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Areal estimates have been computed for individual months and years for the period 1951-70 and for the Pilot Study Year 1975/76. Estimates of areal mean precipitation are also presented for the climatological period 1931-60.

The areal estimates indicate that the long-term average of the yearly precipitation amount for the whole of Baltic Sea, including the Danish Sounds and Kattegat, is between 590 mm and 660 mm, with a probable average of 625 mm. For the period 1951-70 the areal mean precipitation ranged from 479 mm to 726 mm.

The computations of areal precipitation and its spatial and temporal distributions are illustrated in tables and on maps. The results are verified and previous investigations are commented.

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C O N T E N T S

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The results are verified and previous investigations are commented.

DETERMINATION OF AREAL PRECIPITATION FOR THE BALTIC SEA

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1. INTRODUCTION

The main objective of this investigation is to estimate monthly areal precipitation over the subbasins of the Baltic Sea. In this report areal estimates have been made for the periods 1951-1970, the climatological averages for 1931-60 and for the Pilot Study Year, covering the period July 1975 to December 1976.

The determination of areal precipitation is of great importance for a lot of fields such as

- Precipitation cloud parameterization

  The quantitative characteristics of latent heat release and its organization, heat and water budget investigations are of importance for numerical weather prediction models.

- Air pollution budget

  The washing out of impurities by precipitation is of importance for the water quality at sea and consequently for the biological life.

- Balance of salt and mass distribution at sea

  The fresh water supply from precipitation and runoff are important factors related to the salinity and also of importance for the studies of the 'water renewal of the semienclosed sea'.

- Climatological precipitation models

  For an improved knowledge of the distribution of precipitation in coastal zones and for the quantitative evaluation of energy and water budgets on a local or on a global scale it is necessary to determine the precipitation element as accurate as possible.

The areal estimates computed in this report are based on corrected point precipitation data: It is a well-known fact that measurement by gauges gives systematic deficits in precipitation amounts. For each station corrections of the monthly values have been suggested by the respective country. A description of the method of correction has also in general been presented by the respective Baltic bordering country.

For future improvements of the estimates it is important to establish and use techniques based on remote sensing devices, in particular advanced weather radars and satellites.

For the areal estimation of precipitation within the Baltic Sea and its subbasins statistical interpolation has been applied. The normalized fields have been extrapolated from the available climatological point data and some statistical properties of the precipitation pattern are expressed by autocorrelation functions for the respective month.

Methods for determination of areal precipitation have been discussed by Rainbird (1967) and by Dahlström (1976). The fact that the principal part of the point precipitation data are samples representing rather the land conditions than the precipitation regime over the sea may lead to serious errors in the areal estimates. To reduce these effects of the inhomogeneities the statistical interpolation method is applied on normalized precipitation data.

Falkenmark and Mikulski (1974) and (1975), have given general backgrounds to this international project and to the problem of the water balance computation of the Baltic Sea.

The subbasins of the Baltic Sea have been denoted by the figures 1-7, see the Figure 1.

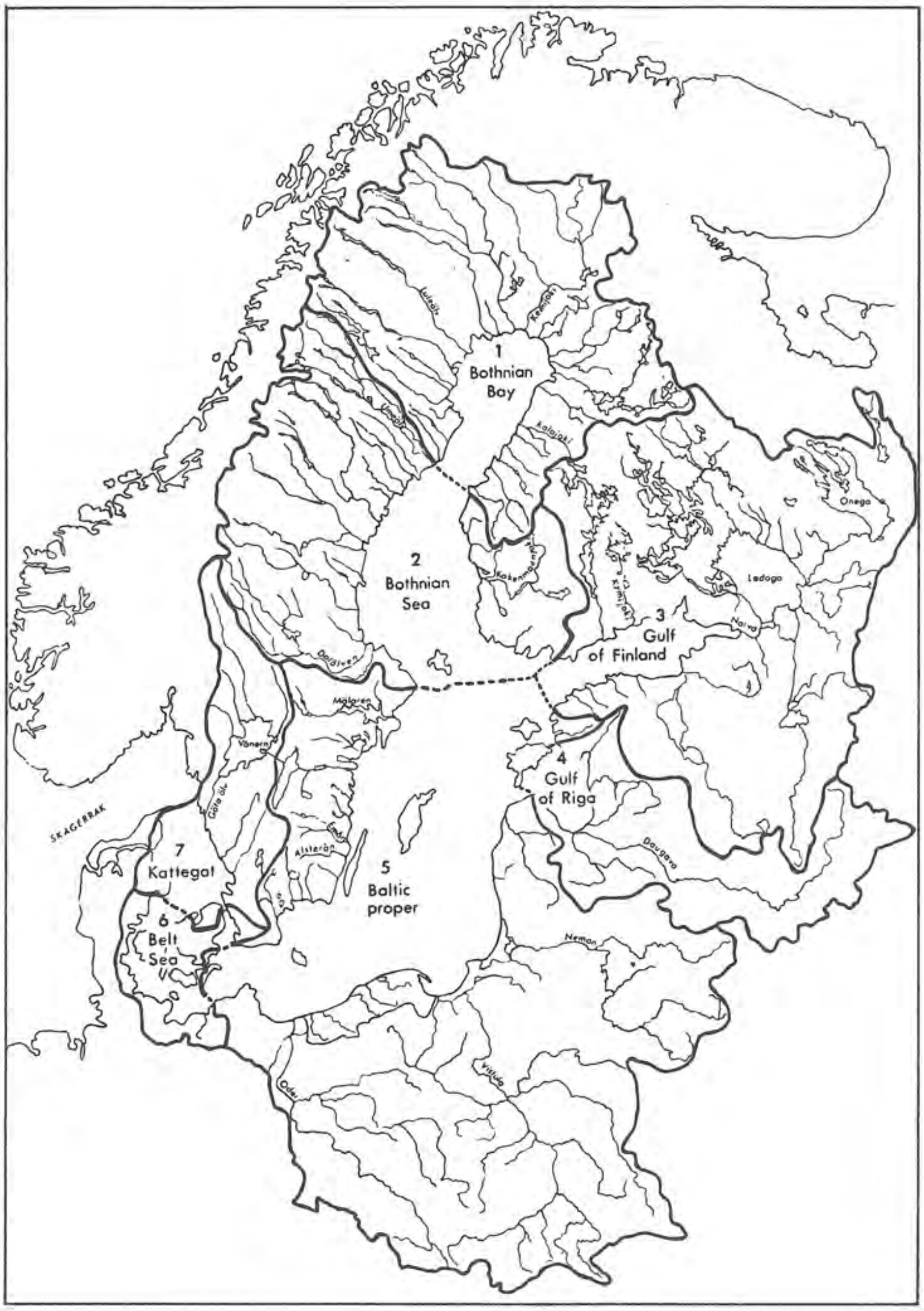


Figure 1 *Drainage basin and subregions of the Baltic Sea and its transition area. Respective rivers indicated by names. Dashed lines show boundaries between Baltic Sea subregions. Thick lines show boundaries between the corresponding drainage basins. (From Falkenmark & Mikulski, 1974).*

2. POINT PRECIPITATION MEASUREMENTS - METHODS OF CORRECTION

The data delivered by the respective Baltic bordering country consisted of monthly and yearly precipitation sums (uncorrected and in general also corrected data), with the following total number of stations:

Period	Number of stations
1931-60	299
1951-70	226
1975/76	464 (the Pilot Study Year)

Some countries had also submitted data for the period 1971-1975.

The data coverage was densiest in the region of Denmark and in the other coastal regions, the density of stations was roughly the same. Below are presented some further information about the data.

2.1 Basic concepts

The conventional measurement of precipitation is a very simple procedure and consists in emptying a bucket and measuring the amount by using a graduated glass. In the case of solid precipitation the content of the gauge is melted and then measured. Despite this simple character of measurement the value obtained is influenced by a variety of errors.

Due to the fact that the error sources frequently interact in causing a deficiency in the precipitation amount it is important to find sutiable amendments for the point measurements. As a lodestar when going through the jungle of possible error influences on point measurements the following mathematical model can be used (cf B Dahlström, 1970).

$$P' = P + \underbrace{\Delta P_E + \Delta P_S + \Delta P_A + \Delta P_W + \Delta P_P}_{\text{errors due to meteorological and instrumental factors combined}} + \underbrace{\Delta P_D}_{\text{purely instrumental error}} + \underbrace{\Delta P_R}_{\text{error caused by the observer or by unforeseen incidents}}$$

The error sources are of individual physical origin and consequently this 'additive' model has been formulated. Explanation of the formula: P' = observed precipitation amount, P = true amount, E = evaporation/condensation, S = splashing/drifting of snow, A = aerodynamic influence (the "wind effect"), W = wetting, P = unsuitable position (effects from interception etc), D = defects of the instrument, R = reading errors and unforeseen incidents.

In the normal case it is sufficient to correct the data for the aerodynamic influence (ΔP_A), the wetting error (ΔP_W) and the error due to evaporation (ΔP_E).

In general the magnitude of the corrections are based on special field investigations designed to reveal the error sources inherent with the respective precipitation equipment. A comprehensive survey of this research field is contained in WMO 1982.

2.2 The applied correction methods

A short description of the methods for correcting the point values is given below. The information below concerns the methods which have been delivered by the respective country to the element coordinator.

2.2.1 Method applied in Finland

The description delivered by R Solantie (1974, 1977), Finland, is summarized below (see also Korhonen, 1944).

The following formula is used:

$$\Delta = C_1 n_1 + C_2 n_2 + \frac{P'}{100} \cdot r \cdot \sum_{i=n,e,s,w} f_i \cdot \frac{\alpha_j}{\bar{\bar{\alpha}}} \cdot b(p)$$

Δ = monthly total correction (mm)

$C_1 = 0.18$, $C_2 = 0.10$

n_1 = number of measurements within the month < 1.0 mm

n_2 = number of measurements between 0.1 mm and 0.9 mm

P' = measured amount (mm)

r = wind velocity related to the climatological mean wind speed

f_i = relative frequency of wind direction i

α_i = measure of the wind exposure (from 0-100) in direction i

b(p) = the percentage correction (of the observed precipitation) for the station with the mean exposure ($\alpha_i = \alpha$). b(p) is 13% for wet snowfall and mixed precipitation and 1.3% for rain. b(p) is in the warm season for drizzle and dry snowfall 16% and in wintertime in northern Finland 41%. p can be related to air temperature.

The Finnish standard gauge which now is gradually changed to the Tretjakov gauge is made of brass. The area of the collecting orifice of the gauge is 500 cm^2. Inside the gauge, there is a funnel. Rain or water from melted snow pours down through a hole at bottom of the funnel. This hole is small enough to prevent the evaporation from the water at the bottom of the gauge. For the same reason, the drain lip is fitted with a tap.

2.2.2 The correction method applied on data from USSR

For the period 1951--1976 the delivered stock of data from USSR has been corrected for the wetting error.

$$\Delta P_W = 0.1 \cdot n_3 + 0.2 \cdot n_4$$

n_3 = the number of days with liquid and mixed precipitation $\geq$ 0.0 mm

n_4 = the number of days with solid precipitation $\geq$ 0.1 mm

To correct also for the deficits due to wind (ΔP_A) the following percentages were used in this report.

J	F	M	A	M	J	J	A	S	O	N	D
0.2	0.2	0.2	0.15	0.1	0.05	0.05	0.05	0.1	0.1	0.15	0.15

For the period 1931--1960 the data delivered from USSR was completely corrected.

From Table I in section 2.3 it is clear that the percentage correction during December-March are higher than the corresponding values in other countries.

In USSR the Tretjakov instrument is used as the standard gauge. A thorough investigation of the magnitude of the errors inherent with this type of instrument is presented by L R Struzer and V G Golubev (1976).

2.2.3 Correctional method applied in Danish data

The method is described by Allerup and Madsen (1980).

The wind effect depends on wind velocity and the size of the precipitation particles. However, it is difficult to measure the particle size, so instead the precipitation intensity (mm/h) is used in the following model:

$$\frac{R_I - R_{II}}{R_{II}} = e^{0.0001-0.0082 \log I_{II}+0.412(\log I_{II})\cdot V+0.0274V-1}$$

R_I and R_{II}: amounts of precipitation at ground level and at 1.5 m, respectively. I_{II}: rain intensity (tenth of mm/h) measured at 1.5 m. V: wind velocity at 10 m. Only cases $R_I \geq 1.0$ mm are considered.

This equation is tabulated and liquid precipitation can be corrected on a daily basis for unsheltered stations. If V = 0 the correction value is assumed to be 0, and for I > 150 the value is 3%.

When correcting data from sheltered stations, then the same procedure is applied as for unsheltered stations and after that the result is multiplied by 3/4.

Concerning solid precipitation (snow) there are two cases: solid precipitation 1) at temperature $\geq 0^{\circ}$ and 2) at $t < 0^{\circ}$. At temperature $\geq 0^{\circ}$ the correction value is 26% for data from unsheltered stations and 15% for sheltered. At temperature $< 0^{\circ}$ the correction values are 50% and 25% respectively. All values are valid on a daily basis. The correction for wetting is obtained as the number of rain days $\geq$ 0.1 mm.

The Danish standard rain-gauge is a 200 cm^2 Hellman placed at 1.5 m height.

2.2.4 The method applied in DDR

This method is described by H Karbaum (1969) and (1970).

The deficit due to evaporation is estimated by

$$\Delta P_E = 0.072\ (E_W - e_2) - 0.034 \text{ mm/day}$$

E_W = saturation water vapour pressure (mm)

e_2 = water vapour pressure in 2 m height

The saturation deficit is evaluated as a monthly mean value using data on temperature and humidity. The monthly evaporational correction is obtained by multiplying by the number of precipitation days.

The wetting error ΔP_W is estimated by

$$\Delta P_W = 0.11 \cdot n + 0.15\ n_0$$

n = number of precipitation days

n_0 = number of days during which the collector has dried up

Correction of the measured sum (P') for the wind effect (ΔP_A) is estimated by

$$\Delta P_A = \frac{P'}{C_i} \cdot 100 \quad \text{(mm)}$$

Rain in summer:	$C_1 = \overline{Hü} \cdot 0.667 + 90.2$
Rain in winter:	$C_2 = \overline{Hü} \cdot 0.652 + 85.7$
Mixed precipitation:	$C_3 = \overline{Hü} \cdot 0.842 + 76.1$
Snow:	$C_4 = \overline{Hü} \cdot 1.615 + 60.4$

$\overline{Hü}$ (Horizontüberhöhung) is a measure of the wind exposure. In DDR the standard Hellman rain-gauge is used. The standard height is 1.5 m.

2.2.5 The method applied on Polish data

A description is presented by Chomicz (1977). Partly on the basis of field studies of error sources monthly percentages expressing the long-term mean wind loss are evaluated. During December-February the wind correction is estimated to 15% of the measured quantity. Mean monthly values of the evaporation loss are presented. The values range from 0.7 mm in February to 5.3 mm in July. The mean monthly losses due to wetting of the gauge range from 2.4 in March to 4.1 in July. The wetting error is also expressed as percentages (10.1% - 13.4%) of the measured monthly sum. The mean annual precipitation correction in Poland is estimated to 19.7%. The instrument type is a Hellman gauge at 1.0 m height.

2.2.6 The correction method applied on Swedish data

The precipitation stations are grouped in 5 classes according to their rate of wind exposure. For each class of exposure fixed percentages for the respective solid and liquid part of precipitation are applied to correct for the deficit due to wind (ΔP_A). Mixed precipitation is treated as if half of the quantity fell as snow and half of it as rain.

The correction is obtained by multiplication of the quantities of solid and liquid precipitation by use of the respective percentages given by the classification.

The percentages given below are mainly based on results from special error studies, see B Dahlström (1973). The correction for snow is uncertain.

Class	Site of the gauge	Percentage correction	
		liquid precipitation	solid precipitation
1	Extremely sheltered. Small glade in a forest. (Inland or coastal regions).	2	10
2	Intermediate position between forest and plain at least 10 km inland from the coast.	5	20
3	Relatively unsheltered location on a plain. at least 10 km inland from the coast.	8	30

Class	Site of the gauge	Percentage correction liquid precipitation	Percentage correction solid precipitation
4	Relatively unsheltered location on the shore or on an coastal island.	11	40
5	Extremely unsheltered location in the coastal regions.	14	50

For the period 1931--1960 a slight modification of the above described method was used.

The wetting (ΔP_W) and the evaporation (ΔP_E) errors are corrected formally by adding 2.0 mm to each monthly sum.

2.3 The quantitative correction effect obtained by the various methods

For the computation of statistical characteristics of the precipitation field it is important that fictitious patterns or large systematical errors are not introduced by the correction method applied.

Table I Comparison of the applied corrections in the respective country: Mean ratio between correction and corresponding corrected precipitation sums 1931-1960. The corrections have been determined by the respective country

	Month: 1	2	3	4	5	6	7	8	9	10	11	12	Year
Sweden													
113 tations	0.20	0.21	0.21	0.16	0.11	0.08	0.09	0.10	0.09	0.12	0.14	0.18	0.14
Finland													
58 grid points	0.30	0.30	0.29	0.18	0.11	0.06	0.05	0.06	0.08	0.13	0.19	0.23	0.15
USSR													
20 stations	0.36	0.33	0.38	0.18	0.15	0.10	0.07	0.09	0.12	0.14	0.22	0.34	0.18
Poland													
18 stations	0.18	0.21	0.15	0.16	0.13	0.09	0.09	0.09	0.10	0.13	0.16	0.17	0.13
DDR													
25 stations	0.21	0.20	0.18	0.16	0.13	0.09	0.10	0.09	0.09	0.13	0.15	0.15	0.13
FRG													
31 stations	0.19	0.20	0.17	0.17	0.12	0.09	0.09	0.09	0.09	0.14	0.17	0.16	0.14
Denmark													
34 stations	0.20	0.20	0.17	0.17	0.12	0.08	0.10	0.09	0.09	0.13	0.16	0.18	0.14

In Table I above the mean relative corrections (expressed relative to the corrected sum) for the respective country are presented. Due to the fact that the estimates of the corrections are based on results from independent field studies the results seem to agree remarkably well. Due to the type of instrument and to the variability of the meteorological conditions the true percentages are not expected to be identical.

In Table II the annual corrections obtained for the Pilot Year 1976 are also illustrated. The magnitude of the relative corrections varies between 0.15 and 0.22 for the individual countries. The variation is thus relatively small.

Table II Comparison of the applied corrections in the respective country. Mean relative correction 1976 (relative to the corrected amount) applied by the respective country.

Sweden 46 stations	0.18
Finland 14 stations	0.19
USSR 18 stations	0.22 x)
Poland 53 stations	0.17
DDR 11 stations	0.19
FRG 1 station	-
Denmark 145 stations	0.15

x) Correction for deficit due to wind by the element coordinator.

2.4 Conclusions concerning the correction of point precipitation

Some conclusions concerning the correction of point precipitation are presented below:

- The different correctional methods give quantitative effects of similar magnitude. The selection of one of the correction methods described here seems therefore not critical. The correction method used by USSR gives during wintertime significantly higher values than the other methods, however.

- The fact that the errors inherent with precipitation measurements have been investigated frequently during the last century imposes the requirement of operational use of corrections: For the future application of corrections on an operational basis it seems important to use automatic, computer-based, methods. The problem of correcting old data will thereby be estimated.

- The possibility of agreeing on a unified standard correction method for the countries in northwestern Europe - and elsewhere - would be discussed by relevant authorities.

- The error limits of the point corrections is not always established. The accuracy of the corrected values is discussed in section 4.1.

3. AREAL ESTIMATES OF PRECIPITATION FOR THE BALTIC SEA

3.1 Some aspects on the areal estimation problem

The basic approaches that have been made in the past to the areal estimation of oceanic precipitation are here summarized in the following way:

1. Methods based on various types of extrapolation of precipitation from coastal and land stations. See Meinardus (1934), Schott (1926), (1935), Drozdov chart (1935) - see Malkus (1926), and for estimates within the Baltic Sea: cfr section 5 in the present paper.

2. Methods related to 1 but sophisticated by considerations of oceanic water balance, energy budget (Albrecht, 1960, Baumgartner & Reichel, 1975) or salinity aspects. The salinity technique (Wüst, 1936, Jacobs, 1951) is based on the assumption that the mean salinity expressed as a function of latitude reflects the difference between evaporation and precipitation. This difference is also obtained by computation of atmospheric vapour flux computations by use of aerological data (Peixoto, 1973, Palmén and Söderman, 1966, Alestalo, 1981, cfr also the contribution on the Baltic evaluation contained in this Monography).

3. Use of information (in particular the code on 'present weather') from oceanic weather stations on ships - and for 'calibration' of statistics also use of data (frequency, mean intensity etc) from land stations. Information on this method is given by Sawyer (1952), Tucker (1961), WMO (1962), USSR-IHD (1974), WMO (1976).

4. Methods that take data from 'new' data sources into account. In particular this information consists of data from remote sensing devices (radars and satellites). See Martin and Shear (1973), Griffith et al (1978), Reynolds and Smith (1979), Lovejoy and Austin (1980), Heymsfield et al (1983), Doviak (1983).

5. It would also be beneficial to include the data given by quantitative precipitation forecasts into an integrated system for areal estimation, in which data from various sources are components.

The determination of areal precipitation over oceans respective over semiclosed seas, such as the Baltic Sea, consists basically of the same problems. However, the data coverage is more satisfactory within the region of the Baltic Sea than within the oceans.

For the evaluation of the oceanic water balance it is of great importance to use the information contained in the reports on 'present' weather from ships. The difficulties of direct measurement of precipitation on board ocean weather ships have been described by the field experiments carried out by Skaar (1955). However, the problems connected with this approach, cfr the references under item 3 above, is well documented.

By use of Tucker's method the precipitation measurements on board the Swedish lightship 'Finngrundet' in the Sea of Bothnia was investigated by Andersson, 1963. The results from this study, where also the adjacent coastal stations were used, indicated that the precipitation amounts measured on board this lightship were too low. The conclusion that lightships in the Baltic Sea suffer losses in the catch has previously also been indicated by Roll, 1958, in a comparative study of the amounts measured on small islands respective on board lightships.

The present investigation has been carried out on the basis of data from conventional precipitation measurements. The basic difference in approach between this investigation and the previous computations of the areal precipitation is that corrected point measurements have been used. The areal estimates have been obtained by simple extrapolation of the climatological field and by use of statistical interpolation.

Consequently, this investigation is related to the approach 1 above with potential for sophisticated verification of the estimates by future studies related to the approach 2.

The great potential for the future determination of the precipitation within the Baltic Sea is connected with the use of 'new' data sources, the approach 4. The approach of statistical inference from densely to sparsely data covered fields seems important, cf the potential of structure data indicated by Dahlström, 1976, p 60.

3.2 Estimation techniques applied for the computation of areal precipitation

Statistical interpolation can be used either by direct computation of areal values from point measurements or indirectly by computing values in a grid and then averaging the gridded data to get areal estimates. In the former case the crosscorrelation functions between the point data and the corresponding areal values have to be determined and in the latter case the covariance functions of the point data sets have to be computed.

The concept of statistical interpolation has been described in detail by A Eliassen, 1954 and by L S Gandin, 1963, 1970.

Statistical interpolation was applied in this study by use of covariance functions to get estimates of the rainfall quantities at grid points. By this method the spatial structure of the computed field can be evaluated. This technique means that the detection of fictitious patterns is somewhat facilitated as compared with the case of 'direct' computation of areal values.

The areal precipitation was obtained by averaging the grid point values for the respective subbasin in the Baltic Sea.

With statistical interpolation the respective grid value is computed by use of the adjacent point precipitation values. It was necessary to use normalized (cfr next section) rainfall data in this study.

On the basis of some numerical tests the maximum region of influence at each estimation was selected as a square 300x300 km^2, centered at the respective point of estimation. The information outside this influencing area turned out to give limited additional information.

To reduce the effects of inhomogeneity of the precipitation field the interpolation was applied with normalized data for the historical data sets 1951-1970 and the Pilot year 1975/76.

3.3 Normalization of the precipitation field

One crucial problem at the interpolation of rainfall over the sea concerns the anisotrophy of the precipitation field. Especially the efficient production rainfall at stations along the coast during the warm season contrasts strikingly to the moderate rainfall at sea. In the autumn the reverse climatological regime exists.

The normalized values used at the computations were obtained as the deviation of the observed rainfall quantities from the long term average, represented by the 1931-1960 rainfall means, see section 3.5.1, and divided by estimates of standard deviation.

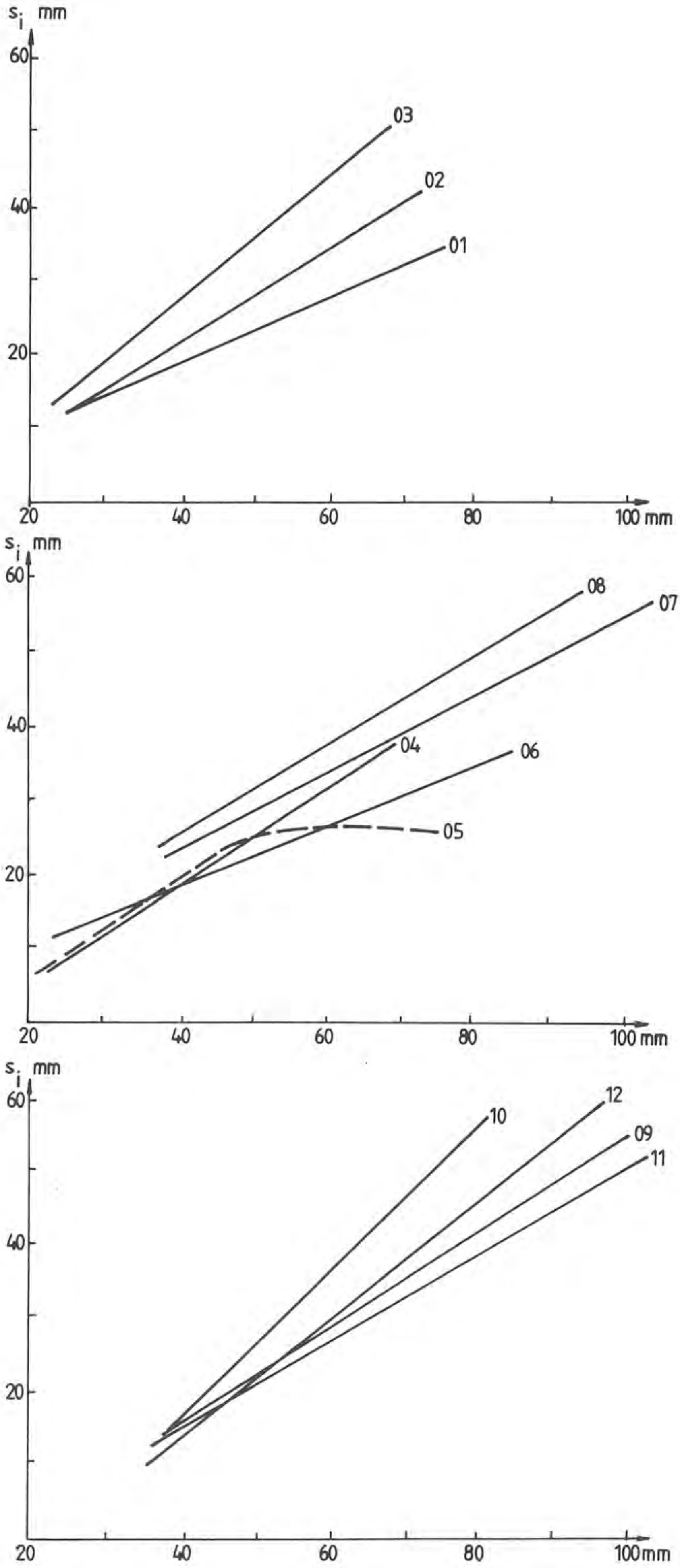
The information for the proper computation of the standard deviation at the location of the respective station was in general only available at certain stations. At grid points no relevant measurement data were available for the computing of statistical quantities.

In addition to this lack of information the relevant estimate of statistical measures of the variability of precipitation at coastal stations is not easy to determine due to the fictive variation caused by the error sources inherent with the measurements. It was therefore decided to normalize the observed values by regression estimates of standard deviation and by climatological averages of precipitation.

These regression estimates were obtained on a monthly and yearly basis by relating the standard deviation of the rainfall values, compared in the usual way at selected stations, to the climatological average of rainfall at the respective stations. Some of the results of these rather crude method are illustrated in figures 1-3.

By use of the climatological averages a simple measure of the variability, here denoted s_i, then can be obtained using the regression relationships developed. The difference, f_i', between the corrected point values and the climatological values ($\overline{f}_i$), were divided by the respective values s_i to get the normalized fields.

The normalization of the rainfall fields using the quantities $\overline{f}_i$ and s_i is performed to reduce the anisotrophy of the precipitation fields and thereby simplifying the determination of the covariance fields. In particular the normalization is aimed to suppress a large part of the undesirable 'non-representative', influence of convective activity or local reinforcements of rainfall systems at coastal or land stations.



Figures 2-4 *Illustration of the functions used for normalization of the data according to the variability. The standard deviation s is expressed as a function of the climatological monthly precipitation. The figures denote the respective month.*

3.4 Statistical interpolation of precipitation at sea

The interpolation of grid values was applied by use of corrected point precipitation data. The deviation of the corrected measurements from the true point values was taken into account at the interpolation.

The corrected point measurement, which in spite of the corrections applied is inaccurate, is here expressed as

$$\hat{f}_i = f_i + \delta_i$$

where

$\hat{f}_i$ = corrected sum of measured precipitation at station i

f_i = true precipitation sum at station i

δ_i = deviation between the true precipitation value and the corresponding corrected point precipitation measurement

The deviation $\hat{f}'_i$ of the observed value from the long term average f_i is used at the interpolation.

$$\hat{f}'_i = f_i - \overline{f}_i + \delta_i$$

or

$$\hat{f}'_i = f'_i + \delta_i, \text{ where } f'_i = f_i - \overline{f}_i$$

The formula applied for the interpolation of the normalized deviation from the average precipitation field reads

$$\frac{\tilde{f}'_o}{s_o} = \sum_{i=1}^{n} \mu_i \frac{f'_i + \delta_i}{s_i} \qquad (1)$$

where

$\tilde{f}'_o$ = interpolated value of the deviation from the average field at point 'o'

μ_i = the weights to be determined

s_i = a measure of the standard deviation at the points i, i=0, 1 ... n

n = the number of neighbouring data

With the estimate $\tilde{f}'_o$ computed the final value at the grid point, $\tilde{f}_o$, is obtained by resubstitution.

The interpolation error e is here expressed as

$$e = \frac{\overline{(\tilde{f}'_o - f'_o)^2}}{s_o} \text{, where } f'_o \text{ is the true deviation at 'o'.}$$

By use of formula (1) the interpolation error is expressed as

$$e = \overline{\left[\sum_{i=1}^{n} \mu_i \frac{f'_i+\delta_i}{s_i} - \frac{f'_o}{s_o}\right]^2} =$$

$$= \sum_{i=1}^{n} \sum_{j=1}^{n} \left[\frac{\mu_i \mu_j \overline{f'_i f'_j}}{s_i s_j} + \frac{2\cdot\mu_i \mu_j \overline{f'_i \delta_i}}{s_i s_j} + \right.$$

$$\left. + \frac{\mu_i \mu_j \overline{\delta_i \delta_j}}{s_i \cdot s_j}\right] - 2 \sum_{i=1}^{n} \left[\frac{\mu_i \overline{f'_i \delta_i}}{s_i \cdot s_j}\right.$$

$$\left. + \frac{p_i \overline{\delta_i f'_o}}{s_i s_o}\right] + \frac{\overline{f'^2_o}}{s_o} \qquad (2)$$

There is limited information available on the statistical nature of the error in the corrected data. It is quite clear that besides the random error in the corrected values there are also probably systematic errors in all the point correction methods used by the respective country.

Due to the fact that no 'true' data sets are available it is difficult to reach quantitative conclusions on the magnitude of the error in the corrected point data.

To further evaluate the expression (2) some qualitative judgements are given below on the error characteristics of corrected data.

1. The spatial error correlation. In a set of neighbouring stations, used at the interpolation of a grid value, the following factors act towards less spatial correlation of errors in the adjusted data:

   a. The stations are - depending on their site - exposed to various meteorological conditions, especially differences in wind exposure of the rain gauge. Consequently, the corrections and the corresponding errors in the corrections are subjected to a certain 'random' influence, connected with the variation of wind speed and other parameters between stations used for the correction. This 'random' influence thus acts towards a low spatial error correlation.

b. The available corrected point data are subjected to different correction methods depending on the techniques and way of application used in Denmark, Finland, Polen, Sweden and USSR. These methods seem to have been developed essentially independently. The fact that different methods have been in use acts partly towards a greater spatial independency of errors between points representing different countries.

c. The point correction methods developed by the respective Baltic bordering country have been developed on the basis of information obtained by special field investigations on error source at precipitation measurement. It seems consequently relevant to expect that the main systematic deficit in precipitation catch is eliminated by the developed point correction methods and that the inaccuracy of the adjusted data is dominated by a random error component.

With reference to the items a-c above

$$\delta_i \; \delta_j = 0, \; i \neq j \qquad (3)$$

is assumed. This assumption seems adequate for the case of liquid adjusted point data. In the case of solid precipitation the errors might be at least partly correlated due to the difficulty of finding adequate corrections. However, spatially un-correlated errors are assumed in the absence of the precise information of the nature of the errors.

2. THE CORRELATION $\delta_i \; f'_j$

In the cases where $i \neq j$ it seems justified to assume nondependency between δ_i and f'_j, due to the random complex of factors determining these quantities, cfr items 1a - 1c above.

In the cases where $i = j$ there might be a correlation between the error and the normalized rainfall value. The magnitude of the correction for deficits in the measured amounts due to the wind influence is basically directly proportional to the precipitation amount (by approximation this error is frequently expressed as 'percentage correction' of the measured amount). A systematic error in the wind correction thus might be correlated with the normalized rainfall value.

However, the fact that the correction formulae are based on specially designed error investigations in the various countries makes it reasonable to assume that

$$\delta_i \; f'_j \approx 0 \qquad (4)$$

The adequacy of this assumption is recommended to be explored in future investigations of the errors inherent with precipitation measurements.

By use of (3) and (4) the expression (2) is simplified

$$e = \sum_{i=1}^{n} \sum_{j=1}^{n} \mu_i \; \mu_j \; m_{ij} + \sum_{i=1}^{n} \mu_i^2 \varepsilon$$

$$- \; 2 \; \Sigma \; \mu_i \; m_{io} + 1 \qquad (5)$$

where

m_{ij}, m_{io} are the autocorrelations between the precipitation amounts at the points i and j respective i and o.

The autocorrelations are described in the end of this section.

ε is the relative accuracy of the adjusted precipitation measurement:

$$\varepsilon_i = \frac{\delta_i^2}{s_i^2}$$

μ_i the weights to be determined.

To determine the weights which give a minimum of the interpolation error we apply

$$\frac{\partial e}{\partial \mu_i} = 0, \quad i = 1, \ldots\ldots, n$$

The following system of equations is obtained:

$$\sum_{j=1}^{n} \mu_j m_{ij} + \varepsilon_i \mu_i = m_{io}, \quad i = 1, 2, 3, \ldots\ldots, n \qquad (6)$$

The relative accuracy ε_i of the corrected point data is assumed to be the same at the different stations and consequently ε_i in (6) is substituted by ε at the computations $\varepsilon = 0.15$ was applied.

By solving (6) the weights μ_i of the neighbouring normalized rainfall values are determined. The normalized value at the grid point is then computed and by resubstitution of the statistical values used for the normalization the final grid estimate of precipitation is obtained.

3.5 Estimation of the climatological information on precipitation for the Baltic Sea - fields for normalization

The methods applied for the estimation of the climatological precipitation fields 1931-1960, the measures of standard deviation and the covariance functions are described in the section below.

3.5.1 Climatological precipitation for the period 1931-1960

The fundamental problem with the spatial estimation of precipitation for the Baltic Sea concerns the lack of observational evidence. For the historical data sets the principal source of information consequently consists of merely the conventional point precipitation measurements. However, for future computations there will be a wealth of additional data sources available, in particular data obtained by remote sensing devices and data given by improved, quantitative models for precipitation forecasts.

The method developed by Tucker (1961) for the computation of precipitation at sea requires access to daily weather reports. However, for the period 1931-1960 only climatological averages were available and in addition a large portion of the stations represents climatological stations that are not reporting the weather characteristics (the ww-code). As indicated in the previous section it was not judged relevant to directly apply statistical interpolation on the climatological data sets representing the period 1931-1960.

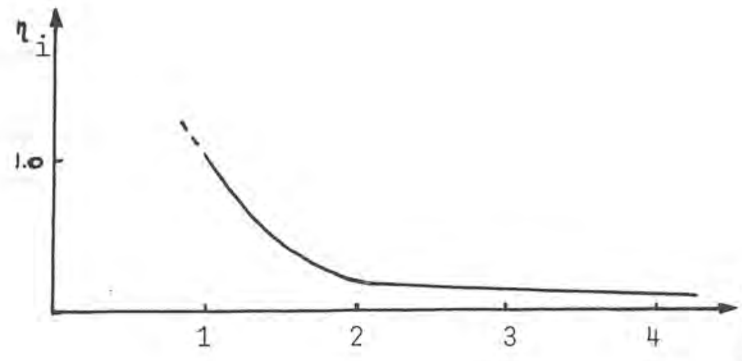
The method applied to determine the climatological fields 1931-60 can be characterized as a rough method based on linear, weighted interpolation with climatological adjustment for the land-sea precipitation gradients. The method consists of the following steps:

1. The monthly precipitation measurements were allocated to the nearest points in a regular cartesian grid covering the Baltic Sea and the nearby land areas. From qualitative judgements a grid distance of 50 km was selected. If more than one station was situated within a distance of 25 km from the specific grid point the arithmetic average of these neighbouring values was allocated to this grid point.

Part of the grid was thus filled with observational data.

The grid data, that were obtained by step 1 above, were used for the estimation of data at the remaining 'empty' grid points. The following procedures were applied.

2. Distance weighting of values within a 7x7 grid matrix. The following weighting function was applied:



$$\tilde{f}^1_{oi} = \frac{\Sigma \eta_i \cdot f_i}{\Sigma \eta_i} \qquad (7)$$

3. <u>Linear interpolation between stations</u> along and perpendicular to the coast. This interpolation scheme is illustrated by the following formula.

$$\tilde{f}^2_{oi} = \{f_{x1} + \frac{f_{x2} - f_{x1}}{dx_1 + dx_2} dx_1\} + \{f_{y1} + \frac{f_{y2} - f_{y1}}{dy_1 + dy_2} dy_1\} \qquad (8)$$

4. <u>Adjustment according to a climatological rainfall land/sea gradient</u>

Information contained in climatological data was taken into account by the following formula:

$$\tilde{f}_{oi} = 0.5(\tilde{f}^1_{oi} + \tilde{f}^2_{oi})(1 - G(d)) \qquad (9)$$

where G represents a probable measure of the relative change of rainfall according to the distance d between the grid point, for which the estimate is made, and the coast line.

The value $\tilde{f}_{oi}$ thus represents the estimated grid value.

The gradient of the climatological precipitation field between land and sea is modelled in nature by a complex of physical factors. The discontinuity of the direct supply of water vapour and the change of roughness and temperature of the earth's surface in the coastal zone influences stability conditions. Consequently, the efficiency of the precipitation mechanisms are affected.

Another important physical factor is connected with the oreigenic precipitation that is forced by the topographic features in the coastal region, see Bergeron (1949).

At present our knowledge is unsatisfactory of the quantitative importance,in a climatological sense, of the various physical factors affecting the distribution of precipitation in the boundary between land and sea.

However, some quantitative results have been indicated in the following studies:

- In a radar investigation by Heikinheimo and Puhakka (1980) some results on echo climatology in the area of the Gulf of Finland were presented. Measurements during two summers (in total 57 days) have been undertaken. Echo-coverage was determined as the areal percentage of echoes exceeding the noise threshold at control areas covering respectively the sea, the coastal zone and the land in the vicinity of Helsinki. Data were analysed in a 180 x 200 km grid with a grid distance of 3 km.

  The average echo coverage (EC) for the respective control areas was computed. The EC-value obtained for the land area was 27.1%, for the coastal area 22.3% and for the area over the sea 20.4%. One of the conclusions made was that the rain showers emanating from land travelled a 'typical maximum distance' of 20 km over the sea (summer conditions). No attempt to convert the radar data to rainfall amounts was made in Heikinheimo and Puhakka (1980).

- Wilson (1977) used 'objective' analysis technique to combine radar and rain gauge data to study the effect of the Lake Ontario on precipitation patterns. Almost one year of data from two radars had been collected and the spatial precipitation distribution was studied in terms of estimated precipitation values.

  The Ontario region was divided into 4 zones: Zone 1 is situated over mid-lake more than 15 km from land; Zone 2 is over the lake within 15 km of the shore; Zone 3 is over land within 15 km of the shore and Zone 4 is over the land 15-30 km from the shoreline.

  On an annual basis the precipitation amount increased relative to the amount in Zone 1 by respectively 1.5% in Zone 2, by 4.4% in Zone 3 and by 6.3% in Zone 4.

It was also concluded and quantitatively shown, that during the warm season the relatively cold lake suppressed shower activity and that during the cold season the lake frequently stimulated precipitation.

- In an investigation by Richards et al (1966) the influence of atmospheric stability and over-water fetch on winds over the lower Great Lakes was studied. With unstable atmospheric conditions the results indicated that there is an increase of wind speed over the lake (at 10 m height) with an increase in fetch up to 30 à 40 km.

  This study cannot directly be used for conclusions in terms of the precipitation gradient, but the length scale - 30 à 40 km - gives at least some indication of the relevant length dimension of the response of the atmosphere at instability conditions.

Encouraged by the above investigations a climatological study of the Baltic Sea precipitation gradient was performed by use of the 1931-60 stocks of data.

Statistics on the mean rainfall land/sea gradient was computed for the coastal areas of the different subbasins and for different months. It turned out that this statistics is highly sensitive to what stations are selected for determination of these gradients.

On the basis of corrected point data from a few stations with acceptable locations the following annual gradients G(d), see formula (9), was computed:

Table III The precipitation gradient of the Baltic Sea. The annual relative reduction of the precipitation from shoreline.

Subbasin No	Precipitation gradient G(d) annual values d = distance from shoreline	
	$d < 100$ km	$d \geq 100$ km
1-2	0.13	0.195
3-7	0.05	0.075

The relatively cold water in the subbasins 1 and 2 with a longer duration of ice cover gives a steeper gradient in these regions than in the other parts of the Baltic Sea. In addition coastal oreigenic effects on the western side of the northern Bothnian Sea make the gradient relatively steep.

The results in the Table III indicates that the precipitation gradient is steeper close to the shoreline than more distant from the shore. This is in agreement with the result obtained by Andersson in his study of the precipitation in the region of southern Bothnian Sea, see Andersson (1963, p 300).

The application of normalized fields

The climatological field 1931-60 obtained by the above 4 steps was used to normalize the data for 1951-70 and for the Pilot Study Year 1975/76 for the application of statistical interpolation.

The final estimates of the 1931-60 areal values were obtained by the normalization of these data by the climatological field 1951-70. Then statistical interpolation was applied on the 1931-60 fields.

Comments to the steps of estimation

- Step 1 This procedure was performed to simplify the subsequent computations. This procedure was possible due to the fact that the locations of the stations could be regarded as randomly distributed with respect to the positions of the grid points: The part of measured rainfall data that were moved 'Balticward' at the allocation to the gridpoints were counterbalanced by values that were moved 'landward'.

- Step 2 With this procedure the estimated field in the interior of the Baltic proper were essentially determined as a smoothed field related tothe surrounding values along the coasts. This effect was caused by the deficiency of observations within this region in connection with the character of the weighting functions applied.

  This effect was prevalent to a lesser extent within the other subbasins owing to the fact that the relative data coverage was more satisfactory within these areas.

- Step 3 Some studies were performed to determine weighting functions for improvement of this simple formula. The improvements on the estimate as interpreted by independent observations close to the grid point were, however, of limited value and it was decided to avoid sophistication of this interpolation scheme.

- Step 4 The gradient values obtained from the study of the corrected point data 1931-60 are not quite satisfactory because of the deficiency of relevant precipitation stations well off from the coast. For future investigations - where the approach would be within dynamic climatology-, where data from radars and satellites will be of great importance, it seems urgent to concentrate on the problem of the magnitude and character of the precipitation gradient in the coastal zone.

3.5.2 Determination of the autocorrelation functions

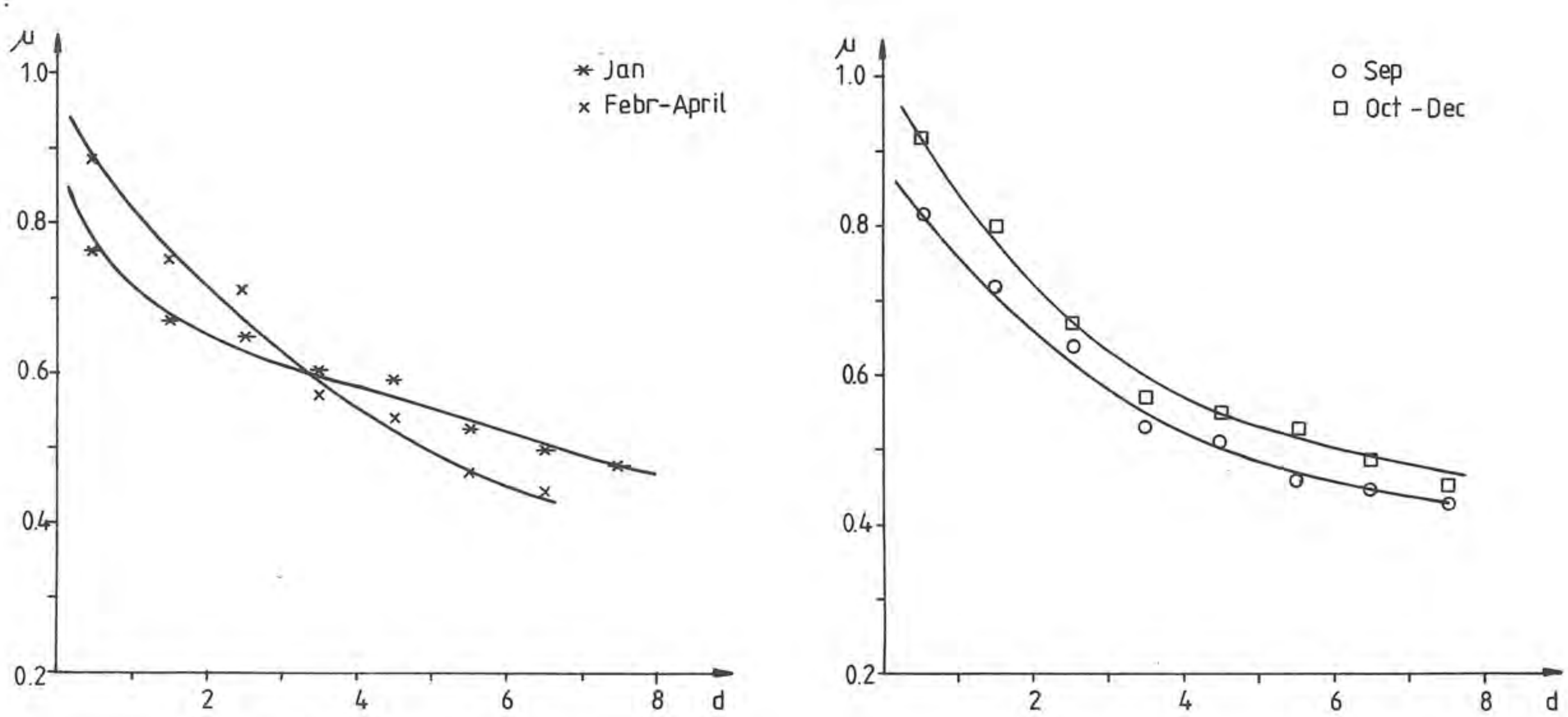
For the computation of the autocorrelations, m_{ij}, three sets of stations were selected, representing the Bothnian Bay/Sea and the central respective the southern part of the Baltic proper. The autocorrelations were computed from corrected monthly sums of precipitation covering the period 1951-1970.

The correlations were computed in a way that made it possible to evaluate the direction between the respective pairs of stations. This way of processing the data was due to the fact that it was of interest to study correlation as a function of direction and in particular the correlation parallel to respective perpendicular to the principal coastal line.

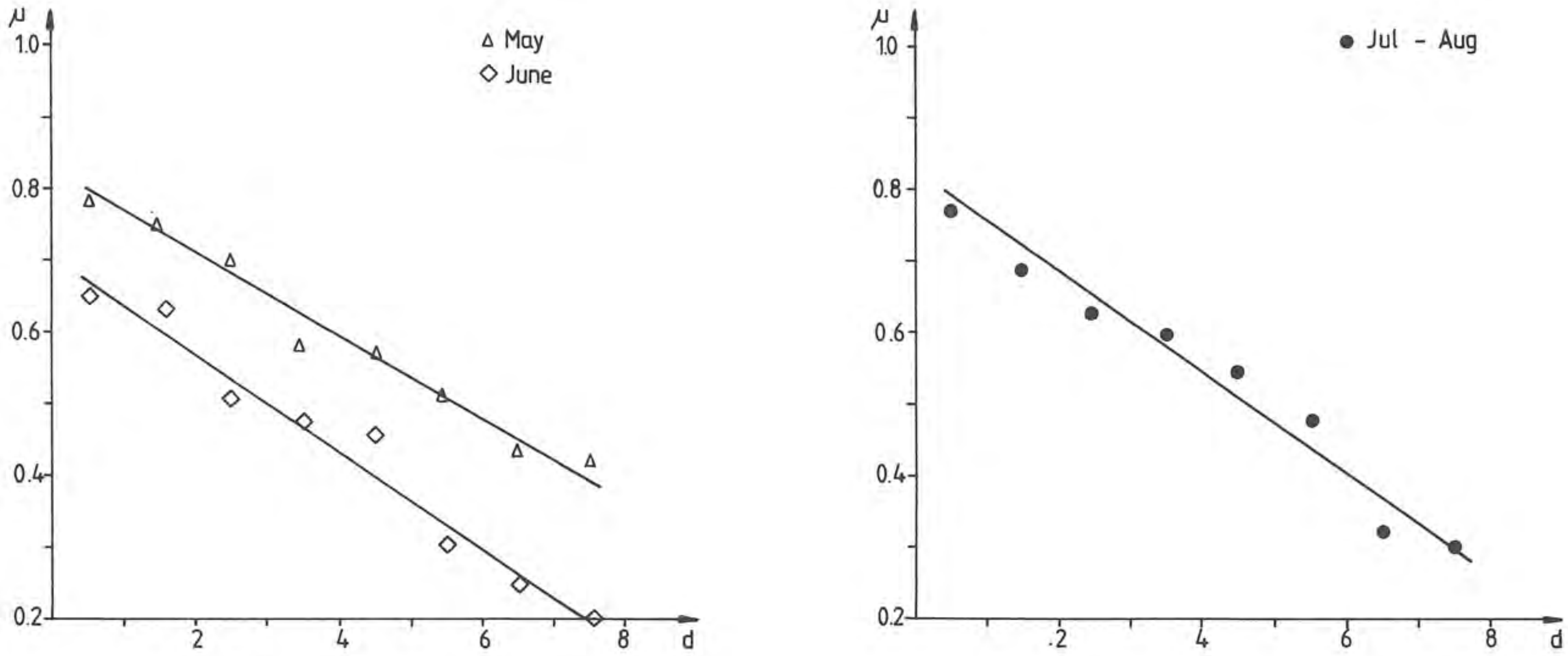
Probably due to the circumstance that monthly sums of precipitation represent the integrated effect of a lot of weather situations/mechanisms no definite results on the correlation according to the direction were obtained.

From statistical considerations - the subsets of data were too small - it was decided to determine the total autocorrelation as a function of distance between stations for all subsets. These results, where the autocorrelation for the respective month is averaged within each distance interval and month is presented in Figures 5-8.

It turned out that the autocorrelations as functions of distance were curved during the cold part of the year, September to April, and during the warm season, May to August, the corresponding shape was such that straight lines could be fitted to the autocorrelations, cfr Figures 7-8.



Figures 5-6 Autocorrelation functions computed by precipitation data from the Baltic Sea. Unit: d = the grid distance, 50 km



Figures 7-8 *Autocorrelation functions computed by precipitation data from the Baltic Sea.*

Unit: d = the grid distance, 50 km

4. THE VERIFICATION OF THE ESTIMATES

The accuracy of the areal estimates are connected with the following computations:

- The correction of point data
- The areal estimation based on corrected point data
- The conversion of precipitation depth to areal values - the reliability of the geometrical data. This error (1 $^o/oo$) is here neglected, see Ehlin and Mattisson (1976).

In the following text the reliability of the computations is investigated.

4.1 The verification of the point correction

The variety of correction methods used for correction of the different stocks of data is briefly presented in the section 2. There is only a limited amount of information available on the accuracy of the corrected point data that were delivered by the respective Baltic bordering country and consequently only a rough error estimate is possible.

A measure of the accuracy of the corrected point values can be expressed as

$$s_\varepsilon^2 = \sum_i \frac{(f_i - f_i)^2}{N}$$

where f_i represents the corrected point value, f_i the true value and N the number of measurements.

In general s_ε is unknown. However, some information on the accuracy of point correction methods is given by special investigations on the errors inherent with precipitation measurements.

The errors due to the aerodynamic deflection of precipitation particles around the gauge has in general the largest magnitude. Other error sources such as the wetting and the evaporation error are about one order of magnitude less. Errors due to the observer, missing data etc can frequently be of importance. However, these errors due to the observer are neglected in this study due to the fact that no information on this subject - which is linked to the operational quality control procedures in the respective country - has been delivered to the element coordinator.

P Allerup and H Madsen (1980) have given approximate expressions for the confidence limits of the correction for the aerodynamic error obtained by the Danish correction method.

For solid precipitation the standard error of the corrected values are of the order 10% (unsheltered station) to 6% (sheltered station) for individual monthly sums of precipitation. For liquid precipitation the corresponding values are reduced approximately by a factor 0.5. The srandard error of the climatological monthly values is estimated to be about 3%, independently of the month.

R Solantie (1977) has estimated the standard error of the total correction for monthly mean values subdivided according to the type of precipitation.

Type of precipitation	Monthly mean sums - Standard error
Dry snow	11
Mixed precipitation and wet snow	5
Rain	2
Drizzle	10

According to L R Struzer and V G Golubev (1976) a system for point correction in USSR gives a correction accuracy of ±10-20% for individual monthly sums and ±2 tp 3% (percentages of the measured monthly sum) for monthly mean precipitation values.

Wielbinska (1977) has undertaken a study on error sources using field data from a special investigation with stations at the Polish coast. From these data the catch coefficient - the ratio between the measured quantity of the standard height of the gauge and the measured value at ground level - was determined for daily and monthly values. The standard deviation of the coefficients ranged for different stations from 16% to 22% for daily measurements and from 4-7% for monthly values. These figures give an indication of the maximum accuracy that can be obtained by use of fixed percentages at the correction.

In conclusion the following figures can be regarded as probable overestimates of the average standard error of correction for the corrected point data sets covering the Baltic Sea.

Table IV Probable overestimates of the average standard errors of correction. Unit: Percentages of the measured value.

Precipitation type	Individual months (%)	Climatological months (%)
Solid	20	10
Liquid	10	5

Individual stations may have larger errors in the corrected monthly sum than the values given in Table IV.

It seems worth noting that no information on the ratio between random and systematic errors in the corrected data seems available.

4.2 The verification of the climatological fields of areal precipitation

The uncertainty of the method applied for the estimation of the areal precipitation 1931-1960 is in particular connected with the weighting function applied and the adjustment of the precipitation gradient by the factor G, cfr section 3.5.1.

The verification, theoretically or experimentally, of the computations is not easy to perform. The accuracy of the estimation procedures is believed to be approximately the same for the coastal areas of all the subbasins. This qualitative statement emanates from the fact that the procedures that have been used for the estimation are basically the same for all subbasins. Sophistication of the method has to a great extent been avoided which somewhat 'facilitates' the verification. The proper verification of the results in the most data sparse areas, such as the interior of the Baltic proper, offers particularly great problems.

Verification by use of independent data. Data from 8 stations along the Swedish coast that were not used at the computation of the climatological grid fields were compared with the corresponding values interpolated from the computed grid fields. For the comparison the point measurements were corrected by the same point correction method which had been used for the point data involved at the estimation of grid values. The result is presented in Table V.

The position of the respective station used for the verification does in general not coincide exactly with a corresponding grid value. Consequently, it seems important to clarify in what way the grid value used for the verification was determined. The following procedures were applied.

- The closest grid value was used for the verification if the distance was less than 10 km to the position of the station.
- The average of two nearby (distance 50 km) grid values was used if the position of the station was lying roughly on a line connecting these grid values.
- The average of the 4 surrounding grid values was used for the verification if the station was located in the central area of the grid square.

Table V *Estimate of the 'accuracy' of the method applied for determination of the climatological precipitation fields 1931-1960. Verification with independent data.*

Station	Deviation between estimated grid values and point values in mm and in % of the measured sum (point corrected value)									
	January		April		July		October		Year	
	mm	%	mm	%	mm	%	mm	%	mm	%
Stora Fjäderägg* - at the border of the Bothnian Sea/Bay 63°49', 21°0'	14	34	-2	-5	0	0	1	2	18	3
Brämö* - at the Bothnian Sea 62°13', 19°2'	14	36	6	19	8	16	7	14	40	8
Grönskär - at the N Baltic proper 59°17', 18°59'	4	9	-2	-6	7	16	0	0	-2	0
Östergarn (at spit of E Gotland) - at the Baltic proper 57°27', 18°59'	-1	-2	0	0	-1	-2	0	0	27	5
Utklippan (Note: Data 1941-60 reduced to 1931-60) - at the southern part of the Baltic proper 55°57', 15°42'	0	0	2	7	6	11	4	9	50	10
Hallands Väderö - at Kattegatt 56°27', 12°33'	-11	-17	0	0	2	2	3	5	9	1
Pater Noster** - at Skagerack 57°54', 11°28'	11	23	4	11	11	18	8	12	91	13
Hållö** - at Skagerack 58°20', 11°13'	-9	-13	-4	-9	2	3	5	6	-61	-14
All stations %		5		1		8		6		4

* The quality of the measurements is not quite satisfactory: at inspection visits leakage of the gauge has been stated at certain periods.

** The closest grid value in Kattegatt, located at about 57°20'N, 11°20'E, was used for the verification.

No attempt was made to use the gradient in the grid field for the interpolation of a quantity for the verification as this mode of action might have biased the result.

The derivations illustrated in Table V are explained by the integrated effect of the following factors:

- error in the point correction
- error in the spatial estimation
- error due to the displacement between grid point data and the corresponding stations

The table V shows a large deviation for some stations in January with a maximum discrepency of 36% between the grid data and the corresponding corrected measured sum at the station 'Stora Fjäderägg'. Some rather large deviations also occur in July, where for instance, 'Pater Noster' indicates a deviation of 18%.

The mean deviation for the respective month and the year is significantly less than the deviation from the individual month: the average monthly deviations range from 1% to 8% and the average yearly deviation is 4%. If the corrected point values thus would represent the true values for these 8 stations then the spatial estimation would give an overestimate of 4% (if we neglect the above indicated 'displacement effect').

However, the limited amount of information in Table V does not permit any detailed conclusions on the reliability of the estimates.

The total error Δ_i at the respective grid point i can be expressed as

$$\Delta_i = \alpha_i + \varepsilon_i, \quad \text{where}$$

α_i represents the systematic effects of the point correction and the spatial estimation of precipitation at point 'i'

ε_i is the random component of the error

At the computation of areal precipitation within the subbasin k with N_k grid points we obtain:

$$\Delta_k = \overline{d}_k + \frac{\Sigma\ \varepsilon_i}{N_k} \quad \text{where} \qquad (10)$$

$\overline{d}_k$ is the average of the systematic errors.

In Table IV it was concluded that the average standard error of the corrected climatological point data was probably overestimated by 10% for solid precipitation and by 5% for liquid precipitation. Consequently the reliability of the grid value cannot be expected to be more accurate than these figures.

To give a rough quantitative example of the accuracy:
The average accuracy of the grid values are assumed to be 20% for solid precipitation and 10% for liquid precipitation. This assumption is not contradicted by the figures in Table V, where the average deviation for the 8 stations is not exceeding 8%.

The ratio between systematic and random errors is unknown. With an influence of systematic errors of 25% we obtain

$$\Delta_k = 5 + \frac{15}{N_k} \quad \text{(solid precipitation)}$$

$$\Delta_k = 2.5 + \frac{7.5}{N_k} \quad \text{(liquid precipitation)}$$

The smallest subbasin contains 7 (= N_k) grid points. The second term consequently ranges from 0% to 2% for solid precipitation and 0% to 1% for liquid precipitation.

The areal estimate will consequently in this example be within ±4% respective ±6% of the true areal, monthly value.

Verification related to spatial consistency. If serious systematic errors exist in some of the stocks of corrected data delivered by the respective Baltic bordering country it is obvious that these errors would cause deviations in the isohyetal pattern at the border of the respective country. From the climatological precipitation maps illustrated in section 5.2 it is quite clear that no such indications of missadaption of isohyets exist.

If a systematic difference existed between the magnitude of the corrected data on for instance the eastern and western side of the Baltic proper, this would be recognized as a E-W gradient in the precipitation field during spring: during this season with relatively cold water no meteorological factors influences the spatial pattern with the result of a general E-W gradient. In this respect the maps for February-April 1931-1960 seems consistent and supports - qualitatively - the impression of small systematic deviations between the magnitude of point corrections between the various countries.

4.3 The verification of the areal estimates for individual months and years

The method for determination of areal values for the individual months/years covering the historical period 1951-1970 and the Pilot Year 1975/76 is described in section 3.2.2. To get an expression for the relative error the equation (6) is substituted into the equation (5) with the following result:

$$e = 1 - \Sigma\Sigma \ \mu_i \ \mu_j \ m_{ij} - \Sigma\varepsilon \ \mu_i^2 \qquad (11)$$

The measure of the relative error E in the areal estimates was then computed

$$E = \frac{\sqrt{(\tilde{f}_o' - f_o')^2}}{\bar{\tilde{f}}_k \cdot N_k} = \frac{s\sqrt{e}}{\bar{\tilde{f}}_k \cdot N_k} \qquad (12)$$

where

$\bar{\tilde{f}}_k$ represents the average of grid point values for subbasin k

N_k is the number of grid points within the respective area

The assumption made in section 3.2.2 may be uncorrect and consequently the formula (7) probably is an underestimate of the error. To get a probable overestimate of the error in the areal precipitation values the following estimate is computed:

$$E^+ = E(1 + q \ N_k) \qquad (13)$$

where q represents an overestimate of the systematic error influence, which is not eliminated at the averaging of the grid data. It seems relevant to assume that q is related to the interpolation error E, (or e) due to the fact that this quantity reflects the available amount of information.

From qualitative judgements it seems reasonable that a systematic error probably is less than 25% of the random part of the error influence. With q = 0.25 the following overestimate is obtained on a monthly respective yearly basis.

Table VI *The relative standard error, E^+, of areal precipitation values - a probable overestimate. The figures are expressed in percentages (of the areal estimates).*

Period: individual months 1951-1970.

	Error estimate E^+. Percentages error of respective areal estimate. Individual months 1951-1970							
Subbasin No	1	2	3	4	5	6	7	1-7
%	12	10	11	13	8	11	10	9

The values on E^+ presented in Table VII represents an overestimate of the areal relative error for an individual month 1951-1970. The variation between months was small.

5. RESULTS OF THE COMPUTATIONS

5.1 Areal estimates and comparison with previous results

The previous investigations on the areal precipitation within the Baltic Sea have not quantitatively taken the error sources inherent with point precipitation measurements into account. These error influences, dominated by the aerodynamic deflection of precipitation particles around the instrument, give the integrated effect of a deficit of precipitation. These error effects is of special importance for the determination of areal precipitation within the Baltic Sea due to the fact that the relevant stations, where data are available, are situated on wind exposed peninsulas, spits, islands and lighthouses.

The fact that corrected point measurements have been used in this project means that the areal estimates can be expected to be larger than the results from the previous investigations, where uncorrected point data in general have been processed.

Witting (1918) investigated the conditions in the Baltic Sea for the period 1892-1912 to acquire information on the spatial pattern of precipitation - and evaporation - over land, respective over the sea. The computations were performed on uncorrected point data.

Schulz (1938) drew a map of isohyets and estimated the precipitation to lie within the limites 400-550 mm.

Simojoki (1949) used precipitation data for the period 1886-1935. For a few stations Simojoki applied point corrections based on a method by Korhonen (1944). Due to the fact that detailed information on the site of the gauges frequently was lacking Simojoki used a relationship ч' for the correction:

$$q = \frac{A}{B}, \text{ where}$$

A = Amount of precipitation during winter

B = Amount of precipitation during summer

If q is known for a station with a location sheltered from wind this factor can be used for the point correction at a wind exposed site. Simojoki estimated the average yearly precipitation by use of data from 78 stations.

Brogmus (1952) made use of data from Simojoki's investigation and also from 93 additional stations. The period covered by these additional stations is not specified precisely. Brogmus refers to the investigation by Wüst (1921, 1936, 1938) and stresses the danger of 'direct' extrapolation of the precipitation pattern from land to sea. The precipitation values measured are recommended by Brogmus - with reference to Wüst's results - to be reduced by a factor of about 0.70 to represent the conditions at sea.

Wyrtki (1954) computed the water balance elements for the Baltic Sea covering the period 1926-1930. An areal estimate of 488 mm was obtained by use of data from 48 stations. The areal estimates were reduced by application of the long-term results presented by Brogmus (1952).

Arsenyeva et al (1980) have presented preliminary results on precipitation and evaporation for some selected parts of the Baltic Sea. In this preliminary report estimates of precipitation within 7 squares, each covering $1^{o}x2^{o}$, along parts of the Baltic coast and the Finnish Bay are listed (not all months are covered). The method used for their estimate is based on the approach by Tucker (1961). The estimates are low compared to other investigations and for instance is the estimate of yearly precipitation in the mouth of the Finnish Bay about 35% lower than the value - for the whole bay - given by Simojoki (1949).

The various results are summarized in Table VII.

Table VII Comparison of areal precipitation estimates for the Baltic Sea

Subbasin No	Areal precipitation (mm) - yearly averages				
	B Dahlström*		W Brogmus	H Simojoki	R Witting
	1931-60	1951-70	(1886-1935)	1886-1935	1898-1912
1	554	535	405	449	533
2	598	572	425	473	554
3	677	593	560	576	595
4	653	590	580	569	560
5	655	628	473	544	570
6	685	692	515		
7	684	701			
1-5	635	603	470	525	565
1-6	638	607	474		
1-7	639	613			

* present investigation

The circumstance that the estimates are made for different periods and the fact that no quantitative error estimate of the areal values has been presented in the previous investigations are factors that make a 'direct' comparison of the estimates difficult.

It seems quite clear that the significantly higher values of the precipitation depth obtained by the present investigation is due to the use of corrected point data.

The relatively low values obtained by W Brogmus are mainly explained by his assumption on the precipitation gradient between land and sea.

On the following pages the areal estimation of the Baltic Sea and its subbasins are illustrated in Tables VIII-XI.

Table VIII The climatological period 1931-60 - Areal estimates

PERIOD: 1931-1960
COMPUTATIONS BASED ON CORRECTED POINT PRECIPITATION DATA

SUB-BASIN	AREA KM**2	PRECIPITATION IN MM YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	36260.00	554	43	33	29	34	30	46	57	64	62	53	55	48
2	79257.00	598	52	35	29	33	45	45	58	69	63	57	64	57
3	29498.00	677	57	41	33	41	45	56	70	79	68	67	64	56
4	17913.00	653	55	40	33	36	41	50	73	73	72	64	58	58
5	209930.00	655	57	44	35	39	40	47	70	72	66	64	61	60
6	20121.00	685	58	45	38	46	46	53	75	81	65	65	53	55
7	22287.00	684	57	43	34	41	39	51	79	78	73	69	63	57
TOTAL	415266.00	639	55	41	33	38	38	48	67	72	66	62	61	58

SUB-BASIN	AREA KM**2	PRECIPITATION VOLUME KM**3 YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	36260.00	20.09	1.56	1.20	1.05	1.23	1.09	1.67	2.07	2.32	2.25	1.92	1.99	1.74
2	79257.00	47.40	4.12	2.77	2.30	2.85	2.62	3.57	4.60	5.47	4.99	4.52	5.07	4.52
3	29498.00	19.97	1.65	1.21	.97	1.21	1.33	1.65	2.06	2.33	2.01	1.98	1.89	1.65
4	17913.00	11.71	.99	.72	.59	.64	.73	.90	1.31	1.31	1.29	1.15	1.04	1.04
5	209930.00	137.54	11.97	9.24	7.35	8.19	8.40	9.87	14.70	15.11	13.86	13.44	12.81	12.60
6	20121.00	13.81	1.17	.91	.76	.93	.93	1.07	1.51	1.63	1.31	1.31	1.17	1.11
7	22287.00	15.25	1.27	.96	.76	.91	.87	1.14	1.76	1.74	1.63	1.54	1.40	1.27
TOTAL	415266.00	265.36	22.84	17.03	13.70	15.78	15.78	19.93	27.86	29.90	27.41	25.75	25.33	24.09

Table IX *The period 1951-70 - Areal estimates*

PERIOD: 1951-1970
COMPUTATIONS BASED ON CORRECTED POINT PRECIPITATION DATA

SUB-	AREA		PRECIPITATION IN MM											
BASIN	KM**2	YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	36260.00	535	41	35	33	29	34	37	48	66	57	48	56	51
2	79257.00	572	47	40	30	33	34	37	52	68	56	54	62	59
3	29498.00	593	43	33	28	35	40	40	66	71	66	64	57	50
4	17913.00	590	41	31	25	34	40	41	66	68	73	63	58	50
5	209930.00	628	51	40	31	39	43	43	65	73	66	57	62	58
6	20121.00	692	54	44	37	46	50	52	76	82	61	62	68	60
7	22287.00	701	57	42	36	46	45	49	72	85	66	74	68	61
TOTAL	415266.00	613	49	39	31	37	41	42	62	72	63	58	62	57

SUB-	AREA		PRECIPITATION VOLUME KM**3											
BASIN	KM**2	YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	36260.00	19.40	1.49	1.27	1.20	1.05	1.23	1.34	1.74	1.39	2.07	1.74	2.03	1.85
2	79257.00	45.34	3.73	3.17	2.38	2.62	2.69	2.93	4.12	5.39	4.44	4.28	4.91	4.68
3	29498.00	17.49	1.27	.97	.83	1.03	1.18	1.18	1.95	2.09	1.95	1.89	1.68	1.47
4	17913.00	10.58	.73	.56	.45	.61	.72	.73	1.18	1.22	1.31	1.13	1.04	.90
5	209930.00	131.87	10.71	8.40	6.51	8.19	9.03	9.03	13.65	15.32	13.86	11.97	13.02	12.18
6	20121.00	13.95	1.09	.89	.74	.93	1.01	1.05	1.53	1.65	1.23	1.25	1.37	1.21
7	22287.00	15.62	1.27	.94	.80	1.03	1.00	1.09	1.60	1.89	1.47	1.65	1.52	1.36
TOTAL	415266.00	254.57	20.35	16.20	12.87	15.36	17.03	17.44	25.75	29.90	26.16	24.09	25.75	23.67

Table X The Pilot Study Year 1975 - Areal estimates

PERIOD: 1975-1975
COMPUTATIONS BASED ON CORRECTED POINT PRECIPITATION DATA

SUB-BASIN	AREA KM**2	PRECIPITATION IN MM YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	36260.00	491	54	14	14	27	42	32	16	80	71	38	52	51
2	79257.00	459	46	18	25	28	46	40	28	50	67	32	38	41
3	29498.00	567	51	23	29	72	42	44	43	59	47	34	55	68
4	17913.00	513	48	15	34	66	47	22	41	25	44	38	46	87
5	209930.00	482	48	17	36	45	43	20	49	32	58	49	40	45
6	20121.00	517	77	15	31	61	32	20	57	27	68	36	58	35
7	22287.00	578	96	13	28	55	33	26	62	46	76	45	56	42
TOTAL	415266.00	493	52	17	31	44	43	27	42	42	61	42	44	48

SUB-BASIN	AREA KM**2	PRECIPITATION VOLUME KM**3 YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	36260.00	17.81	1.96	.51	.51	.98	1.52	1.16	.58	2.90	2.57	1.38	1.89	1.85
2	79257.00	36.39	3.65	1.43	1.98	2.22	3.65	3.17	2.22	3.96	5.31	2.54	3.01	3.25
3	29498.00	16.73	1.60	.68	.86	2.12	1.24	1.30	1.27	1.74	1.39	1.00	1.62	2.01
4	17913.00	9.18	.86	.27	.61	1.18	.84	.39	.73	.45	.79	.68	.82	1.56
5	209930.00	101.22	10.08	3.57	7.56	9.45	9.03	4.20	10.29	6.72	12.18	10.29	8.40	9.45
6	20121.00	10.39	1.55	.30	.62	1.23	.64	.40	1.15	.54	1.37	.72	1.17	.70
7	22287.00	12.89	2.14	.29	.62	1.23	.74	.58	1.38	1.03	1.69	1.00	1.25	.94
TOTAL	415266.00	204.71	21.59	7.06	12.87	18.27	17.86	11.21	17.44	17.44	25.33	17.44	18.27	19.93

Table XI The Pilot Study Year 1976 - Areal estimates

PERIOD: 1976-1976

COMPUTATIONS BASED ON CORRECTED POINT PRECIPITATION DATA

SUB-	AREA		PRECIPITATION IN MM											
BASIN	KM**2	YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	36260.00	412	47	39	27	21	17	23	51	19	45	26	60	37
2	79257.00	517	42	29	37	20	18	39	39	30	68	30	80	85
3	29498.00	548	52	22	46	37	27	50	56	44	61	29	60	64
4	17913.00	593	75	13	40	58	36	57	39	35	53	27	71	89
5	209930.00	567	79	14	36	41	46	32	45	27	51	41	54	101
6	20121.00	493	90	12	21	25	71	15	27	16	43	64	39	70
7	22287.00	541	66	19	17	25	51	21	22	19	48	113	58	82
TOTAL	415266.00	539	67	20	35	34	38	33	43	27	54	41	60	87

SUB-	AREA	YEAR	PRECIPITATION VOLUME KM**3											
BASIN	KM**2	YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	36260.00	14.93	1.70	1.41	.98	.76	.62	.83	1.85	.69	1.63	.94	2.18	1.34
2	79257.00	40.99	3.33	2.30	2.93	1.59	1.43	3.09	3.09	2.38	5.39	2.38	6.34	6.74
3	29498.00	16.17	1.53	.65	1.36	1.09	.80	1.47	1.65	1.30	1.80	.86	1.77	1.89
4	17913.00	10.61	1.34	.23	.72	1.04	.64	1.02	.70	.63	.95	.48	1.27	1.59
5	209930.00	119.05	16.58	2.94	7.56	8.61	9.66	6.72	9.45	5.67	10.71	8.61	11.34	21.20
6	20121.00	9.91	1.81	.24	.42	.50	1.43	.30	.54	.32	.87	1.29	.78	1.41
7	22287.00	12.06	1.47	.42	.38	.56	1.14	.47	.49	.42	1.07	2.52	1.29	1.83
TOTAL	415266.00	223.83	27.82	8.31	14.53	14.12	15.78	13.70	17.86	11.21	22.42	17.03	24.92	36.13

5.2 Illustrations of the spatial and temporal distribution of precipitation

The spatial distribution

Figures 9 to 21 illustrate the climatological precipitation fields for the period 1931-60.

Some mechanisms that influences the spatial distribution of precipitation in the Baltic Sea are summarized below:

Precipitation is enhanced by the following factors:

I Reinforcement or creation of precipitation systems due to vertical transport upwards of sensible and latent heat from a relatively warm sea surface.

II "Spill-over"*) effect of convective activity over land. The convective cells/systems created over land are advected from land to the coastal zone and to the sea. The decay/regeneration of the precipitation systems are dependent on the atmospheric stability conditions over the sea.

III Effects of the configuration of ice covered surfaces and free water surfaces. Formation of cold air above an ice covered surface and - for instance - advection of this cold air southward can sharpen the thermal contrasts and intensify precipitation systems.

IV Influence on precipitation from frictional convergence. If the wind blows along the coast with land to the right there will be a region of frictional convergence, and consequently upward motion and increased precipitation, along the coast.

"Spill-over"*) effects due to oreigenic**) features.

a. Effects due to oreigenic upglide with increased condensation and precipitation. The retardation of fronts due to topographic features may also be important.

b. Horizontal deflection and convergence of the air current due to topographic features.

V Miscellaneous mechanisms which are not discussed here.

The above factors can analogously be discussed in terms of damping influences on precipitation systems. For instance cold sea water, subsidence etc acts towards less efficiency of the precipitation processes.

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*) "Spill-over effects" is here introduced for a precipitation system, in particular convective mechanisms, which are generated over land (or land features as islands) but affects precipitation over the sea.

**) "Oreigenic" (="generated by mountain") is, in accordance with the proposal of T Bergeron used instead of orographic ("described by mountain").

Discussion of some selected features on the precipitation maps

January: Southern part of the Baltic Sea: Rather smooth distribution with some maxima along the coasts and in the northern part of the Baltic proper, mainly due to the effects I and IV.

In the western, middle part of the Gulf of Bothnia there is a conspicious maximum zone of precipitation. This maximum zone has previously been indċated by Brogmus (1952, p 25) on a map for November-April and also by Simojoki, but less pronounced, on a yearly map (Simojoki, 1949, p 17).

The main physical factor behind this maximum zone is probably of type IV: A part of the Swedish coast, named "the high altitude coast", is situated within this zone and the terrain is composited by large elements of roughness. The stirring of the atmosphere when the general flow passes this region probably generates large turbulent eddies and the precipitation release of type IV is generated. The oreigenic effects may also interact with the effects due to ice configuration (III).

February and March: Due to the damping effects connected with cold sea water (reverse of effect I) practically no gradients occur in the precipitation field.

April and May: Maximum zones (in April) are moving from the southern part of the Baltic proper upwards along the eastern coast (cfr the map of May). These features are due to the onset of the convective season over land (effect II).

June-August: The gradient in the Baltic proper in the N-S direction is probably the result of an intensified convective activity southward (effect II).

The interesting E-W gradient in the Baltic proper might tentatively be explained by a general subsidence in the large scale flow in a zone east of the Swedish coast. More distant from the Swedish coast the subsidence then would cease and explain the E-W gradient of the precipitation field.

September-December: The precipitation distribution is to a large extent explained by the effect I.

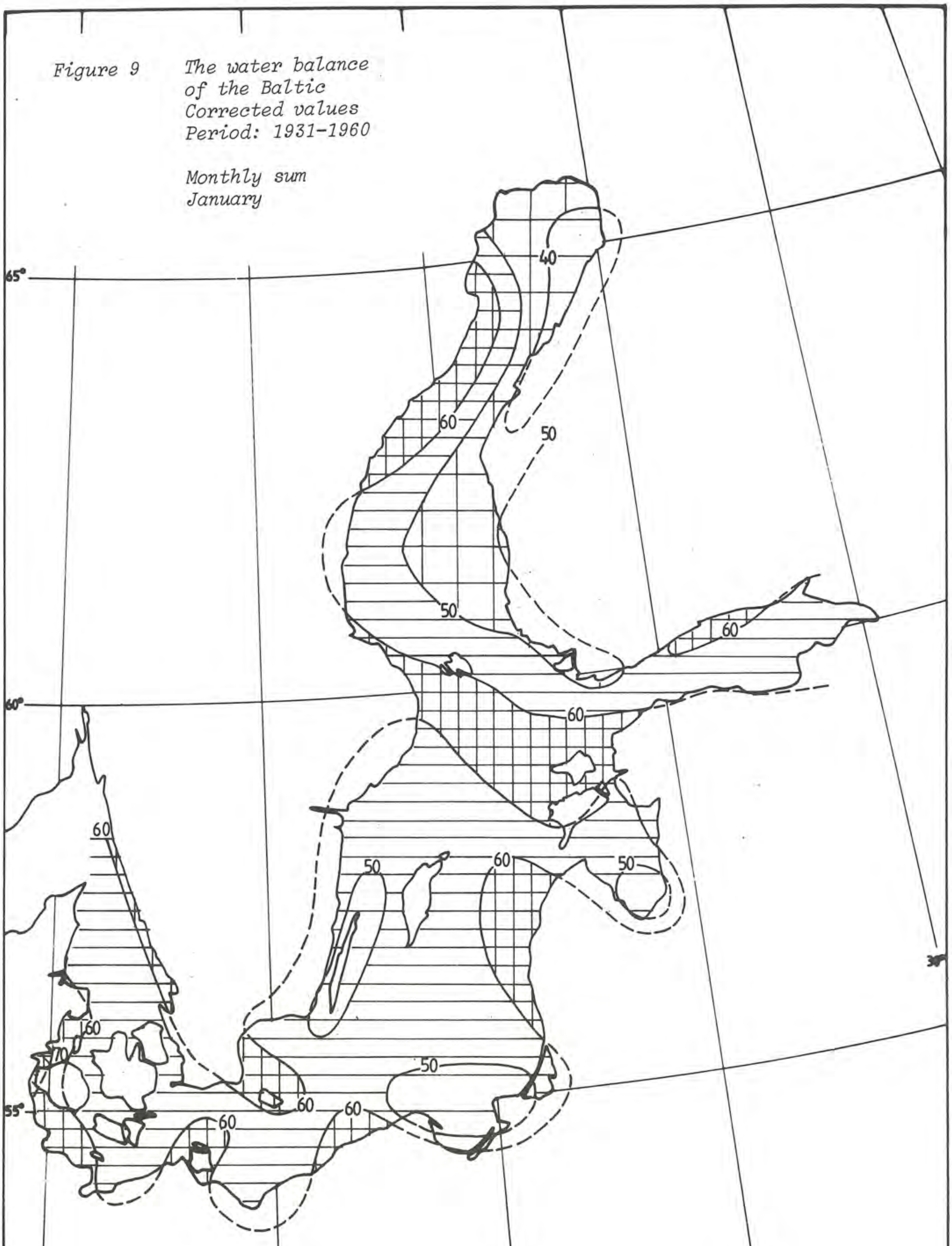
Figure 9
The water balance of the Baltic
Corrected values
Period: 1931-1960
Monthly sum
January
65°
60°
55°
10°
15°
20°
25°
30°
40
60
50
50
60
60
60
50
60
50
60
70
50
60
60
60

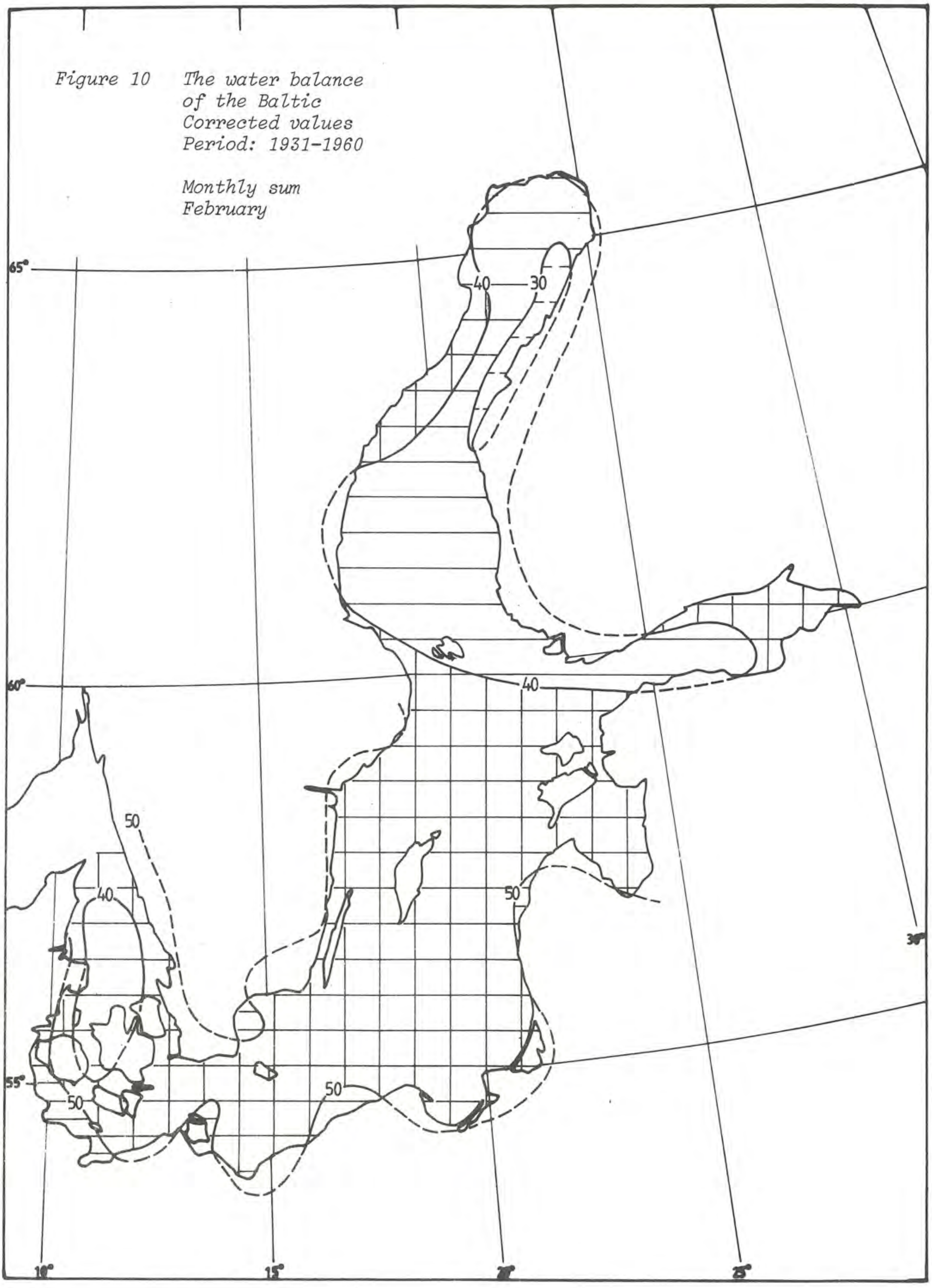
Figure 10 The water balance of the Baltic
Corrected values
Period: 1931-1960
Monthly sum
February
65°
60°
55°
10°
15°
20°
25°
30°
40
30
40
50
40
50
50
50

Figure 11 The water balance of the Baltic
Corrected values
Period: 1931-1960
Monthly sum
March
30
30
30
40
40
65°
60°
55°
10°
15°
20°
25°
30°


Figure 12 The water balance of the Baltic
Corrected values
Period: 1931-1960
Monthly sum
April
40
40
40
40
40
40
50
50
65°
60°
55°
30°
10°
15°
20°
25°

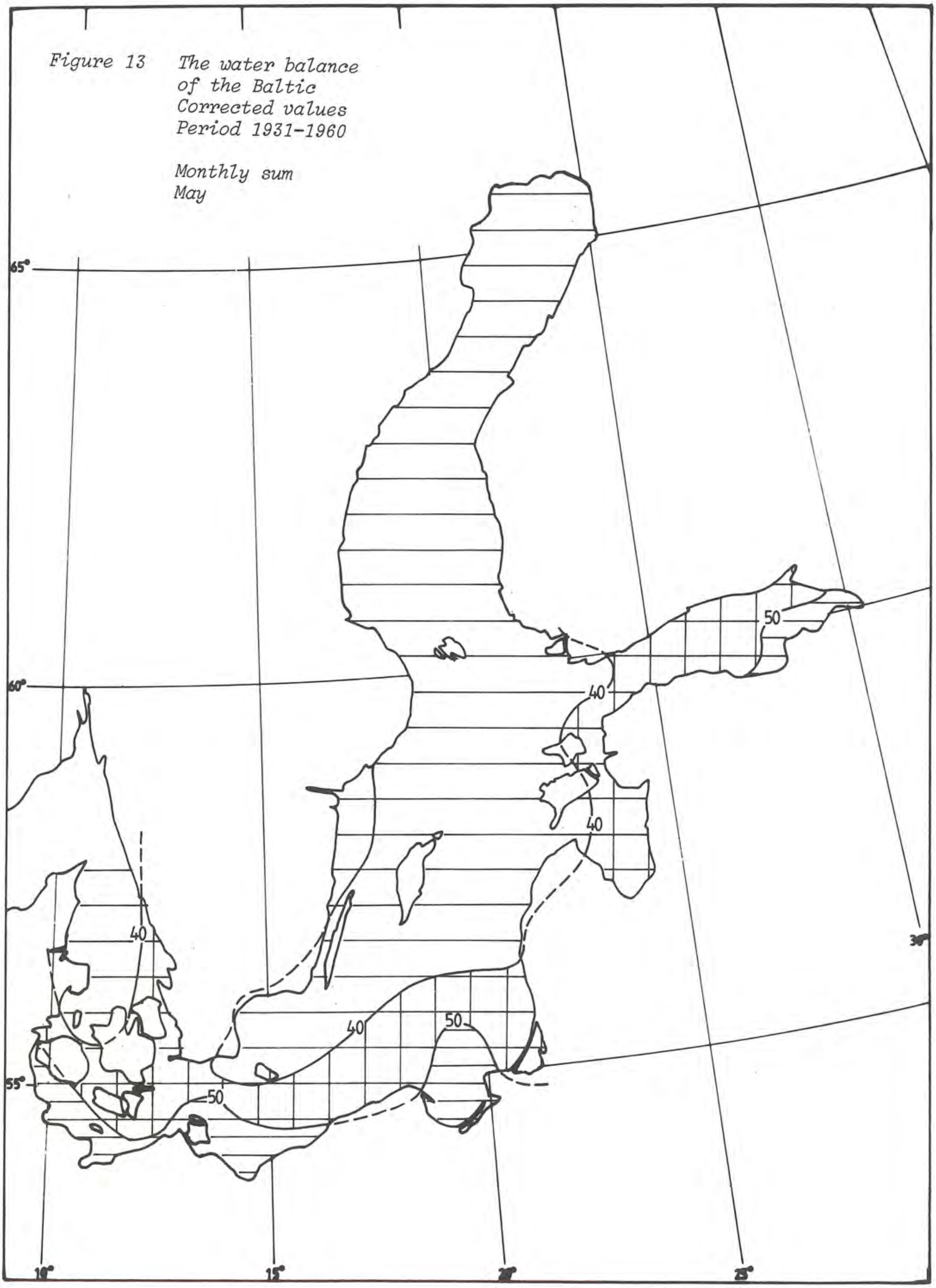
Figure 13 The water balance
of the Baltic
Corrected values
Period 1931-1960

Monthly sum
May
65°
60°
55°
10°
15°
20°
25°
30°
50
40
40
40
40
50
50

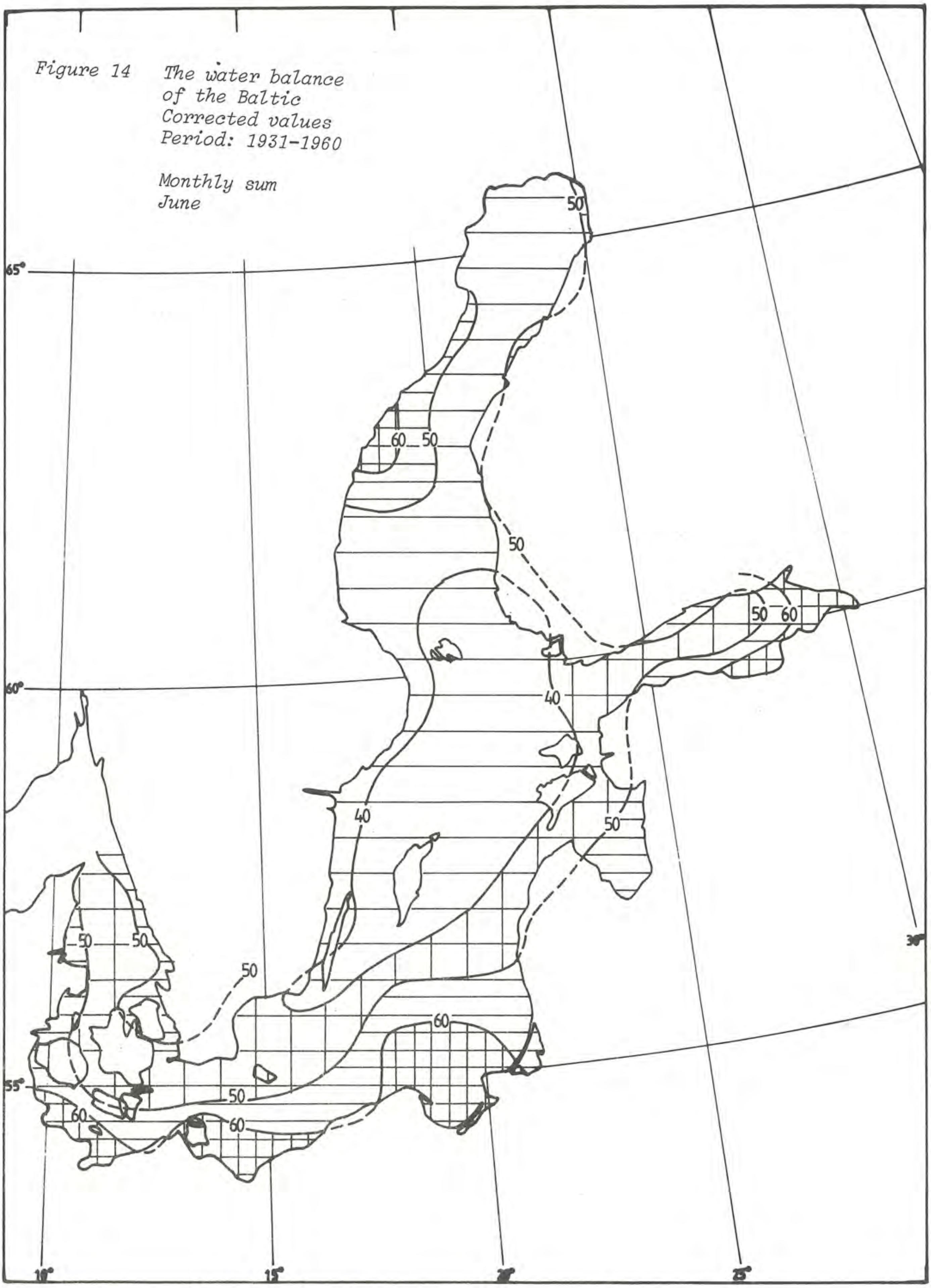
Figure 14 The water balance
of the Baltic
Corrected values
Period: 1931-1960
Monthly sum
June
65°
60°
55°
10°
15°
20°
25°
30°
50
60
50
50
40
40
50
50
60
50
50
50
60
50
60
60

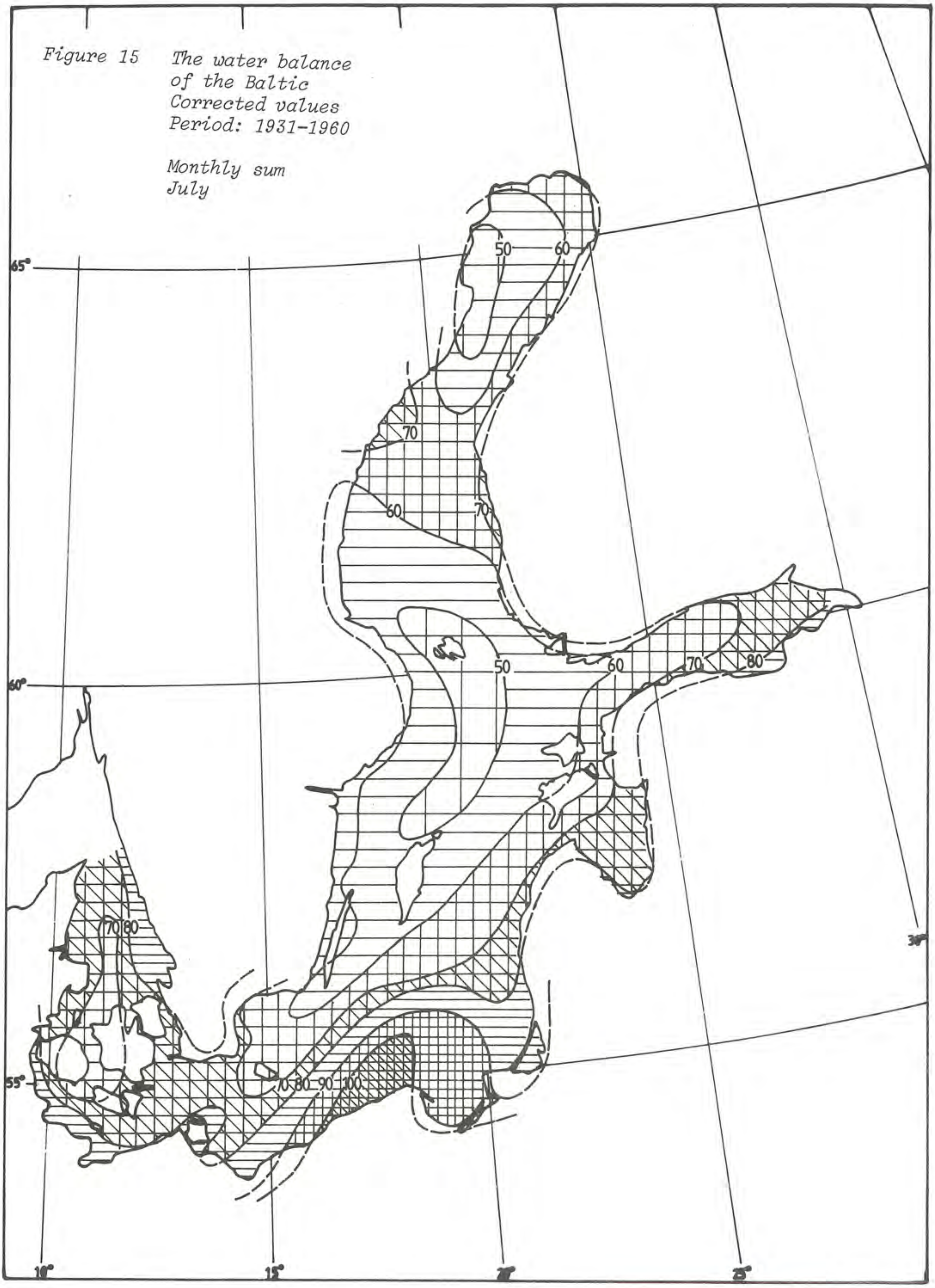
Figure 15 The water balance of the Baltic
Corrected values
Period: 1931-1960
Monthly sum
July
50
60
70
60
70
50
60
70
80
70
80
70
80
90
100
65°
60°
55°
10°
15°
20°
25°
30°

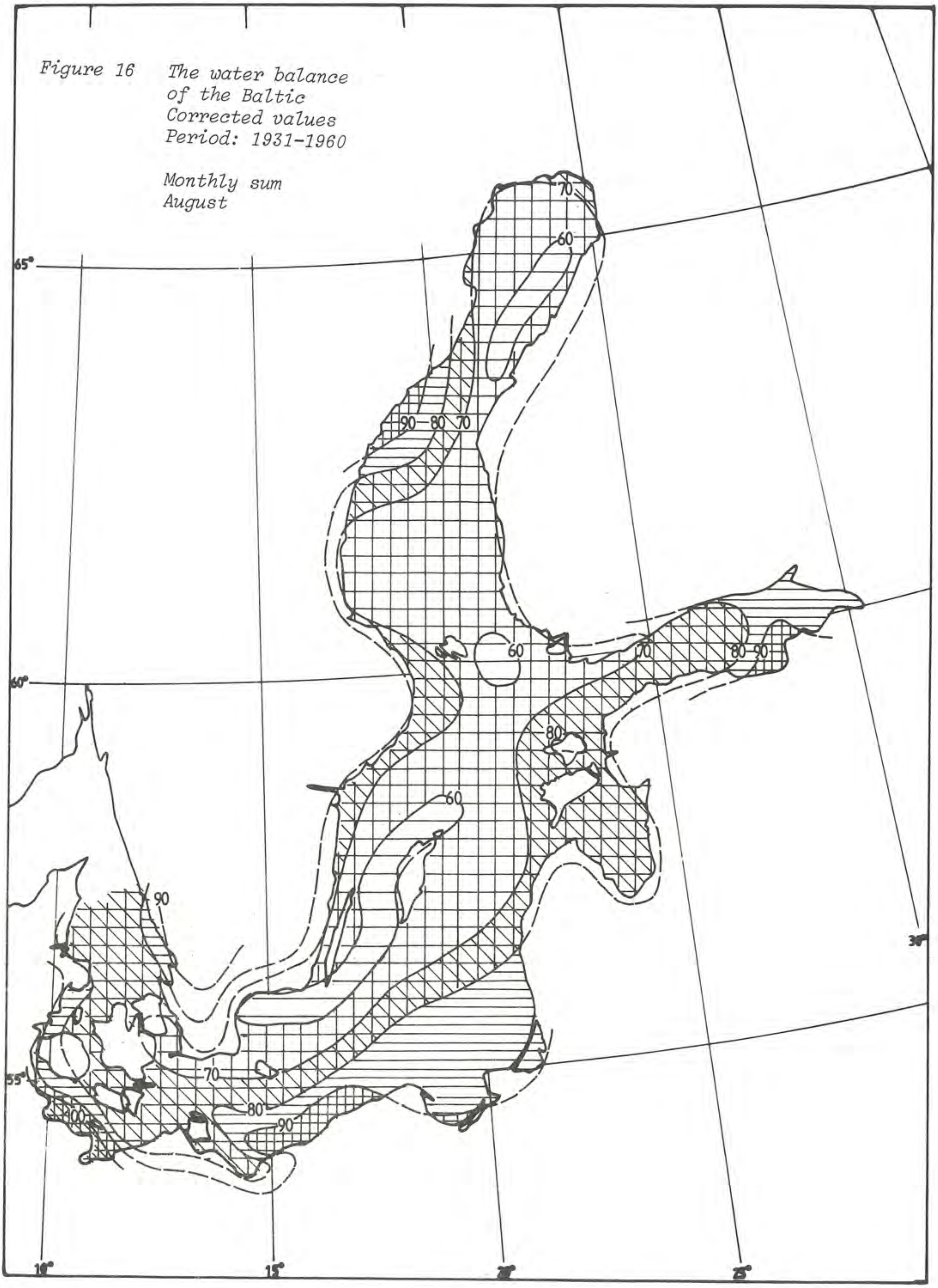

Figure 16 The water balance of the Baltic Corrected values Period: 1931-1960

Monthly sum August

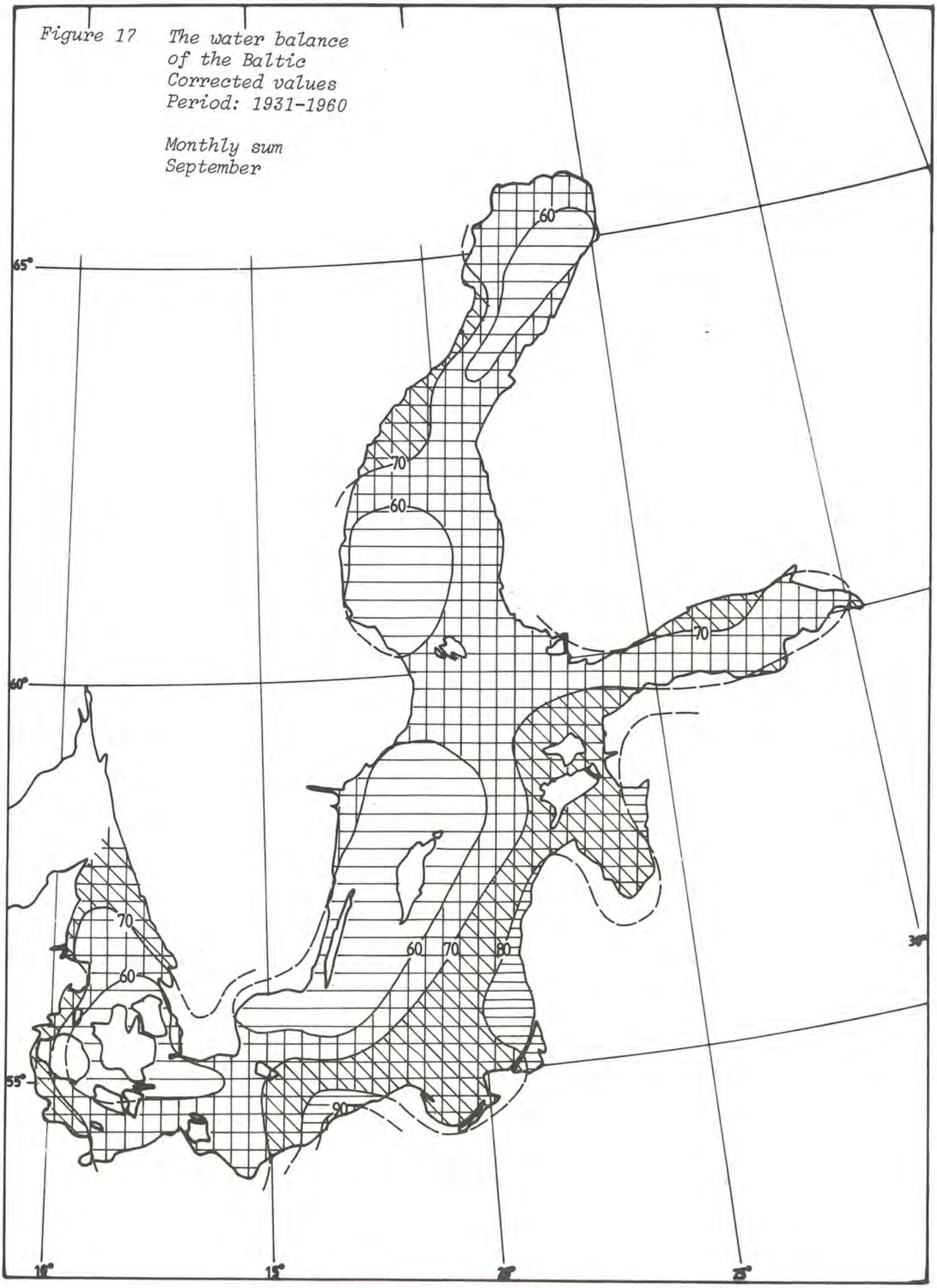
Figure 17 The water balance
of the Baltic
Corrected values
Period: 1931-1960

Monthly sum
September
60
70
60
70
70
60
60
70
80
90
65°
60°
55°
30°
10°
15°
20°
25°

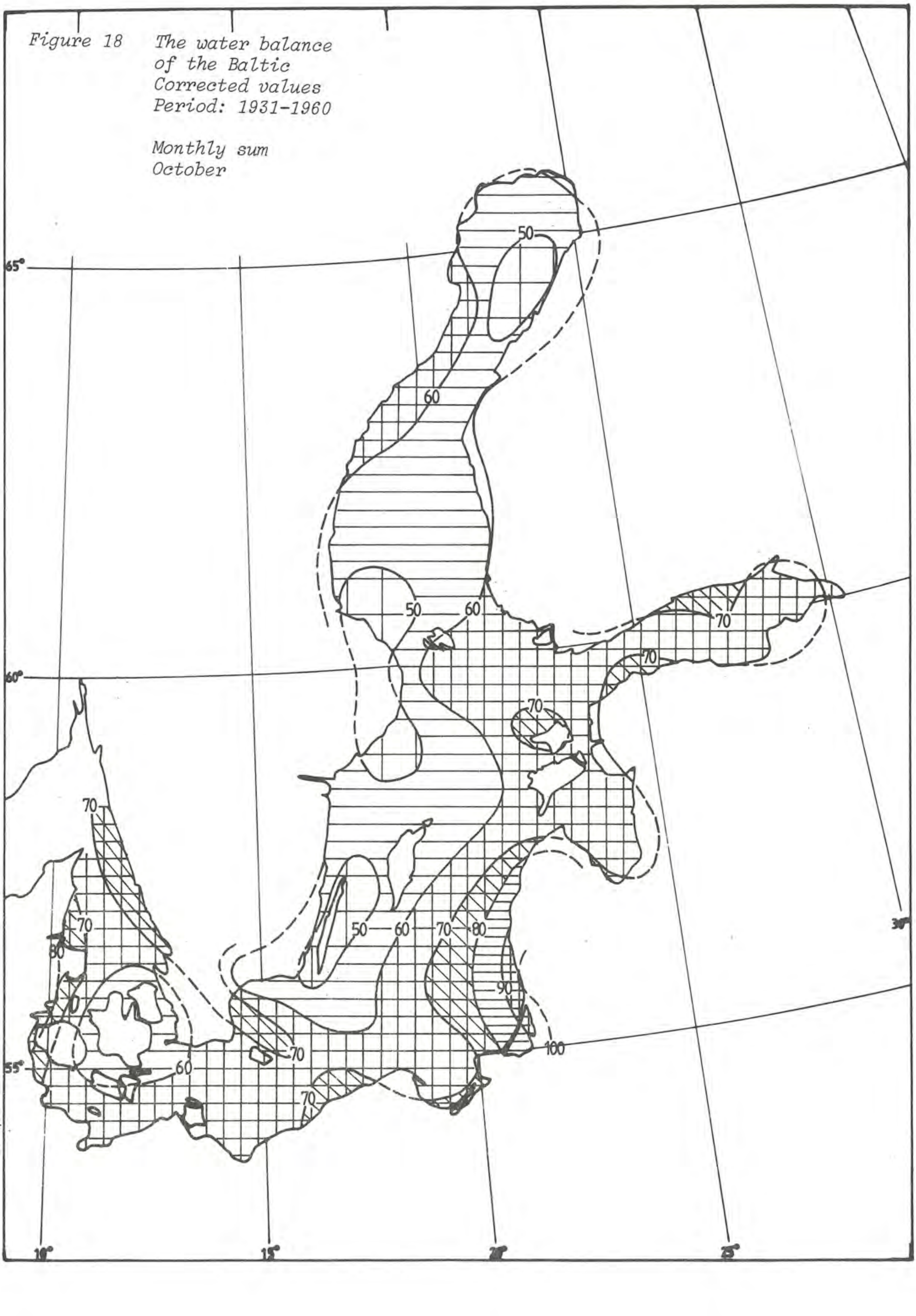
Figure 18 The water balance
of the Baltic
Corrected values
Period: 1931-1960

Monthly sum
October
50
60
50
60
70
70
70
70
70
80
50
60
70
80
90
100
70
60
70
65°
60°
55°
30°
10°
15°
20°
25°

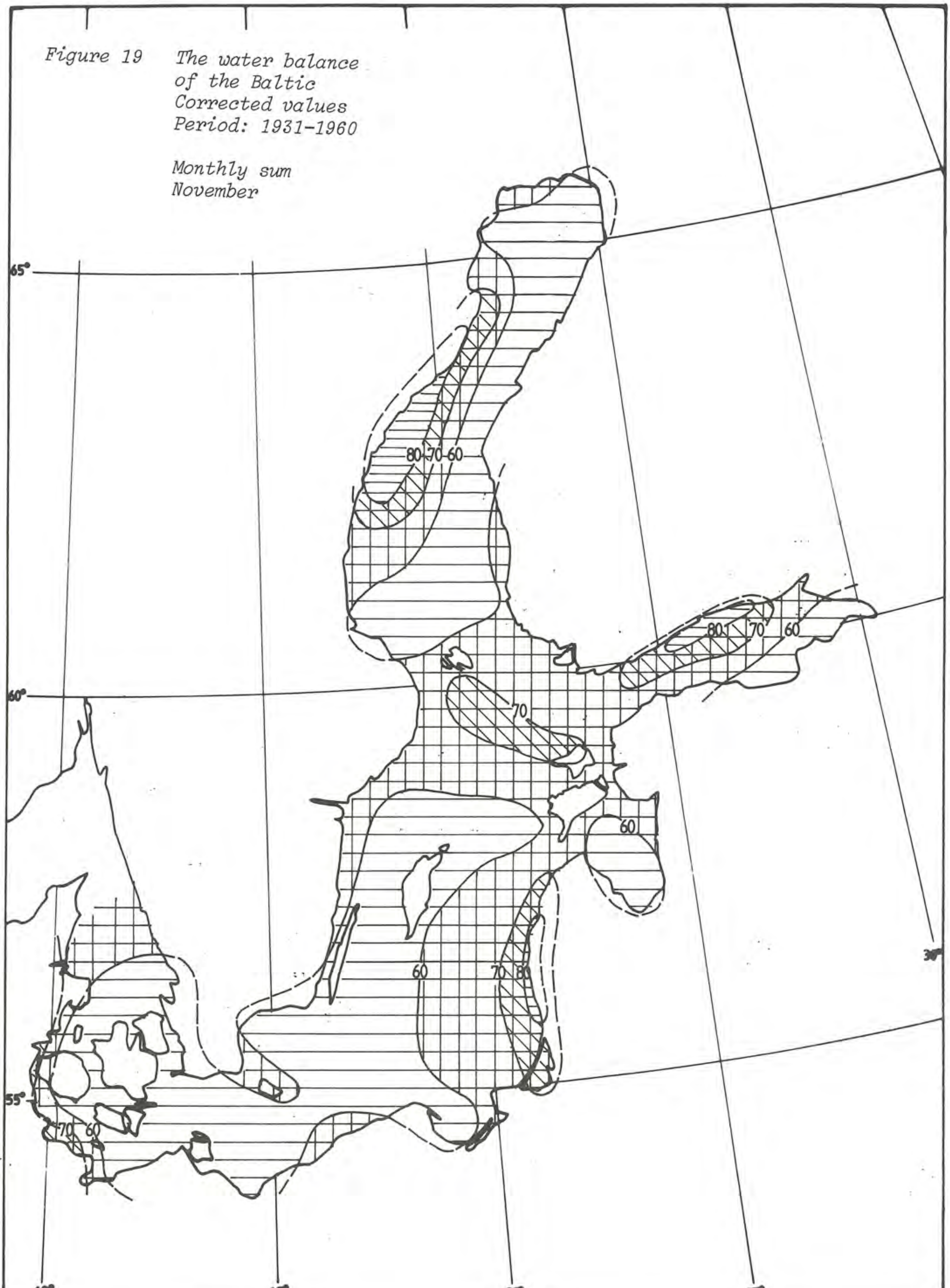

Figure 19 The water balance of the Baltic
Corrected values
Period: 1931-1960
Monthly sum
November
65°
60°
55°
10°
15°
20°
25°
30°
80 70 60
80 70 60
70
60
60
70 80
70 60

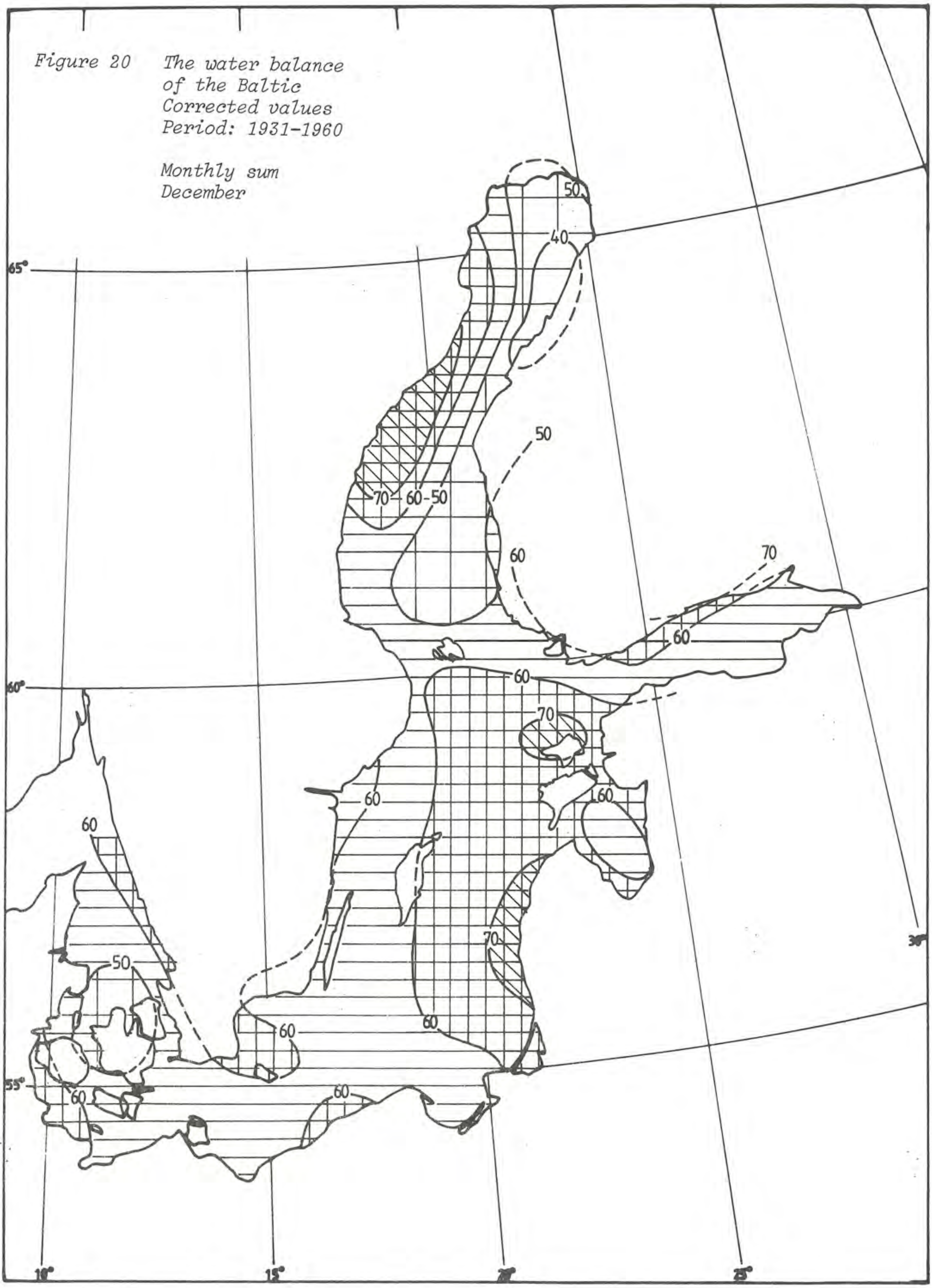

Figure 20 *The water balance of the Baltic*
Corrected values
Period: 1931-1960

Monthly sum
December

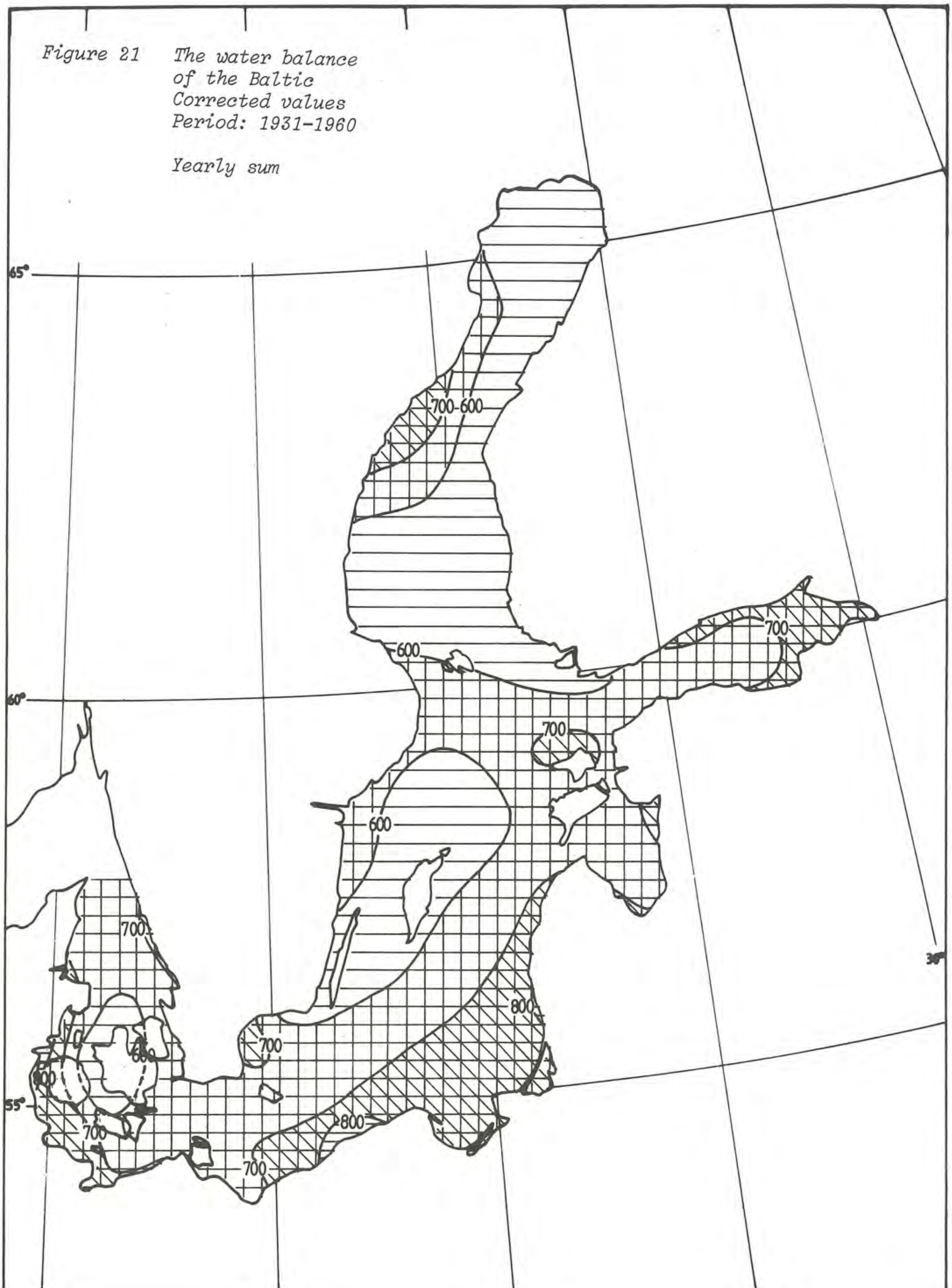

Figure 21 *The water balance of the Baltic Corrected values Period: 1931-1960*

Yearly sum

5.3 Illustrations of the temporal distribution of precipitation

In the following diagrams the temporal distribution of precipitation is illustrated.

The monthly variation of precipitation for the climatological fields (1931-60 and 1951-70) and for the individual months of the Pilot Study Years (1975 and 1976) are presented in the figure 22.

From this figure it is evident that the total precipitation amount for the Pilot Study Years was less than the climatological average.

The average monthly precipitation amounts for the Baltic Sea and its main subbasins is illustrated for the period 1951-70 in figure 23.

The monthly climatological maximum of precipitation in August is due to the "spill-over" effect of convective activity over land. The convective cells/systems created over land are advected from land to the coastal zone and to the sea. Due to the relatively warm sea water a rapid decay of the systems over the sea is prevented (factor II in section 5.2).

The secondary maximum of precipitation in November is due to reinforcement or creation of precipitation systems due to efficient transport upwards of sensible and latent heat from the relatively warm sea surface.

The figures 24 and 25 illustrate the precipitation sums for individual years for 1951-70.

The yearly total for all subbasins ranged from 479 mm in 1964 to 726 mm in 1960.

It is also evident that the yearly precipitation amounts for the respective subbasins are strongly correlated.

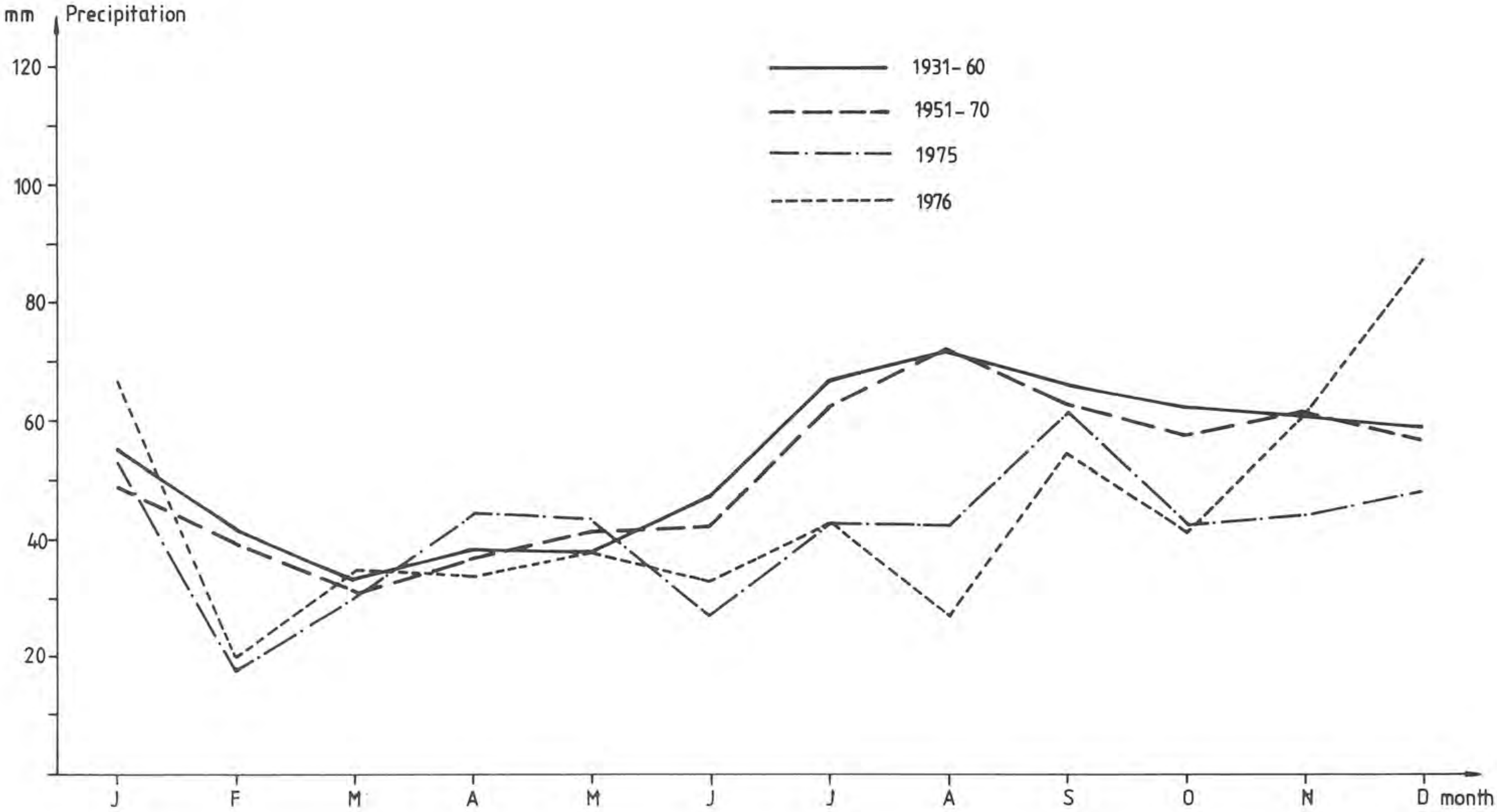

Figure 22 *The monthly variation of precipitation for the climatological fields (1931-60 and 1951-70) and for the Pilot Study Years (1975 and 1976). Monthly averages for all subbasins.*

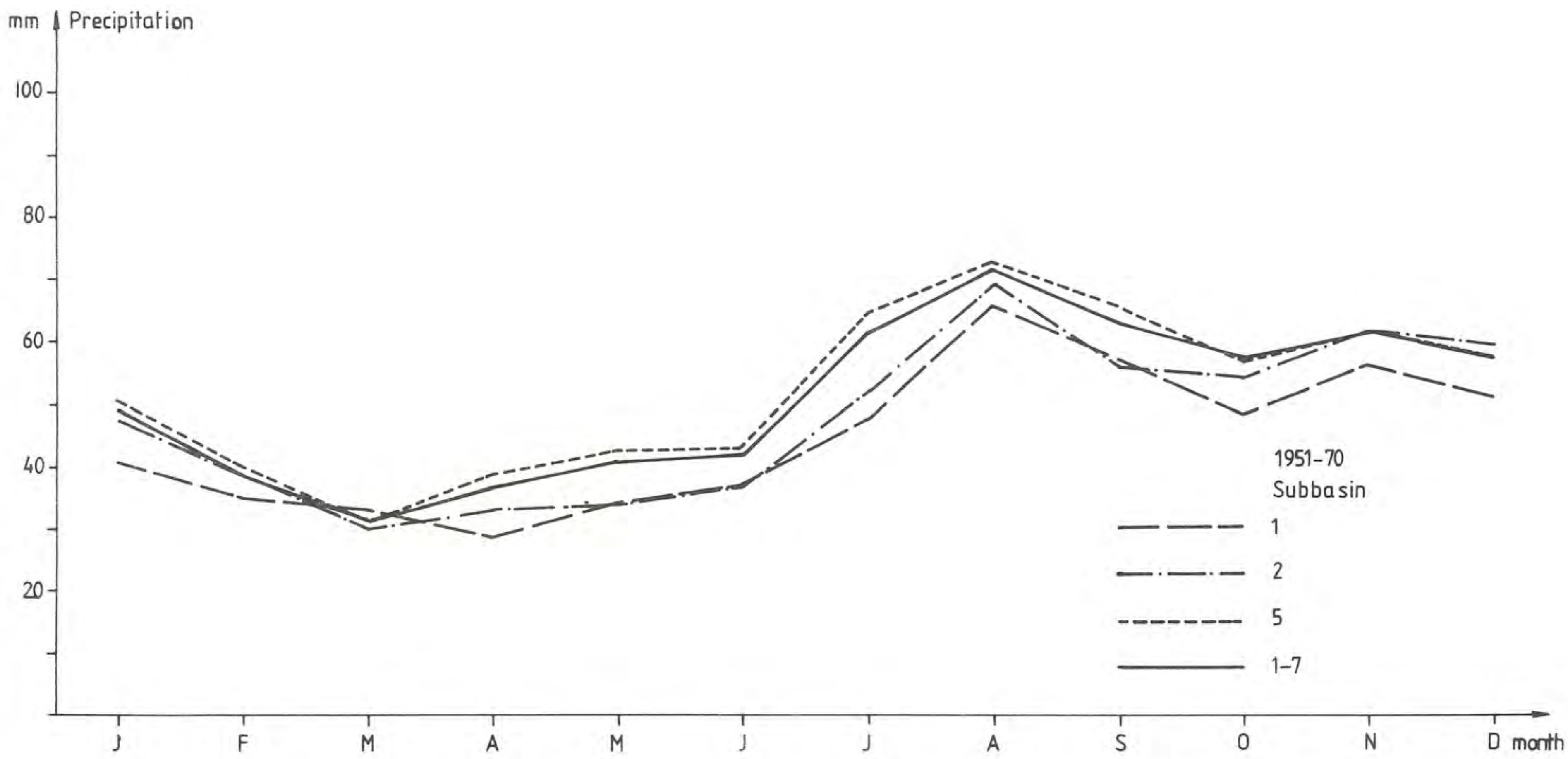

Figure 23 *The average monthly precipitation amounts for the Baltic Sea and its main subbasins for the period 1951-70.*

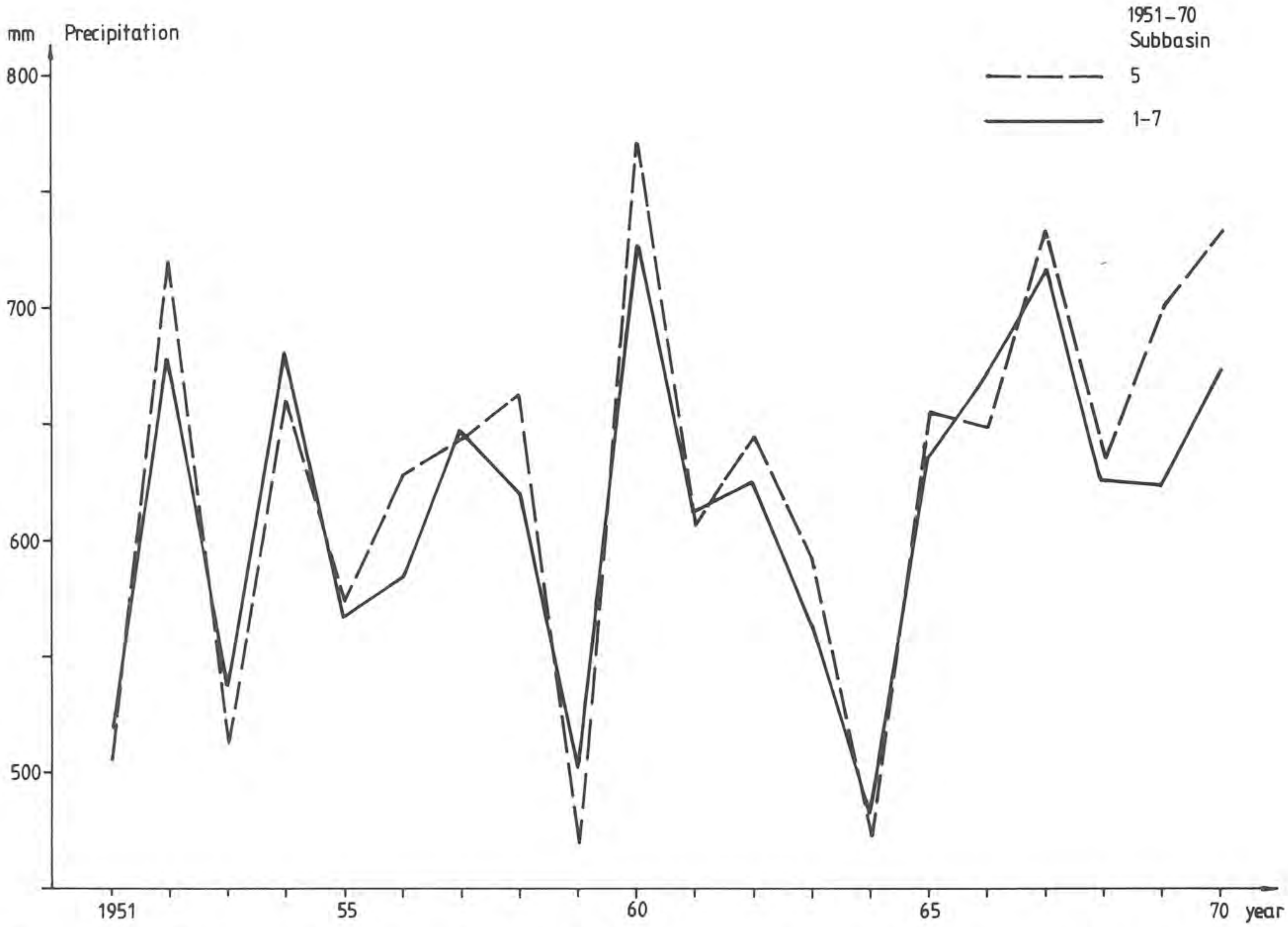

Figure 24 *The precipitation amounts for individual years 1951-70. Subbasins 1-7 and subbasin 5.*

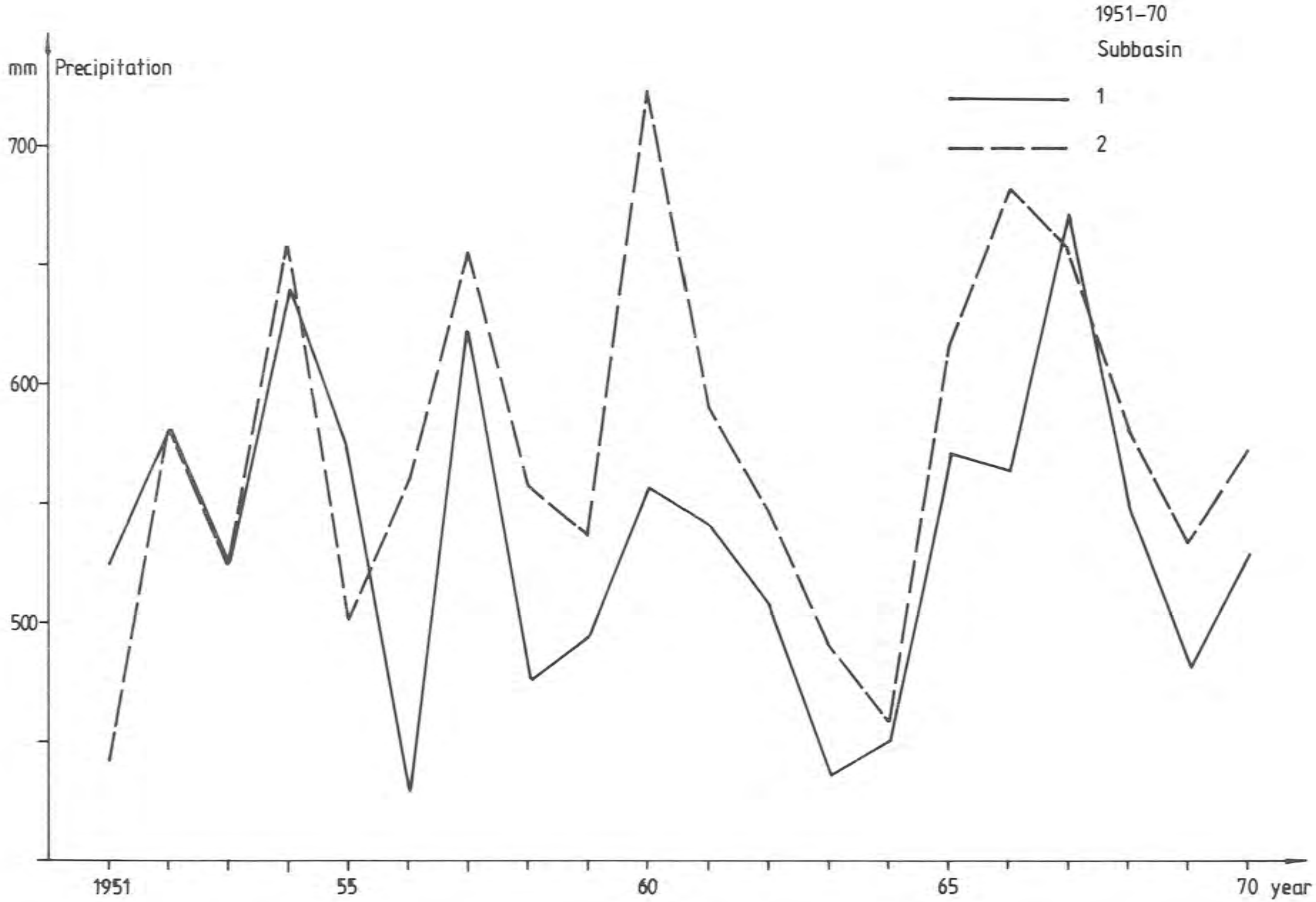

Figure 25 The precipitation amounts for individual years 1951-70. Subbasins 1 and 2.

6. CONCLUSIONS

• The estimation problem

The corrections of point precipitation data within this project were - with some exception - applied by the respective Baltic bordering country. The methods of correction were of different kinds according to the type of precipitation gauge and the results from special investigations on error sources of precipitation measurement in the respective country.

Consequently the point correction can be regarded as a procedure independent from considerations of the spatial structure of precipitation within the Baltic Sea. This fact seems important with regard to the circumstance that the error sources at point measurement is one factor and the meteorological mechanisms that determine the yearly, spatial distribution of precipitation is another factor that influences the spatial pattern towards decreasing amounts with increasing distance from land. The two factors are thus compounded, but have been possible to separate from each other in a basically independent way in this investigation.

The paramount problem at the areal estimation concerns the lack of reliable observational evidence in the interior parts of the respective subbasin. Nevertheless, the study of the covariance field by use of monthly precipitation sums reveals that there is a considerable correlation between values from coastal stations and values well off from the coast. Consequently a large amount of information on the conditions in the data sparse areas are contained in the data from stations on spits, lighthouses, islands etc.

• The estimates

1. The areal estimates of the present investigation indicates that the long-term average of yearly precipitation amount for the whole Baltic Sea, with the subbasins 1-7 (Danish sounds and Kattegatt are included) is about 639 mm, (265.77 km^3), for the period 1931-1960 and 613 mm (254.25 km^3), for the period 1951-1970. With consideration to error limits the average precipitation on a long term basis is estimated to be within 600 mm to 650 mm per year and with a probable average of 625 mm (259.54 km^3).

The maximum areal value for the subbasins 1-7 for the period 1951-70 occurred in 1960 with 726 mm (301 km^3) and the minimum value in 1964 with 479 mm (199 km^3).

• Urgent future activities

1. For future computations of areal precipitation it seems important to include information from remote sensing devices and also information contained in the quantitative numerical precipitation forecast.

In particular it seems important to understand quantitatively the physical mechanisms that determine the efficiency of precipitation release in the coastal zone and at sea. Separate investigations on this topic by use of numerical models in connection with conventional data and new data sources are encouraged.

2. For environmental and economic reasons it is important that the precipitation element, as a component in the water balance, is determined on an operational basis. The main problem connected with this task concerns the flow of data between the Baltic bordering countries. It is here proposed that the feasibility of an operational evaluation is investigated by the relevant authorities.

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