. DATA USED

2.1 Generation of the data

The data used in this study consists of monthly means of sea level observations collected during the period 1922-1985 by the 13 Finnish tide gauge stations operated by the Finnish Institute of Marine Research. The positions of the tide gauge stations are listed in Table 1 and shown in Figure 1. Table 1 also includes the starting years.

The monthly means are based on 6 evenly spaced recordings a day during 1922-1970 and 24 recordings a day during 1971-1985. The resolution of the records obtained is 1 cm for the interval 1922-1970 and 1 mm for the interval 1971-1985. The data are relative to the reference surface of the Finnish sea level observations.

Table 1: Tide gauges on the coast of Finland.

Name	No.	Latitude	Longitude	Operating since
Kemi	1	65°44'	24°33'	1922
Oulu	2	65 02	25 26	1922
Raahe	3	64 42	24 30	1922
Pietarsaari	4	63 43	22 42	1921
Vaasa	5	63 06	21 34	1921
Kaskinen	6	62 23	21 13	1925
Mäntyluoto	7	61 36	21 29	1925
Rauma	8	61 08	21 29	1933
Turku	9	60 25	22 06	1921
Degerby	10	60 02	20 23	1923
Hanko	11	59 49	22 58	1887
Helsinki	12	60 09	24 58	1904
Hamina	13	60 34	27 11	1928

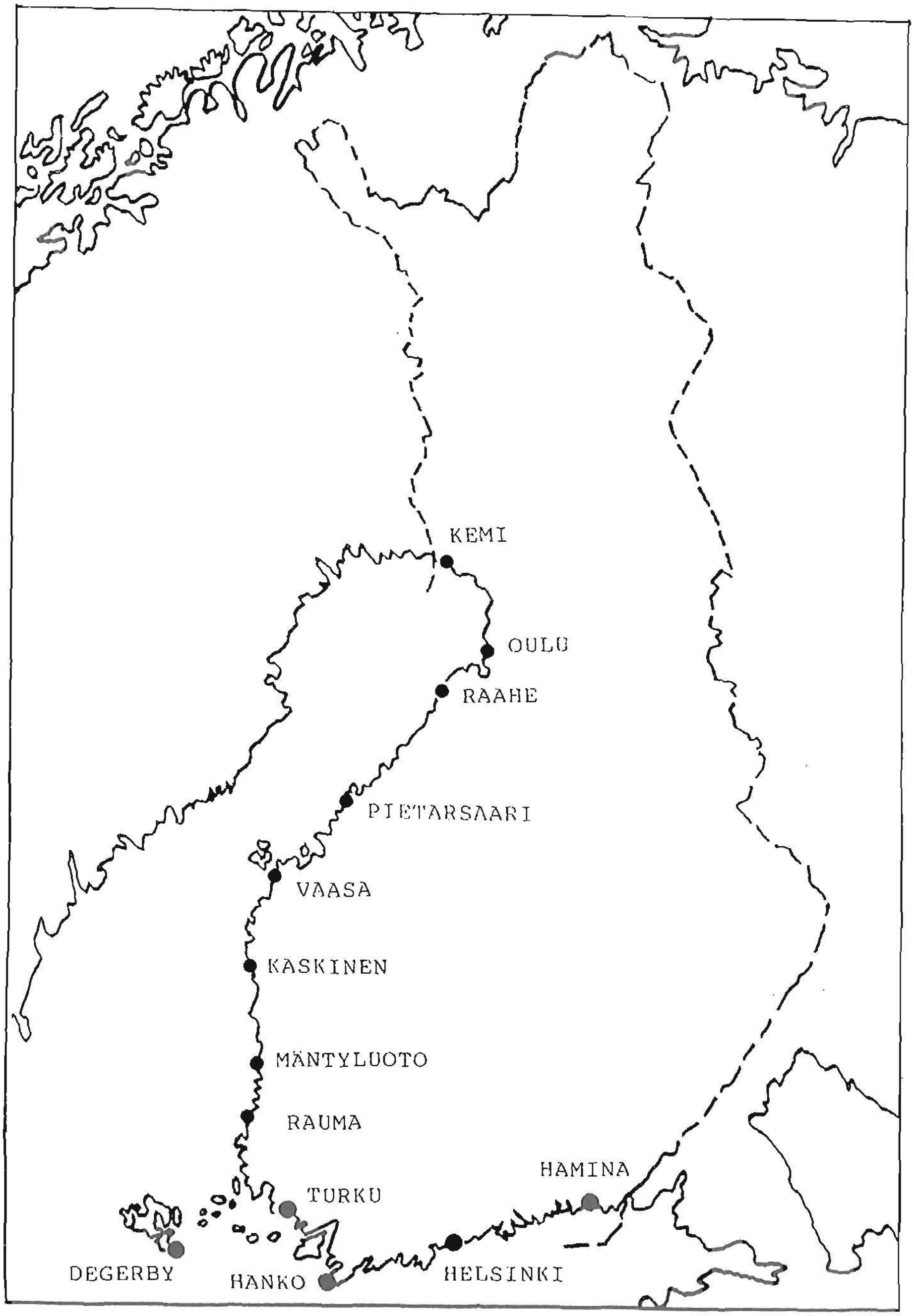

Figure 1: The 13 tide gauges on the Finnish coast.

2.2 Completeness of the data

Gaps are unavoidable in long time series. In the Second World War during the years 1939-1942 the tide gauge of Hanko was in the area leased to the Soviet Union: 33 months are completely missing from the data. From the data of Degerby 31 months are missing during the years 1968-1971 because of rebuilding of the tide gauge. In addition, there are several shorter gaps in the data of each station.

Because there is a clear annual cycle in the Baltic Sea level (cf. Chapter 7 and appendixes II and III), proper treatment of these gaps is essential. The method which has been used in the previous studies is to interpolate the individual missing values using the recordings from the nearby tide gauges. Tests have shown that this usually leads to good results, but e.g. in cases of travelling waves large errors have been found, particularly in the end parts of the bays. Persistent smaller offsets are also common. Both types of interpolation errors have to be corrected subjectively. Because the present study is based on monthly averages and not on the yearly averages, as all the previous studies, another option becomes available. It is to omit all months which are not complete. As Table 2 and Figure 2 show, the 30 % of the months which are rejected are distributed fairly evenly throughout the year, and there are no significant differences between the intervals 1922-1955 and 1956-1985.

The greater absence of more recent records is probably the consequence of taking readings more densely during the years 1971-1985 compared with earlier: generally it is only one reading which is missing from a month's observations. There are no remarkable differences in the absences of separate months. So the seasonal bias in observation availability is admirably small.

If there exist at least 4 stations with fully measured data for a month, one of them being the fixed base station chosen, the corresponding means for the month concerned will be used in the adjustment computations. For the period 1922-1985 fully measured data is available for at least 4 stations since April 1922 and besides for at least 5 stations since January 1923. So it depends on the choice of base station how many months will appear in the computations. On the other hand there is only one month, September 1985, for which all 13 stations have fully measured records.

The frequencies of usable means for a month during the 64 year period 1922-1985 are given in Table 2.

Table 2: Frequencies of the monthly means with fully measured data for tide gauge stations during 1922-1985

Tide gauge	J	F	M	A	M	J	J	A	S	O	N	D
Kemi	45	43	44	45	41	46	54	55	45	42	40	44
Oulu	48	46	43	43	44	44	53	46	48	50	49	47
Raahe	33	32	32	44	43	40	36	36	43	42	35	34
Pietarsaari	54	54	55	55	56	48	55	61	57	56	54	56
Vaasa	46	42	44	41	45	43	43	45	46	46	45	45
Kaskinen	37	34	35	35	32	41	33	36	47	44	41	36
Mäntyluoto	55	55	59	57	59	54	56	53	58	58	56	59
Rauma	44	46	48	51	48	49	49	50	47	50	50	49
Turku	38	39	42	39	44	49	45	47	42	40	42	39
Degerby	40	41	41	39	41	41	36	38	44	35	43	38
Hanko	47	51	51	56	56	51	53	49	46	45	48	43
Helsinki	53	57	57	53	60	58	53	53	58	53	57	52
Hamina	46	49	46	40	38	43	45	51	49	46	49	50

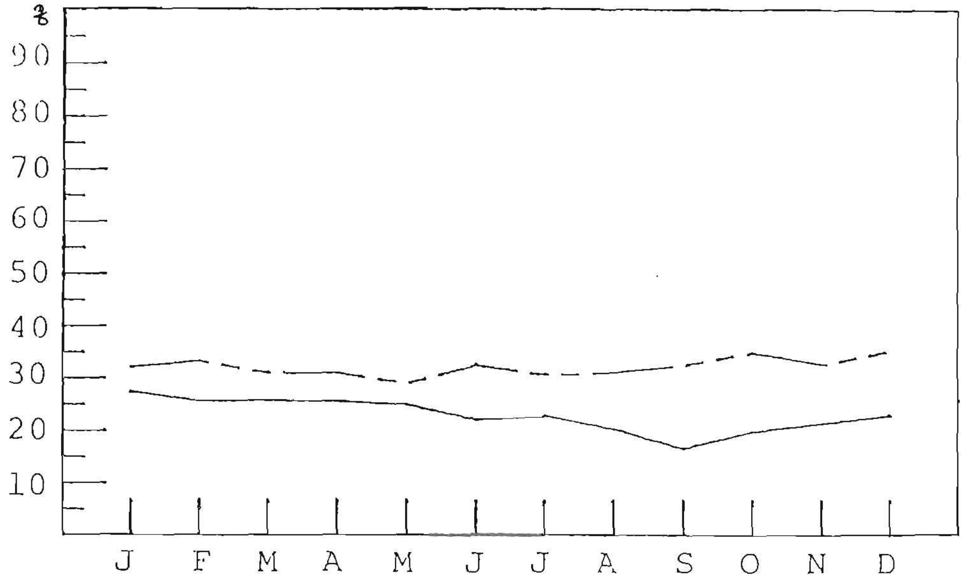

Figure 2: Defectively measured months in percentages during 1922-1955 (solid line) and 1956-1985 (dashed line) at all tide gauge stations.

3. COMMON TIDE GAUGE ADJUSTMENT

3.1 Principles

In the Baltic Sea, sea level variation due to tidal forces are slight, of the order of a centimeter only. Much larger sea level variability, of the order of meters, is caused by meteorological forcing. This impact is twofold: firstly due to conditions in the Danish Sounds, water flows in to and out from the Baltic Sea, causing low frequency variations with quasiperiodicity of the order of weeks, even months. Secondly due to wind stress, the surface of the basin tilts, causing, in particular at the ends of the basin, water level variations with considerable amplitude. The time scale of these variations is typically that of the synoptic scale of single meteorological disturbances.

The changes in instantaneous sea level as observed in the 13 Finnish tide gauges are highly correlated: changes in the total water volume in the Baltic Sea affect all tide gauges in approximately the same way at approximately the same time. These common variations can be filtered out by performing a "plane fit adjustment" for every month for which sufficient data is available.

A cautionary note is in place, that the method of analysis chosen here would not give advantages for more open seas in which such a strong correlation does not exist.

Because of the Fennoscandian land uplift, the tide gauge registation time series should be theoretically modelled by assuming not only a "constant term" for each tide gauge, but also a "linear change in time" coefficient, which is geophysically interesting as it corresponds to the local *land uplift value*.

We performed an adjustment on all tide gauges together aimed at determining high-quality *relative* land uplift values between them. *Absolute* uplift values are more problematic to obtain: they require knowledge of the long-term secular rate of change in world sea level, which can only be obtained by averaging very long existing tide gauge time series. This averaging process is highly sensitive to the choice of averaging interval, and its theoretical accuracy is poor.

At the same time we intended to use the residuals from the adjustment, one per tide gauge and per month of observations, to show us possible local movements of the tide gauges if there are any.

In the adjustment, the following unknowns have to be determined:

- The plane fit coefficients a, b and c for every month for which sufficient data is available;

- Two unknowns for every tide gauge: its constant, tide gauge specific correction as well as its linear change in time, which we shall call its "uplift value".

Mathematically, we can write the problem as a set of observation equations as follows:

$$h_i(t) = a(t) + b(t)(\phi_i - \phi_0) + c(t)(\lambda_i - \lambda_0) + z_i + u_i(t - t_0) + \epsilon_i(t); \qquad (3.1)$$

$i = 1,\ldots,13$

where

- $a(t)$, $b(t)$ and $c(t)$ are the bias and tilt coefficient time series of a plane fit through simultaneous tide gauge readings,
- z_i and u_i are the tide gauge additive constants and trend constants ("land uplifts"), respectively,
- $\epsilon_i(t)$ is the adjustment correction, and
- ϕ_i and λ_i are geographic latitude and longitude of the tide gauge stations,
- ϕ_0 and λ_0 are "linearization values" used; e.g. the arithmetic means of latitude and longitude of all 13 tide gauges, and
- t_0 is the "mean epoch" near the middle of the time interval considered.

The problem formulated like this contains *six* indeterminacies, which can be removed by additionally requiring both the *means* and the *trends* of the time series $a(t)$, $b(t)$ and $c(t)$ to vanish.

Problem (3.1) falls naturally apart into two subproblems, a plane fit in the space domain and a trend fit in the time domain.

3.2 Plane fitting in the space domain

To fit a plane surface through the observations made in one month in up to 13 tide gauges, we use the following simple technique.

We choose one "base station" that we keep fixed. All other stations are referred to this reference station.

For every month in which sufficient data is available (i.e. in addition to the adjustment base station observation, there are observations in at least 3 other stations in order to obtain at least one overdeterminacy) a plane is fitted with least squares to *the other stations but the base station*. In the adjustment, the observation equations formed for a given month are:

$$h_i - h_0 = b\,(\phi_i - \phi_0) + c\,(\lambda_i - \lambda_0) + \epsilon_i; \qquad (3.2)$$

$i = 1, \ldots, 13$

where h_0 is the monthly mean - i.e. the realisation of the sea level observation time series - for this month at the base or reference station, ϕ_i and λ_i are latitude and longitude and ϕ_0 and λ_0 are base station latitude and longitude. h_i is the sea level monthly mean - i.e. the observation variate - obtained for this month in tide gauge i, $i = 1..13$, and ϵ_i is the adjustment correction.

For brevity, in (3.2) the time arguments to h_0, h_i, b, c and ϵ_i - all of which are time series - have been omitted. This adjustment, which has only two unknowns b and c, for every month of observation, can be done rapidly for all these months, which provides us with the time series $b^{(0)}(t)$ and $c^{(0)}(t)$ as well as residuals $\epsilon_i(t)$.

3.3 Trend fitting in the time domain

This was done by a simple technique which uses the following model:

$$q(t) = q_0 + q_1(t - t_0) + \epsilon(t) \tag{3.3}$$

where t_0 is the epoch time used, equal to the arithmetic mean of the times on which there are useful observations. Now, q_0 is simply the average of q(t) *over time*:

$$q_0 = \Sigma\, q(t)/n \tag{3.4}$$

where n is the number of values q(t) available. Computation of q_1 is performed by accumulating the product quantities $(q(t) - q_0)\ (t - t_0)$ over all observations, and dividing by the accumulated product $(t - t_0)^2$, as follows:

$$q_1 = \frac{\Sigma\ (q(t) - q_0)\ (t - t_0)}{\Sigma\ (t - t_0)^2} \tag{3.5}$$

where t_0 is the epoch time used. This amounts to a simple least squares linear regression. The procedure described here is applied not only to the observations, but also to the coefficients b and c, as will be shown below.

3.4 Iterative solution

Determining all the unknowns of the problem in one computation is possible but extremely demanding in computational resources. The number of unknowns is twice the number of months or several thousands. Therefore we choose an iterative approach in which we alternately adjust the plane coefficients b and c *separately for every month,* and the tide gauge additive constant and "uplift value" in a linear fit to the time dependent coefficients of this space domain adjustment.

The procedure is repeated as often as is needed for the tide gauge constants and uplift values found in the time domain linear fit to converge to their final values. In detail, we proceed as follows:

1. We apply Eq. (3.2) to obtain a first set of values for the coefficient time series, $b^{(0)}(t)$ and $c^{(0)}(t)$;

2. We apply the time domain trend fit described generally in Eqs. (3.3)-(3.5) to these coefficient time series, in other words we solve the equations

$$\begin{aligned} b^{(0)}(t) &= b_0 + b_1\ (t - t_0) + \epsilon_b(t) \\ c^{(0)}(t) &= c_0 + c_1\ (t - t_0) + \epsilon_c(t) \end{aligned} \tag{3.6}$$

   in order to obtain values for the unknown coefficients $b_0^{(0)}$, $b_1^{(0)}$, $c_0^{(0)}$ and $c_1^{(0)}$. The parenthesised superscripts (0) and (1) have been added to mark the iteration round;

3. Next, we write down the time domain adjustment observation equations as follows:

$$h_i(t) - h_0(t) = \delta b^{(0)}(t)\ (\phi_i - \phi_0) + \delta c^{(0)}(t)\ (\lambda_i - \lambda_0) + \delta z_i + \delta u_i(t - t_0) + \epsilon_i(t) \qquad (3.7)$$

   where it should be noted that the time series

$$\begin{aligned} \delta b^{(0)}(t) &= b^{(0)}(t) - b_0^{(0)} - b_1^{(0)}(t - t_0) \\ \delta c^{(0)}(t) &= c^{(0)}(t) - c_0^{(0)} - c_1^{(0)}(t - t_0) \end{aligned} \qquad (3.8)$$

   are "computable" at this phase and have both a *mean* and a *trend* in time of *zero.*

4. Eq. (3.7) can be rewritten as

$$dh_i^{(0)}(t) = \delta z_i + \delta u_i\ (t - t_0) + \epsilon_i(t) \qquad (3.9)$$

   with adjustment unknowns δz_i and δu_i (two for every tide gauge) and the left hand side of it as the following "computable" expression:

$$dh_i^{(0)}(t) = h_i(t) - h_0(t) - \delta b^{(0)}(t)\ (\phi_i - \phi_0) - \delta c^{(0)}(t)\ (\lambda_i - \lambda_0) \qquad (3.10)$$

5. Following this, we solve from Eq. (3.9) the unknowns $\delta z_i^{(0)}$ and $\delta u_i^{(0)}$, two for every tide gauge;

6. We use this solution again in the space domain adjustment, for which we write the observation

equations (compare Eq. (3.2)):

$$Dh_i^{(1)}(t) = b(t)(\phi_i - \phi_0) + c(t)(\lambda_i - \lambda_0) + \epsilon_i(t) \qquad (3.11)$$

where

$$Dh_i^{(1)}(t) = h_i(t) - h_0(t) - \delta z_i^{(0)} - \delta u_i^{(0)}(t - t_0) \qquad (3.12)$$

is a "computable" expression again. Now we find the solution time series $b^{(1)}(t)$, $c^{(1)}(t)$, with which the iteration is repeated by returning to point 2. Iteration is stopped when the values of δz and δu have stabilised. Experimentally, ten rounds were found to be well sufficient.

7. Finally we want to derive the tide gauge zero constant and land uplift rate for every tide gauge in the adjustment. These values are obtained by the following addition:

$$z_i = z_0 + \delta z_i^{(\infty)} \ ; \quad u_i = u_0 + \delta u_i^{(\infty)} \qquad (3.13)$$

where, of course, z_0 and u_0 are the base station values obtained from the observation time series h_0 of the base station by time domain linear fit according to Eqs. (3.3)-(3.5), the observation equation being:

$$h_0(t) = z_0 + u_0\,(t - t_0) + \epsilon_0(t), \qquad (3.14)$$

t_0 being the epoch time (mean of all observation times) as stated above.

3.5 Residuals of the adjustment

A measure for the quality of the observational material is provided by the residuals of the plane fit for every month. The residuals found were in general in the range 1-3 cm, occasionally more; the biggest outlier found in the Degerby adjustment was 57 mm for Hanko in October 1976. The observation was checked but apparently correct; weather conditions were known to be exceptional at the time.

A measure for the appropriateness of the functional model used - plane fit - is the RMS value of all residuals together. This value was very consistently between 7 and 9 mm for all adjustments performed regardless the choice of base station, which is pretty good.

The residuals for every month for every tide gauge give us also a possibility to detect possible small motions in the tide gauges with respect to one another. The RMS being as small as it is, this ought to be a very sensitive method. In Figure 3 we have plotted the monthly residual values as a set of graphs, one for every tide gauge. It is seen that no clear motions of the kind we are looking for can be seen, with one exception: In Pietarsaari, a clear skip can be seen at December 1953, give or take a month.

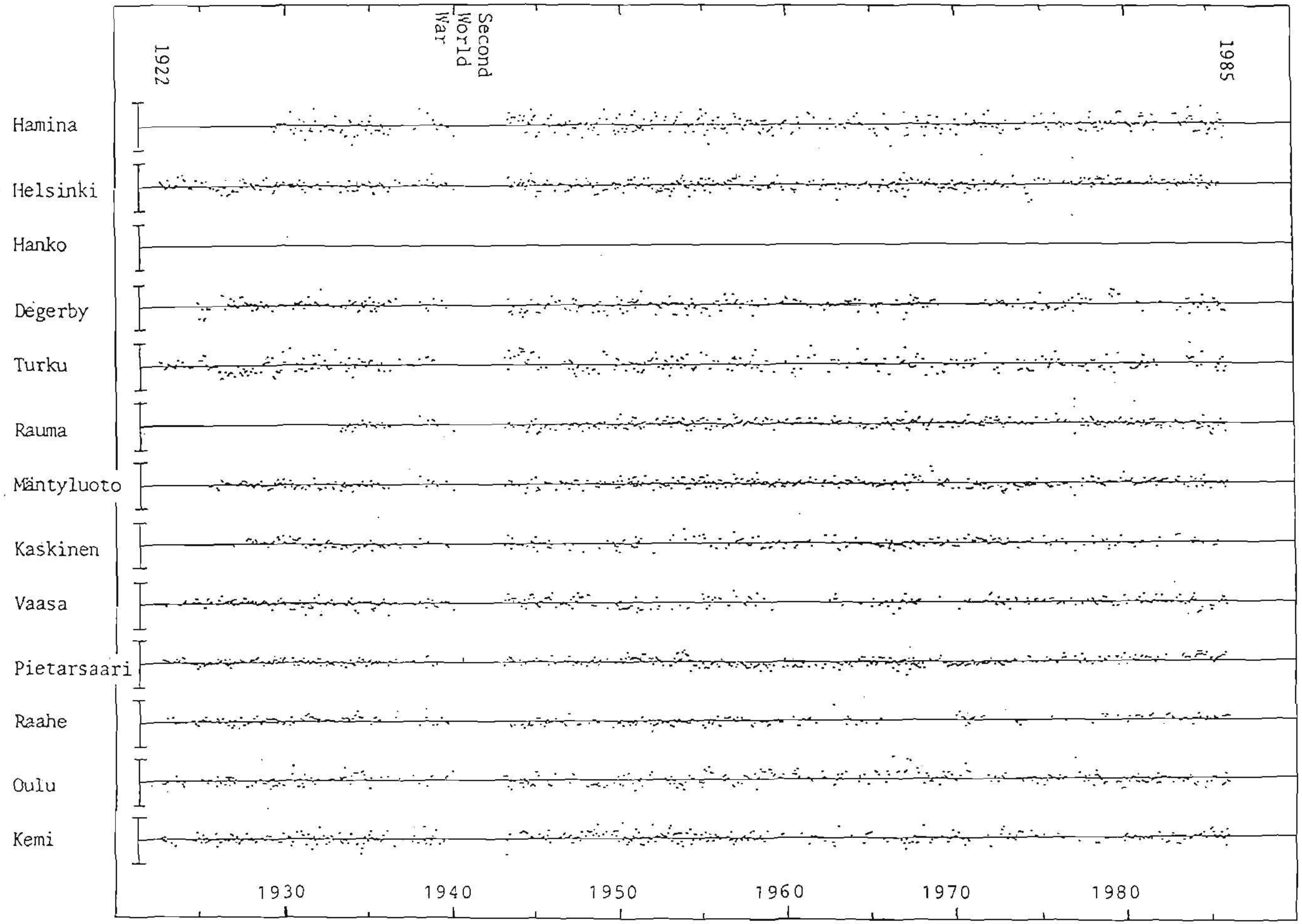

Figure 3: Monthly residuals of tide gauge adjustment. Hanko was used as the base station; The scale bars on the left represent the range -50 mm to +50 mm.

The magnitude of the skip has been determined by comparing separate tide gauge adjustments for the periods up to and starting from end 1953 with the results of the complete adjustment. By looking at the differences between the monthly residuals for the year before and the year after the skip, respectively, and taking the average of these differences, we found that the skip amounted to 15.1 ±0.4 mm, the accuracy stated being derived from this averaging process. The tide gauge has moved upwards.

According to *M. TAKALO* (personal comm.), in Pietarsaari both the tide gauge and the local bench mark are not in the bedrock but on a rock plate, and building activities have been going on in the neighbourhood. In 1975, a new levelling connection to a remoter, bedrock benchmark was made routinely, and it was found that this tide gauge has moved by fairly precisely 15 mm in the time since the previous levelling connection. The time on which the movement occurred was not known until the present determination and therefore the readings collected inbetween were never corrected for the event. The shift is simply absorbed into the land uplift value for Pietarsaari.

From the files of the Finnish Institute of Marine Research we find the heights of the tide gauge reference point w.r.t. the nearby bench mark **BM 1196E**, as given in Table 3.

Table 3: Pietarsaari tide gauge height w.r.t. **BM 1196E**

Year:	1940	1941	1942	1943	1944	1945	1946	1947
Value:	-	-	-	-	1720	1721	-	-
Year:	1948	1949	1950	1951	1952	1953	1954	1955
Value:	1718	-	-	1693	1693	1692	1692	1690
Year:	1956	1957	1958	1959	1960	1961	1962	1963
Value:	1690	1684	1685	1686	1689	-	-	-
Year:	1964	1965	1966	1967	1968	1969	1970	1971
Value:	-	-	-	-	-	-	-	1688

From this data, we see that no skip of the type sought for has occurred around 1953 *between the tide gauge and its nearby bench mark*. We do see a skip, however, between 1948 and 1951, of 25 mm; this skip should not show in the tide gauge adjustment residuals, as the above values have been used in reducing the observation values used in it. It must be an unrelated event, which does confirm, however, that motions of this magnitude actually occur in Pietarsaari.

BM 1196E has been connected with another bench mark nearby, **48224**, but no relative movement was found here either. In 1954 a height difference of 23.1 mm was found, and in 1956 one of 23.9 mm.

If the 1953 skip found is to be believed, also this land uplift value must be wrong by some amount. A preliminary estimate is, that it is approx. 0.6 mm/year too high, as could be seen when adjusting the pre- and post- December 1953 data intervals separately. The proper procedure would be, of course, to correct the primary tide gauge data for this event and recompute the adjustment.

Whenever such a motion is found, of course the first suspicion ought to be that the tide gauge has moved. Some of the tide gauges used are not in the bedrock and can therefore not be used to detect any geophysically interesting anomalous vertical crustal displacements. The present find should be seen as an illustration of this.

4. RELATIVE AND ABSOLUTE LAND UPLIFT VALUES

4.1 Combining results for all base tide gauges

The adjustment described above was repeated for all 13 tide gauge stations, each station in turn serving as the adjustment base or reference station. In order to remove any possible dependencies of the result upon this arbitrary choice, we decided to average the sets of land uplift values found this way. The process of averaging is depicted in Table 4. The top row gives the base station number, the column of land uplift values below it is referred to this station. On the right is given the *row average*; at bottom right, below this column, the value 5.48 is the average of this column.

All columns were averaged, and these averages subtracted from the grand average 5.48 in order to obtain the "column corrections" written on the row below the upper half of the table. This row is marked "corr."; the column averages themselves are not written.

The lower half of the table gives the residuals obtained when from every "raw" land uplift value in the table is first subtracted the row average, and then the column correction is added to it. The purpose of this is to obtain residuals in which possible base station dependent biases are no longer present. It can be seen from Table 4 that the columns are separated from each other by column-specific constants; this reflects the fact that *relative* land uplift values can be determined much more precisely than absolute ones. An irrelevant factor like the choice of computational base station is seen to influence strongly on the absolute land uplift values found, but hardly at all on the differences in land uplift between stations.

Studying the residuals of this "column correction procedure" shows again what we mean: they represent the quality of the *relative* land uplift values obtained by this procedure.

4.2 Choice of reference station

One may expect that the results of the adjustment described above will differ for different choices of reference or base station. This is only natural, especially if the assumption of a linear relationship between sea level and geographical position is invalid. In that case, choosing the base station close to the center of the region will tend to limit the nonlinearity errors.

From our adjustment results, however (Table 4) it shows that this is not the case. This may indicate that in general, the shape of the surface describing sea level is pretty close to a flat plane. We see that although Hamina displays some large residual values, similarly large values are found for Rauma.

An alternative approach is to choose a reference station close to the center of the area, e.g. Hanko or Degerby. In Hanko, the column correction is -0.10 mm/year, and in Degerby - chosen by *HELA (1953)* as a reference station for a similar computation - only 0.02 mm/year, so this approach would also have given quite acceptable results.

A computational experiment with enlightening results was performed by limiting our monthly data only to the interval 1933-1985. It should be noted that in Hamina and Rauma, observations did not start until 1928 and 1933, respectively, whereas in the other tide gauges the time series are (often considerably) longer. This leads, when using Rauma or Hamina as the computational base stations, to not using the earlier data at all, which might explain why their residuals stand out in Table 4.

In Table 5 we see that the residuals of both Hamina and Rauma are much reduced. We will however use the data interval of Table 4 for our final results, as they are based on longer time series.

Table 4: Results of our adjustment

uplift		1	2	3	4	5	6	7	8	9	10	11	12	13	avg.:
KEMI	1	6.51	7.62	7.89	7.48	7.36	7.51	7.08	7.30	7.48	7.29	7.39	7.35	7.45	7.36
OULU	2	6.06	7.18	7.55	7.06	6.91	7.00	6.62	6.82	7.05	6.90	6.96	6.89	6.94	6.92
RAAH	3	6.64	7.63	7.98	7.56	7.43	7.65	7.16	7.16	7.61	7.50	7.50	7.40	7.38	7.43
PIET	4	7.19	8.24	8.51	8.09	7.98	8.19	7.69	7.73	8.13	7.92	8.04	7.98	7.88	7.97
VAAS	5	6.92	7.97	8.22	7.82	7.73	7.77	7.40	7.48	7.81	7.63	7.76	7.67	7.54	7.67
KASK	6	6.49	7.53	7.73	7.26	7.33	7.36	6.93	6.91	7.33	7.19	7.29	7.22	7.04	7.20
MÄNT	7	5.60	6.62	6.82	6.46	6.42	6.50	6.06	6.06	6.50	6.28	6.42	6.35	6.15	6.33
RAUM	8	4.75	5.73	5.91	5.56	5.48	5.62	5.11	5.09	5.45	5.37	5.55	5.45	5.20	5.41
TURK	9	3.40	4.44	4.55	4.24	4.22	4.36	3.83	3.88	4.28	4.07	4.23	4.15	3.95	4.12
DEGE	10	3.63	4.60	4.85	4.44	4.41	4.44	4.03	3.90	4.45	4.24	4.35	4.33	4.01	4.28
HANK	11	2.06	3.06	3.22	2.90	2.86	2.95	2.49	2.30	2.94	2.76	2.90	2.82	2.45	2.75
HELS	12	1.47	2.49	2.64	2.34	2.26	2.38	1.89	1.70	2.37	2.16	2.33	2.24	1.85	2.16
HAMI	13	0.86	2.01	2.13	1.85	1.68	1.88	1.41	1.29	1.80	1.63	1.88	1.82	1.43	1.67
corr.:		0.74	-0.30	-0.52	-0.14	-0.06	-0.18	0.27	0.28	-0.15	0.02	-0.10	-0.03	0.15	5.48

resid.		1	2	3	4	5	6	7	8	9	10	11	12	13	s.d.:
KEMI	1	-11	-4	1	-2	-6	-3	-1	22	-3	-5	-8	-4	24	0.11
OULU	2	-11	-4	11	0	-7	-10	-2	18	-2	1	-6	-6	17	0.10
RAAH	3	-5	-10	3	-1	-6	4	0	1	3	9	-3	-6	10	0.06
PIET	4	-3	-2	2	-2	-5	4	0	4	1	-2	-3	-2	7	0.04
VAAS	5	-1	0	3	1	0	-8	0	9	-1	-2	-1	-3	2	0.04
KASK	6	3	3	1	-8	7	-2	0	-1	-2	1	-1	-1	-1	0.03
MÄNT	7	2	0	-2	0	3	-1	1	1	2	-2	-1	-1	-2	0.02
RAUM	8	9	3	-1	2	1	3	-2	-4	-10	-1	4	1	-5	0.05
TURK	9	2	2	-9	-2	3	6	-2	4	1	-3	0	0	-2	0.04
DEGE	10	9	2	5	2	6	-2	2	-10	2	-2	-4	2	-12	0.06
HANK	11	6	2	-5	1	5	2	2	-17	4	4	5	4	-14	0.07
HELS	12	5	3	-4	4	3	4	0	-18	6	2	6	5	-16	0.08
HAMI	13	-6	5	-6	4	-5	3	2	-10	-2	-1	11	12	-8	0.07

Table 5: Our adjustment method for 1933-1985

uplift	1	2	3	4	5	6	7	8	9	10	11	12	13	avg.:
KEMI 1	6.02	7.60	8.05	7.29	7.25	7.22	6.92	7.30	7.31	7.15	7.69	7.22	7.24	7.25
OULU 2	5.52	7.13	7.63	6.85	6.74	6.73	6.43	6.82	6.85	6.74	7.21	6.72	6.73	6.78
RAAH 3	5.94	7.40	7.88	7.18	7.13	7.22	6.82	7.16	7.24	7.21	7.57	7.07	7.09	7.15
PIET 4	6.52	7.99	8.37	7.71	7.69	7.79	7.37	7.73	7.77	7.63	8.08	7.63	7.64	7.69
VAAS 5	6.27	7.80	8.08	7.47	7.46	7.43	7.11	7.48	7.45	7.30	7.82	7.34	7.38	7.41
KASK 6	5.70	7.19	7.40	7.76	6.90	6.87	6.49	6.91	6.86	6.73	7.21	6.74	6.77	6.81
MÄNT 7	4.88	6.35	6.56	6.03	6.06	6.09	5.71	6.06	6.05	5.89	6.38	5.92	5.95	5.99
RAUM 8	3.97	5.41	5.57	5.05	5.09	5.06	4.73	5.09	5.05	4.93	5.44	4.95	4.98	5.02
TURK 9	2.69	4.23	4.29	3.83	3.91	3.91	3.51	3.88	3.82	3.69	4.18	3.73	3.75	3.80
DEGE 10	2.79	4.23	4.45	3.89	3.98	3.95	3.59	3.90	3.87	3.73	4.14	3.77	3.80	3.85
HANK 11	1.14	2.64	2.68	2.30	2.34	2.36	1.98	2.30	2.28	2.19	2.66	2.17	2.19	2.25
HELS 12	0.51	2.05	2.05	1.68	1.69	1.75	1.36	1.70	1.63	1.54	2.07	1.56	1.55	1.63
HAMI 13	0.08	1.65	1.59	1.25	1.19	1.27	0.89	1.29	1.18	1.05	1.67	1.12	1.10	1.18
corr.:	-1.14	0.37	0.60	0.04	0.05	0.06	-0.30	0.06	0.04	-0.08	0.41	-0.07	-0.05	5.14

resid.	1	2	3	4	5	6	7	8	9	10	11	12	13	s.d.:
KEMI 1	-9	-2	20	0	-5	-10	-3	-1	2	-2	3	4	4	0.07
OULU 2	-12	-2	25	4	-8	-11	-5	-2	3	4	2	1	0	0.09
RAAH 3	-7	-12	13	0	-6	1	-3	-5	5	14	1	-1	-1	0.08
PIET 4	-3	-7	8	-1	-4	4	-2	-2	4	2	-1	1	0	0.04
VAAS 5	-1	1	7	2	0	-5	0	0	-1	-4	0	-1	1	0.03
KASK 6	3	1	-1	-9	4	0	-2	4	1	0	-1	0	1	0.03
MÄNT 7	2	-2	-3	0	2	3	2	0	1	-3	-2	-1	0	0.02
RAUM 8	8	1	-5	-1	2	-3	1	0	-2	-2	1	-1	0	0.03
TURK 9	3	5	-11	-1	6	4	1	2	-2	-3	-3	0	0	0.05
DEGE 10	7	0	0	0	8	3	4	-2	-3	-4	-12	-2	0	0.05
HANK 11	3	2	-17	1	4	5	3	-1	-1	2	0	-1	-1	0.05
HELS 12	2	5	-18	2	2	6	3	1	-4	-1	4	0	-3	0.06
HAMI 13	4	10	-19	3	-4	3	1	5	-4	-5	8	1	-3	0.07

5. COMPARISONS WITH EARLIER DETERMINATIONS

5.1 General

Earlier determinations of the Fennoscandian land uplift using tide gauge data have been done among others by *HELA (1953)*, *LISITZIN (1964)*, *KÄÄRIÄINEN (1975)* and *SUUTARINEN (1983)*. Below we will compare our results with theirs.

It will be found that significant differences are present, for which there may be various reasons. One obvious reason is the different time interval during which data was collected for inclusion in the determination. To find out about this, it is necessary to apply our method to the same time intervals that these earlier determinations have used.

Another reason for (minor) differences is possibly the use of monthly instead of yearly means of tide gauge readings. This can be tested by "lumping" our monthly data into years and repeating the determination.

Finally it must be noted that there may be many small differences in procedure that may lead to significant differences in the end result. As an example we can mention data interpolation; where this is used, various techniques, ranging from the very simple to the sophisticated, will lead to slightly different results if the percentage of interpolated values is more than negligible. For this reason we have abstained from using any data interpolation in our approach.

5.2 Influence of the data interval used

5.2.1 General

In the past, several determinations of the land uplift on the basis of tide gauge recordings have been made. Of these, the determination of *SUUTARINEN (1983)* is the most recent one, using the longest data set (yearly averages) up to and including 1980. Of the older determinations, we will use for comparison also *LISITZIN (1964)*, because her determination has served as the standard result for the Finnish Institute of Marine Research. In addition we will make a comparison with *HELA (1953)*. This determination, which only covers a rather short time span (1922-1951) is known to be inferior because of an unfortunate choice of data interval, but has similarly served as a standard for the Finnish Geodetic Institute for many years.

In the following tables, we use the following names:

Mean difference is the "bias" between our result for all tide gauges and the corresponding result of the earlier author.

RMS difference is the root-mean-square difference over all tide gauges between us and the earlier author.

Standard deviation refers to the root-mean-square difference computed *after* we have shifted our results to those of the earlier author using the "mean difference" above.

The squared RMS difference is equal to the square of the mean difference plus the square of the standard deviation.

5.2.2 The determination of SUUTARINEN (1983)

The determination of *SUUTARINEN (1983)* can be seen as a continuation of the work of *KÄÄRIÄINEN (1966, 1975)* which determined the land uplift both from precise levelling results and from tide gauge observations. In his treatment of precise levelling results, Kääriäinen used some approximative techniques, because only mechanical calculators were available at the time. These approximations were questioned by the well-known Danish geodesists *O. REMMER* and *O. BEDSTED ANDERSEN* (*SUUTARINEN 1983*), and therefore a formally correct re-adjustment was undertaken. The results were not significantly different from those of *KÄÄRIÄINEN*.

Here, we will use the *SUUTARINEN* results obtained using tide gauge data only. It must be stressed that this does not imply any quality judgment, just a limitation of the work to be done.

Table 6: Our adjustment applied to *SUUTARINEN* data interval

uplift	1	2	3	4	5	6	7	8	9	10	11	12	13	avg.:
KEMI 1	6.25	7.92	8.55	7.50	7.72	7.90	7.56	7.59	8.11	7.53	7.84	7.70	7.77	7.69
OULU 2	5.77	7.44	8.26	7.04	7.25	7.39	7.06	7.04	7.68	7.12	7.36	7.19	7.22	7.22
RAAH 3	6.60	8.06	8.86	7.68	7.91	8.11	7.76	7.60	8.36	7.93	8.06	7.88	7.86	7.90
PIET 4	7.15	8.68	9.42	8.25	8.48	8.64	8.29	8.20	8.87	8.31	8.59	8.43	8.34	8.43
VAAS 5	6.79	8.30	8.99	7.89	8.14	8.20	7.88	7.80	8.48	7.91	8.21	8.02	7.86	8.04
KASK 6	6.45	7.90	8.57	7.42	7.76	7.81	7.47	7.26	8.02	7.53	7.79	7.61	7.43	7.62
MÄNT 7	5.58	7.02	7.67	6.59	6.90	6.95	6.60	6.46	7.23	6.65	6.93	6.76	6.56	6.76
RAUM 8	4.68	6.07	6.66	5.62	5.92	6.06	5.59	5.43	6.13	5.71	5.99	5.81	5.56	5.79
TURK 9	3.40	4.85	5.37	4.38	4.71	4.83	4.38	4.28	5.04	4.46	4.75	4.57	4.39	4.57
DEGE 10	3.67	4.99	5.69	4.57	4.91	4.89	4.55	4.28	5.18	4.61	4.84	4.73	4.40	4.72
HANK 11	2.14	3.51	4.11	3.07	3.40	3.45	3.06	2.74	3.73	3.20	3.44	3.25	2.92	3.23
HELS 12	1.51	2.94	3.56	2.53	2.80	2.89	2.49	2.12	3.20	2.61	2.90	2.70	2.33	2.66
HAMI 13	0.80	2.46	3.04	2.04	2.21	2.41	2.02	1.71	2.69	2.08	2.45	2.31	1.94	2.17
corr.:	1.23	-0.26	-0.92	0.17	-0.10	-0.21	0.16	0.33	-0.46	0.09	-0.18	-0.01	0.17	5.91

resid.	1	2	3	4	5	6	7	8	9	10	11	12	13	s.d.:
KEMI 1	-21	-3	-6	-2	-7	0	3	23	-3	-7	-3	0	25	0.12
OULU 2	-22	-4	12	-1	-7	-4	0	15	1	-1	-4	-4	17	0.10
RAAH 3	-7	-10	4	-5	-9	0	2	3	1	12	-2	-3	13	0.07
PIET 4	-5	-1	6	-2	-6	-1	1	9	-2	-4	-3	-2	7	0.05
VAAS 5	-2	1	3	2	0	-5	0	9	-1	-4	-1	-3	-1	0.04
KASK 6	6	2	3	-3	4	-2	1	-3	-5	0	1	-2	-2	0.03
MÄNT 7	5	0	-1	0	4	-2	0	3	1	-2	-1	-2	-3	0.02
RAUM 8	12	2	-5	0	3	6	-4	-3	-11	1	2	1	-6	0.06
TURK 9	6	2	-12	-2	4	5	-3	4	1	-2	0	-1	-1	0.05
DEGE 10	18	2	5	2	9	-4	-1	-11	1	-2	-6	0	-15	0.08
HANK 11	14	2	-4	1	7	1	-1	16	4	5	3	0	-14	0.08
HELS 12	8	2	-2	4	4	2	-1	-21	8	4	6	3	-16	0.09
HAMI 13	-14	4	-5	4	-6	3	1	-13	7	0	10	13	-6	0.08

Table 7: *SUUTARINEN* adjustment compared with ours

Station name	nr	*SUUTARINEN* result	Our result value	diff	Our result* value	diff
Kemi	1	-	7.36	-	7.69	-
Oulu	2	6.98	6.92	-0.06	7.22	0.24
Raahe	3	7.50	7.43	-0.07	7.90	0.40
Pietarsaari	4	8.35	7.97	-0.38	8.43	0.08
Vaasa	5	8.04	7.67	-0.37	8.04	0.00
Kaskinen	6	7.49	7.20	-0.29	7.62	0.13
Mäntyluoto	7	6.66	6.33	-0.33	6.76	0.10
Rauma	8	5.36	5.41	0.05	5.79	0.43
Turku	9	4.61	4.12	-0.49	4.57	-0.04
Degerby	10	-	4.28	-	4.72	-
Hanko	11	3.15	2.75	-0.40	3.23	0.08
Helsinki	12	2.62	2.16	-0.46	2.66	0.04
Hamina	13	1.86	1.67	-0.19	2.17	0.31
Mean diff.:				-0.27		+0.16
Standard dev.:				±0.17		±0.14
RMS diff.:				±0.32		±0.22

*Our method applied to *SUUTARINEN's* interval, i.e. until 1980. However, *SUUTARINEN* also used some early tide pole values, which were not included in our data. All values are relative to mean sea level, i.e. no eustatic correction applied.

5.2.3 The determination of LISITZIN (1964)

This determination by a knowledgable marine researcher has served as the standard result for the Finnish Institute of Marine Research for many years. The data used covers the interval 1924-1960 and is based on yearly averages.

It should be noted here that the values for Rauma and Hamina were left out from *LISITZIN's* results. They are taken from the older *HELA (1953)* determination as the standard ones for the Finnish Institute of Marine Research.

Table 8: Our adjustment applied to *LISITZIN* data interval

uplift	1	2	3	4	5	6	7	8	9	10	11	12	13	avg.:
KEMI 1	7.08	6.86	7.18	7.24	5.89	8.17	7.42	6.84	7.88	7.32	6.94	7.39	7.40	7.20
OULU 2	6.83	6.63	7.02	6.90	5.69	7.75	7.09	6.43	7.65	7.08	6.62	7.04	6.99	6.90
RAAH 3	7.66	7.40	7.76	7.77	6.59	8.79	7.97	7.20	8.44	7.91	7.51	7.91	7.76	7.74
PIET 4	8.11	7.99	8.23	8.21	7.08	9.28	8.50	7.74	8.89	8.33	7.95	8.45	8.11	8.22
VAAS 5	7.74	7.52	7.76	7.87	6.85	8.47	8.00	7.01	8.51	8.02	7.56	8.01	7.34	7.74
KASK 6	7.38	7.18	7.43	7.23	6.73	8.25	7.66	6.41	8.12	7.57	7.17	7.67	6.96	7.37
MÄNT 7	6.40	6.20	6.46	6.38	5.63	7.24	6.63	5.50	7.20	6.64	6.17	6.70	5.89	6.39
RAUM 8	5.56	5.27	5.55	5.43	4.87	6.56	5.71	4.48	6.01	5.75	5.22	5.75	4.90	5.47
TURK 9	4.26	4.06	4.31	4.31	3.48	5.21	4.46	3.37	5.08	4.49	3.96	4.52	3.78	4.25
DEGE 10	4.62	4.39	4.66	4.65	3.93	5.41	4.79	3.38	5.39	4.82	4.27	4.88	3.82	4.54
HANK 11	3.13	2.92	3.23	3.19	2.43	3.95	3.30	1.71	4.01	3.40	2.86	3.41	2.29	3.06
HELS 12	2.54	2.34	2.62	2.68	1.74	3.46	2.72	1.00	3.44	2.80	2.28	2.80	1.79	2.48
HAMI 13	1.64	1.62	1.83	1.98	0.59	2.80	1.95	0.14	2.45	1.92	1.62	2.10	1.20	1.68
corr:	0.01	0.20	-0.08	-0.06	0.89	-0.95	-0.24	0.91	-0.77	-0.23	0.22	-0.28	0.37	5.62

resid.	1	2	3	4	5	6	7	8	9	10	11	12	13	s.d.:
KEMI 1	-11	-14	-10	-2	-42	2	-2	55	-9	-11	-4	-9	57	0.27
OULU 2	-6	-7	4	6	-32	-10	-5	44	-2	-5	-6	-14	46	0.22
RAAH 3	-8	-14	-6	-4	-27	10	-2	37	-8	-7	-1	-11	39	0.19
PIET 4	-10	-3	-7	-7	-25	11	4	43	-10	-12	-5	-5	26	0.18
VAAS 5	0	-2	-6	7	-1	-22	1	18	0	5	4	-1	-3	0.09
KASK 6	2	2	-1	-20	25	-6	5	-5	-2	-3	3	3	-4	0.10
MÄNT 7	2	2	0	-7	13	-9	0	2	4	2	1	4	-13	0.07
RAUM 8	10	1	1	-10	29	15	0	-8	-23	5	-2	1	-20	0.14
TURK 9	1	1	-2	0	11	1	-4	3	6	1	-7	-1	-10	0.05
DEGE 10	9	6	4	5	28	-8	1	-25	8	5	-5	6	-35	0.16
HANK 11	7	6	9	6	25	-6	-1	-44	17	10	2	7	-40	0.20
HELS 12	7	7	7	14	15	4	0	-57	19	9	3	5	-32	0.21
HAMI 13	-3	14	7	24	-20	17	3	-63	0	1	16	14	-11	0.23

Table 9: *LISITZIN* adjustment compared with ours

Station		*LISITZIN*	Our result		Our result[*]	
name	nr	result	value	diff	value	diff
Kemi	1	7.3	7.36	0.06	7.20	-0.10
Oulu	2	7.1	6.92	-0.18	6.90	-0.20
Raahe	3	7.8	7.43	-0.37	7.74	-0.06
Pietarsaari	4	8.2	7.97	-0.23	8.22	0.02
Vaasa	5	8.0	7.67	-0.33	7.74	-0.26
Kaskinen	6	7.4	7.20	-0.20	7.37	-0.03
Mäntyluoto	7	6.4	6.33	-0.07	6.39	-0.01
Rauma	8	-	5.41	-	5.47	-
Turku	9	4.4	4.12	-0.28	4.25	-0.15
Degerby	10	4.6	4.28	-0.32	4.54	-0.06
Hanko	11	3.1	2.75	-0.35	3.06	-0.04
Helsinki	12	2.5	2.16	-0.34	2.48	-0.02
Hamina	13	-	1.67	-	1.68	-
Mean diff.:				-0.24		-0.08
Standard dev.:				±0.13		±0.09
RMS diff:				±0.27		±0.12

[*] Our method applied to *LISITZIN's* interval 1924-1960. All values are relative to mean sea level, i.e. no eustatic correction applied.

5.2.4 The determination of HELA (1953)

HELA's (1953) determination was done not long after the Second World War. It is the oldest of those considered here, and also the poorest, based on the shortest time interval of observations. In addition, at both ends of the interval are World Wars. E.g. during the First World War observations were only done now and then, and yearly averages based on these would of course have been highly uncertain.

Table 10: Our adjustment applied to *HELA* data interval

uplift	1	2	3	4	5	6	7	8	9	10	11	12	13	avg.:
KEMI 1	7.14	5.75	6.04	7.03	6.35	4.73	5.97	3.63	6.75	6.14	6.25	7.06	6.22	6.08
OULU 2	7.38	5.96	6.39	7.26	6.59	5.17	6.36	4.76	6.91	6.46	6.51	7.23	6.81	6.45
RAAH 3	8.16	6.73	7.15	8.02	7.36	6.12	7.16	4.96	7.80	7.18	7.29	8.01	7.39	7.18
PIET 4	8.44	7.12	7.50	8.28	7.75	6.35	7.41	4.87	8.19	7.35	7.55	8.36	7.27	7.42
VAAS 5	8.34	6.96	7.44	8.12	7.66	6.14	7.32	4.93	8.16	7.46	7.55	8.21	6.91	7.32
KASK 6	8.38	6.99	7.49	8.12	7.80	6.30	7.41	4.46	8.31	7.26	7.47	8.27	6.95	7.32
MÄNT 7	7.25	5.89	6.46	7.08	6.65	5.25	6.35	3.69	7.27	6.31	6.46	7.22	5.85	6.29
RAUM 8	6.78	5.48	5.99	6.70	6.19	5.20	5.94	3.22	6.26	5.72	5.93	6.72	5.38	5.81
TURK 9	5.23	3.72	4.46	5.01	4.61	3.30	4.30	2.11	5.21	4.35	4.53	5.15	4.08	4.31
DEGE 10	5.82	4.48	5.13	5.66	5.14	4.04	4.99	2.39	5.85	4.91	5.04	5.76	4.35	4.89
HANK 11	4.35	2.91	3.71	4.16	3.79	2.52	3.62	0.71	4.37	3.61	3.72	4.39	2.91	3.44
HELS 12	3.79	2.38	3.19	3.69	3.31	1.93	3.05	-.07	3.90	3.14	3.21	3.86	2.50	2.91
HAMI 13	2.78	1.06	2.06	2.70	2.03	0.85	2.09	-1.10	2.55	2.18	2.54	3.15	1.91	1.91
corr.:	-0.96	0.45	-0.13	-0.81	-0.30	1.03	-0.05	2.52	-0.78	-0.06	-0.21	-0.93	0.22	5.49
resid.	1	2	3	4	5	6	7	8	9	10	11	12	13	s.d.:
KEMI 1	10	12	-17	14	-3	-32	-16	7	-12	0	-4	5	35	0.17
OULU 2	-3	-3	-18	1	-16	-24	-13	84	-32	-4	-14	-14	58	0.33
RAAH 3	2	0	-16	3	-12	-3	-7	30	-16	-6	-10	-10	43	0.18
PIET 4	6	16	-5	5	3	-4	-6	-3	-1	-13	-8	1	7	0.07
VAAS 5	5	9	-1	-1	4	-15	-5	13	5	8	2	-4	-20	0.09
KASK 6	9	12	4	-1	18	1	4	-34	20	-12	-6	2	-16	0.15
MÄNT 7	0	6	4	-1	6	0	1	-8	20	-3	-4	1	-22	0.09
RAUM 8	1	13	5	8	8	42	8	-7	-33	-15	-9	-2	-21	0.18
TURK 9	-4	-14	2	-11	0	2	-6	32	11	-2	1	-9	-2	0.12
DEGE 10	-3	4	11	-4	-5	18	5	2	18	-4	-6	-6	-32	0.13
HANK 11	-6	-8	14	-9	5	11	13	-21	14	11	7	2	-32	0.14
HELS 12	-9	-8	15	-3	10	5	9	-46	20	17	9	2	-20	0.18
HAMI 13	-9	-39	2	-2	-18	-2	13	-49	-14	22	42	31	22	0.27

Table 11: *HELA* adjustment compared with ours

Station		*HELA*	Our result		Our result*	
Name	nr	result	value	diff	value	diff
Kemi	1	6.4	7.36	0.96	6.08	-0.32
Oulu	2	6.3	6.92	0.62	6.45	0.15
Raahe	3	7.4	7.43	0.03	7.18	-0.12
Pietarsaari	4	7.6	7.97	0.37	7.42	-0.18
Vaasa	5	7.2	7.67	0.47	7.32	0.12
Kaskinen	6	7.6	7.20	-0.40	7.32	-0.28
Mäntyluoto	7	6.5	6.33	-0.17	6.29	-0.21
Rauma	8	5.9	5.41	-0.49	5.81	-0.09
Turku	9	4.8	4.12	-0.68	4.31	-0.49
Degerby	10	5.1	4.28	-0.82	4.89	-0.21
Hanko	11	3.5	2.75	-0.75	3.44	-0.08
Helsinki	12	3.1	2.16	-0.94	2.91	-0.19
Hamina	13	2.2	1.67	-0.53	1.91	-0.29
Mean diff.:				-0.18		-0.17
Standard dev.:				±0.59		±0.15
RMS diff.:				±0.62		±0.24

*Our method applied to *HELA's* interval 1922-1951. All values are relative to mean sea level, i.e. no eustatic correction applied.

5.2.5 Conclusions

We see from the above calculations that generally the result of our computation agrees considerably better with those of the older determinations, if we limit the data span used to coincide with that used by these earlier authors.

The improvement is not very spectacular but clearly visible. All three measures of difference decrease: mean difference, RMS difference and standard deviation (RMS difference after correcting for mean difference). This demonstrates:

1. Our method produces valid results, the rather large

difference with the earlier determinations being ascribable to the different data interval used;

2. The "quality" of our method, showing from the good agreement in the above comparison when using the same data interval as the older determinations, is *at least* of the order of ±0.25 mm/year;

3. The choice of data interval has a significant influence on the results obtained, especially on the bias term affecting all tide gauges equally. Only in the case of the *(HELA 1953)* determination, it is the standard deviation rather than the mean difference that diminishes, but this may be attributed to the time series being too short for reliable land uplift determination.

We studied the influence of the data interval also in the following way: from the data we successively left out the years 1985, 1984, 1983, 1982 and 1981. Table 12 shows the change in computed land uplift. Hanko served as the base or reference station in this set of adjustments. The effect of these last five years is surprisingly large; it is known that we have had some unusually high sea levels, which apparently produced this effect.

This also shows that it is probably illusory to try to determine an accurate eustatic sea level rise value from tide gauge data; do such sequences of years of unusual sea level belong to the "signal" or should they be seen as "noise"? Even statistically the problem is not an easy one.

Table 12: Influence of the last observation time included on the computed land uplift figures. *Hanko* was chosen as the base station. No air pressure correction.

	1980	1981	1982	1983	1984	1985	80-85
Kemi	7.77	7.66	7.64	7.27	7.31	7.38	+0.39
Oulu	7.29	7.19	7.05	6.79	6.87	6.95	+0.34
Raahe	7.99	7.84	7.67	7.41	7.46	7.49	+0.50
Pietarsaari	8.52	8.36	8.25	7.97	8.00	8.04	+0.48
Vaasa	8.15	7.99	7.89	7.63	7.72	7.76	+0.39
Kaskinen	7.72	7.54	7.42	7.18	7.25	7.29	+0.43
Mäntyluoto	6.87	6.67	6.59	6.32	6.40	6.42	+0.45
Rauma	5.91	5.73	5.67	5.41	5.50	5.55	+0.36
Turku	4.71	4.49	4.43	4.15	4.22	4.24	+0.47
Degerby	4.78	4.57	4.50	4.24	4.33	4.36	+0.42
Hanko	3.37	3.16	3.09	2.82	2.90	2.90	+0.47
Helsinki	2.82	2.61	2.53	2.23	2.31	2.33	+0.49
Hamina	2.39	2.19	2.13	1.74	1.85	1.90	+0.49
average:	6.02	5.85	5.76	5.47	5.55	5.59	+0.43

5.3 A methodical test of adjustment techniques

As has been noted earlier and seen from the above results, there are many differences in treatment of the data by the various authors considered, which all lead to slight differences in the outcomes. It is however difficult to judge how much of the differences in the results are due to different data (data interval, interpolated data) used, and how much may be attributed to different adjustment techniques.

To obtain an answer to the latter question, we performed the following computation. We took the data compiled by *SUUTARINEN (1983)* p. 11 Table 8, and treated it with our method, using in turn all 13 tide gauges as base stations and averaging to obtain the final solution, just as we already described above. The results are summarised in Table 13. In Table 14, we perform the comparison between our solution obtained above, our solution as described here making use of the original *SUUTARINEN (1983)* data, and *SUUTARINEN's* original solution of *1983*.

All values are relative to mean sea level, i.e. no eustatic correction has been applied.

It is seen that the second set of differences in Table 14 is much smaller than the first set. We can say that this second set of differences is caused only by the difference in *method* used: Our method certainly is not much poorer than *SUUTARINEN's* adjustment technique.

We have also asked ourselves, "does the use of yearly values instead of monthly ones lead to biases in the results because some months (the summer months) are over-represented in the data, and sea level recordings show a clear yearly cycle (cf. section 7.2)?". However, we did not find such an overrepresentation of some months in our set of observations. On the contrary, the frequency distribution around the year was found to be statistically random (cf. Figure 2).

Table 13: Our adjustment applied to the *SUUTARINEN* yearly data.

uplift	1	2	3	4	5	6	7	8	9	10	11	12	13	avg.:
KEMI 1	7.78	7.24	7.54	7.38	7.38	7.46	7.29	7.42	7.60	7.35	7.44	7.37	7.42	7.44
OULU 2	7.53	7.00	7.31	6.98	7.09	7.25	7.02	7.20	7.36	7.16	7.15	7.09	7.22	7.18
RAAH 3	7.79	7.29	7.57	7.44	7.45	7.43	7.34	7.21	7.65	7.39	7.51	7.44	7.33	7.45
PIET 4	8.65	8.39	8.43	8.36	8.46	8.37	8.40	8.25	8.52	8.28	8.52	8.46	8.28	8.41
VAAS 5	8.28	7.98	8.10	7.95	8.06	7.97	7.98	7.90	8.20	7.97	8.11	8.05	7.87	8.03
KASK 6	7.76	7.52	7.60	7.52	7.60	7.47	7.45	7.27	7.67	7.46	7.63	7.56	7.32	7.53
MÄNT 7	6.94	6.65	6.79	6.62	6.76	6.66	6.68	6.55	6.90	6.62	6.80	6.74	6.52	6.71
RAUM 8	5.93	5.72	5.77	5.71	5.78	5.70	5.62	5.46	5.79	5.65	5.85	5.80	5.49	5.71
TURK 9	4.65	4.45	4.50	4.44	4.54	4.39	4.42	4.27	4.63	4.35	4.58	4.55	4.26	4.46
DEGE 10	4.77	4.68	4.64	4.65	4.70	4.47	4.61	4.27	4.78	4.51	4.74	4.71	4.31	4.60
HANK 11	3.37	3.16	3.23	3.12	3.26	3.07	3.17	2.81	3.37	3.10	3.31	3.24	2.88	3.16
HELS 12	2.79	2.57	2.62	2.54	2.68	2.47	2.58	2.15	2.78	2.47	2.73	2.67	2.27	2.56
HAMI 13	2.36	1.95	2.22	2.00	2.13	1.99	2.09	1.74	2.28	2.02	2.19	2.23	1.86	2.08
corr.:	0.25	-0.06	0.08	-0.05	0.04	-0.05	-0.05	-0.22	0.17	-0.08	0.09	0.04	-0.18	5.79

resid.	1	2	3	4	5	6	7	8	9	10	11	12	13	s.d.:
KEMI 1	9	-14	3	-1	-10	7	-9	20	-1	-1	-9	-11	16	0.11
OULU 2	10	-13	5	-15	-13	12	-11	24	1	6	-13	-14	22	0.14
RAAH 3	9	-10	4	4	-4	3	-6	-2	3	2	-3	-5	6	0.06
PIET 4	-1	3	-6	-1	0	1	4	5	-6	-6	1	0	4	0.04
VAAS 5	0	0	-1	-3	-2	-1	0	9	0	1	-2	-3	1	0.03
KASK 6	-2	5	0	4	3	-1	-2	-4	-2	1	1	-1	-3	0.03
MÄNT 7	-2	0	0	-4	1	0	2	6	2	-1	0	-1	-1	0.02
RAUM 8	-3	6	-2	4	2	4	-4	-4	-9	1	4	4	-5	0.05
TURK 9	-7	4	-4	2	3	-3	1	2	0	-4	2	4	-3	0.04
DEGE 10	-8	13	-4	9	5	-8	6	-12	1	2	4	6	-12	0.08
HANK 11	-4	6	-1	1	6	-4	6	-13	4	2	5	3	-10	0.06
HELS 12	-2	6	-2	2	7	-4	7	-20	5	-2	7	6	-12	0.08
HAMI 13	3	-8	6	-3	1	-4	6	-12	3	2	1	10	-4	0.06

Table 14: *SUUTARINEN* adjustment compared with ours

Station name	nr	*SUUTARINEN* result	Our result value	diff	Our result* value	diff
Kemi	1	7.76	7.36	-0.40	7.44	-0.32
Oulu	2	6.98	6.92	-0.06	7.18	0.20
Raahe	3	7.50	7.43	-0.07	7.45	-0.05
Pietarsaari	4	8.35	7.97	-0.38	8.41	0.06
Vaasa	5	8.04	7.67	-0.37	8.03	-0.01
Kaskinen	6	7.49	7.20	-0.29	7.53	0.04
Mäntyluoto	7	6.66	6.33	-0.33	6.71	0.05
Rauma	8	5.36	5.41	0.05	5.71	0.35
Turku	9	4.61	4.12	-0.49	4.46	-0.15
Degerby	10	4.49	4.28	-0.21	4.60	0.11
Hanko	11	3.15	2.75	-0.40	3.16	0.01
Helsinki	12	2.62	2.16	-0.46	2.56	-0.06
Hamina	13	1.86	1.67	-0.19	2.08	0.22
Mean diff.:				-0.28		0.03
Standard dev.:				±0.16		±0.16
RMS diff.:				±0.32		±0.17

*Our method applied to the exact *SUUTARINEN* data as given in *SUUTARINEN (1983)* p. 11 Table 8.

6. DEPENDENCE ON PHYSICAL PARAMETERS

6.1 Air pressure variations

This was studied by using a file of monthly mean air pressures for a number of locations in Finland: Oulu, Sodankylä, Vaasa, Mariehamn, Helsinki and Lappeenranta. This file was rather complete although some minor gaps existed. The file was provided by the Finnish Meteorological Institute, and from this data, a tape was generated containing interpolated mean air pressures for the tide gauge locations. This interpolated set was very complete: only in some tens of station-months for which there were tide gauge monthly averages, corresponding air pressure values could not be reasonably interpolated.

For the data with corresponding air pressure values we did the tide gauge adjustment both with (Table 16) and without applying the "inverse barometer" correction for atmospheric pressure. Results are summarised in Table 15: it is seen that the influence of including this correction is to reduce the adjustment residuals somewhat - which is heartening - but however we did not find any significant change in the land uplift values resulting from the adjustment, changes being random-looking and of the order of one unit in the last decimal printed (0.01 mm/year uplift).

The tide gauge constants found from the "air pressure" adjustment differed from the ones computed without correction; this should be seen as caused by a systematic deviation of the mean air pressure over Finland from the value we assumed in the program, 101 300 Pa.

Applying the air pressure correction improved the residual RMS for the tide gauge adjustment. In the Table 15 we summarise the *residual RMS values* (expressed in mm) without and with this correction, with all the 13 tide gauges serving in turn as base station.

The column "months without pressure" gives the total number of months, for all stations except the base station used, where there was no mean air pressure value available although the mareograph readings for that station and that month were complete. These months were left out of this adjustment, wich is thus based on a slightly smaller data set than the one without air pressure correction. As can be seen, the amount of observations left out this way is small.

Table 15: Residual RMS (in mm) for tide gauge adjustment without and with air pressure correction

Tide gauge	before air pressure	after corr.	months without pressure
Kemi	8.05	8.06	53
Oulu	8.53	8.42	34
Raahe	7.95	7.87	47
Pietarsaari	8.43	8.41	54
Vaasa	8.78	8.14	56
Kaskinen	8.25	8.19	9
Mäntyluoto	7.68	7.58	29
Rauma	7.41	7.40	27
Turku	8.46	8.64	10
Degerby	8.03	7.88	15
Hanko	8.24	8.17	4
Helsinki	7.38	7.26	64
Hamina	7.50	7.40	27
Average	8.05	7.95	

As can be seen, the improvement is very modest. We also did the "averaging scheme" computation using the air pressure correction as was done earlier without this correction, i.e. averaging the land uplift values obtained with each tide gauge serving in turn as base station. The computation and its results are in Table 16.

Also this computation produces a very modest improvement: all standard deviations go down by approx. 0.01 mm/year. The changes in the computed land uplift values are also slight, the largest one being 0.07 mm/year. The grand average of land uplift values changes only by 0.02 mm/year, dwindlingly small.

Table 16: Tide gauge adjustment of our data set applying air pressure correction

uplift	1	2	3	4	5	6	7	8	9	10	11	12	13	avg.:
KEMI 1	6.59	7.47	7.73	7.36	7.26	7.65	7.09	7.37	7.40	7.39	7.30	7.26	7.71	7.35
OULU 2	6.12	7.01	7.37	6.93	6.80	7.12	6.64	6.90	6.96	7.00	6.85	6.79	7.22	6.90
RAAH 3	6.71	7.47	7.82	7.45	7.31	7.78	7.18	7.24	7.53	7.60	7.41	7.32	7.67	7.42
PIET 4	7.30	8.12	8.39	8.03	7.92	8.38	7.77	7.85	8.10	8.08	8.00	7.94	8.22	8.01
VAAS 5	7.05	7.87	8.14	7.79	7.69	8.00	7.51	7.61	7.80	7.82	7.75	7.66	7.89	7.74
KASK 6	6.59	7.42	7.64	7.22	7.26	7.57	7.03	7.03	7.30	7.36	7.27	7.19	7.40	7.25
MÄNT 7	5.69	6.50	6.72	6.41	6.34	6.70	6.15	6.18	6.45	6.44	6.39	6.32	6.49	6.37
RAUM 8	4.83	5.61	5.81	5.51	5.41	5.82	5.19	5.20	5.40	5.53	5.52	5.41	5.55	5.45
TURK 9	3.45	4.30	4.42	4.16	4.11	4.53	3.90	3.99	4.22	4.21	4.17	4.09	4.29	4.14
DEGE 10	3.64	4.44	4.71	4.34	4.26	4.58	4.07	3.98	4.36	4.36	4.28	4.24	4.31	4.27
HANK 11	2.06	2.89	3.08	2.79	2.71	3.08	2.50	2.37	2.85	2.87	2.81	2.72	2.75	2.73
HELS 12	1.46	2.31	2.51	2.21	2.10	2.50	1.89	1.78	2.29	2.26	2.21	2.13	2.16	2.14
HAMI 13	0.93	1.86	2.04	1.76	1.57	2.04	1.44	1.40	1.76	1.78	1.81	1.75	1.78	1.69
corr.:	-.70	0.14	0.38	0.04	-.06	0.33	-.24	-.20	0.07	0.10	0.02	-.05	0.15	5.50

resid.	1	2	3	4	5	6	7	8	9	10	11	12	13	s.d.:
KEMI 1	-7	-2	0	-3	-4	-3	-2	21	-3	-6	-8	-4	21	0.10
OULU 2	-9	-3	9	-1	-5	-11	-2	20	-1	0	-7	-6	17	0.09
RAAH 3	-2	-9	2	-1	-6	3	0	1	3	8	-4	-5	10	0.05
PIET 4	-1	-3	0	-2	-3	4	0	4	2	-2	-3	-2	6	0.03
VAAS 5	1	-1	2	1	1	-7	1	7	-1	-1	-1	-3	0	0.03
KASK 6	3	3	1	-7	6	-1	2	-3	-3	1	-1	-1	0	0.03
MÄNT 7	2	-1	-3	0	3	0	2	1	1	-2	0	0	-3	0.02
RAUM 8	8	3	-1	3	2	4	-2	-5	-12	-1	5	1	-5	0.05
TURK 9	0	2	-10	-2	2	6	0	5	0	-3	0	0	0	0.04
DEGE 10	6	3	6	3	4	-2	3	-10	1	-1	-2	1	-12	0.05
HANK 11	3	2	-3	2	4	2	1	-16	5	5	6	4	-13	0.07
HELS 12	2	3	-1	3	2	3	-1	-16	8	3	5	4	-13	0.07
HAMI 13	-6	3	-2	4	-6	2	-1	-9	0	0	10	11	-6	0.06

6.2 The influence of the Baltic water balance

The long term mean influx of fresh water into the Baltic Sea amounts to some 470 km^3 per year (*MIKULSKI 1980*), with a standard deviation of some 12 %. This corresponds to a layer of approx. 1.3 m of fresh water, if distributed evenly and once a year over the entire surface area of the basin. Because of the wide latitudinal range (54° N to 66° N) of the sea, the spring flood period due to snow melt is spread out over three months, hence the seasonal cycle is modest and cannot be discerned in annual water level variations. Short range variability, even in the scale of several months, is dominated by the exchange of water through the Danish Straits as well as regional water level tilt, both due to meteorological disturbances. The natural variability of the amount of water in the Baltic Sea amounts to approx. 370 km^3, which corresponds to a ± 50 cm variation of water level around the long term mean. These variations may last up to several months and, therefore, contribute much to the scatter of annual mean values. This scatter is typically ± 7 cm. The main effect of the fresh water input is indirect: because of variable annual inflow the salinities of the uppermost water layers, say, above the permanent halocline, vary slightly and the hydrostatic balance varies from year to year. The annual mean salinity above the halocline in the Gulf of Finland varies between 5 ‰ and 7 ‰ (*LAUNIAINEN and KOLJONEN 1982; ALENIUS 1986*). This means a ± 2 cm change in the sea level; somewhat less than half of the actual scatter of the annual mean of sea level.

All measurements made during this century show that salinity has somewhat increased (*HELA 1966, MÄLKKI and TAMSALU 1985, LAUNIAINEN et al. 1987*). The increase in the central basins seems to be of the same order both above and below the halocline (*KULLENBERG 1981*). Because the eustatic change is not known very accurately, such an overall increase of salinity becomes important only if our land uplift rates are compared with places outside the Baltic Sea area. More important is that the increase of salinity seems not to have occurred uniformly; in the Bothnian Bay practically no changes have been observed. Based on the salinity time series from Utö and Ulkokalla (*LAUNIAINEN and KOLJONEN 1982*) we estimated that the land uplift could be underestimated by 0.1 mm/year in Kemi, Oulu, Raahe and Pietarsaari, when compared with Hanko.

Our adjustment method assumes that the monthly mean sea levels form a rigid plane. Mainly because there is a permanent difference in the salinity in different parts of the Baltic Sea, the surface where sea level would be in balance is not an accurate plane. This causes a bias of the order of centimeters in the additive constants presented in Table 19. This bias is largest in the end of the Bothnian Bay. On the other hand, numerical simulation showed that the land uplift values in Table 18 are affected much less than the standard deviation.

Correlations have been presented between time series of salinity and river runoff with a conclusion that the long-term variations of fresh water runoff may explain salinity variations surprisingly well (e.g., *LAUNIAINEN et al. 1987*). We want to emphasize that such a relation may be valid only for long term variations. The observed variations in annual mean salinities at fixed points are related to changes in the large scale structure of salinity. Even if we assume that there is no salty water entering through the Kattegat and that the fresh water were distributed uniformly to the upper layer above the halocline, the annual fresh water input would lower the salinity only by about 3 %. In the Gulf of Finland e.g. this would mean a change from 6 ‰ to 5.8 ‰ which is only about 10 % of the observed variation.

A correlation of about r = 0.5 can be seen between the long term variations of mean sea level at Hanko and the discharge of Vuoksi river (a major river running to Lake Ladoga, having an r = 0.87 correlation with the total discharge of fresh water to the Gulf of Finland). It would be tempting to assume that this correlation is related to the correlation between salinity and fresh water runoff, but this seems not to be the case. The time lag between these two time series is opposite to what it should be if it is assumed that the increase of sea level in Hanko is caused by increased river runoff. As Figure 4 shows, the sea level of Hanko leads the discharge at the Vuoksi, i.e. the peaks occur half a year earlier in Hanko than in the Vuoksi. Cross correlations calculated from the annual means are:

time lag (years)	correlation r
-2	-0.15
-1	-0.10
0	0.41
1	0.51
2	0.06

Because variations in the water level in the Baltic Sea hardly can affect the fresh water runoff, there apparently is a common external cause involved. We propose that this common factor is the number of cyclonic weather disturbances (air pressure lows or storms) passing over Fennoscandia and releasing their rain and snow over the Vuoksi discharge area, i.e. the better part of Finland's lake district. These lows generally also pass over central

Scandinavia, and the wind direction in the Kattegat during such a pass will cause an inflow into the Baltic Sea.

The complexity of the relations between mean sea level in the Baltic Sea and other physical factors does not support any simple corrections to the tide gauge observations, but we have taken them into account when estimating the error bounds for the final results in Table 18.

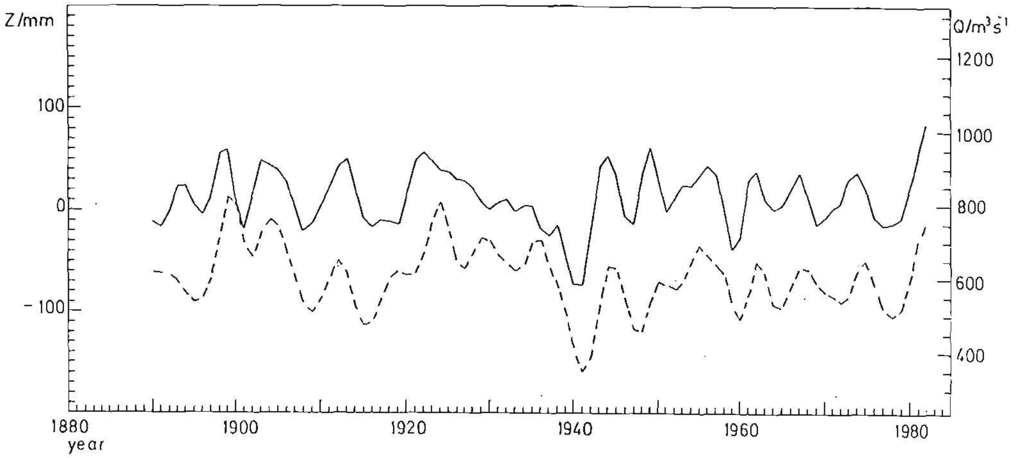

Figure 4: Correlation between sea level in Hanko and Vuoksi river discharge. Drawn line = sea level in Hanko; broken line = Vuoksi river discharge. 5 year gaussian filtered yearly means.

7. SPECTRAL ANALYSIS OF TIDE GAUGE DATA

7.1 General

A spectral analysis of data from Swedish tide gauges was recently published by *SJÖBERG AND FAN (1986)*. We decided to replicate this investigation using the Finnish tide gauge data.

In the spectra obtained (Appendix II) the amplitudes

$$A_n = \sqrt{(a_n^2 + b_n^2)} \qquad (7.1)$$

of the Fourier series

$$f(t) = \frac{1}{2} a_0 + \sum_{n=1}^{\infty} (a_n \cos \frac{2n\pi}{T} t + b_n \sin \frac{2n\pi}{T} t) \qquad (7.2)$$

are plotted versus the frequency. The interval over which Fourier analysis was done, was taken as 1000 months or 83 years, which covers neatly the period over which data was available for most tide gauges (1904-1985). The left edge in the graph represents infinity, the first peak a period of 1000 months, the next 500 months, the next 333 months, etc. The rightmost peak (number 200) represents 5 months.

Before applying the Fourier algorithm, both tide gauge constant and land uplift value (from the common tide gauge adjustment) were subtracted out in order to remove the zero-order term and satisfy the periodic boundary condition. Missing months were replaced by zeros. The adjusted values however may not precisely correspond to the values that would be derived from the time series itself, which leads to the zero-order term not being precisely zero, and excess energy being present in the low-frequency part of the spectrum. This can be seen especially in Raahe.

7.2 The annual and semiannual peaks

In the spectra (Appendix II) the annual and semiannual peaks are prominently present. This is not surprising; they are harmonics of a yearly periodicity in the tide gauge readings which is also evident from Appendix III, where the yearly cycle for every tide gauge has been estimated from the data.

The main cause of the yearly variation is presumably the *wind direction* over the Danish straits: this defines the direction of a pumping effect that increases or decreases the total amount of water in the Baltic Sea basin. Of course this variation is of necessity long-periodic, as the volume of water in the Baltic is itself very large.

In addition, there is a yearly variation in air pressure which is of climatic origin, and a slightly varying influx of rain and snow melting water from the great rivers discharging into the Baltic. Both these latter effects are slight.

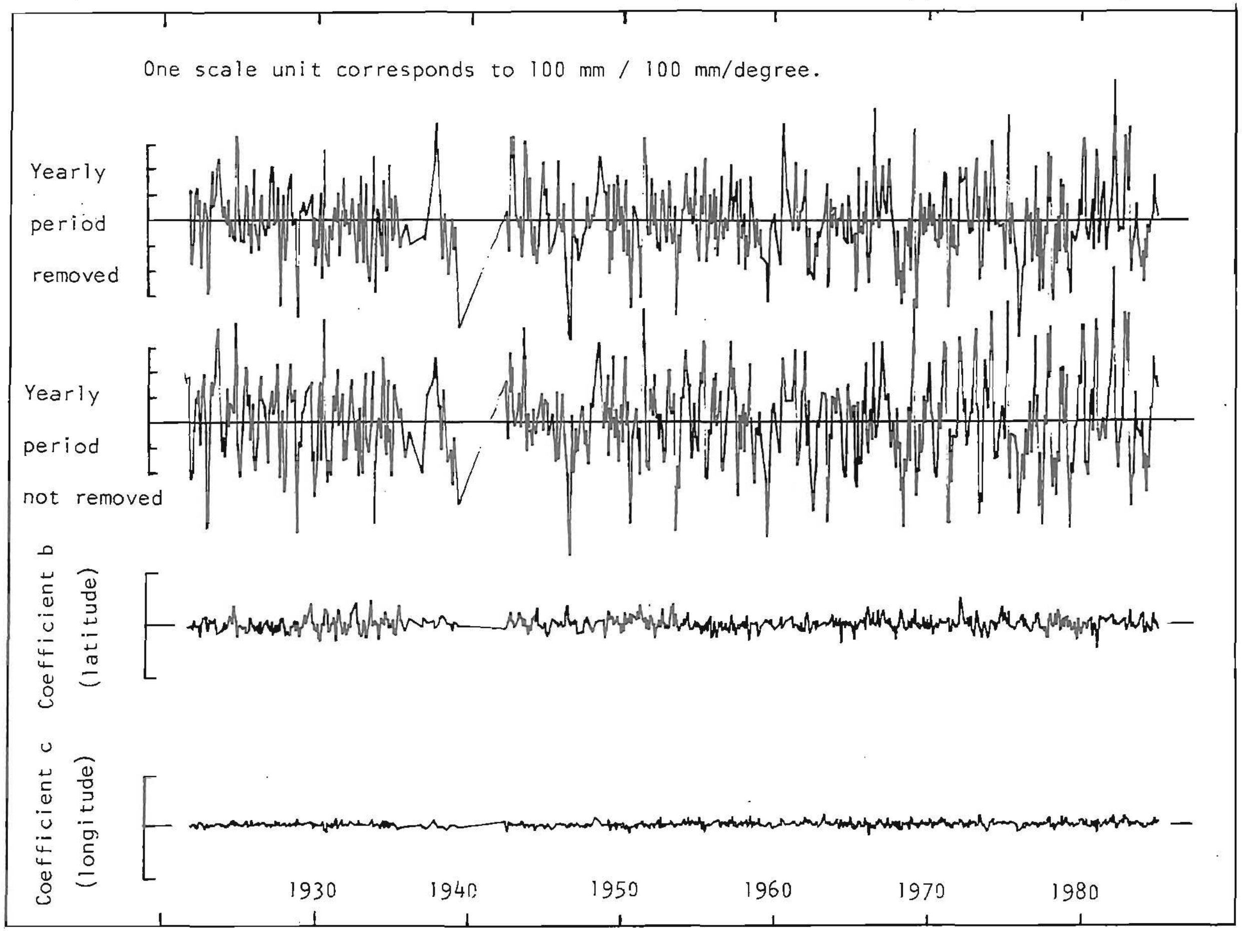

Figure 5: Coefficients a, b and c from the tide gauge adjustment. Vertical scales differ. The reduction in noise when taking out the yearly cycle is clearly seen.

Appendix III was generated by taking, for every tide gauge, all observations of the same month made in different years together and averaging. At the same time it was found that all months were represented equally in the data in question; i.e. the yearly periodicity is not likely to have any significant influence on the land uplift values determined from extended time series.

It was attempted to remove the yearly periodicity by simply subtracting out the average value for the corresponding month from every observation (Figure 5). As is seen, this does somewhat reduce the noise, but not very significantly.

7.3 Other peaks

Besides the prominent annual peak the spectrum is rather white. Confidence limits for a white noise spectrum were calculated for each spectrum from the RMS amplitude (excluding the annual peak). About 10 % of the amplitudes fall above and 10 % below the 80 % confidence limits just as they should. The probabilities for the occurrence of the highest peaks are also close to those predicted from white noise. For example, the 435 days peak in Turku almost reaches the 1 % probability limit. As there are 200 independent amplitudes in the spectrum, the probability that by chance one of them exceeds the 1 % limit is about 87 %. Therefore the spectra alone do not support the existence of any other peak than the annual peak.

If there is an independent e.g. *physical* reason for a peak to exist at a certain frequency, the peaks denoted by the periods in Appendix II have to be considered significant. One of them, the 182 days peak, is the first harmonic of the annual peak and for that reason undoubtedly real. The Chandler peak of 438 days is discussed in 7.4.

Among the other peaks there are a peak of 982 days or 2.69 years, 2341 days or 6.4 years and 242 days or 2/3 year. The latter is suggestive of a harmonic of one year, but unfortunately that explanation doesn't work: it would have to be the second harmonic of two years, and the two year period itself is conspicuously absent from the data.

The 6.4 year period is reported also in *SJÖBERG, FAN (1986)* and attributed to *CURRIE (1976)*. Its physical nature - if any - is unknown.

Longer periods that could theoretically be expected and were demonstrated from the data by *CURRIE (1976)*, cannot be observed here. However, as *SJÖBERG, FAN* remark, the method used is not very suitable for these long periods.

Since there are no clear independent reasons for these peaks they should be considered random. Even their occurrence in several of our spectra, and in the spectra of *SJÖBERG, FAN* (1986) can be explained by the strong correlations inevitably present in tide gauge time series on the same, near-landlocked sea.

7.4 The suspected Chandler peak (polar tide)

It was found that besides the well known yearly period, and its harmonic the semiannual period, the spectra of the tide gauges showed also a peak at approx. 438 days. This peak is thought to correspond to the Chandler wobble period and to be caused by the polar motion, the so-called *polar tide*.

This study attempts to replicate the *SJÖBERG, FAN (1986)* result. In our spectra we also find a period, of 435 days, and the amplitude is, like in Sweden, 20-40 mm. The strength of the peak increases toward the North of the Gulf of Bothnia, like in the Swedish publication.

If this peak is real, it is surprising that the amplitude found is so much more than the theoretical (equilibrium tide) amplitude of 5 mm (*SJÖBERG, FAN* p. 5). For long periods like this one should expect the real tide to be almost equal to its equilibrium value, as the regime is very nearly static.

Contrary to *SJÖBERG, FAN* we do not find that the peak stands out clearly against the noise for all tide gauge stations. In some of the spectra (Degerby, Hanko, Rauma, Kaskinen) there are obvious noise peaks that are as high or higher than the 435 day peak.

The RMS noise level for all our spectra is about 1.77 cm. A 5 mm peak above this random noise would increase the expected amplitude to about 1.84 cm. The 80 % confidence limits for 1.77 cm noise are 0.56 cm to 2.7 cm and therefore it is not possible to detect a 5 mm amplitude polar tide from the observations.

As an example we estimated the probabilities for amplitudes which, when added to the random background noise, would produce the observed peak at Turku. The 80 % confidence limits were from 2.8 cm to 4 cm and the probability that a 5 mm amplitude polar tide together with noise would add up to the observed peak was slightly above 1 % - essentially the same as without the 5 mm polar tide.

Therefore we would like to offer an alternative explanation: the 435 (or 438) day peak is also a spurious (noise) peak. The presence of this peak in most of the Finnish and all of the Swedish tide gauge spectra can be explained by the existing strong correlation between all Baltic tide gauge time series. Similarly also the increase of the peak towards the North only indicates the still stronger correlation between the tide gauges on the Bothnian Bay. The real polar tide peak, according to this explanation, is only 5 mm and drowns completely in the noise.

8. THEORETICAL MEAN SEA LEVEL

For some purposes, e.g. when water level distributions and extreme values are studied, it is necessary to use a theoretical mean sea level which takes into account the land uplift. A value based on the mean of the last 10 years was used in the first half of this century, but from 1963 on the theoretical mean sea level has been calculated based on the relative land uplift rates by *LISITZIN (1964)* using the following equations for the theoretical mean sea level of the year y:

$$MW_i(y) = a_i \ (1960 - y) + c_i \ ; \qquad (8.1)$$

$i = 1,...,13$

where, for the tide gauge i, a_i is the annual change of the mean sea level by *LISITZIN (1964)* and c_i is the theoretical mean sea level of 1960 by *LISITZIN (1966)*. The theoretical mean sea level of 1960 is based on the mean of the years 1931-1960 and the annual change of mean sea level by *LISITZIN (1964)*; it is given in column A of Table 17.

In spite of the fact that such theoretical mean sea levels have relatively little scientific value, they have gained wide use in practical applications and several coastal engineering designs have been referred to the theoretical mean sea level of a particular year. The land uplift rates by *LISITZIN* have been used continuously although better recent determinations by *KÄÄRIÄINEN (1975)* and *SUUTARINEN (1983)* have been available. The reason for this is that the differences were not considered significant enough to justify the confusion which a change in these equations would cause. The analysis of the present data shows, however, that if the equations are continued to be used in the future, the extrapolation will go too far.

Ideally one would require that:

1. The annual change of the theoretical mean sea level equals the recommended value in Table 18.

2. There is no offset or trend in the difference between the theoretical mean sea level and the actual sea level.

3. The theoretical mean sea levels already established in the past are not changed.

Except by mere chance, it is not possible to fulfill these requirements simultaneously. Taking into account the practical use of the concept of theoretical mean sea level, we have chosen to give highest priority to requirement 3 and keep the established values unchanged. We also consider that requirement 1 is more important than a small offset, particularly when we take into account the bias in the additive constants of Table 19, which we discussed in Section 6.3. Our solution therefore is to define the theoretical mean sea level by the following equations:

$$MW_i(y) = \begin{cases} a_i\ (1990 - y) + d_i\ ;\ y \leq 1990\ , \\ b_i\ (1990 - y) + d_i\ ;\ y \geq 1990\ ; \end{cases} \qquad (8.2)$$

$i = 1,\dots,13$

where, for the tide gauge i, a_i is the annual change of mean sea level by *LISITZIN (1964)*, b_i is the recommended annual change of mean sea level (Table 18) and d_i is the theoretical mean sea level of 1990 based on the theoretical mean sea level of Eq. (8.1), as tabulated in Table 17.

Example:

For Hanko: $a_i = 3.1$, $b_i = 2.7$, $c_i = 1876$, $d_i = 1783$

From Eq. (8.2) we have

$MW(1960) = 3.1\ (1990 - 1960) + 1783 = 1876$ (Table 17, col. A)
$MW(1991) = 2.7\ (1990 - 1991) + 1783 = 1780$
$MW(2000) = 2.7\ (1990 - 2000) + 1783 = 1756$
$MW(2020) = 2.7\ (1990 - 2020) + 1783 = 1702$

and from Eq. (8.1) we have

$MW(1991) = 3.1\ (1960 - 1991) + 1876 = 1780$
$MW(2000) = 3.1\ (1960 - 2000) + 1876 = 1752$
$MW(2020) = 3.1\ (1960 - 2020) + 1876 = 1690$

Table 17 shows that the difference between column F, which is the best estimate for the theoretical mean sea level in 1990, and column d_i, which is defined for (8.2), is not larger than the standard deviation of the additive constants in Table 19. The difference between columns F and E (the additive constants in Table 19) is not smaller than the difference $F - d_i$. Although the difference C - A (of the 1960 estimates) is smaller than the differences above, we still conclude that the theoretical mean sea level given by Eq. (8.2) is within the present error bounds of the current best estimates of mean sea level.

Table 17: Theoretical mean sea level comparison table.

Tide gauge	A	B	C	d_i	$F - d_i$	E	F - E	F
Kemi	1741	1703	1741	1522	-1	1482	39	1521
Oulu	1746	1733	1739	1533	-1	1525	6	1532
Raahe	1704	1662	1718	1470	25	1439	56	1495
Pietarsaari	1666	1653	1672	1420	12	1413	19	1432
Vaasa	1695	1672	1705	1455	18	1440	33	1473
Kaskinen	1722	1716	1724	1500	8	1498	9	1507
Mäntyluoto	1747	1748	1753	1555	7	1557	5	1562
Rauma	1760	1792	1772	1583	26	1628	-19	1609
Turku	1829	1821	1837	1697	16	1697	16	1713
Degerby	1817	1812	1830	1679	23	1684	18	1702
Hanko	1876	1893	1887	1783	22	1811	-6	1805
Helsinki	1900	1912	1910	1825	21	1848	-2	1846
Hamina	1915	1936	1928	1849	28	1885	-8	1877

A = MW60 by *LISITZIN (1966)* based on the mean of the years 1931-1960 and the annual change of mean sea level by *LISITZIN (1964)*
B = MW60 based on the values of Column E and the annual change of mean sea level computed in this report (Table 18)
C = MW60 as the mean of the years 1933-1987
d_i = MW90 based on the values of column A and the annual change of mean sea level by *LISITZIN (1964)*
E = MW90 as in Table 19
F = MW90 based on the values of column C and the annual change of mean sea level computed in this report (Table 18)

9. CONCLUSIONS

We give here this report's final, *recommended values* of the land uplifts for the tide gauge stations as computed above. The set we give here is the one computed using air pressure corrections as listed also in Table 16.

For comparison, we also give the values of *earlier authors*, however rounded to one decimal only. The second decimal in our data, although not really significant in the absolute sense, nevertheless contains significant information on relative land uplift values between tide gauges.

All values given are *without eustatic correction*, i.e. they state a relative motion of Earth's crust and sea surface expressed in mm/year.

Table 18: Tide gauge adjustment final result.
No eustatic correction applied

		RECOMMENDED VALUES		TIDE GAUGE ANALYSIS					LEVELLING	
Tide gauge		uplift	est. err.	Hela	Rossiter	Lisitzin	Kääriäinen	Suutarinen	Kääriäinen	Suutarinen
name	nr	(mm/yr)		1953	1960	1964	1976	1982	1966	1982
Kemi	1	7.35	±0.4*)	6.4	8.5	7.3	7.5	-	7.8	-
Oulu	2	6.90	±0.4	6.3	7.0	7.1	6.8	7.0	7.6	7.8
Raahe	3	7.42	±0.4	7.4	8.0	7.8	7.7	7.5	8.3	8.5
Pietarsaari	4	8.01	±0.4	7.6	9.2	8.2	8.4	8.3	8.1	8.2
Vaasa	5	7.74	±0.4	7.2	7.6	8.0	7.9	8.0	7.6	7.7
Kaskinen	6	7.25	±0.4	7.6	6.7	7.4	7.4	7.5	7.0	7.1
Mäntyluoto	7	6.37	±0.4	6.5	5.3	6.4	6.6	6.7	6.3	6.4
Rauma	8	5.45	±0.4	5.9	3.9	-	5.5	5.4	6.2	6.5
Turku	9	4.14	±0.4	4.8	2.5	4.4	4.4	4.6	4.7	5.1
Degerby	10	4.27	±0.4	5.1	-	4.6	4.6	-	-	-
Hanko	11	2.73	±0.4	3.5	1.1	3.1	3.2	3.2	2.9	3.2
Helsinki	12	2.14	±0.4	3.1	-0.4	2.5	2.6	2.6	2.2	2.7
Hamina	13	1.69	±0.4	2.2	-0.4	-	2.0	1.9	1.9	2.6

*) The error given is dominated by the influence of the Baltic water volume variations over the years (cf. Table 12) and is common to all tide gauges. For the *internal* accuracies (standard deviations) which express *relative* accuracies between tide gauges, cf. Table 16 2nd part, last column.

We also computed the tide gauge additive constants, i.e. the reading for every tide gauge corresponding to mean sea level. The values computed by us are given, in the epoch 1990.5, in Table 19.

Table 19: The mareograph additive constants computed using air pressure correction. Values in mm, reduced to epoch 1990.5.

constant	1	2	3	4	5	6	7	8	9	10	11	12	13	avg.:
KEMI 1	1553.23	1472.10	1469.25	1472.15	1487.48	1467.29	1487.03	1481.00	1475.31	1479.88	1470.99	1478.66	1467.82	1481.71
OULU 2	1572.36	1522.24	1501.87	1521.49	1532.79	1516.82	1528.92	1523.27	1524.19	1522.78	1522.28	1524.07	1518.31	1525.49
RAAH 3	1493.53	1431.55	1460.07	1428.08	1445.95	1416.04	1441.90	1440.08	1429.05	1427.68	1426.24	1436.24	1427.33	1438.75
PIET 4	1454.61	1404.63	1394.89	1418.68	1419.08	1404.63	1418.15	1411.66	1411.50	1411.93	1406.14	1411.27	1407.94	1413.47
VAAS 5	1481.79	1428.66	1417.81	1428.41	1467.32	1421.45	1442.91	1446.74	1437.47	1437.19	1433.84	1435.55	1438.08	1439.76
KASK 6	1539.70	1486.94	1477.12	1505.98	1499.99	1496.20	1496.59	1494.22	1501.35	1490.89	1498.64	1500.85	1486.70	1498.09
MÄNT 7	1599.43	1550.15	1543.43	1556.87	1565.63	1540.78	1559.64	1551.64	1559.05	1554.97	1556.84	1555.58	1548.60	1557.12
RAUM 8	1669.18	1626.06	1618.39	1628.59	1644.37	1617.63	1629.61	1605.69	1637.21	1626.13	1627.33	1624.90	1612.75	1628.29
TURK 9	1735.79	1688.71	1680.16	1692.69	1700.30	1684.88	1701.89	1698.98	1707.11	1697.54	1689.60	1687.81	1694.36	1696.91
DEGE 10	1722.41	1676.45	1664.78	1678.32	1688.42	1667.56	1684.49	1687.57	1686.86	1695.30	1679.95	1679.18	1683.33	1684.20
HANK 11	1848.05	1805.56	1794.19	1806.42	1817.54	1804.88	1818.19	1817.94	1807.60	1806.66	1799.59	1802.96	1813.50	1811.00
HELS 12	1887.62	1840.58	1831.19	1843.21	1854.60	1840.30	1854.14	1852.81	1843.20	1845.14	1841.62	1841.73	1849.83	1848.15
HAMI 13	1926.65	1878.54	1871.29	1880.28	1893.51	1876.51	1889.42	1883.67	1883.49	1884.58	1877.20	1874.76	1881.31	1884.71
corr.:	44.36	-7.35	-14.09	-3.60	8.41	-11.75	3.48	-.95	-.33	-2.08	-5.96	-4.16	-5.99	1608.28

Resid.	1	2	3	4	5	6	7	8	9	10	11	12	13	s.d.
KEMI 1	27.17	-2.26	1.63	-5.96	-2.63	-2.67	1.84	0.25	-6.07	0.25	-4.77	1.12	-7.90	30.37
OULU 2	2.51	4.10	-9.53	-0.40	-1.11	3.07	-0.05	-1.27	-0.97	-0.63	2.75	2.74	-1.20	12.01
RAAH 3	10.42	-0.15	35.41	-7.08	-1.21	-10.96	-0.33	2.28	-9.37	-8.99	-6.55	1.65	-5.44	42.23
PIET 4	-3.22	-1.49	-4.49	8.81	-2.80	2.91	1.20	-0.85	-1.64	0.54	-1.38	1.96	0.45	11.74
VAAS 5	-2.34	-3.76	-7.86	-8.02	19.15	-6.57	-0.33	7.93	-1.97	-0.50	-0.03	-0.05	4.30	25.32
KASK 6	-2.75	-3.81	-6.87	11.49	-6.50	9.86	-4.98	-2.91	3.59	-5.13	6.51	6.92	-5.40	23.08
MÄNT 7	-2.05	0.37	0.40	3.35	0.10	-4.60	-0.96	-4.53	2.25	-0.08	5.68	2.62	-2.54	10.44
RAUM 8	-3.47	5.11	4.19	3.89	7.67	1.08	-2.16	-21.65	9.24	-0.09	4.99	0.77	-9.55	28.40
TURK 9	-5.48	-0.86	-2.65	-0.62	-5.02	-0.28	1.50	3.02	10.53	2.71	-1.35	-4.94	3.44	15.21
DEGE 10	-6.15	-0.41	-5.33	-2.29	-4.19	-4.89	-3.19	4.32	2.98	13.18	1.70	-0.86	5.12	18.83
HANK 11	-7.31	1.90	-2.72	-0.99	-1.88	5.63	3.71	7.89	-3.08	-2.27	-5.46	-3.89	8.48	17.55
HELS 12	-4.89	-0.22	-2.87	-1.35	-1.96	3.89	2.51	5.62	-4.62	-0.93	-0.58	-2.26	7.67	13.32
HAMI 13	-2.42	1.18	0.68	-0.83	0.39	3.55	1.24	-0.08	-0.89	1.95	-1.56	-5.79	2.59	8.36

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APPENDIX I : Tide gauge adjustment sample run

This sample run is from the adjustment with Hanko as the base station, not using any air pressure correction.

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RESIDUALS
=========
TIME    KEMI   OULU   RAAH   PIET   VAAS   KASK   MENT   RAUM   TURK   DEGE   HANK   HELS   HAMI         A      B      C
----------------------------------------------------------------------------------------------------------------------------
22.08    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0   -0.0    0.0 /   182.6   -6.5   -9.6
22.17    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0   -0.0    0.0 /  -223.1   -4.4   -4.5
22.33    0.0    0.0    0.0    0.0   -0.7    0.0    0.0    0.0    3.4    0.0    0.0    1.0    0.0 /  -194.7   -9.0   -2.7
22.42    0.0    0.0    0.0    0.0   -1.9    0.0    0.0    0.0    9.1    0.0    0.0    2.6    0.0 /   -29.4    9.2    5.9
22.50    0.0    0.0    0.0    0.0   -2.3    0.0    0.0    0.0   11.0    0.0    0.0    3.1    0.0 /    96.8   -2.3    3.5
22.58    3.9   -7.8    0.0    6.1   -3.9    0.0    0.0    0.0    7.0    0.0    0.0    7.6    0.0 /    86.1   -4.4   -4.9
22.67   -4.5    2.9    0.0    4.9   -2.9    0.0    0.0    0.0    3.2    0.0    0.0    0.0    0.0 /   131.3   -3.3   -9.8
22.75    5.8   -5.4    0.0    5.7   -6.9    0.0    0.0    0.0   -6.3    0.0    0.0   -4.6    0.0 /    34.5   -3.7   -0.4
22.83   -6.6   -0.5    9.1    0.0    0.0    0.0    0.0    0.0   -3.6    0.0    0.0   -2.8    0.0 /   -83.2  -23.1    5.3
22.92    0.0   -7.5    0.0    8.9    0.0    0.0    0.0    0.0    1.6    0.0    0.0   11.2    0.0 /   109.0    0.8    6.9
23.00    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0   -0.2    0.0    0.0   -0.1    0.0 /   195.3   12.6    3.5
23.17  -10.8    1.3   11.1    0.0    0.0    0.0    0.0    0.0    4.9    0.0    0.0    0.6    0.0 /   -33.2   16.2   -9.0
23.25   -0.9   -0.4    0.0    1.3    0.0    0.0    0.0    0.0    3.1    0.0    0.0    2.8    0.0 /  -416.0    2.2   -4.8
23.33    1.8    0.0   -2.9    2.5   -1.6    0.0    0.0    0.0   -0.8    0.0    0.0   -0.3    0.0 /  -383.8  -12.6   -2.3
23.42  -17.0   11.3   -0.0    9.1    0.5    0.0    0.0    0.0    6.2    0.0    0.0    3.9    0.0 /   -76.5    9.2   -3.5
23.50    0.0   -4.7   -4.0    6.6    0.0    0.0    0.0    0.0   19.8    0.0    0.0   18.3    0.0 /   162.7    5.3   -1.1
23.58   -1.1   -1.7    0.9    6.9   -4.7    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0 /   115.0    4.3   -0.9
23.75   -0.4  -10.7   -3.6   14.4    1.8    0.0    0.0    0.0   10.1    0.0    0.0   23.8    0.0 /   188.5    9.9   -0.2
23.83    1.0  -13.7    2.6   10.4    1.7    0.0    0.0    0.0    1.5    0.0    0.0   17.3    0.0 /   310.7   -0.8   -2.7
23.92    0.0   -4.1   -2.9    1.9    6.7    0.0    0.0    0.0    2.8    0.0    0.0   13.4    0.0 /  -374.9  -18.5    2.7
24.17   -0.3    0.0    2.0   -0.9    0.0    0.0    0.0    0.0   -4.9   -1.0    0.0   -5.0    0.0 /    -7.3  -12.9    1.8
24.25   -2.3    0.0    2.4    1.3    0.0    0.0    0.0    0.0    0.0   -4.9    0.0   -6.2    0.0 /  -107.1  -12.4    0.3
24.33    1.3    0.0    0.7   -1.9    0.0    0.0    0.0    0.0   -3.8    0.0    0.0   -3.5    0.0 /   -58.9  -10.8   -0.3
24.42   -3.4    0.0    4.2   -3.5    3.3    0.0    0.0    0.0    3.2    0.0    0.0    2.7    0.0 /  -130.6    3.9   -1.8
24.50   -1.7   -1.9   -5.7   -1.1   15.4    0.0    0.0    0.0    0.0   -6.7    0.0   10.0    0.0 /   -42.4   -9.2   -3.3
24.58   -4.3    0.0    0.0   -4.4   10.3    0.0    0.0    0.0    5.5    2.1    0.0   15.2    0.0 /   136.9   -3.5   -3.4
24.67   15.5    0.0   -9.5  -15.0    3.0    0.0    0.0    0.0    2.9    3.1    0.0    0.3    0.0 /   -10.9    9.1   -3.5
24.75   -1.4    0.0   -1.9   -5.4   10.5    0.0    0.0    0.0    9.6  -10.2    0.0    0.0    0.0 /    79.4   15.9    5.3
24.92   -8.6    3.5    6.3   -0.9    0.0    0.0    0.0    0.0    1.9    7.1    0.0    7.6    0.0 /    63.8    2.7    7.8
25.00    6.9   -6.6    1.5   -3.3   -1.8    0.0    0.0    0.0   10.0   -3.2    0.0    0.0    0.0 /    47.1   37.0    7.3
25.08   -3.7    0.0    9.7   -3.8   -3.7    0.0    0.0    0.0    3.4    3.1    0.0   -2.1    0.0 /   395.3   20.3   12.2
25.17   -9.3    0.0    2.8    0.2    9.9    0.0    1.8    0.0    2.9   -3.4    0.0   10.4    0.0 /   229.6    7.1    0.1
25.25    2.7   -6.5    0.0   -3.9   12.3    0.0    0.0    0.0   -8.2   -8.6    0.0   -0.7    0.0 /   -82.2  -23.6    5.2
25.33   -6.5   -1.3    4.7    3.0    6.2    0.0   -3.9    0.0   -3.4   -3.5    0.0   -1.1    0.0 /  -118.0   -3.5    2.5
25.42   -2.6    4.2    0.0   -3.3    5.2    0.0   -4.3    0.0   -1.8   -0.9    0.0   -5.2    0.0 /  -210.7   -2.8   -1.1


85.00   20.1    0.8    0.0    6.6  -20.3    0.0  -13.6  -22.2    0.0  -13.7    0.0  -14.3  -28.6 /    -3.7   19.1   -1.6
85.08    9.4    2.2    6.7   -1.2  -12.8    0.0    0.0  -28.4    0.0    0.0    0.0   -5.6  -19.0 /  -184.5  -19.0   -7.2
85.17    3.9    2.4    7.0   -4.1    0.0   -6.0    0.0  -13.5    0.0  -16.7    0.0   -9.4  -18.8 /  -131.2  -17.3   -6.6
85.25   -5.2   -0.7    4.3    3.7    0.0    0.0    1.1   -2.5    0.0   -0.1    0.0    5.1   -2.0 /  -277.0    0.4   -7.3
85.33    1.3   -2.8    0.0    6.5    0.0   -7.2    1.3   -2.0    0.0    2.8    0.0    0.0    0.0 /  -140.8   -5.2   -2.1
85.42   -2.5    0.0    0.0    6.6   -3.0    3.0    0.0   -2.1   -2.0   -7.7    0.0    0.0   -4.3 /  -183.5  -10.4   -3.5
85.50    3.0    0.0    0.0    8.0   -2.7    0.0   -3.6   -8.2   -7.3  -19.8    0.0   -6.7  -16.2 /   -34.3  -16.1   -3.3
85.58    9.8  -18.7    6.3    0.0    4.5    0.0   -2.4   -2.8    1.7   -4.6    0.0    1.8    1.3 /    52.0  -13.4   -1.5
85.67   -6.8  -17.3    0.0   12.8   12.4    0.0    4.2    8.8    8.0   -2.0    0.0    2.9   21.3 /    78.2   18.5   -3.4
85.75   -6.3  -14.5    7.3   12.3   10.3    0.2   -0.3   -1.5   -6.2   -9.6    0.0   -3.9    6.6 /   257.5   -0.0    4.1
85.83  -22.6   10.3    0.6   18.5    5.0    0.0   -5.1   -2.5   -2.8    2.7    0.0    0.0    3.6 /   175.7    4.0    9.6
85.92   17.2   -6.7    9.5    0.0   -7.6    0.0  -12.3  -19.2  -22.4  -14.6    0.0    0.0  -33.3 /   177.9   -1.2    1.6
86.00    3.7  -10.7    8.9    0.0    0.0    0.0    6.3   -1.9  -13.8  -15.2    0.0    0.0   -9.0 /   139.2  -10.1    5.3

EPOCH:   55.78
A,B,C AVERAGES & TILTS:
=================================
 1904.56   -2.90
 -36.96   -1.12
  23.13    0.63

 OBSERV.  RMS:    1587.909
 RESIDUAL RMS:    8.244245
    ----------------------------------------
    EPOCH, MAREOGRAPH OFFSET, LAND UPLIFT:
    ========================================
  KEMI  1    52.18 1771.11    -7.39
  OULU  2    55.57 1782.57    -6.96
  RAAH  3    49.46 1750.75    -7.50
  PIET  4    54.53 1713.32    -8.04
  VAAS  5    52.81 1744.59    -7.76
  KASK  6    56.06 1766.05    -7.29
  MENT  7    57.18 1784.65    -6.42
  RAUM  8    61.56 1800.28    -5.55
  TURK  9    52.27 1860.36    -4.23
  DEGE 10    52.99 1850.11    -4.35
  HANK 11    55.78 1904.56    -2.90
  HELS 12    54.60 1926.52    -2.33
  HAMI 13    58.58 1940.89    -1.88
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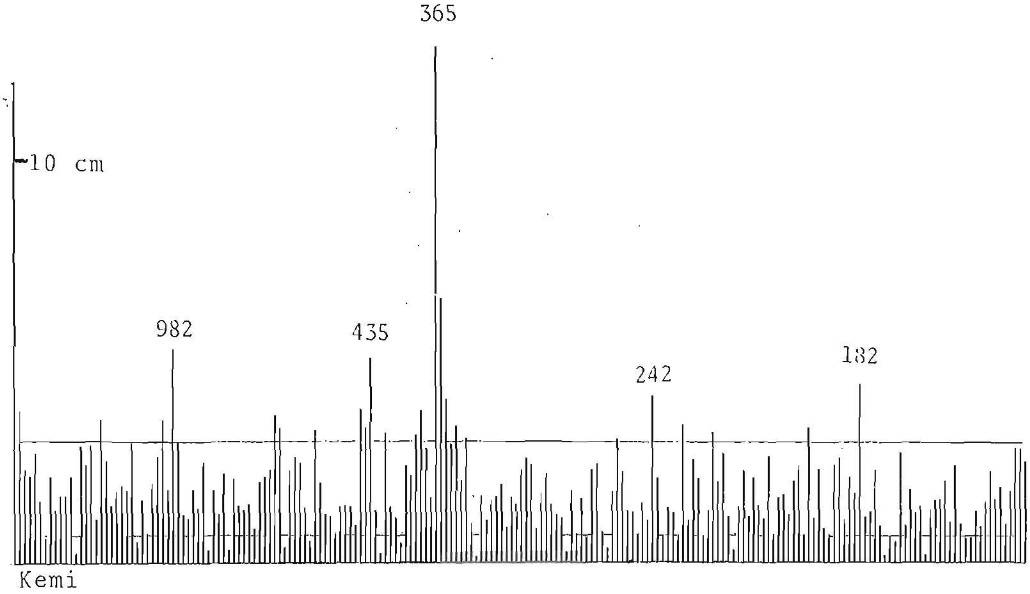
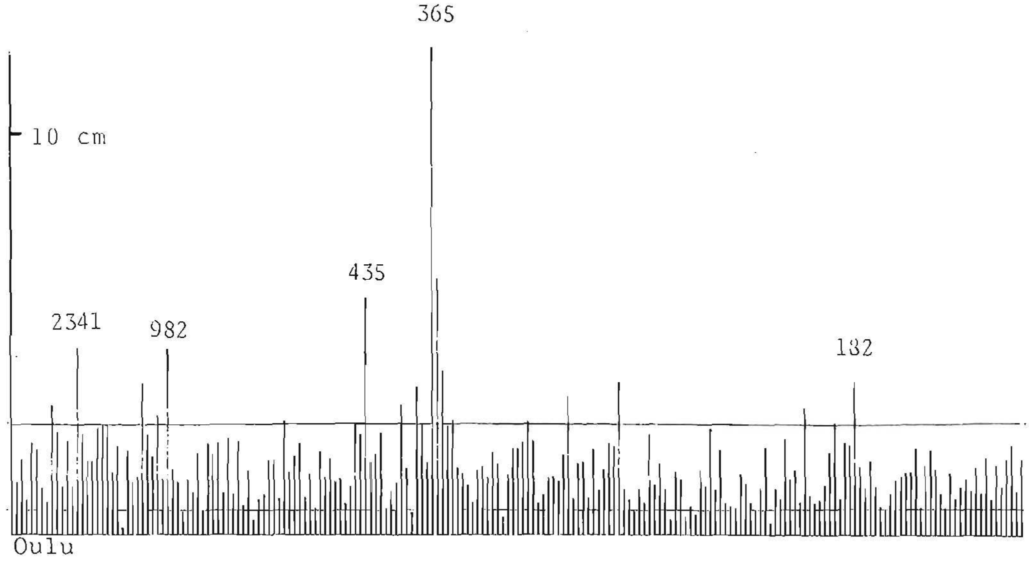
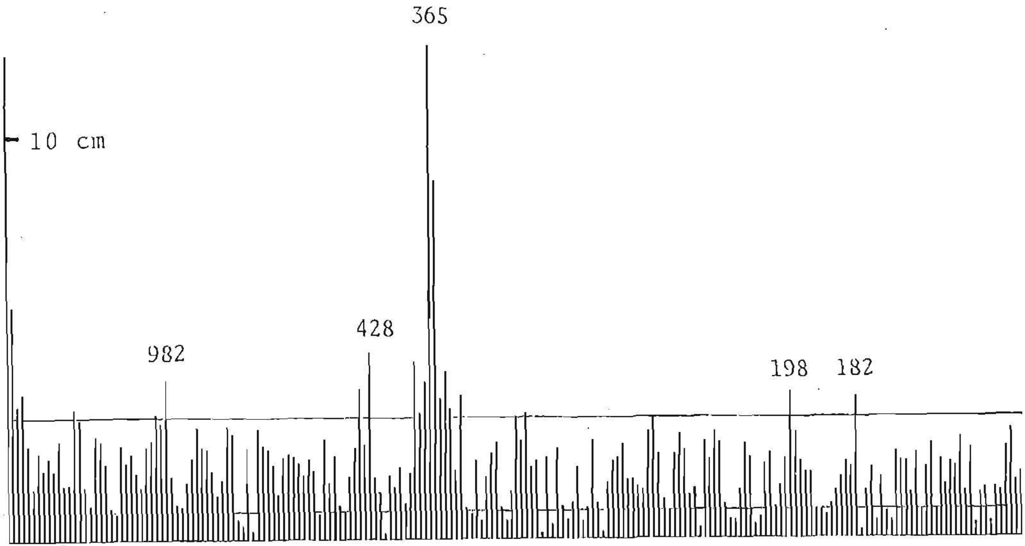
APPENDIX II : Fourier spectra of tide gauges

In each figure, the pair of horizontal lines indicate the 80% rejection limits for single spectral peaks of which the location is not known *a priori*.







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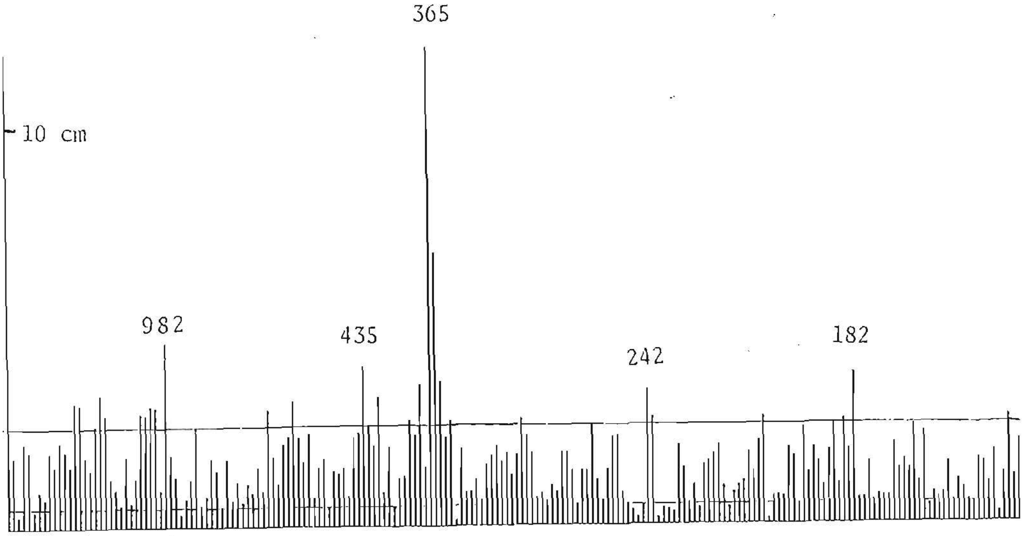

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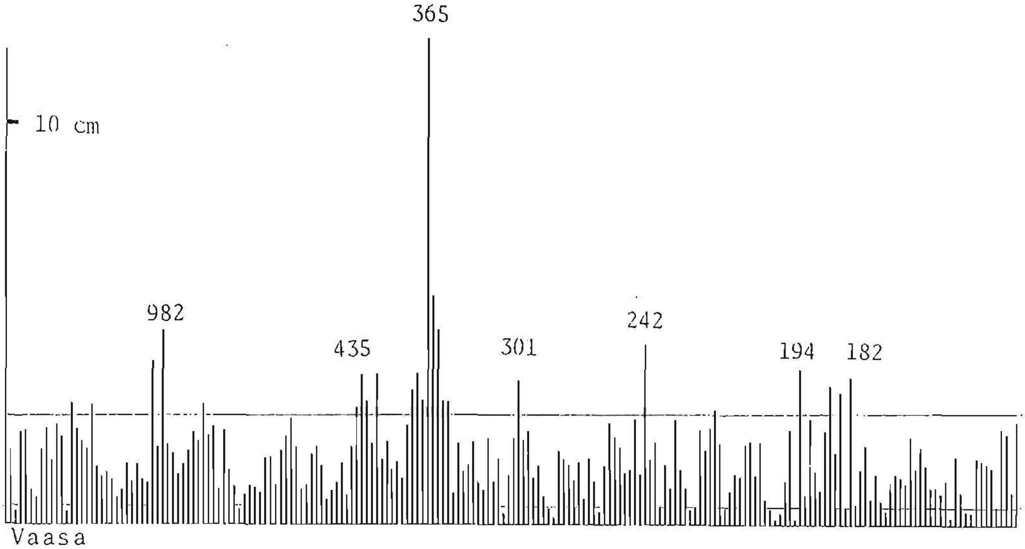

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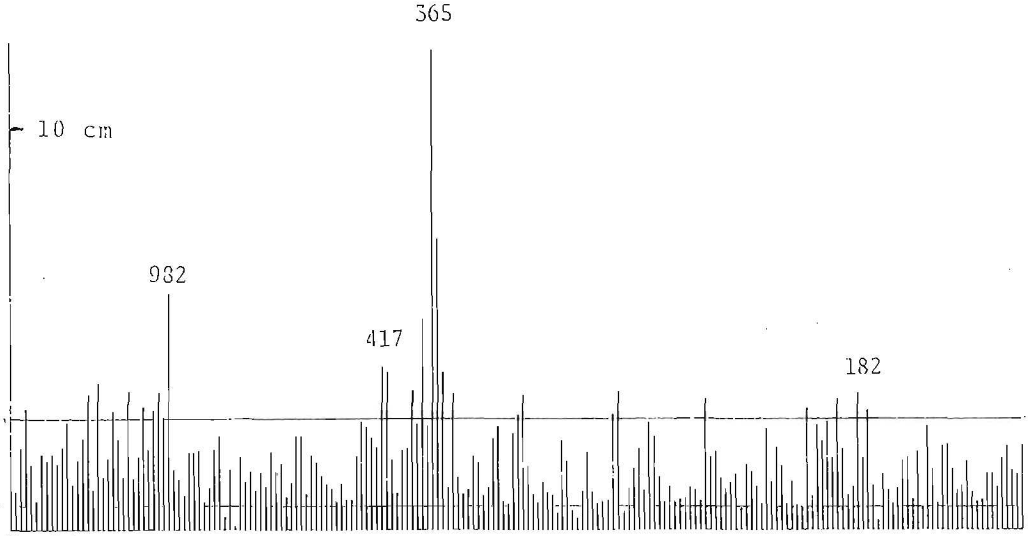
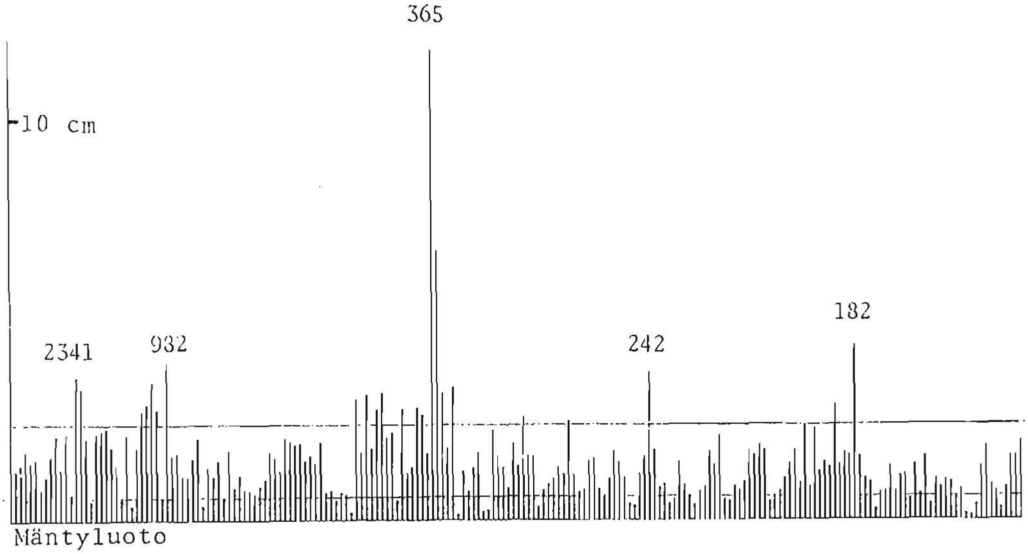


Kaskinen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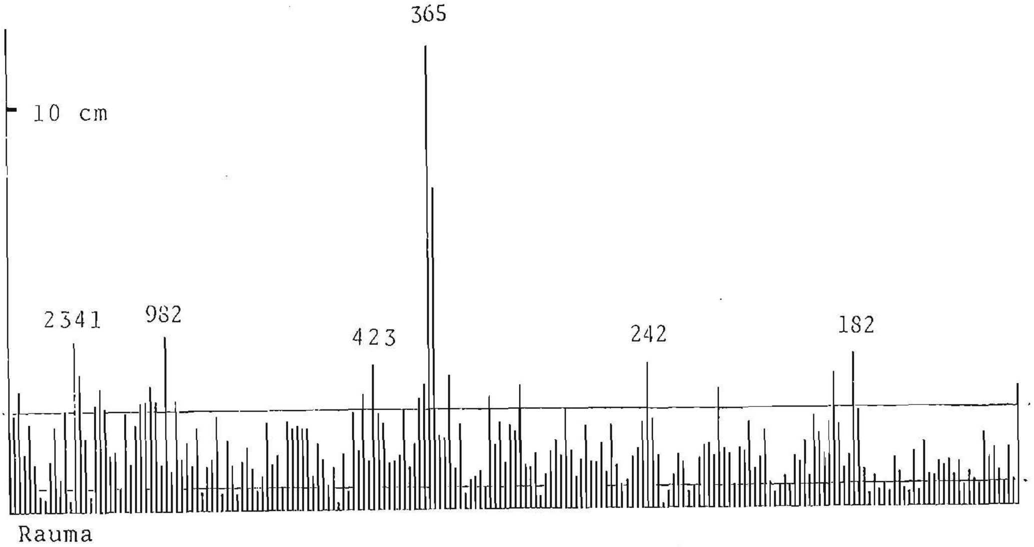
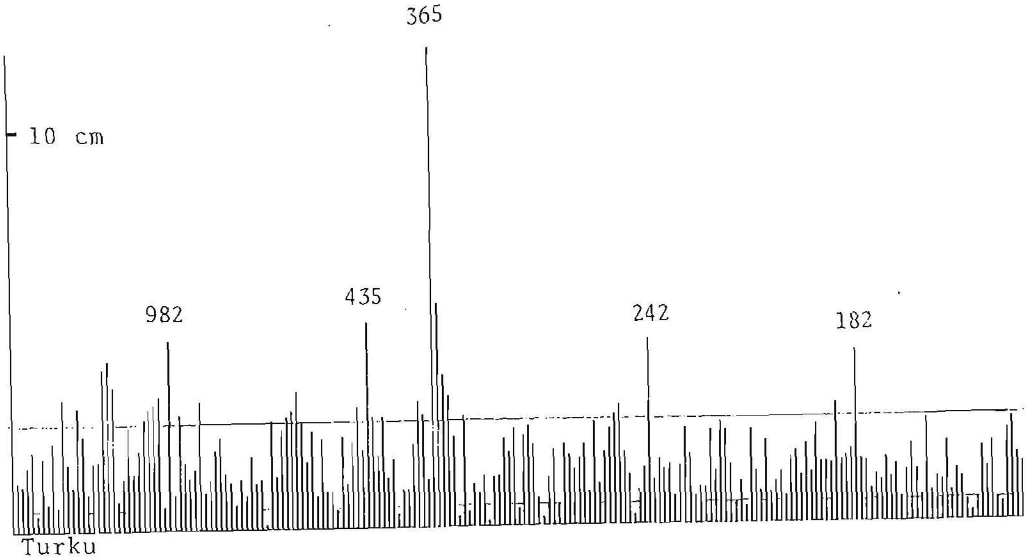
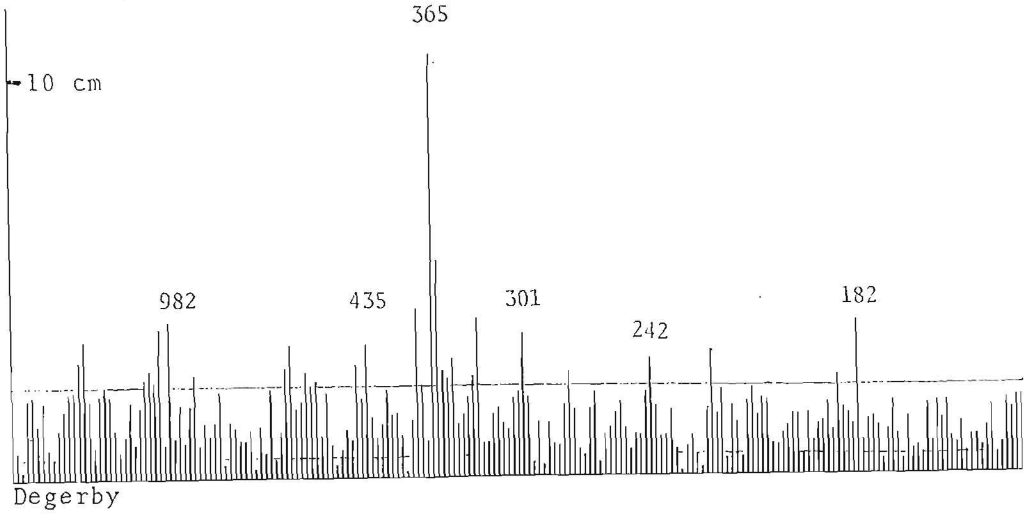
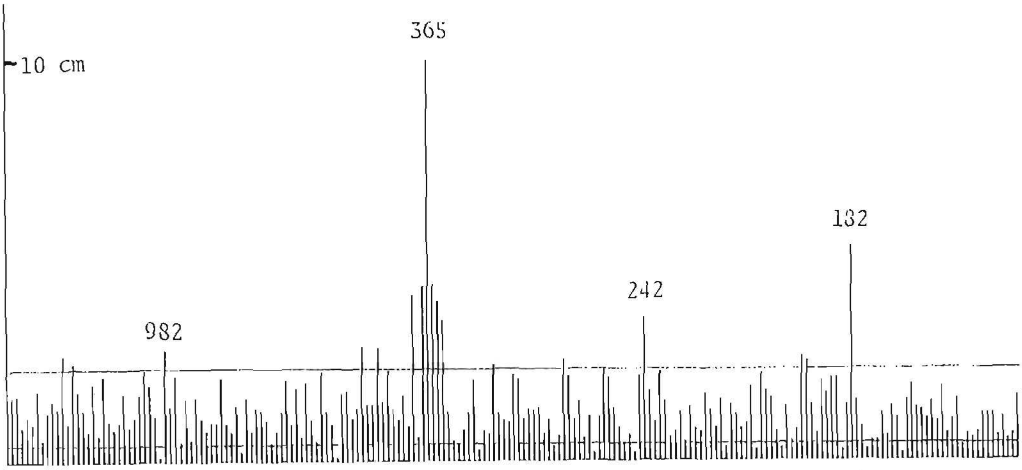
10 cm
2341
932
242
182
Mäntyluoto

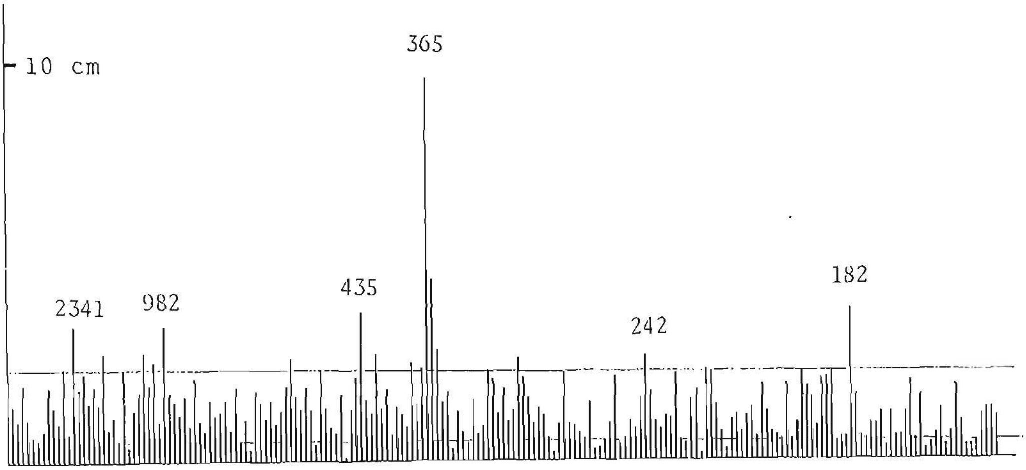

365
10 cm
2341
932
423
242
182
Rauma


365
10 cm
982
435
242
182
Turku

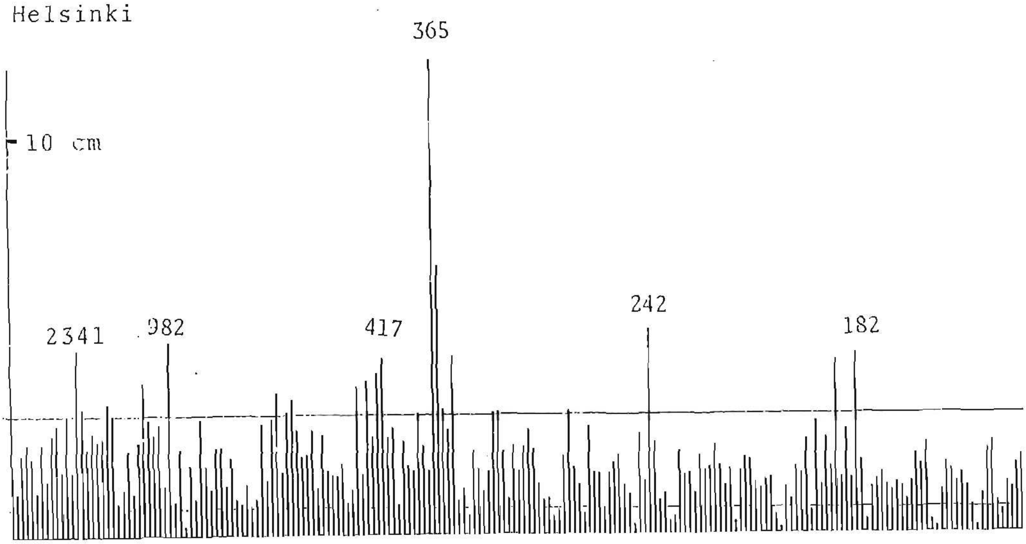

365
10 cm
982
435
301
242
182
Degerby



Hanko



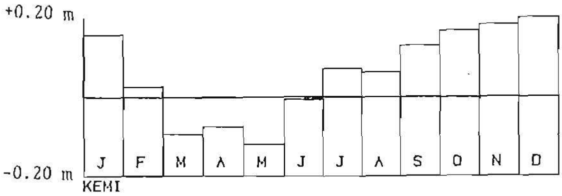
Helsinki

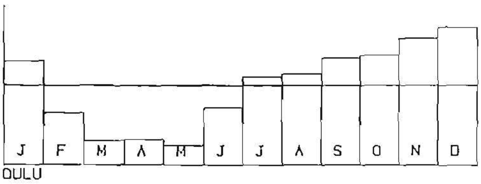


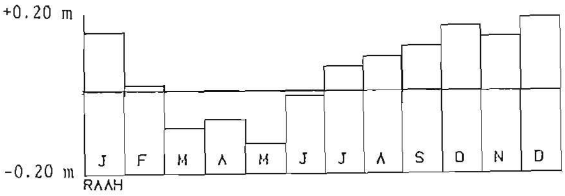
Hamina

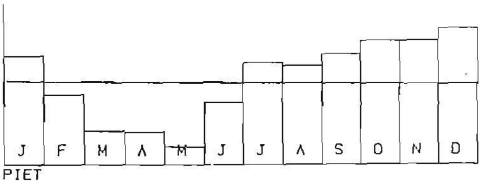
APPENDIX III: Yearly cycles of tide gauge readings

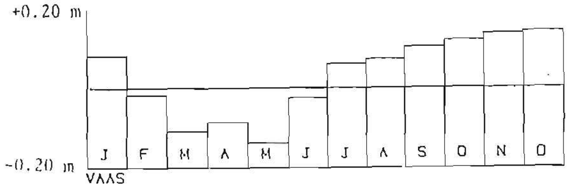
Monthly values were averaged for each tide gauge over all years of measurement; then the grand average for all months was subtracted. Horizontal line indicates this yearly mean level.

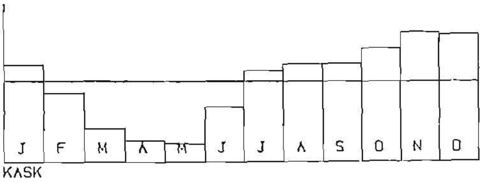


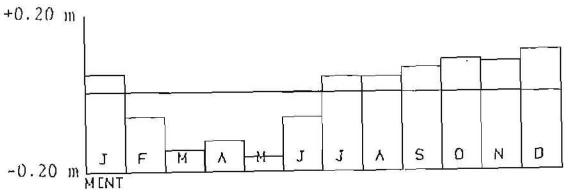


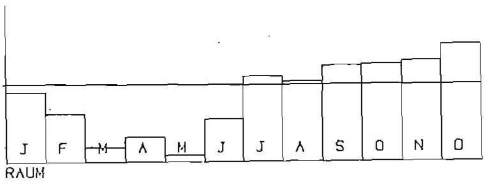


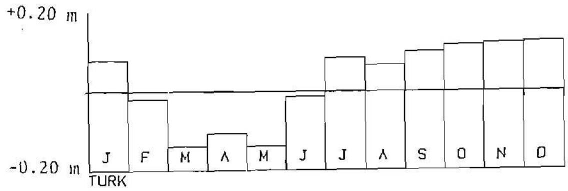


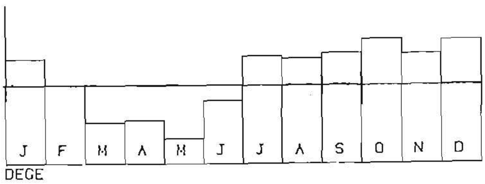


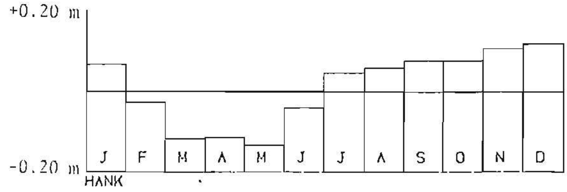











+0.20 m
-0.20 m
J
F
M
A
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J
J
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S
O
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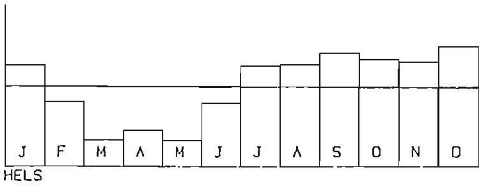
HANK


J
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J
J
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O
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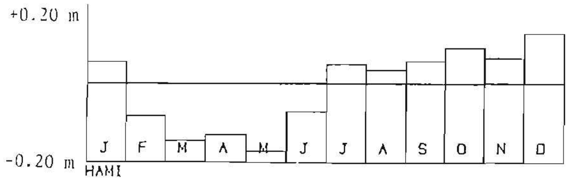
D
HELS


+0.20 m
-0.20 m
J
F
M
A
M
J
J
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S
O
N
D
HAMI

Finnish Marine Research No. 256 (1988)

SEDIMENTARY RECORD OF SEASONAL PRODUCTION AND GEOCHEMICAL FLUXES IN A NEARSHORE COASTAL EMBAYMENT IN THE NORTHERN BALTIC SEA

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Eeva-Liisa Poutanen

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P.O. Box 33, SF-00931 Helsinki

ABSTRACT

The algal and chemical composition of alternating black and light coloured laminae were studied in a multi-laminated surface sediment core from the semi-stagnant sedimentary basin at Hanko Bay. The results seem to indicate that the black layers contain abundant amounts of algae and lipid-rich organic material corresponding to periods of high phytoplankton production, usually the vernal diatom bloom. The light layers contain much mineral particles, little algal remains and old organic material corresponding to low production stages and/or result of resuspension. We conclude that there is a seasonally modulated supply of phytoplankton to the sediments in the area directly related to periods of primary production, the vernal diatom bloom being the major source of this geochemical flux.

The background of the formation of the laminae is discussed. It is postulated that the sequence of laminae in these sediments may be used as a long-term record of productivity cycles in the area.

Key words: sediments, geochemical fluxes, Baltic Sea, seasonal production, organic compounds, laminae, coastal embayment

INTRODUCTION

The post-glacial sediments in the Baltic Sea are organic-rich mud deposits which in some sections show strongly laminated structures (Winterhalter et al. 1981). The opinion has been that these different layers are markers caused by effects of

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storms and water movements rather than annual varves. Some of the nearshore sedimentation basins contain sediments of this nature (Werner et al. 1987) and laminae exist throughout the core including the uppermost part. However - as suggested by Ignatius (1958) "it is quite likely that at least some of the microstructures in the post-glacial Baltic sediments are annual records of primary deposition or physico-chemical and biochemical features of an annual nature".

Earlier studies have revealed long-term variations which are in accordance to the known hydrographical changes of the Baltic Sea (Hallberg 1974, Niemistö & Voipio 1974). The near surface basin sediments have been the subject of considerable scientific study in recent years (Niemistö & Voipio 1981, Naik & Poutanen 1984, Emelyanov 1986, Brügmann & Niemistö 1987a,b). However, sampling procedures have not generally been arranged to sample discrete light or dark laminae. Thus any evidence of possible compositional differences between such laminae would have been missed, as one sample might contain several or no separate light/dark bands.

This paper presents the results of a microscopic and chemical study of 15 such alternating light/dark bands in the top 15 cm of one core sample. Our major objective was to determine the cause of these structures. In discussing our results we have attempted to consider most of the processes which might be expected to have some influence on sedimentary conditions and the nature and composition of the geochemical flux at this particular site.

2. SEDIMENTS AND SEDIMENTATION

The strong salinity stratification in the Baltic Sea results in reduced circulation in the deeper basins and a concomitant lowering of oxygen levels below the halocline. Under such stagnant or semi-stagnant conditions biological activity at the sediment-water interface and in the surficial sediments is very restricted. Such sedimentary environments are ideal for the formation of a sedimentary record undisturbed by bioturbation and in several areas a continuous sediment record is to be found stretching from the present to the end of the last glaciation, a period of some 12 000 years (Winterhalter et al. 1981).

These post-glacial sediments are organic-rich mud deposits which in the older sections show strongly "laminated" structures (Ignatius 1958, Jerbo 1965, Ignatius et al. 1968). Such features can occur, although to much lesser depths, in some of the more recent sediments of basin areas where they take the form of alternating light and dark, almost black bands (Fig. 1). The formation of such sediments is probably connected to the microphytoplankton production, especially to the diatom pulses.

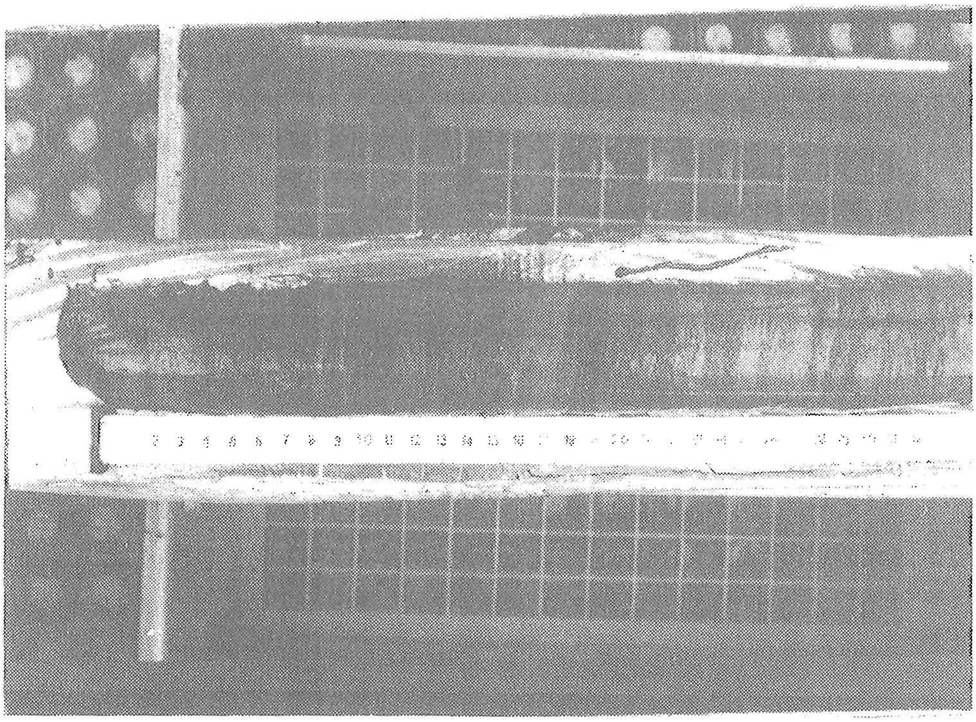


Figure 1. A photograph of the sediment core studied. For details see Fig. 3.

In the northern Baltic Proper the phytoplankton production and species composition show a marked seasonal fluctuation (off Hanko e.g. Purasjoki 1947, Niemi 1973, 1975, Niemi & Ray 1975, 1977).

After the break-up of the ice in late April, a strong vernal production of marine cold water diatoms and dinoflagellates occurs. Owing to the absence of effective zooplankton grazing during the vernal stage (Kaitala et al. 1987) a great share of the produced particular organic matter, mainly the diatoms, sinks to the sediment making up the main sedimentary input of fresh material (Jansson 1978, Leppänen 1985). After the development of the summer thermocline in May the concominant low production stage does not give rise to significant amounts of sedimentary detrital material (Laakkonen et al. 1981). The same is true for the strong blue-green algal blooms in late summer, but in some years the autumnal blooms of centric marine diatoms (Niemi & Ray 1977, Hällfors & Niemi 1981) can often give rise to a significant flux of particulate organic matter. Thus the input of fresh plankton material occurs regularly in spring, usually in several pulses (Niemi & Åström 1987), but in some years also in autumn.

Another important input to the sediment is the result of strong resuspension of shallow sediments in connection with storms. Such sedimented materials consist of old material; small pieces of diatom frustules, mineral particles and a lot of littoral species not characteristic of the autochthonous input.

In sediment the diatom frustules seem to be well preserved except for the very small species. Sometimes dinoflagellate cysts are observed, often resting spores of chrysophytes.

An essential factor in determining sedimentary conditions at many sites in the Baltic Sea is the periodic development of anoxic conditions in the sediment surface and in the sediment water interface. This will prevent the development of an active benthic faunal community which would normally destroy any sediment structure by bioturbation.

3. STUDY AREA - HANKO BAY

The small nearshore basin is a part of one of the fracture zones in the Precambrian crystalline basement, stretching from the middle of the Gulf of Finland to the northwest and reaching the Bothnian Sea (Fig. 2). This fracture zone has been cut off by the Salpausselkä end moraine, which today forms the Hanko peninsula limiting the basin in the southeast. In its post-glacial history the basin has been subject to very active basin filling sedimentation.

The deep part stretches to the northwest some 5 kilometers. The basin is sheltered from the open seaswell by a chain of small islands and very shallow areas. The deep part of the basin, max 78 m, is surrounded by a flat sea bed area with depths varying between 10-30 meters. The basin is surrounded by the well developed archipelago with shallow shores and long coast-line. Thus rough weather will cause resuspension of material form shallow bottoms and an input of littoral elements. The absence of major rivers in the area studied will cause negligible input of fresh water elements.

In summer the near bottom water in this sheltered basin is at least occasionally anoxic, and oxygenated water flows in the basin in winter (measurements in January 1987). The semi-stagnant conditions probably prevent the occurrence of macrobenthic animals causing bioturbation.

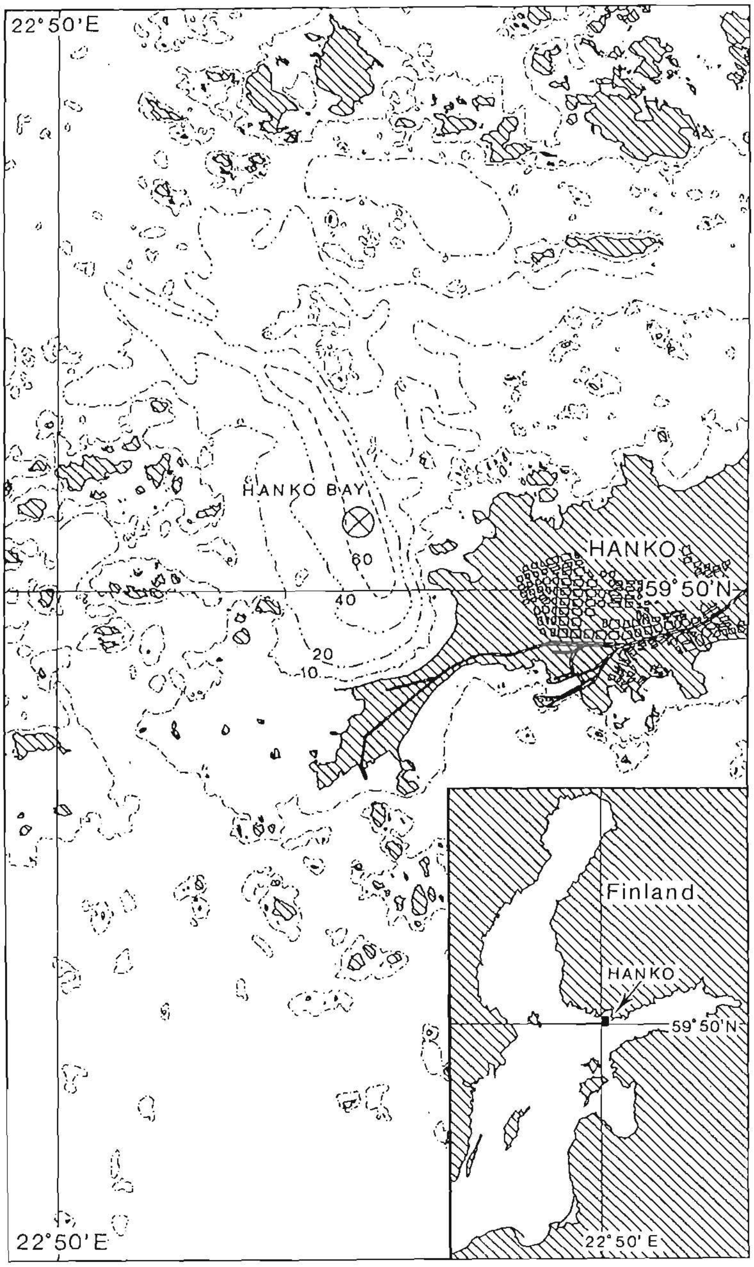


Figure 2. Location of the sampling site.

4. MATERIALS AND METHODS

During a cruise of R/V Aranda in July 1985 we were able to sample the surface, unconsolidated sediment with a minimum of disturbance. A 60 cm core sample was taken with a 10 cm square box gravity corer (Morris, unpublished) from the deepest part (78 m) of the Hanko Bay (Fig. 2). With the core in the near vertical orientation, two sides of the core barrel were removed and the exposed core carefully "dressed" with a flat bladed knife in order of expose any sediment structures.

Our sampling strategy was that samples for both microscopic and chemical analyses were taken, if possible, from every obvious light/dark layered structure from the sediment interface down to 20 cm depth (Figs. 1 & 3). Sometimes the fineness of the layers allowed only sufficient sample for microscopic analysis. Slides were made from fresh sediment material and a preliminary microscopic analysis made immediately on board ship, using a phase contrast objective with 40x magnification (Wild Fluotar). Additional sample was preserved in formalin for a more detailed analysis back at the laboratory. Duplicate

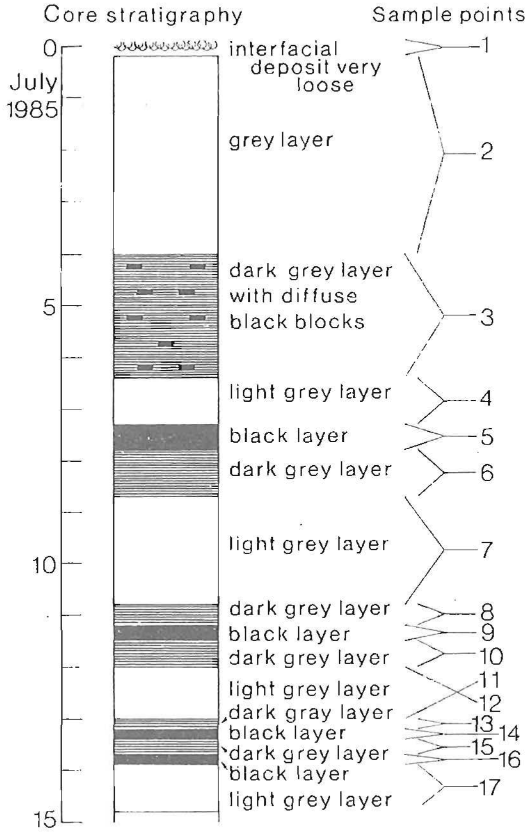


Figure 3. Schematic presentation of the sediment core showing the laminae, their colour and thickness. The bars on the right show the sampling points. The first laminae represent the ooze layer developed before the sampling in July 1985.

slides were made from each sample. Diatom content was estimated and the percental occurrences of different species calculated. The occurrence of the following species/groups were used to indicate seasonality (Fig. 4):

a) *Achnanthes taeniata*, vegetative cells and resting cells. Dominant vernal species. In summer and especially in autumn *Achnanthes* frustules are scarce in plankton.

b) *Chaetoceros wighamii* and *C. holsaticus*, vegetative cells. Dominant species during the vernal bloom. *C. holsaticus* is restricted to the spring. *C. wighamii* occurs sparsely also in summer plankton.

c) Resting spores of *Chaetoceros wighamii* and *C. holsaticus* occur in plankton abundantly in spring and become more sparse toward summer.

d) Small centric diatoms probably *Thalassiosira* spp., diameter 4-12 µm, and *Skeletonema costatum* are abundant in spring but occur sparsely also during other seasons.

e) *Thalassiosira baltica* and *T. bramaputrae* (= *T. lacustris*) are vernal species. *T. baltica* occurs sparsely in summer and winter but may occasionally develop high abundances in autumn.

f) Obligate vernal cold water diatoms (e.g. *Nitzschia frigida*, *N. cylindrus*, *Navicula vanhoeffenii*, *Pinnularia quadratarea* v. *stuxbergii* and *Chaetoceros holsaticus*. Such species usually occur sparsely in diatom slides.

g) *Actinocyclus octonarius* occurs chiefly in summer and autumn but sparsely during other seasons.

h) *Coscinodiscus granii* is a typical late summer-autumnal species.

i) *Cyclotella caspia* is most abundant in summer and autumn.

j) Littoral benthic diatoms.

The relative amount (%) of most species or groups in the diatom slides were calculated from the total number of specimens counted with a 100x oil immersion objective. However, the big centric diatoms (*Actinocyclus octonarius*, *Thalassiosira baltica*, *T. bramaputrae*, *Coscinodiscus granii*) were counted with lower magnification from both the diatom slides, and their percental occurrence in the slides was calculated from the total number counted. The nomenclature is according to Edler et al. (1984).

Bulk samples for chemical analysis were taken from the major layers and frozen under N_2 immediately. At the laboratory aliquotes of the fresh sample were taken for total amino acid after acid hydrolysis (Troll & Cannon 1953), carbohydrate (Dubois et al. 1956), water content and total organic carbon determinations (Salonen 1979). A further aliquote was directly extracted in $CHCl_3$/MeOH (2:1) using sonication under N_2. The chloroform-methanol was then washed with 0.5 M KOH (Folch et al. 1957) to give a 2-phase system. The chloroform layer was separated, rotary evaporated to dryness under vacuum at 30 ^oC and the total lipids quantified. The component fatty acids were then determined by gas chromatography and linked gas chromatography-mass spectrometric analysis (Morris 1984) after saponification and methylation of the total lipids. The methanol-water phase was rotary evaporated to dryness under vacuum at 50 ^oC and the levels of soluble amino acids and carbohydrates determined (Troll & Cannon 1953; Dubois et al. 1956).

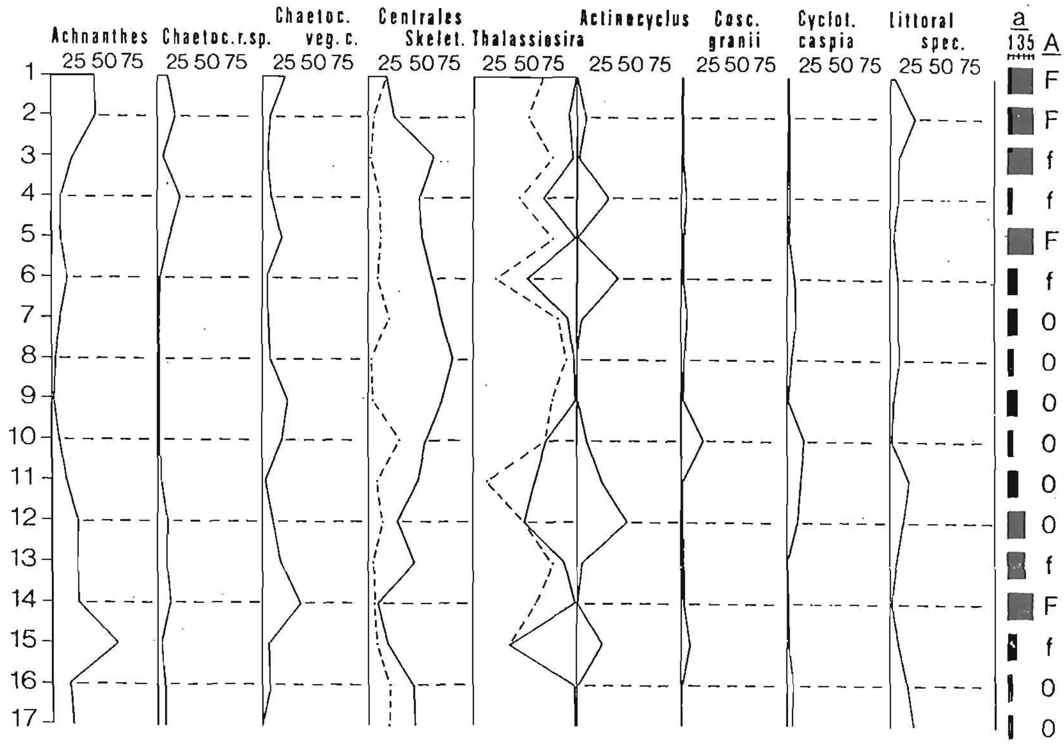


Figure 4. Percental occurrences of species or groups indicating the season of sedimentation (details and methods on p. 84 and 85). The layers 1-17 are presented in chronological order; no. 1 is the surface layer. The abundance of algae (the a column) is assessed from fresh material and diatom slides and presented in 5 abundance classes: 1 = very sparse (in microscopial fields of view some or no algae), 2 = sparse (some algae in the fields of view), 3 = moderately abundant (5-15 specimens in the fields of view), 4 = abundant (16-30 specimens in the fields of view), 5 = very abundant (>30 in the fields of view). The column A indicates occurrences of specific Arctic cold water diatoms typical of the vernal bloom (p. 84):
F = several specimens observed, f = few specimens observed, 0 = no specimens observed.

Assessment of the sedimentation season

Layer 1. Spring. Algae abundantly. Plenty of *Achnanthes*, *Chaetoceros*, *Thalassiosira baltica* and *T. bramaputrae*. Several specimens of specific Arctic coldwater species and *Melosira arctica*. Weak influence of littoral element. The vernal species were totally dominant in fresh material.

Layer 2. Spring. Algae very abundantly. Plenty of the vernal *Achnanthes*, *Chaetoceros*, *Skeletonema*, *Thalassiosira baltica* and *T. bramaputrae*. Several specimens of Arctic coldwater diatoms. Apparent influence of freshwater and the littoral.

Layer 3. Early spring. *Skeletonema* dominant. Considerable amounts of *Achnanthes* and *Chaetoceros* resting spores and also of *Thalassiosira baltica* and *T. bramaputrae*. In fresh material several specimens of the specific vernal *Chaetoceros holsaticus* were observed. Observations on *Cyclotella caspia* point to an autumnal influence on the sedimentating material.

Layer 4. Spring. Algae sparsely. The composition consists of vernal elements as in the above-mentioned layer. Mineral particles are abundant as also small pieces of diatoms. Furthermore there are several littoral species. The layer is probably a result of sedimentation after rough weather with resuspension of sediments from shallow bottoms.

Layer 5. Spring bloom. Vernal species abundantly. The specific Arctic marine coldwater species are well represented: *Nitzschia frigida*, *N. cylindrus*, *Navicula vanhoeffenii* and *Pinnularia quadratarea* v. *stuxbergii*. The sample contained very little littoral species.

Layer 6. Winter or early spring. Vernal diatoms occur but sparsely. *Skeletonema* most abundant. Several specimens of *Cyclotella caspia* and *Actinocyclus* and some *Coscinodiscus granii* are probably rest from an autumnal production (Hällfors & Niemi 1981). The sample contained quite much littoral elements and mineral particles.

Layer 7. Autumn. Much small mineral particles and small pieces of diatom frustules. Much littoral diatoms. Very few vernal species. On the contrary occurrences of *Cyclotella caspia*, *Actinocyclus* and *Coscinodiscus granii* point to autumnal production. *Thalassiosira* and *Skeletonema* may also grow abundantly in autumn. Strong influence of resuspended matter.

Layer 8. Summer. Not very much algae. Vernal species sparsely. *Skeletonema* and *Chaetoceros wighamii* most abundant. Quite much *Diatoma elongatum* and *Cyclotella caspia*. Relative much littoral species.

Layer 9. Early summer. *Chaetoceros wighamii* and *Skeletonema* most abundant but *Diatoma elongatum* also common (a late spring species). *Thalassiosira bramaputrae* points to the spring. Much influence from the littoral.

Layer 10. Sedimentation after a resuspension. Algae very sparsely. Abundantly small pieces of different diatoms from different seasons. Also much influence of littoral species.

Layer 11. ? Autumn-winter, or result after strong resuspension. Much small pieces of different diatoms, also of littoral origin. *Cyclotella caspia* common.

Layer 12. Probably late autumn or winter or a result after a resuspension. Vernal species of moderate amounts but autumnal species as *Cyclotella caspia* and *Coscinodiscus granii* (in fresh material) also common. In the sample markedly much littoral elements and small pieces of diatom frustules.

Layer 13. Spring. In relation to the layer above, a marked increase in the proportion of vernal species, especially *Skeletonema*. Hardly any autumnal species at all. Also occurrences of specific Arctic marine diatoms.

Layer 14. Marked spring bloom. Abundantly of diatoms belonging to the vernal bloom: *Chaetoceros holsaticus*, *C. wighamii*, and specific Arctic marine diatoms. Autumnal species absent and very little littoral algae.

Layer 15. Sediment layer probably originating from a resuspension, probably in late winter or spring. Much mineral particles and small pieces of diatom frustules. Very little algae - *Achnanthes* most common.

Layer 16. Winter or late autumn. Algae sparsely. Both vernal species (*Achnanthes*, *Chaetoceros*, *Skeletonema*, *Thalassiosira*) and autumnal species (*Cyclotella caspia*, *Coscinodiscus granii* and *Actinocyclus*). Very much small pieces of as well planktonic as littoral diatom frustules pointing marked influence of resuspension.

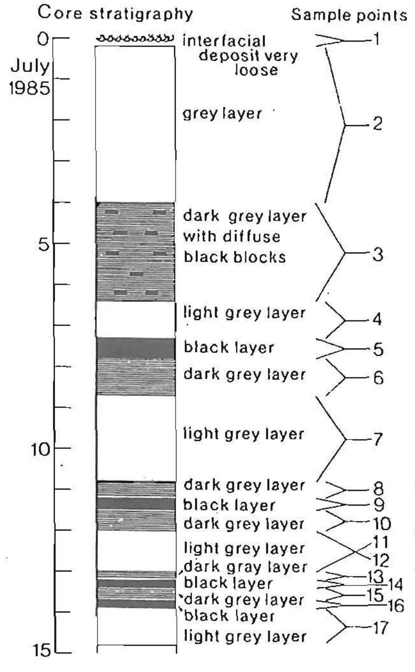
Layer 17. Winter or late autumn. In the sample very little algae, in fresh samples algae were very difficult to observe in a slide sample. Much mineral particles and abundantly small pieces of diatom frustules pointing to resuspension. Both vernal coldwater species and autumnal algae as *Cyclotella caspia*. The littoral element in the sample.

5. RESULTS AND DISCUSSION

The diatom slide analyses (Fig. 4) clearly show that the sediment core studied here is not from a homogeneous, well turbated deposit. There are clear distinctions to be seen between the various light and dark bands which relate to different contributions of diatom species and/or resuspended material. In addition these contributions appear to be strongly linked to seasonal succession. Thus samples 1-6 are dominated by vernal species but show a variable input in the amounts of diatoms present. The greatest number of diatoms is seen in samples 3 and 5 which contain the major vernal species and correspond to the first 2 dark layers. Underlying this core section samples 7 and 11 from light bands only contain a few winter/ autumn diatom species but sandwich samples 8-10 which are rich in vernal and summer species, particularly sample 9 from a distinct black band and (resuspension of fresh material from the littoral?). At the bottom of the core samples 11 and 17 from the light bands again contain few diatoms, all of which are winter species, yet in the dark layers between them samples 13-15 are rich in vernal and early summer diatom species. At this stage it should be noted that sample 16 came from a very thin black layer which contained considerable amounts of detrital organic material but few diatoms and those that were present were winter species. Unfortunately the small sample size prevented further analysis.

Thus on the basis of the diatom slide analyses the sediment core appears to represent only 3 complete cycles of diatom succession. All the major black layers of the core contain large numbers of vernal species whilst the light coloured bands only contain small numbers of winter diatom species. Phytoplankton production data (Niemi 1973, 1975, Niemi & Ray 1975, 1977) show that there is a strong seasonal succession of phytoplankton production during the year. The vernal maximum, comprising ca. 1/3 - 1/2 of the annual phytoplankton production, is dominated by diatoms (60-80 %). The level of phytoplankton biomass in the water drops sharply away by the end of May and throughout June-July. During the summer microalgal production is normally dominated by dinoflagellates with the blue-green algae becoming increasingly important during late July until by August mid-September blue-green algal production can equal or exceed that of dinoflagellates. From mid-September until the end of October biomass levels in some years rise slightly during an autumn peak and diatoms once again become the dominant groups (70-90 %). Biomass levels then fall gradually away during November to the winter production minimum. From these studies the vernal peak in diatom production in the Hanko area clearly corresponds to the peak in total phytoplankton biomass. Sediment trap data from this area in (Laakkonen et al. 1981) suggest that the peak in organic carbon flux to the sediments occurs before the end of May. On the basis of the phytoplankton studies of Niemi & Ray (1975, 1977) it seems reasonable to assume that this organic flux is directly related to the vernal diatom blooms particularly as previous work has indicated that sedimentation of diatoms in the Baltic is mainly local with little influence from littoral transport (Hällfors & Niemi 1975). In the study basin the littoral influence, however, seems to be an important factor.

From the sediment microscopic analysis presented in Fig. 4 the dark layers in the Hanko Bay sediment correspond to detrital inputs from the vernal diatom bloom. From the work of Laakkonen et al. (1981) these inputs should be organic-rich. The organic data in Figure 5 clearly confirms this hypothesis. The sediment layers marked by large numbers of vernal diatom species contain higher levels of organic carbon, amino acids, carbohydrates and lipids than those light coloured layers in-



Sample points	Water content %	Org. carbon content %	Total lipid mg/g	Total fatty acids mg/g	Total amino acids mg/g	Soluble amino acids (free) µg/g	Total carbohydrate mg/g	Soluble carbohydrate µg/g
2	86.0	5.4	32.3	1.4	36	45	29.9	280
5	88.2	5.2	11.8	2.0	33	34	27.9	157
7	70.4	2.7	3.0	0.2	19	8	15.8	43
8–10	83.7	4.3	6.4	1.0	32	24	24.5	80
11–12	72.5	3.1	2.5	0.4	30	12	20.5	58

Figure 5. The results of chemical analyses of different laminae. The water content and organic carbon content are given in per cents, other determinants either in mg/g or µg/g dry weight. Based on the sedimentation succession (Fig. 4) the time scale is given on the left.

dicative of a winter input including resuspension. The most striking results are shown by the levels of total fatty acids in the various layers (Fig. 5). The darker layers are characterized by very high levels of extractable fatty acids, the major components being 14:0, 16:0 and 16:1 acids.

In the Hanko Bay area the type of sedimentary organic matter can be expected to be quite varied. Terrigeneously derived material rich in peat/humus material and vegetable matter will be an important part of the organic geochemical flux throughout the year, the main changes in this input being related to freshwater discharges, ice cover and resuspension of older sediments following storms (Werner et al. 1987, p. 229). The organic matter presented in these inputs will be generally old, of a refractory nature and will contain little easily extractable lipids. The other important organic flux will be controlled by production in the euphotic layers. Detrital organic matter reaching the sediments from this source will generally be quite young and will contain high levels of easily-extractable, labile lipids. The fatty acid composition of these lipids will vary with the algal groups involved in the production as diatoms, dinoflagellates etc. and are known to contain fatty acids with specific chain lengths and degrees of unsaturations (Smith et al. 1983). For example diatoms contain mainly C_{14}-C_{16} saturated and unsaturated fatty acids whereas dinoflagellates contain mainly C_{18} saturated and unsaturated acids.

From the lipid analyses on the Hanko sediment we suggest that there is clear evidence that the dark layers, rich in vernal diatom remains, contain large amounts of young, "fresh" organic matter derived directly from these vernal diatom blooms. Furthermore the organic composition of these dark layers is not only much richer but also very different from the light coloured sediment layers which contain relatively much lower amounts of fresh organic material.

As to the cause of the dark grey/black colour of these diatom rich/organic rich layers in the sediment we can only speculate. One possibility is that these deposits rich in fresh, labile planktonic organic matter support high bacterial activity with a concomitant development of strongly anoxic conditions in the associated sediment pore waters. Under such conditions sulphate-reduction would quickly commence leading to H_2S production. This in turn could result in the formation of ferrous sulphite within the sediment layer giving the characteristic black pigmentation. As soon as the supply of organic-rich material to the sediments stops, bacterial activity slows down, weakly oxic conditions at the sediment-water interface are restored and sulphate-reduction abruptly ceases.

6. CONCLUSIONS

We have presented data from microscopic and chemical analysis of a recent banded or laminated sediment from the Hanko Bay area which we believe provides substantial evidence that:

- There is a seasonally modulated supply of lipid-rich organic material to the sediments in the area.
- This organic geochemical flux is directly related to annual periods of phytoplanktonic production in the overlying waters.
- The banding or laminae in the recent sediments from this area are a direct result of changes in the type and amount of organic input.

  The structure of these layers can be used as a record of productivity cycles in the area.

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FINNISH ICE SERVICE

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This article is partly based on professor Wang Renshu's manuscript which he wrote during his stay in Finland in winter 1988 for the Chinese authorities.

ABSTRACT

In every average winter all Finnish ports are surrounded with ice during the winter months. The ports are kept open with the assistance of the state icebreaker fleet. An ice service is provided by the Finnish Institute of Marine Research during the winter months in order to coordinate movements of the icebreaker fleet and make their assistance as effective as possible. This paper handles the history of the Ice Service and the operational work at present.

Key words: Baltic Sea, sea ice, ice forecasting, winter traffic, ice service, icebreakers

1. BACKGROUND

Finland is located on the north-eastern coast of the Baltic Sea. It adjoins the Bothnian Bay, the Bothnian Sea and the Gulf of Finland (Fig. 1). The geographical location of Finland emphasizes the importance of foreign trade. As 85 per cent of foreign trade relies on shipping, maritime connections are vital for the country's prosperity.

However, the sea areas surrounding Finland are covered with ice during the winter months. Ice formation at the coast usually begins at the end of November in the Bothnian Bay and at the beginning of December in the Gulf of Finland (SMHI & Institute

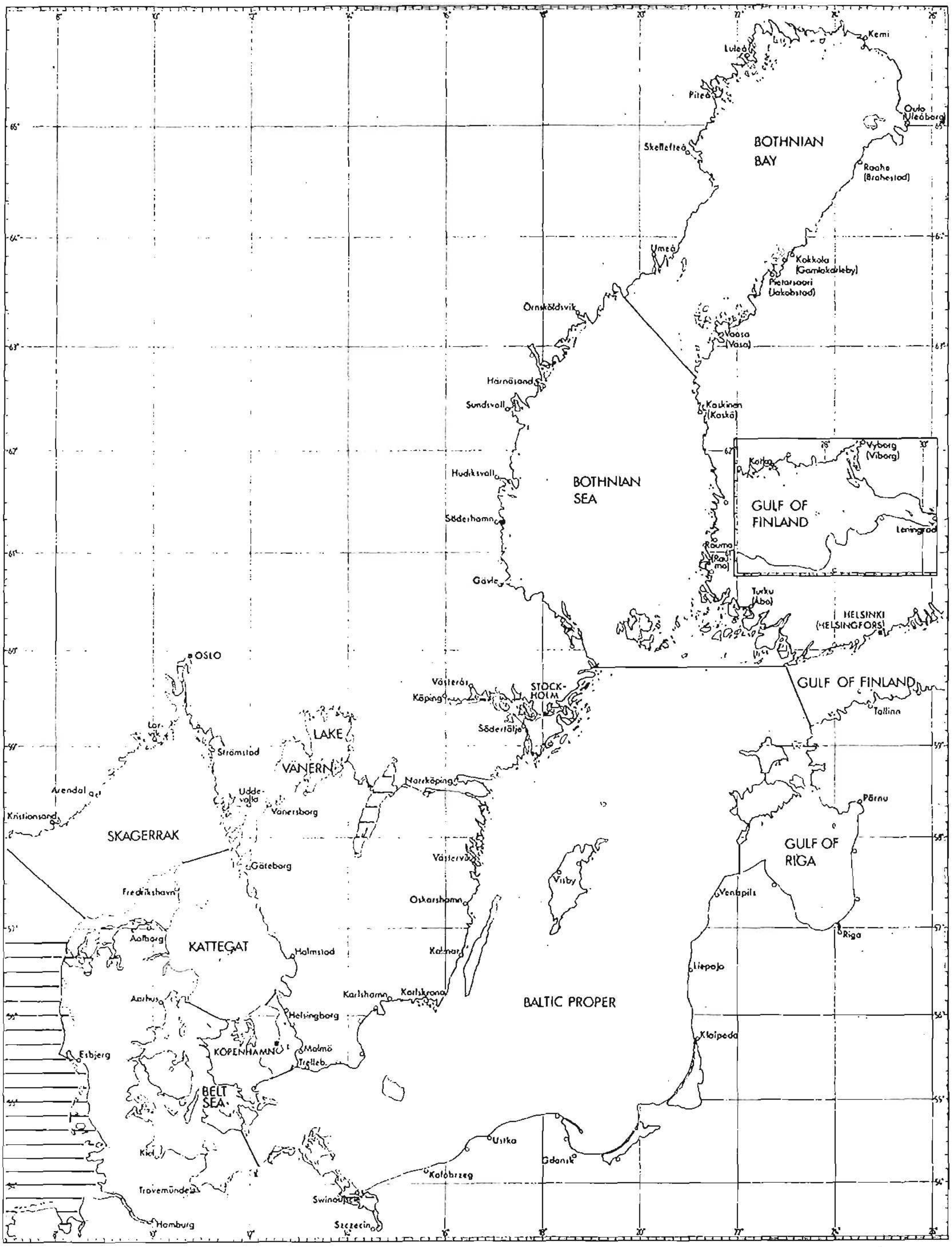


Figure 1. Sub-basins of the atlas regions (from SMHI & Inst. Mar. Res., 1982.

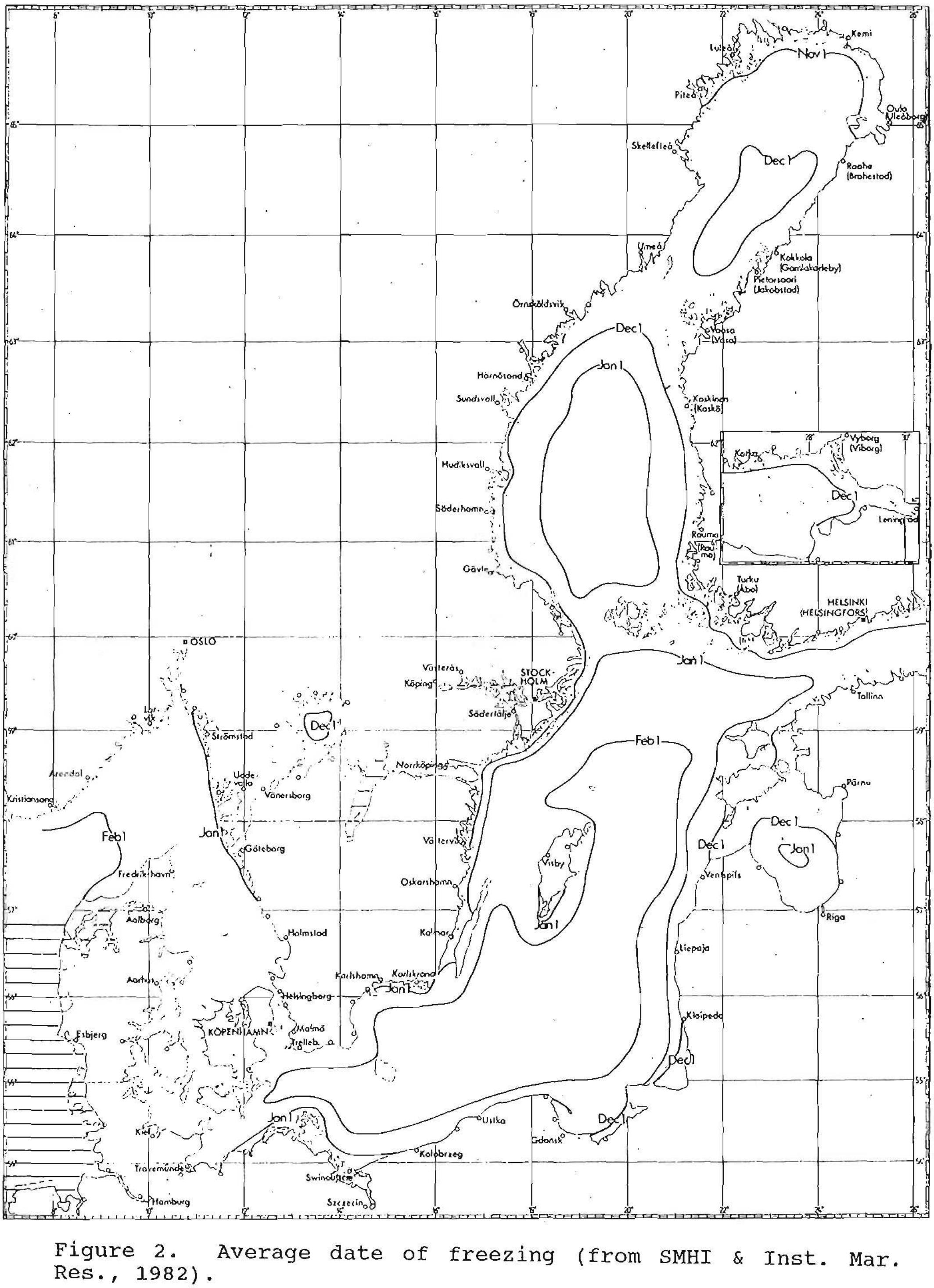


Figure 2. Average date of freezing (from SMHI & Inst. Mar. Res., 1982).

of Marine Research, 1982). After the coastal regions have frozen, the ice edge gradually progresses out into the open sea in the Bothnian Bay and Bothnian Sea; in the Gulf of Finland from east to west (Fig. 2). The maximum extent of ice coverage is generally reached at the end of February or beginning of March (Fig. 3) (National Board of Navigation, 1975). The maximum thickness of level ice in the middle of the sea areas of the Bothnian Bay is between 50 and 70 cm, in the Bothnian Sea 25 to 40 cm and in the Gulf of Finland 25 to 50 cm (Fig. 4). The level ice is thicker in the archipelago areas. The record is 122 cm off Tornio near the city of Kemi.

The ice cover begins to break up in March; during May these sea areas become free of ice (Fig. 5). The average number of days with an ice cover varies between the different sea areas. In the Bothnian Bay the ice period lasts 4 to 6 months, in the Bothnian Sea and the Gulf of Finland 2 to 4 months. Despite this, the 22 Finnish ports are novadays visited by 7,500 ships carrying between 17 and 20 million tonnes of cargos, about one third of the annual volume, during the winter months (National Board of Navigation 1988). The harbours are kept open by the state icebreaker fleet of Finland.

Level ice which is not drifting does not, however, represent any problems for modern icebreakers and merchant ships. However, ships encounter real difficulties far out to sea when the ice is drifting and at the same time forming ridges, and there is pressure in the ice field. The speed of the ships is thus slowed down considerably or, in the worst conditions, they may come to a complete halt. During severe storms merchant ships are sometimes in danger of suffering structural damage when they are compressed by ice, despite icebreaker assistance.

An ice service is provided by the Finnish Institute of Marine Research during the winter months in order to help coordinate movements of the icebreaker fleet and make their assistance as effective as possible.

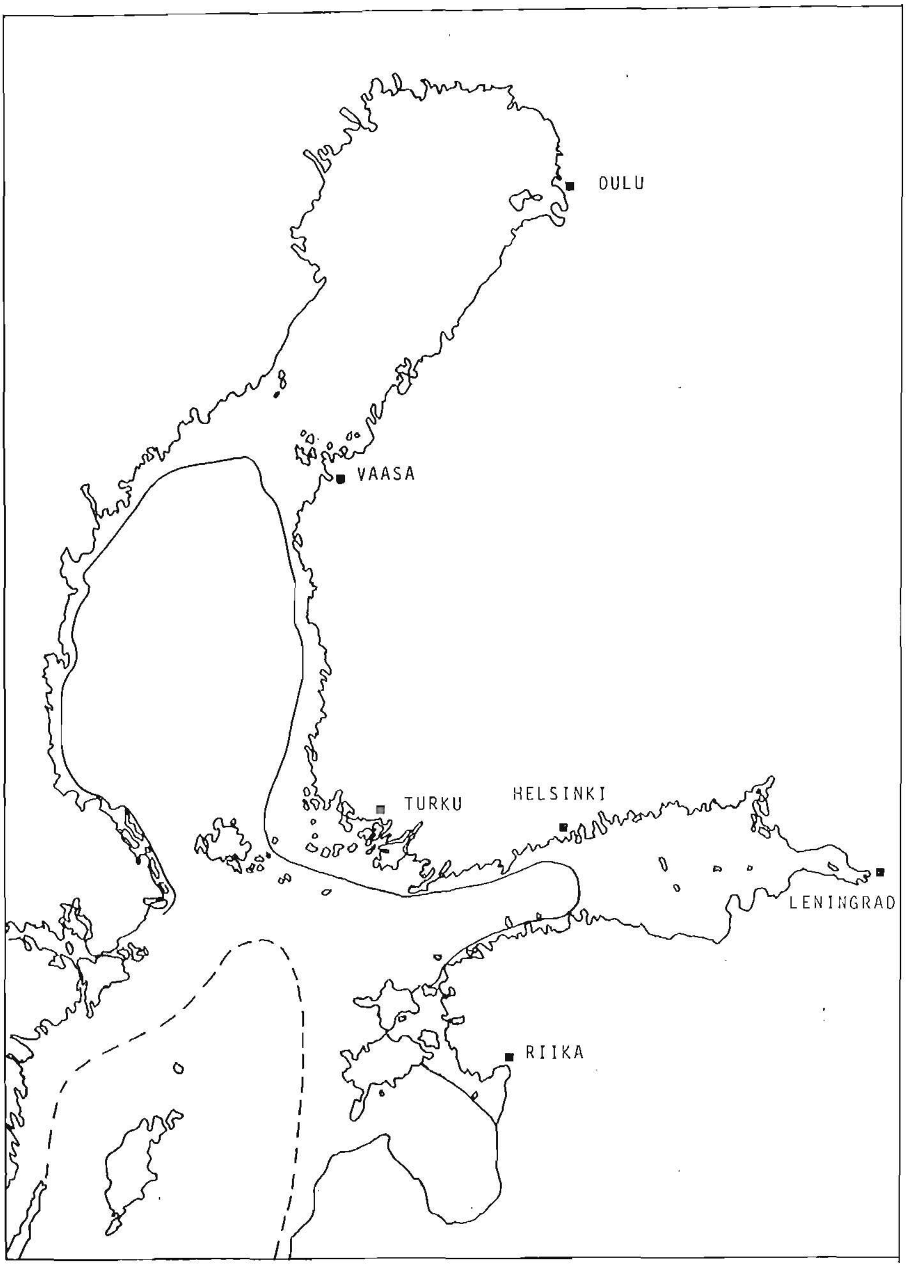


Figure 3. The maximum extent of ice cover in the mild winter (——) and in the average winter (- - -). (From National Board of Navigation, 1975).

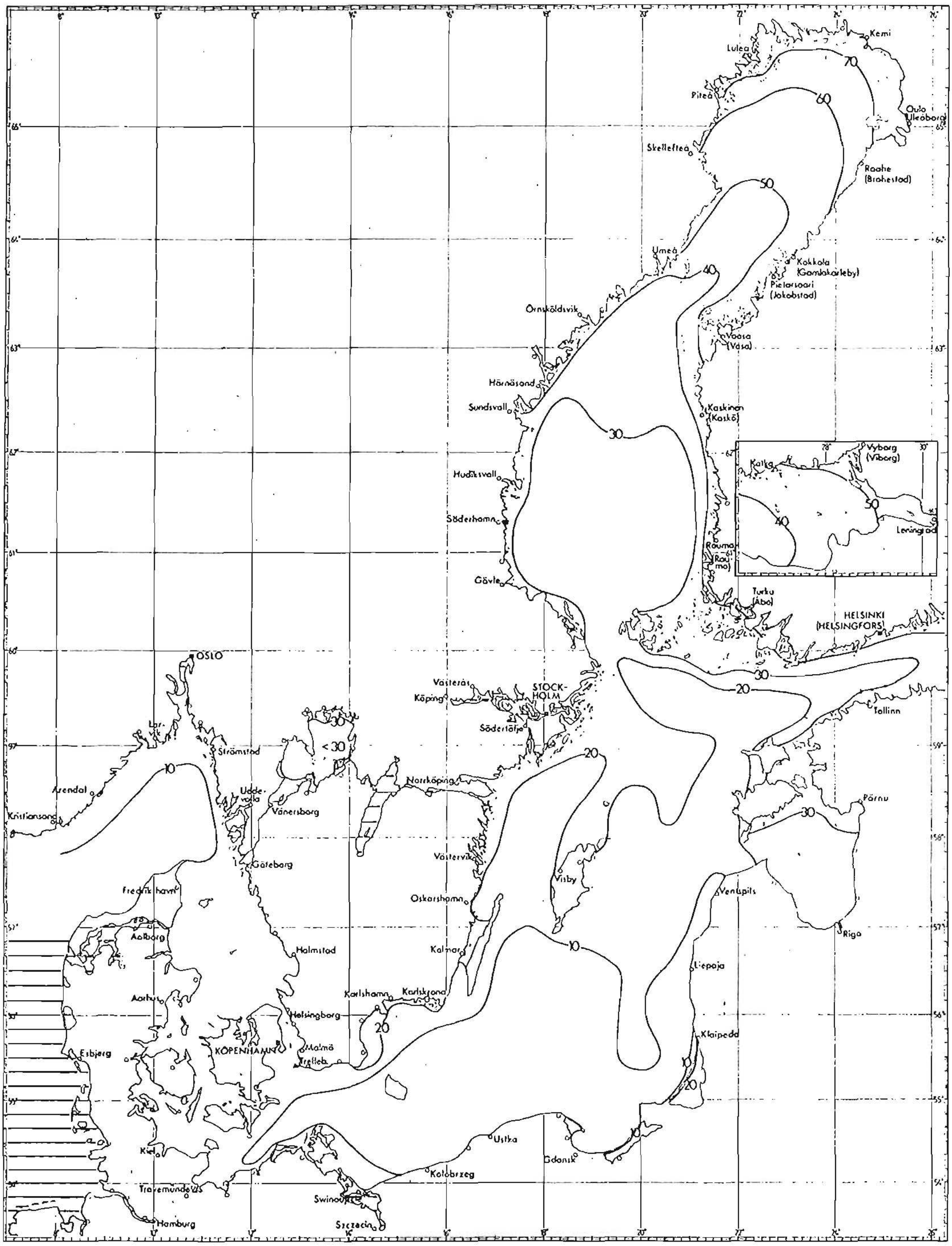


Figure 4. Mean maximum annual ice thickness, in cm (from SMHI & Inst. Mar. Res., 1982).

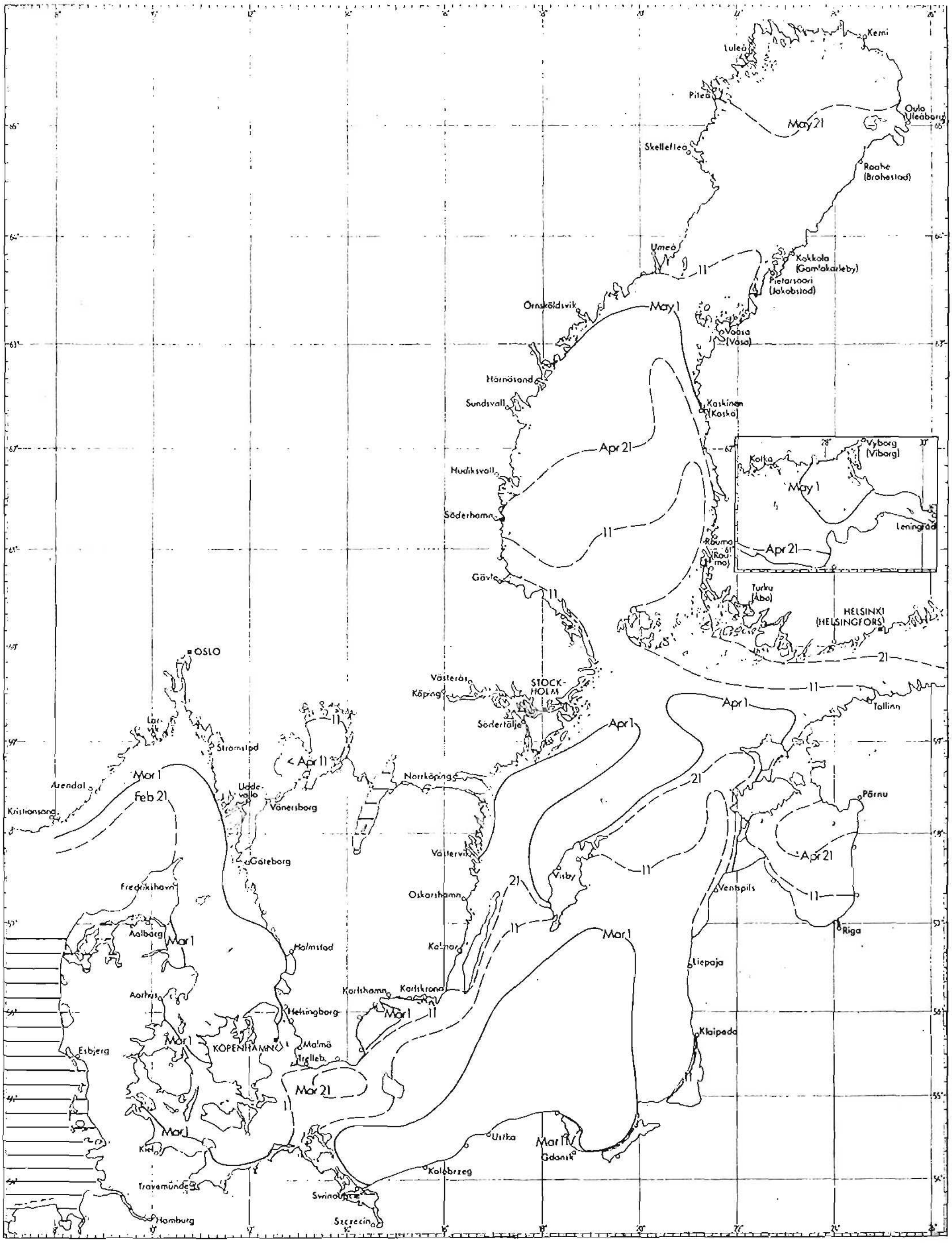


Figure 5. Average date of break-up of ice (from SMHI & Inst. Mar. Res., 1982).

2. HISTORY OF THE ICE SERVICE

The Ice Service has always tried to follow closely the needs of winter sea traffic. Ice observation has a long tradition in Finland. The first ice observations in the world were made in Finland in 1846. Winter traffic in Finland started in 1878 when the predecessor of the icebreaker, the steamer Expressen, made her first voyage on the Hanko-Stockholm route. The first icebreaker in Finland was introduced in 1890. Regular ice observations were first carried out at the Hanko lighthouse in 1893. Up until 1915 the ice observations were recorded monthly by the light houses. Owing to the increased need for information as a result of the First World War, however, the recording stations were ordered to send in an ice chart once a week. This marks the time when we can talk for the first time of an ice service that was nearly real time.

Developments continued rapidly when the Finnish Institute of Marine Research was established in 1919, and ice research at once became one of the most important tasks of the Institute. In 1919 some observation stations were ordered to report the information once a week by telephone to the Ice Service. In 1922 the ice reports were given by number codes via radio, and in 1925 Sweden, Esthonia and Finland agreed on the use of a common ice code (Lisitzin, 1979).

In 1927 merchant ships were obliged to keep a special ice logbook. At the same time the number of observation stations was increased to over sixty.

When the first diesel-electric icebreaker in Finland under the name Sisu, came into service in 1939 winter traffic could be extended to several ports. In fact already in the 1920's and 1930's ships started to visit to some extent also the ports on the Bothnian Sea and along the Gulf of Finland right up to Helsinki, but the old winter ports of Hanko and Turku were still the prime harbours when the ice conditions became more difficult. Before the outbreak of the Second World War an aircraft was used for making ice observations and, after the war, in spite of the decline of the icebreaker fleet, winter traffic was extended also to the ports along the Bothnian Bay. The navigation season remained short. However, by the end of 1950's the time when ports were closed in the winter began to get shorter as new icebreakers were gradually introduced.

After the Tarmo and Atle class icebreakers had been delivered in the 1960's and 1970's, all the Finnish ports could be kept open throughout the year. At the same time the Ice Service received new obligations that it has tried to fulfill by adopting modern technology both for the observation work and for communications.

3. THE ICE SERVICE AT PRESENT

The Finnish Institute of Marine Research operates the Ice Service in close co-operation with the National Board of Navigation throughout the winter months. The Ice Service consists of three operative systems; these consist of an ice observation network, an ice analysis and forecast system, and an ice information communication system (Fig. 6).

The Ice Service has an effective observation network: there are altogether approximately 35 ground-based ice observation stations. These stations are primarily located in the vicinity of the winter harbours. They monitor the ice conditions every day and send reports about the ice conditions once a week to the Ice Service.

The Finnish state icebreaker fleet has nine icebreakers. At the same time as the icebreakers are assisting ships, they report ice conditions along their route, as well as some observations made by merchant ships, to the Ice Service three times every day by telex.

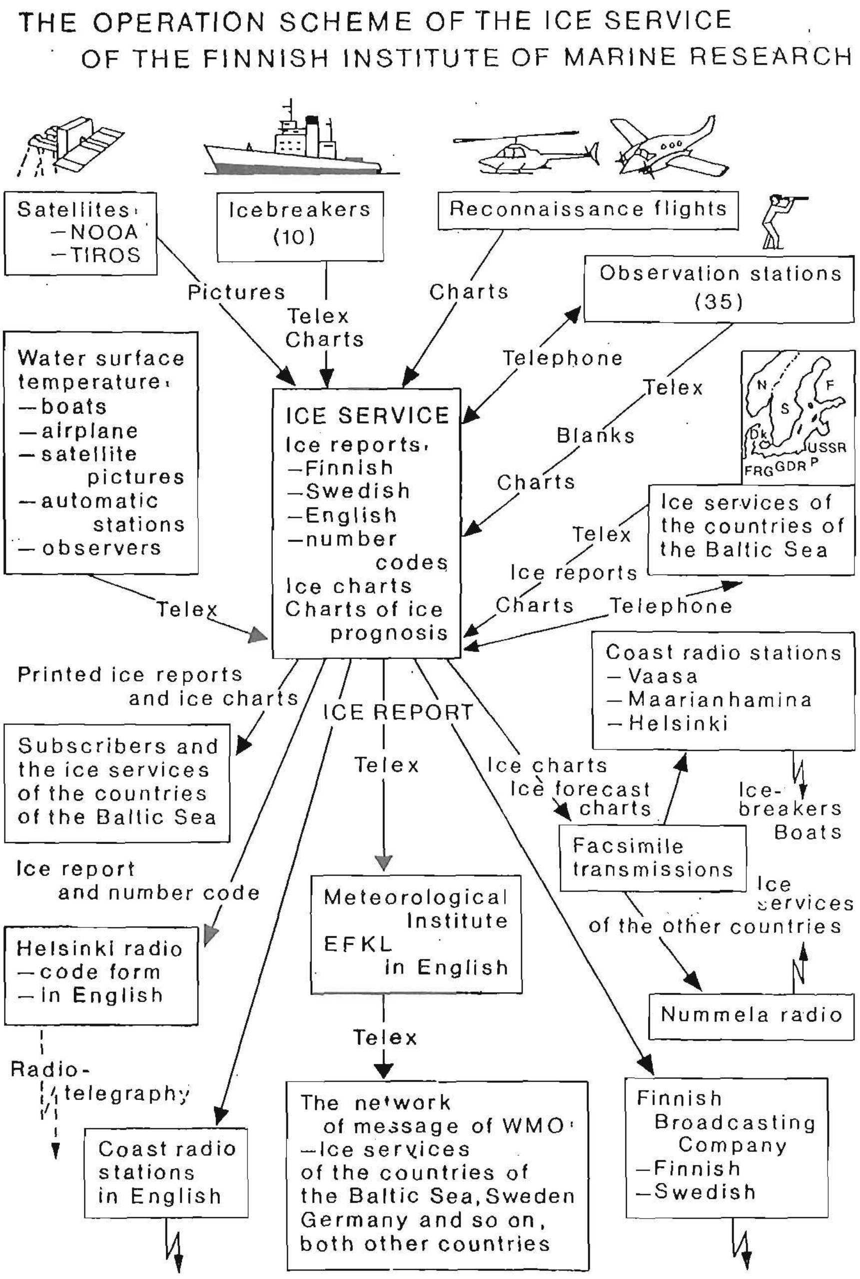


Figure 6. The operation scheme of the Ice Service of the Finnish Institute of Marine Research.

Since 1965 the icebreakers have been equipped with a helicopter for carrying out ice reconnaissance work. The usage of helicopters has been increased to the extent that, at the moment, the icebreakers have three helicopters at their disposal. Two of them are based on icebreakers, and the third is ready in Helsinki for service with the icebreakers in the Gulf of Finland. The results of the reconnaissances will be sent from the icebreakers via facsimile to the Ice Service. The Ice Service carries out, when necessary flight reconnaissance over all the sea areas adjoining Finland using a two-motor light aircraft that is fitted with a Decca Navigator position device and with an infra-red thermometer for determining the temperature of the water surface. The flights are made from Helsinki. An experienced ice observer participates in these flights. Nowadays such flights are made 10-15 times annually. The number of flights was earlier considerably greater.

Satellite pictures are nowadays perhaps the most important means of obtaining information about the ice conditions. The first pictures were received by the Ice Service in 1967 when photographs were occasionally received from American ESSA and Nimbus weather satellites. In clear weather the limits of the ice fields could be seen on the pictures (the resolution was about four kilometres). The supply of ice information became more effective especially in those areas where it had earlier been difficult to get any information: e.g. when the ports in the Bothnian Bay were closed and when the traffic to the north of Åland passed through the Archipelago Sea.

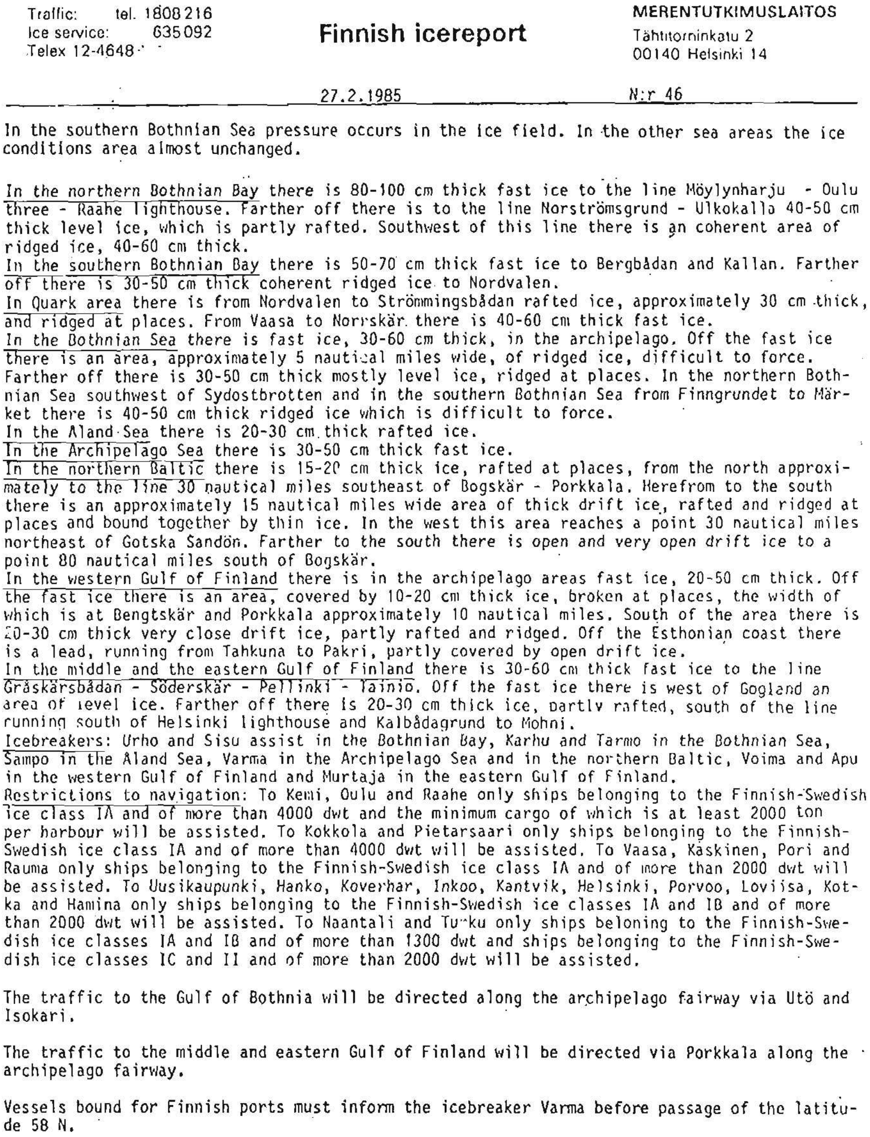
In winter 1981 the Finnish Institute of Marine Research opened its own station for receiving satellite pictures of the American NOAA series (Grönvall & Kalliosaari, 1982). At the moment there are three satellites of this kind at our disposal. The resolution of the pictures is about one kilometre, and darkness is no problem because pictures can also be taken using the infra-red channel. The pictures are received by the Ice Service in real time.

In an area such as the Baltic Sea co-operation between neighbouring countries is very important. A considerable proportion of the ice observations are received from other Baltic Sea countries. The exchange of information has already continued for several decades. Details such as codes and ice symbols are agreed on in the Baltic Sea ice conferences, that are held about every second or third year. Finland also has significant bilateral co-operation between the ice services of Sweden and the Soviet Union.

All the information about the ice collected using a variety of means is collated by the Ice Service and the observations are analysed and distributed in various forms to the organizations working within shipping and winter traffic. The information is sent via radio, telephone, telex and facsimile, or by mail.

At present information about the ice conditions is given in the following forms: once a day both a plain language and a codeform ice report is given. The ice report is read in Finnish and Swedish over the Finnish radio in connection with marine weather reports. An English report (Fig. 7) is read via all the coastal radio stations for merchant ships. It is also sent to the other Baltic Sea ice services. An ice chart is drawn daily (Fig. 8) that usually covers all the sea areas down to about Gotland. The chart is sent daily via facsimile to all interested parties. The ice report is sent to subscribers via mail from Monday to Thursday either in Finnish or in Swedish, both being furnished with an English translation. The ice chart is sent every Monday and Thursday to subscribers.

The real ice information is inputted to the computer center of the Finnish Institute of Marine Research for forecasting future ice conditions (for 30 hours) in the Finnish sea areas using a numerical forecast model (Leppäranta 1981). The forecast that includes ice concentration, ice movements and the areas where it is likely to be expected pressure of ice is sent to the Finnish icebreakers.



Traffic: tel. 1808216
Ice service: 635092
Telex 12-4648

Finnish icereport

MERENTUTKIMUSLAITOS
Tähtitorninkatu 2
00140 Helsinki 14

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In the southern Bothnian Sea pressure occurs in the ice field. In the other sea areas the ice conditions area almost unchanged.

In the northern Bothnian Bay there is 80-100 cm thick fast ice to the line Möylynharju - Oulu three - Raahe lighthouse. Farther off there is to the line Norströmsgrund - Ulkokallo 40-50 cm thick level ice, which is partly rafted. Southwest of this line there is an coherent area of ridged ice, 40-60 cm thick.
In the southern Bothnian Bay there is 50-70 cm thick fast ice to Bergbådan and Kallan. Farther off there is 30-50 cm thick coherent ridged ice to Nordvalen.
In Quark area there is from Nordvalen to Strömmingsbådan rafted ice, approximately 30 cm thick, and ridged at places. From Vaasa to Norrskär there is 40-60 cm thick fast ice.
In the Bothnian Sea there is fast ice, 30-60 cm thick, in the archipelago. Off the fast ice there is an area, approximately 5 nautical miles wide, of ridged ice, difficult to force. Farther off there is 30-50 cm thick mostly level ice, ridged at places. In the northern Bothnian Sea southwest of Sydostbrotten and in the southern Bothnian Sea from Finngrundet to Märket there is 40-50 cm thick ridged ice which is difficult to force.
In the Aland Sea there is 20-30 cm thick rafted ice.
In the Archipelago Sea there is 30-50 cm thick fast ice.
In the northern Baltic there is 15-20 cm thick ice, rafted at places, from the north approximately to the line 30 nautical miles southeast of Bogskär - Porkkala. Herefrom to the south there is an approximately 15 nautical miles wide area of thick drift ice, rafted and ridged at places and bound together by thin ice. In the west this area reaches a point 30 nautical miles northeast of Gotska Sandön. Farther to the south there is open and very open drift ice to a point 80 nautical miles south of Bogskär.
In the western Gulf of Finland there is in the archipelago areas fast ice, 20-50 cm thick. Off the fast ice there is an area, covered by 10-20 cm thick ice, broken at places, the width of which is at Bengtskär and Porkkala approximately 10 nautical miles. South of the area there is 20-30 cm thick very close drift ice, partly rafted and ridged. Off the Esthonian coast there is a lead, running from Tahkuna to Pakri, partly covered by open drift ice.
In the middle and the eastern Gulf of Finland there is 30-60 cm thick fast ice to the line Gråskärsbådan - Söderskär - Pellinki - Tainio. Off the fast ice there is west of Gogland an area of level ice. Farther off there is 20-30 cm thick ice, partly rafted, south of the line running south of Helsinki lighthouse and Kalbådagrund to Mohni.
Icebreakers: Urho and Sisu assist in the Bothnian Bay, Karhu and Tarmo in the Bothnian Sea, Sampo in the Aland Sea, Varma in the Archipelago Sea and in the northern Baltic, Voima and Apu in the western Gulf of Finland and Murtaja in the eastern Gulf of Finland.
Restrictions to navigation: To Kemi, Oulu and Raahe only ships belonging to the Finnish-Swedish ice class IA and of more than 4000 dwt and the minimum cargo of which is at least 2000 ton per harbour will be assisted. To Kokkola and Pietarsaari only ships belonging to the Finnish-Swedish ice class IA and of more than 4000 dwt will be assisted. To Vaasa, Kaskinen, Pori and Rauma only ships belonging to the Finnish-Swedish ice class IA and of more than 2000 dwt will be assisted. To Uusikaupunki, Hanko, Koverhar, Inkoo, Kantvik, Helsinki, Porvoo, Loviisa, Kotka and Hamina only ships belonging to the Finnish-Swedish ice classes IA and IB and of more than 2000 dwt will be assisted. To Naantali and Turku only ships beloning to the Finnish-Swedish ice classes IA and IB and of more than 1300 dwt and ships belonging to the Finnish-Swedish ice classes IC and II and of more than 2000 dwt will be assisted.

The traffic to the Gulf of Bothnia will be directed along the archipelago fairway via Utö and Isokari.

The traffic to the middle and eastern Gulf of Finland will be directed via Porkkala along the archipelago fairway.

Vessels bound for Finnish ports must inform the icebreaker Varma before passage of the latitude 58 N.

Figure 7. Example of an ice report of the Baltic Sea.

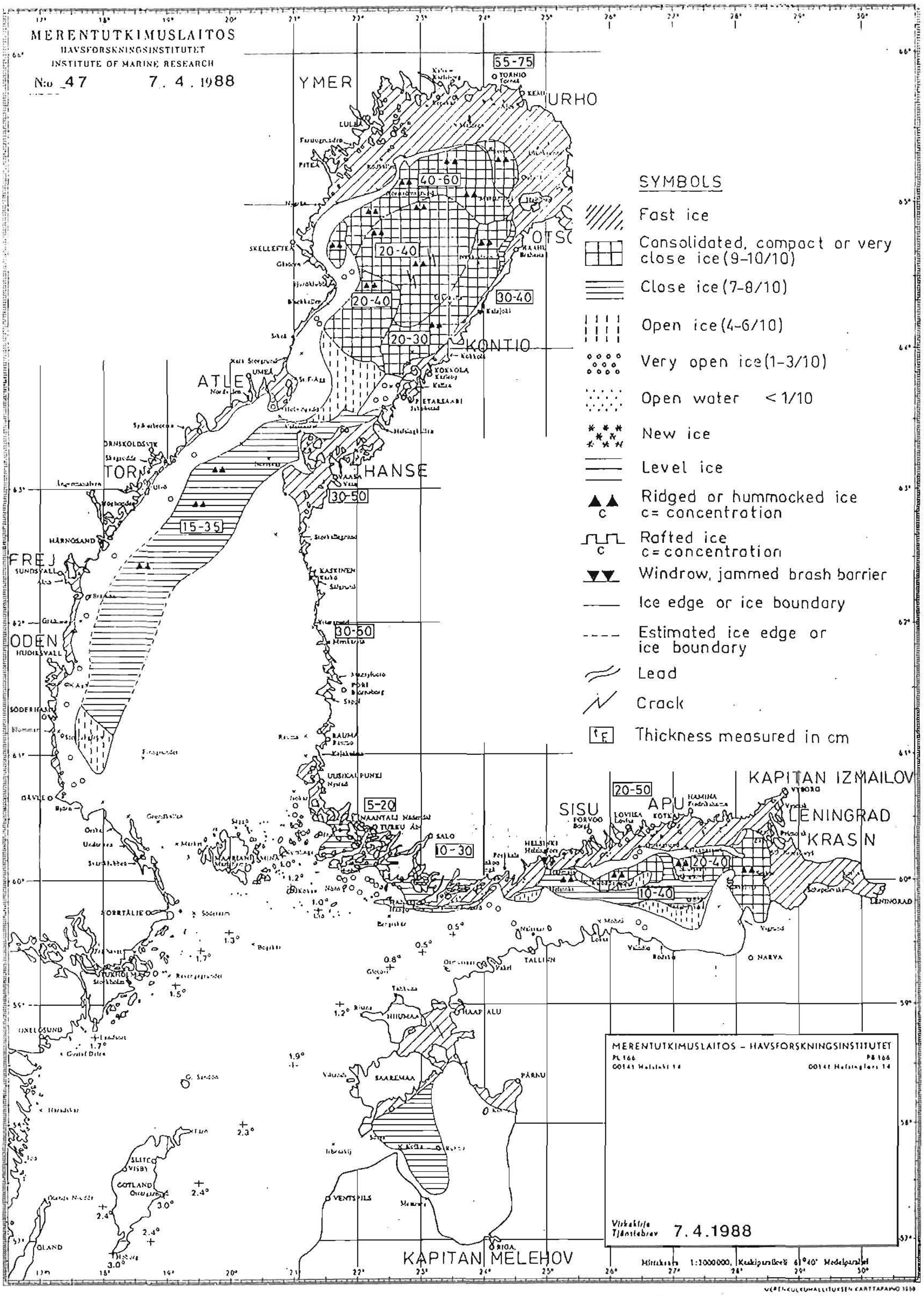

Figure 8. Example of an ice chart of the Baltic Sea.

In addition to the usual products, the Ice Service supplies a lot of special information e.g. for the traffic office of the Board of Navigation, for the shipping and harbour authorities. Various types of special information etc. is supplied for use by the radio and press.

The Finnish Institute of Marine Research has published during the last few years several average charts and statistics concerning the Baltic Sea ice conditions and surface temperatures, that are useful for navigation, ship design and harbour building (Leppäranta & al., 1988, Grönvall & al., 1987).

4. THE IMMEDIATE FUTURE OF THE ICE SERVICE

As was mentioned earlier, the Ice Service obtains lot of information from the coastal ice observation stations, the icebreakers, aircraft and helicopters, satellite pictures and ice sea services of other countries adjoining the Baltic Sea. At the moment, satellite pictures account for about 40 per cent of all the observations. This proportion would be even greater if weather did not hinder the use of pictures and if their resolution could be improved. During the next few years a number of countries will be launching several satellites that are fitted with radar.

The first radar satellite, the European Satellite ERS-1 will be launched in 1990. Sea ice remote sensing is one the the main research fields in the preparation for ERS-1 in the Baltic Sea. It is expected that Synthetic Aperture Radar (SAR) will provide a major improvement in operational sea ice mapping and forecasting. For the preparation of ERS-1 an international experiment BEPERS (Bothnian Experiment in Preparation of ERS-1) was performed during the first half of March 1988 by more than 50 participants from several countries. The key problems will be:

- development of algorithms for determination of geophysical sea ice parameters and processing of SAR sea ice images and
- potentials of SAR in operational sea ice mapping and forecasting using numerical models.

The weather will not hinder the functioning of the radar. It would thus also be important for the Finnish winter traffic if Finland could receive the material from the future radar satellites in real-time for its use latest when the satellites will take pictures sufficiently often and of a sufficiently large part of the Baltic Sea. In practice this situation will be achieved in 10-20 years' time.

The theoretical and operational aspects of ice forecasting will be studied continuously. Forecasting ice modeling of various time spans will be operated by the Ice Service.

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