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NORDIC HYDROLOGY

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Nordic Hydrology, 32 (4/5), 2001, 285-314

Precipitation Estimates over the Baltic Sea: Present State of the Art

Anna Rutgersson[1, 2], Karl Bumke[3], Marco Clemens[3], Valentin Foltescu[1], Ralf Lindau[3], Daniel Michelson[1], and Anders Omstedt[1, 4]

Precipitation is one of the main components in the water balance, and probably the component determined with the greatest uncertainties. In the present paper we focus on precipitation (mainly rain) over the Baltic Sea as a part of the BALTEX project to examine the present state of the art concerning different precipitation estimates over that area. Several methods are used, with the focus on 1) interpolation of available synoptic stations; 2) a mesoscale analysis system including synoptic, automatic, and climate stations, as well as weather radar and an atmospheric model; and 3) measurements performed on ships. The investigated time scales are monthly and yearly and also some long-term considerations are discussed. The comparison shows that the differences between most of the estimates, when averaged over an extended period and a larger area, are in the order of 10-20%, which is in the same range as the correction of the synoptic gauge measurements due to wind and evaporation losses. In all data sets using gauge data it is important to include corrections for high winds. To improve the structure of precipitation over sea more focus is to be put on the use of radar data and combinations of radar data and other data. Interpolation methods that do not consider orographic effects must treat areas with large horizontal precipitation gradients with care. Due to the large variability in precipitation in time

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and space, it is important to use long time periods for climate estimates of precipitation

Ship measurements are a valuable contribution to precipitation information over sea, especially for seasonal and annual time scales.

Introduction

The water balance of the Baltic Sea is a main concern in the Baltic Sea Experiment (BALTEX) research program (BALTEX 1995). The balance is controlled by the net precipitation (precipitation minus evaporation), the river runoff, and the in- and outflows through the Baltic Sea entrance area. One of the least-known components of the water balance is the precipitation, which is often neglected in the water balance investigations over the Baltic Sea. The project PEP in BALTEX (pilot study of evaporation and precipitation over the Baltic Sea) is investigating this problem using measurements and models for estimating precipitation and evaporation over the Baltic Sea. During the past few decades, one of the most detailed studies of the water balance over the Baltic Sea is the HELCOM study (HELCOM 1986). Precipitation in the HELCOM study was determined using corrected rain-gauge data and statistical interpolation into basins for the period 1931 to 1970. Recent studies were also done for a three months period during 1995 (Rubel 1996; Rubel 1998) within the framework of the BALTEX project. Rubel uses the synoptic network and interpolates to equidistant grid points for the Baltic Sea drainage basin. In Rubel (1998), comparison with two limited-area models showed similarities in the precipitation fields between synoptic data and the models, but still there were large uncertainties in the amounts.

In this study annual and long-time data are used, which also includes winter months and solid precipitation. However, the main focus is on rain. Several methods have been used for precipitation estimation, including model simulations. It appears to be a general feature, in regional as well as global scale models, that precipitation is overestimated over the Baltic Sea (Bengtsson 1998; Omstedt *et al.* 2000; Omstedt and Rutgersson 2000). In Omstedt *et al.* (2000) the precipitation over the Baltic Sea was shown to be too high using dynamic down-scaling of a global climate model, and even higher using the regional-scale model REMO. It thus appears to be too early to use models alone when estimating precipitation; they must therefore be used in combination with other sources. The mesoscale analysis system MESAN (see the Methods Section) was in Michelson *et al.* (2000) shown to be a useful tool for estimating precipitation for larger areas. In this system different data sources are weighted together to give reliable estimates. They also showed that radar added further precipitation information over sea.

The sparseness of measurements over sea is a great problem, and most of our knowledge is based on measurements on land and at coastal stations. Often the be-

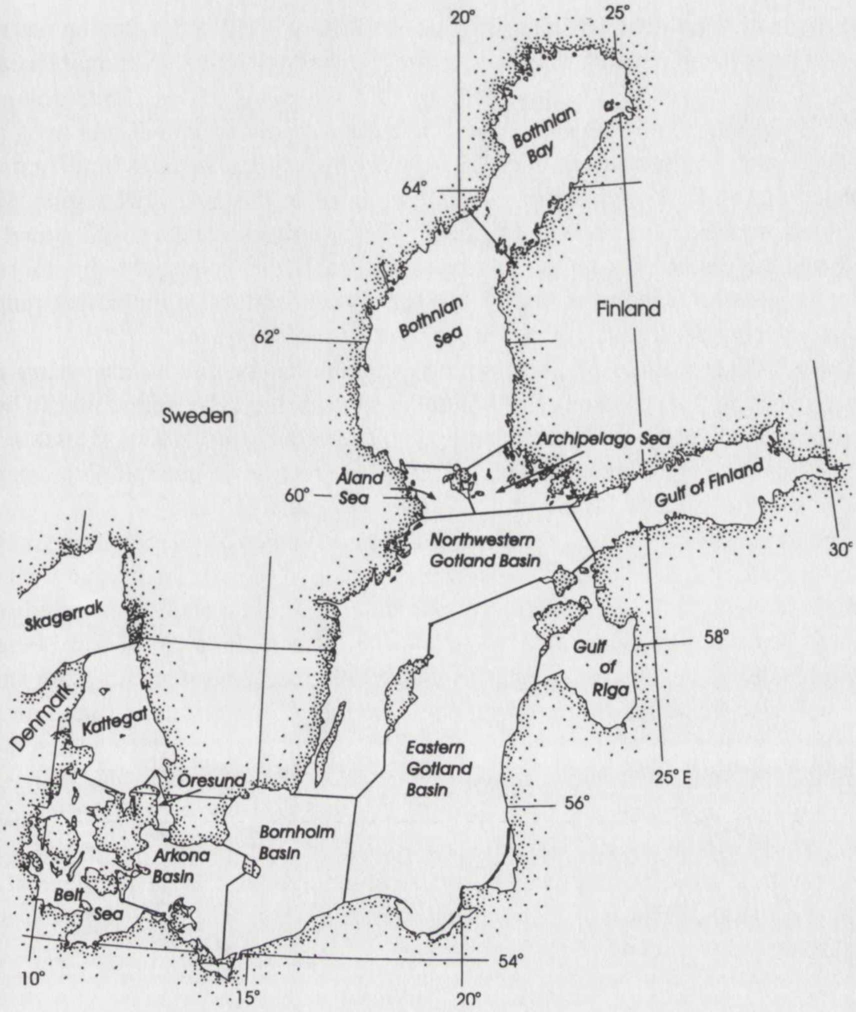


Fig. 1. The division of the Baltic Sea in the mean precipitation calculations. The basins are enumerated as follows: 1=Kattegat (KA), 2=Belt Sea (BE), 3=Arkona Basin and Öresund (AR), 4=Bornholm Basin (BH), 5=Eastern Gotland Basin (EG), 6=Northwestern Gotland Basin (NWG), 7=Gulf of Riga (GR), 8=Gulf of Finland (GF), 9=Bothnian Sea, Archipelago Sea and Åland Sea (BS), 10=Bothnian Bay (BB).

haviour over the Baltic Sea is assumed to follow an extrapolation of the coastal stations (Schönne *et al.* 1993). In a satellite study of the cloudiness over the Baltic Sea it was, however, shown that the sea has a strong signal (Karlsson 1994). Cloud frequencies were typically 10-20% lower over sea areas compared to land areas in spring and early summer, caused by differential heating of land and sea surfaces. This feature is also expected to influence the precipitation patterns over sea.

The estimation of precipitation using remote sensing is still a developing research field. Methods using data from sensors aboard American NOAA (National Oceanographic and Atmospheric Administration) and DMSP (Defense Meteorological Satellite Program) platforms can, at best, locate precipitating clouds and even precipitation itself (Simmer 1996). Yet retrieving precipitation intensities is still a major problem, especially at high latitudes such as those of the BALTEX region. Data from weather radar systems has long been acknowledged as being well suited for monitoring the spatial distribution of precipitation at high spatial and temporal resolution (Joe 1996). Quantitative use of this data is problematic at increasing ranges, especially during winter conditions.

The traditional method of determining precipitation at the surface using rain gauges is not without problems. Corrections for losses due to blowing rain can be of the order of 50% at 11 ms^{-1} and even larger for higher wind speeds (Hasse *et al.* 1998). In Rubel and Hantel (1999) the average correction of precipitation (mainly rainfall) is in the order of 5-10% for the Baltic Sea drainage basin.

The purpose of this paper is to review various estimates of precipitation (mainly rain) over the Baltic Sea and analyse the present state of the art. Traditional methods based on the synoptic network (the synoptic data are interpolated on an equidistant grid) will be used, together with MESAN, which is a combination of data sources. We will also show results from direct as well as indirect measurements from ships. There will also be some discussion of the variability of precipitation in time and space. We consider three months of the PIDCAP period (Isemer 1996), which is the first BALTEX study directed towards precipitation. We also examine two years within the field experiment PEP in BALTEX, 1997 to 1998, to cover the yearly cycle. To get a climatological estimate of the precipitation, however, two years is a too short period, so some long-term estimates of precipitation are also discussed. To be able to investigate spatial differences, the Baltic Sea is divided into ten subbasins, which can be seen in Fig. 1.

Methods

SMHI (1×1)°, Database using Optimal Interpolation

The SMHI (1×1)° database covers the Baltic Sea drainage basin with a grid of (1×1)° squares. The database uses all available synoptic weather stations in the area (see Fig. 2c). There are generally 700-800 precipitation observations twice a day (most of the observations cover land areas). These are interpolated in space using a two-dimensional optimum interpolation scheme (Gustafsson 1981; Daley 1991). The degree of spatial filtering of optimum interpolation is determined by an isotropic autocorrelation function, and this function was estimated from the database. A quality-control algorithm to reject erroneous observations was built into the objective analysis scheme. From the derived grid-point values, regional, monthly and yearly means for the ten sub-basins were calculated. No correction was made for precipitation losses at high wind speeds at the synoptic stations used in the SMHI (1×1)° database. The database is, however, influenced by land surfaces, where orographic effects modify precipitation rates. The modifications will mainly increase the precipitation, but can also give lower precipitation, for example in lee of mountains. Whether the land influence and neglected wind corrections cancel each other out is, of course, an open question and will be further discussed below. The database covers the period 1979 to 1998 and is a valuable tool for investigating precipitation over extended periods.

MESAN, Mesoscale Analysis

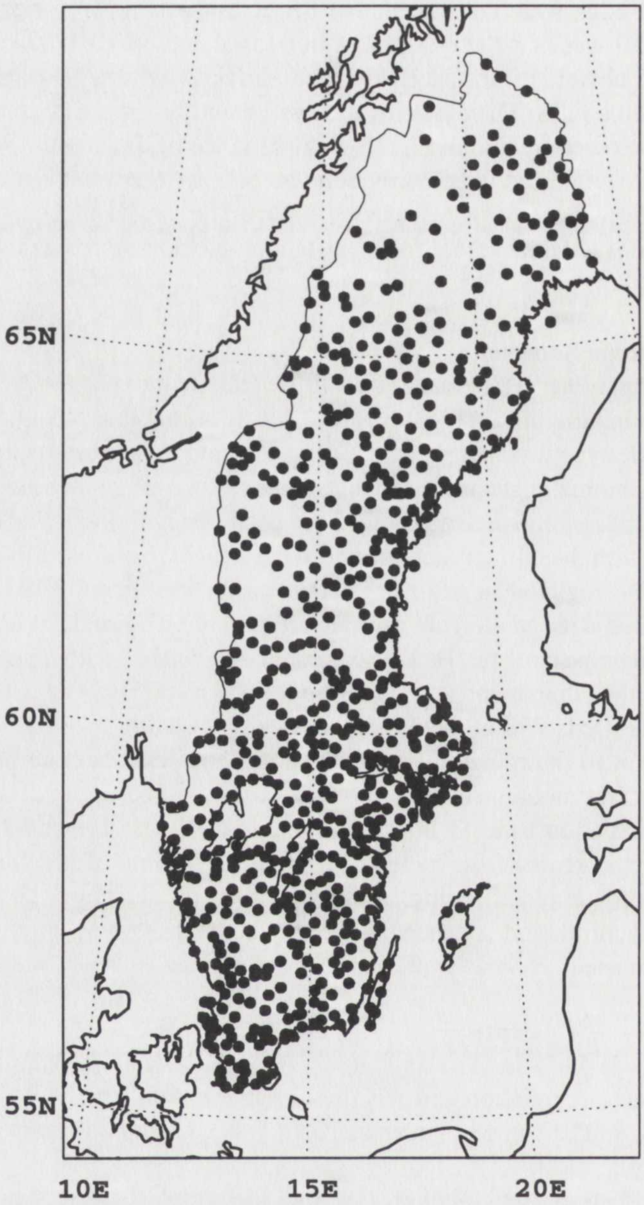
In the MESAN approach (Häggmark *et al.* 1997; Häggmark *et al.* 2000; Michelson *et al.* 2000), precipitation is analysed by employing optimal interpolation. Observational data include synoptic data, using the present weather code (ww) or direct measurements from automatic gauges. Climatic stations using gauge measurements, and also 19 weather radar are included. In Fig. 2 the positions of the synoptic stations are shown together with the climate stations and radar coverage used in MESAN.

Fields from the regional numerical weather prediction model HIRLAM (High Resolution Limited Area Model) are used as initial fields. The analysis area includes the whole drainage basin of the Baltic Sea, mainly calculated with a spatial resolution of 0.1°. For the comparison with the Ship Rain Gauge (SRG) data a spatial resolution of 0.5° is used. Within the MESAN system, a quality control is performed before submission to interpolation, so large or systematic errors can be identified and eliminated. The auto-correlation functions used by the optimal interpolation vary with accumulation time (3 hours, 12 hours, 24 hours, 1 month) due to the changing horizontal scale of the meteorological phenomenon of precipitation. The functions are predetermined, being estimated from the database. The horizontal scale of the auto-correlation is dependent on the integration time, and the following relation has been used

$$w = 0.5\left[\exp(-\frac{x}{R}) + \exp(-\frac{2x}{R})(1 + \frac{2x}{R})\right] \qquad (1)$$

where w is the auto-correlation and x is the distance in km. The typical horizontal scale is given by R (110 km, 180 km and 270 km for 3, 12 and 24–hour integration time respectively).

Orographic effects on precipitation (such as topographic enhancement and enhancement by coastal convergence) are indirectly taken into account. The interpolation method is based on a climatological regression analysis which considers the following parameters: 1) the frequency of wind directions multiplied by the upslope gradient of topography, 2) the roughness length, and 3) the latitude. The result is a field containing the climate of the current weather situation. If the wind direction is not known, the climate field is used.



(a) Climate stations.

Fig. 2. The observation networks used in the MESAN system including (a) Swedish climate stations, (b) radar coverage and (c) synoptic stations, which are also used in SMHI (1×1)º data-base.

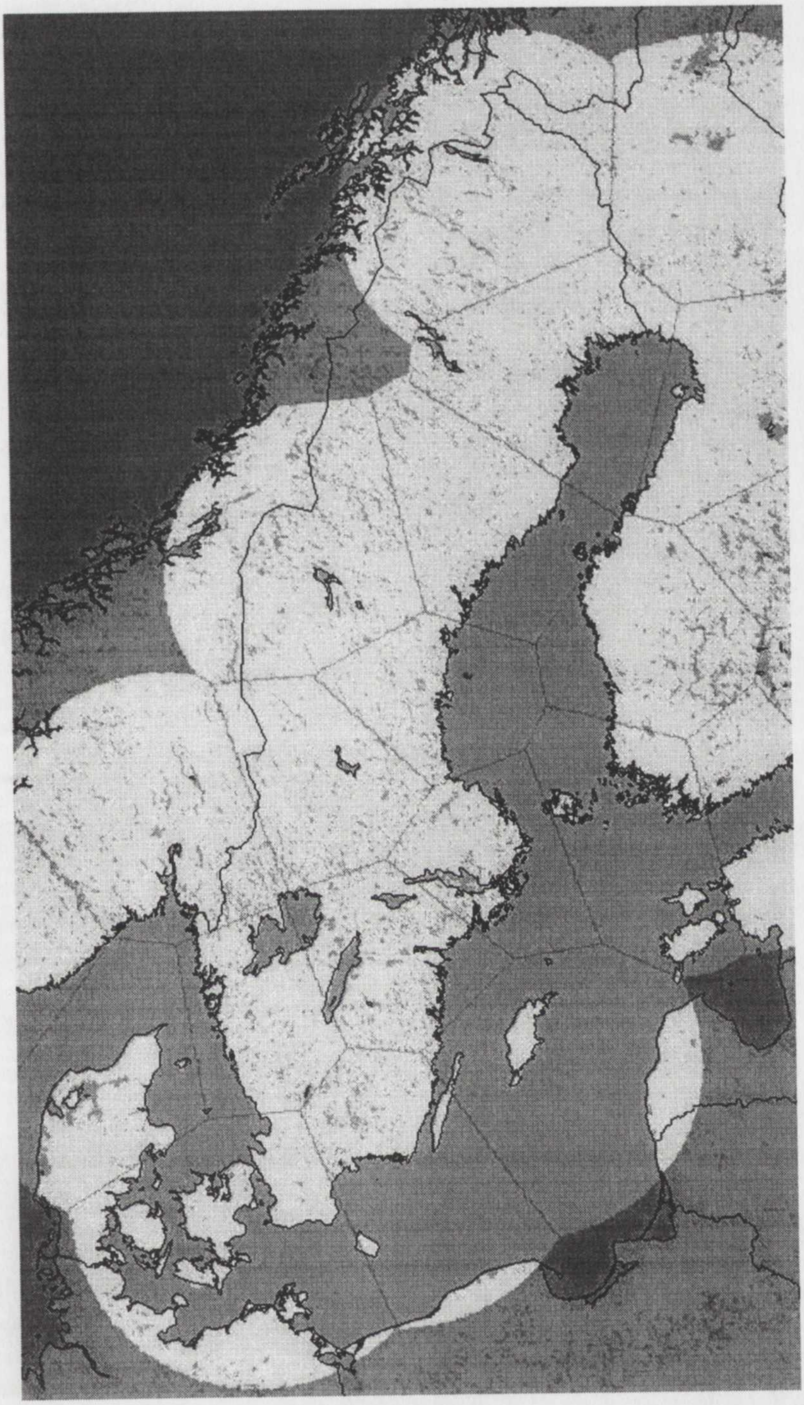


Fig.2 (b) Radar coverage.

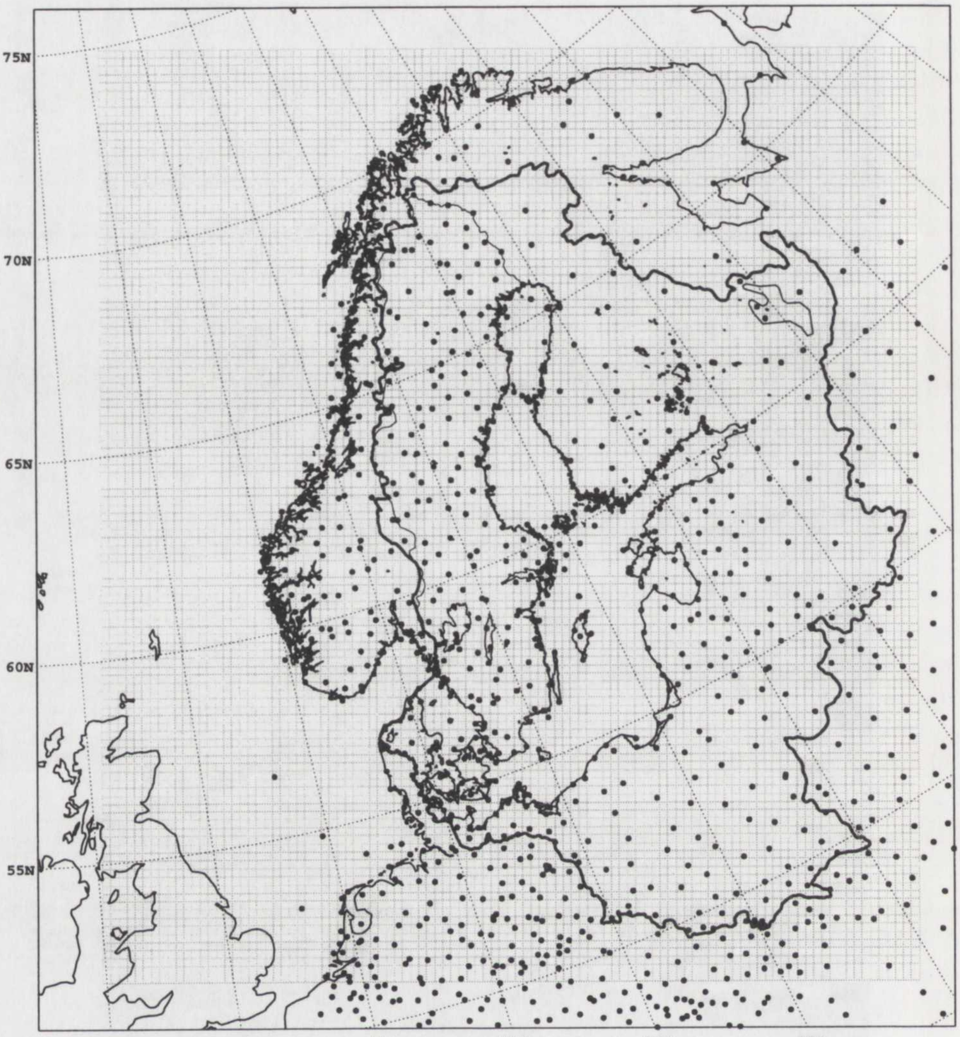


Fig.2 (c) Synoptic stations.

COADS

Hardly any direct measurements of precipitation over open sea exist due to a lack of suitable instruments and observation platforms. Therefore other methods must be used to derive estimates of precipitation from available information. One possibility is to apply a method similar to that from Tucker (1961), who parameterised precipitation rates from synoptic observations of the present synoptic weather code (ww).

Such synoptic observations over the sea are available from the Comprehensive Ocean and Atmosphere Data Set (COADS) (Woodruff *et al.* 1987; Woodruff *et al.* 1998). A new algorithm to estimate monthly precipitation sums over sea from synoptic observations of voluntary observing ships have been derived (Isemer and Lindau 1998). It is based on about 20 years of measurements using a marine conical rain gauge and synoptic observations performed on light vessels in the German Bight. Global application of this algorithm gave good agreement with satellite estimates. Precipitation measurements were corrected for wind speed applying a formula given by Grossklaus (pers.comm.). Precipitation is calculated using the relation $P=an(ww)q$ where a is a constant, q the specific humidity and n a function of the weather-code ww.

Direct Ship Measurements

As mentioned above, few instruments give reliable measurements of precipitation over sea. This prompted the development of a new type of rain gauge, specially designed to measure rain under high wind speeds, for example, on moving ships. The result is the so-called Ship Rain Gauge (SRG, which in principal is a rain collector). A unique feature of the SRG is an additional vertical collecting surface, which is especially effective under high wind speeds (Hasse *et al.* 1998). Calibration of the SRG was performed by simultaneous measurements of an optical disdrometer (Grossklaus *et al.* 1998) on the R.V. Alkor, so effects such as wetting of internal walls of the SRG and loss by evaporation from the upper funnel were included. The calibration is a function of the wind speed relative to the instrument, which was measured by a cup anemometer placed directly beneath the SRG.

Since 1994, at least five voluntary observing ships have been equipped with SRGs as part of the BALTEX project, to routinely measure precipitation over the Baltic Sea on their way between Germany and Finland. Furthermore, measurements took place on cruises of the research vessels Alkor and Heincke during the four-week intensive field campaign of PEP.

Raw precipitation data, relative wind speeds, and GPS positions are continuously stored on-board in 8-minute intervals. Mounted on moving ships, it follows that precipitation measurements are not only averages over 8 minutes, they represent also averages over a distance of several kilometres. In case of a ship's speed of about 20 knots the 8 minutes average is representative for a 5 km track along the ship's cruise. Because measurements during snow are very unreliable, all winter months are excluded in this study.

The direct ship observations in the Baltic Sea during 1997 to 1998 are analysed on the same 55-km grid as is used in MESAN. The number of observations in each grid box ranges from 200 to more than 60.000 and is thus quite unevenly distributed. To interpolate the SRG data, every measurement is weighted by the function Eq.(2) referring to its distance to the centre of each grid box

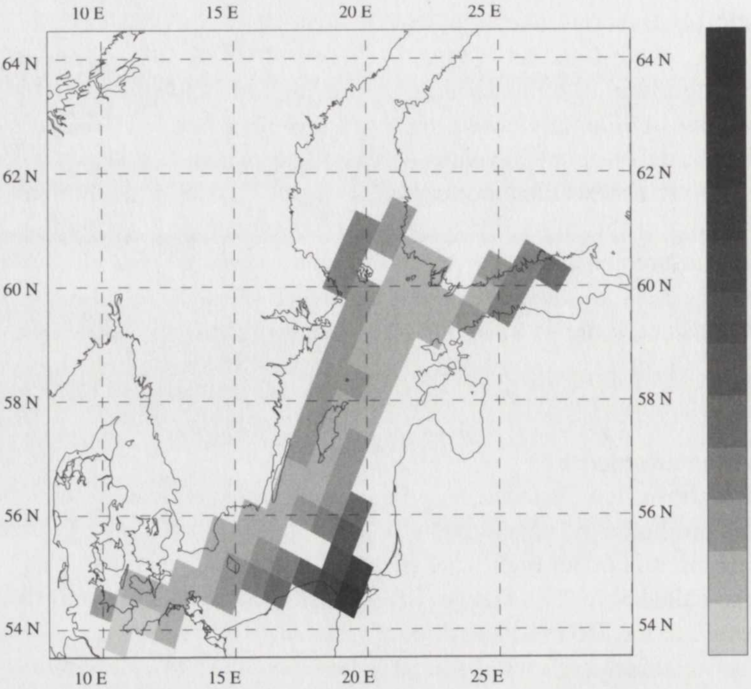


Fig. 3. Relative error (%) of the SRG field according to Eq. (4) for a 16 months period (April to November 1997 and 1998), data are analysed on the same 55 km grid as is used in the MESAN system.

$$\overline{RR}_{\mathrm{Grid}} = \frac{\sum_{i=1}^{n} w_i rr_i}{\sum_{i=1}^{n} w_i} \tag{2}$$

$\overline{RR}_{Grid}$ is the averaged rain rate of the corresponding grid-box, rr_i the single measurements and n denotes the whole number of SRG data. The weights, w_i, are derived from the statistical model, $w_i = \exp(-x_i/L)$, where x_i is the distance and L the decorrelation length. The decorrelation distances used Eq.(2) are a function of the season based on the 8-minutes integration intervals of the measurements. They range from 62 km in autumn to 99 km in spring.

The error variances of each grid-box j are estimated by

$$\sigma^2_{\mathrm{Grid}} = \frac{\sum_{i=1}^{n} w_i (rr_i - \overline{RR}_{\mathrm{Grid}})^2}{\sum_{i=1}^{n} w_i} \tag{3}$$

and the error is given by

$$err_{\mathrm{Grid}} = \sqrt{\frac{\sigma^2_{\mathrm{Grid}}}{\sum\limits_{i=1}^{n} w_i}} \tag{4}$$

The errors are shown in Fig. 3 and are relatively low, except in the south-east corner of the area, where we have lower coverage of ships.

A further SRG is mounted on the small island of Östergarnsholm east of Gotland. In contrast to measurements on ships, wind speeds relative to the rain gauge were taken from the flux measurement system at the same site, described in Smedman *et al.* (1999). Wind speeds were reduced to the height of precipitation measurements using a logarithmic wind profile. Precipitation measurements on Östergarnsholm were available for 123 days in 1998.

Corrections

Rain gauges used in the synoptic network are affected by a number of errors. The most important errors for Nordic gauges are due to high wind speed, wetting of the collector, and evaporation, all of which result in an underestimation of measured precipitation (Førland *et al.* 1996). For solid precipitation (snow and hail), the resulting correction can be as high as 30-50%, but it is generally lower for liquid precipitation. Sevruk (1982) estimated the respective errors (due to high wind speed, wetting of the collector, and evaporation) in the order of 2-10%, 2-10% and 0-4%, respectively, which leads to a total loss of from 4% up to more than 20%. One major problem with gauge measured precipitation is that different gauges gives different results. To improve the use of gauge measurements in SMHI (1×1)° and MESAN the different gauges should be corrected to one type. This is, however, difficult to perform since the different correction factors are not well known.

The SRG measurements at Östergarnsholm are compared to synoptic measurements from a nearby automatic station. The synoptic site and the SRG site at Östergarnsholm are only a few hundred meters apart and both sites are exposed to winds. The result is given in Fig. 4. Precipitation measurements of the SRG and automatic station at Östergarnsholm are highly correlated (correlation coefficient r=0.91).

Excluding a heavy precipitation event on 28-July-1998, when the automatic station had 42.7 mm(day)$^{-1}$ and the SRG 47.4 mm(day)$^{-1}$, the correlation coefficient decreases from 0.91 to 0.90. Generally there is a bias (mean difference) between measurements using automatic station and SRG at Östergarnsholm in the order of 20-30%; the integrated precipitation at the synoptic station is 145 mm and at the SRG gauge 189 mm. It should be remembered that measurements at the synoptic station are not corrected for losses due to wind and evaporation, while the SRG mea-

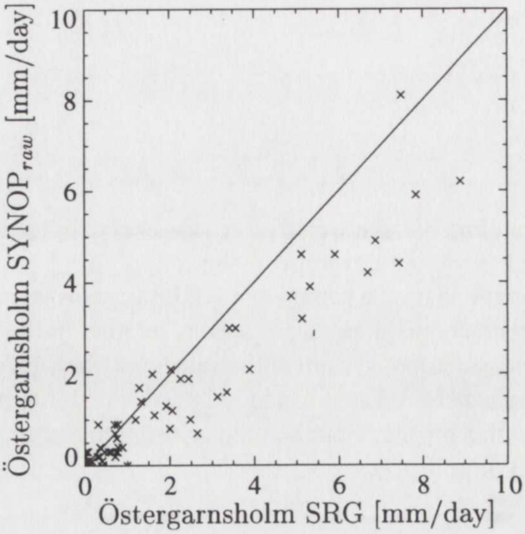


Fig. 4. Comparison of daily precipitation data from the ship rain gauge (SRG) and the synoptic station at Östergarnsholm (crosses). Solid line is the one-one relation. Included data are from 123 days in 1998 with liquid precipitation.

surements takes these corrections into account. Most of the bias between the measurements can thus be explained by loss due to high wind speeds at the synoptic station. Applying a correction for wind speed (Dahlström 1973) and for wetting and evaporation losses (Dahlström 1980), the corrected precipitation rate is calculated by

$$rr_{corr} = 0.2 + rr_{raw}\ (1.0 + 0.002U^2 + 0.06\ \frac{1}{rr_{raw}}) \quad (5)$$

where rr_{corr} is the corrected precipitation in mm, rr_{raw} the measured precipitation in mm, and U the measured wind speed in ms^{-1}. The correction by Eq. (5) increases the amount of measured precipitation from the automatic station by about 25%. This correction is above the range given by Sevruk (1982) and that given by Rubel and Hantel (1999) for the Baltic Sea drainage basin. Higher corrections at Östergarnsholm can be explained by the fact that the wind speeds are in general higher over sea compared to land, and that the automatic station at Östergarnsholm is very exposed to winds. When the correction is applied, the integrated precipitation from the synoptic station increased to 184 mm, which is in better agreement with the SRG precipitation. The *rms* (root-mean-square) error decreased from 0.70 mm(day)$^{-1}$ to 0.56 mm(day)$^{-1}$. These corrections are not included in the SMHI (1×1)° data and only partly considered in MESAN. Few of the coastal stations are as exposed to winds as the Östergarnsholm site, but it should be remembered that we have a possible bias for uncorrected synoptic data of 5-20%.

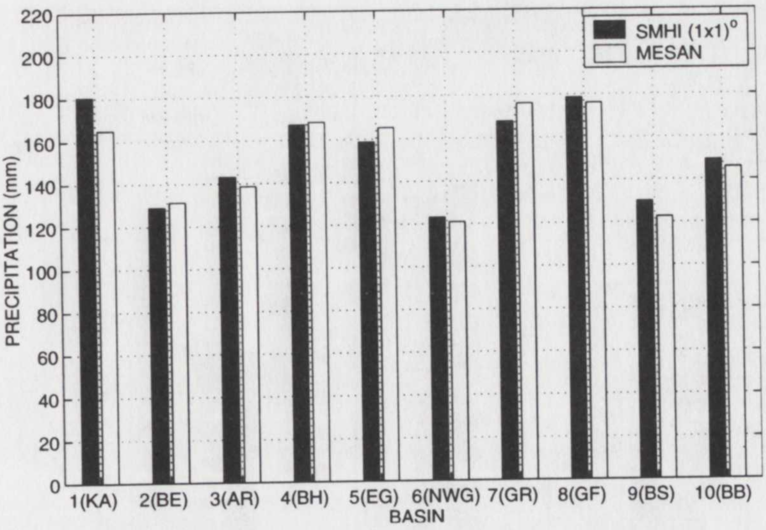


Fig. 5. Basin averages of precipitation for the three-month PIDCAP period. The number of each basin is explained in Fig. 1. Black bars are in SMHI (1×1)° and white are MESAN.

Results

In this work, we analyse the best available data sets on three different time scales. Firstly, we consider the monthly time scale by analysing three months of the PIDCAP period (August to October 1995). During PIDCAP, the first and third months were relatively dry, with precipitation mostly as showers; the second month had frequent cyclonic activity and strong rainfall (Isemer 1996). Secondly, we consider the yearly time scale by analysing two years, 1997 and 1998. These two years both had mild winters and were, on average, warm (1997 in particular). The year 1997 was a dry year, mostly due to the warm and dry summer, and the year 1998 was wet. The two years together can be considered warmer and slightly wetter than normal. Thirdly, we study the time period 1980 to 1995, which can be considered wet, because the 1980s were the wettest decade of the last 70 years (Bergström and Carlsson 1994).

Precipitation for August to October, 1995

Monthly and basin averages of MESAN and SMHI (1×1)° data for August to October 1995 (the PIDCAP period) are shown in Fig. 5; the values can be found in Appendix A, Tables I and II. MESAN and SMHI (1×1)° agree well for all basins except for the Kattegat (Basin 1) at the west-coast of Sweden, where SMHI (1×1)° gives higher precipitation amounts for these three months. It is interesting to note that the rather coarse treatment of the Baltic Sea – divided into ten sub-basins – still captures

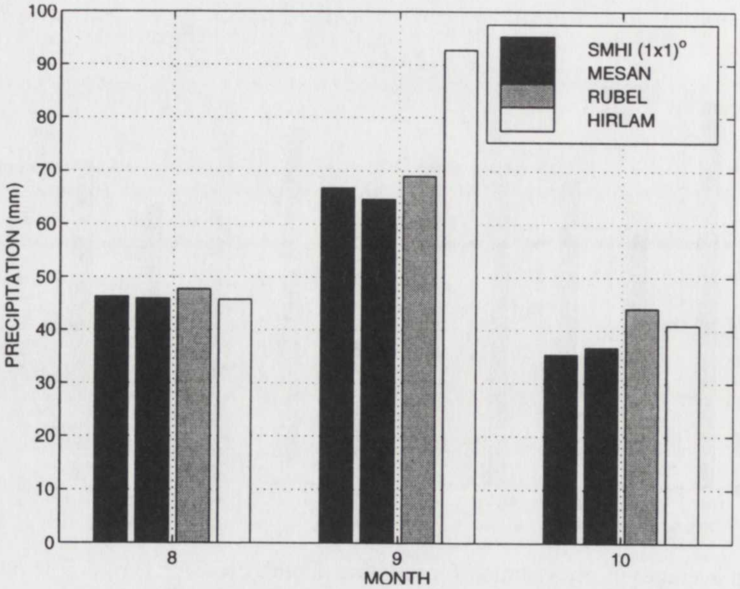


Fig. 6. Monthly averages of precipitation for the entire Baltic Sea for the PIDCAP period. Black bars are SMHI (1×1)° data, dark grey are from MESAN, light grey are estimates from Rubel (1998), and white bars are data from the regional model HIRLAM.

large regional variations. The area of the lowest precipitation rates is the Northwestern Gotland Basin (Basin 6), and the two wettest regions are the Kattegat and the Gulf of Finland (Basins 1 and 8).

For the PIDCAP period, several precipitation estimates exist. Fig. 6 includes the synoptic interpolated estimates of Rubel (Rubel 1998) and modelled precipitation using a High Resolution Limited Area Model (HIRLAM, described in Källén 1996) as monthly averages for all of the Baltic Sea.

The estimates from MESAN and SMHI (1×1)° agree well, and the estimates of Rubel are slightly higher (~ 10%). The estimates are based in part on the same data sets, basically from land-based synoptic and climate stations. An increase in precipitation due to correction for wind speed is taken into account by Rubel, but not by SMHI (1×1)° and only partly by MESAN; this correction is probably slightly larger than the difference between the two methods (see Correction-section). For the PIDCAP period, the precipitation modelled by HIRLAM agrees fairly well for the two drier months (August and October), but for September, the month with higher precipitation amount, the model gives far too much precipitation.

For a part of the PIDCAP period (20.8-31.10) and for the Baltic Proper (Northwestern Gotland Basin, Eastern Gotland Basin, Bornholm Basin and Arkona Basin in Fig. 1), some additional precipitation estimates are available (ship data and the SSM/I (Special Sensor Microwave/Imager) satellite sensor), all shown in Table 1.

Table 1 – Accumulated precipitation for the Baltic Proper from 20.8 to 31.10 1995 using five different methods.

STUDY	mm	m^3s^{-1}
MESAN	138	4619
SMHI (1×1)°	142	4743
SRG	128	4275
COADS	100	3354
SSM/I	98	3267

The estimates using the MESAN and SMHI (1×1)° methods agree well. Ship measurements, both from direct data using SRG and COADS data, give lower precipitation for this period, as does the SSM/I.

Precipitation for 1997-1998

Results from an extended period of two years can be seen in Figs. 7 and 8, and the values can be found in Appendix A, Tables III and IV.

Fig. 7 shows the two year annual averages for the different basins. For this period SMHI (1×1)° gives larger values of precipitation than MESAN, especially in Kattegat, the Gulf of Riga, and the Gulf of Finland (Basins 1, 7, and 8). MESAN gives higher precipitation only in the Eastern Gotland Basin.

There are two major differences between the two data sets over sea, radar information in MESAN and the inclusion of orographic effects in the interpolation procedure in MESAN. Radar information in MESAN would have the greatest effect in the largest basins with very few synoptic stations (as in the Baltic Proper, Basins 5 and 6). The similar precipitation pattern for the larger basins between MESAN and SMHI (1×1)° database is an indication of small influence of radar data in MESAN. Since the differences are small in those basins, the radar can be expected to influence the precipitation field in MESAN only slightly. In Häggmark *et al.* (2000) the radar in MESAN improved the analysis only marginally over land, since the gauge network is significantly denser over land there is less need of the radar data. This might lead to insufficiently account taking for the radar data or that radar data often might be assumed erroneous also over sea, where it is more needed. To correctly include the radar information over the sea, the MESAN could probably be improved in this sense.

The large differences in basins 1, 7 and 8 can thus mainly be explained by Fig. 9, where the yearly average for 1997 using MESAN is shown. In Fig. 9 a land/sea difference can be seen in the precipitation pattern, with minima over sea and precipitation maxima over land.

The interpolation method in SMHI (1×1)° does not consider any orographic effects as in MESAN and that, in combination with the rather coarse resolution,

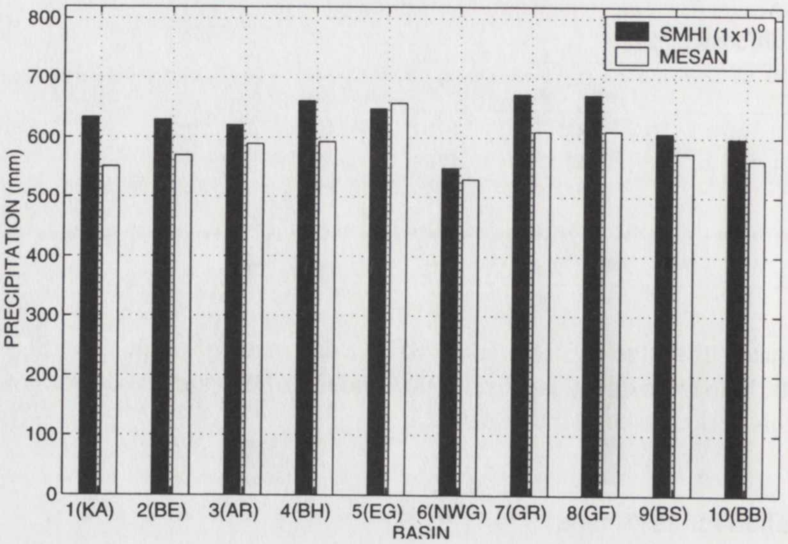


Fig. 7. Basin and annual averages of precipitation for the two-year period 1997-1998. The number of each basin is explained in Fig. 1. Black bars SMHI (1×1)° data and white bars are from MESAN.

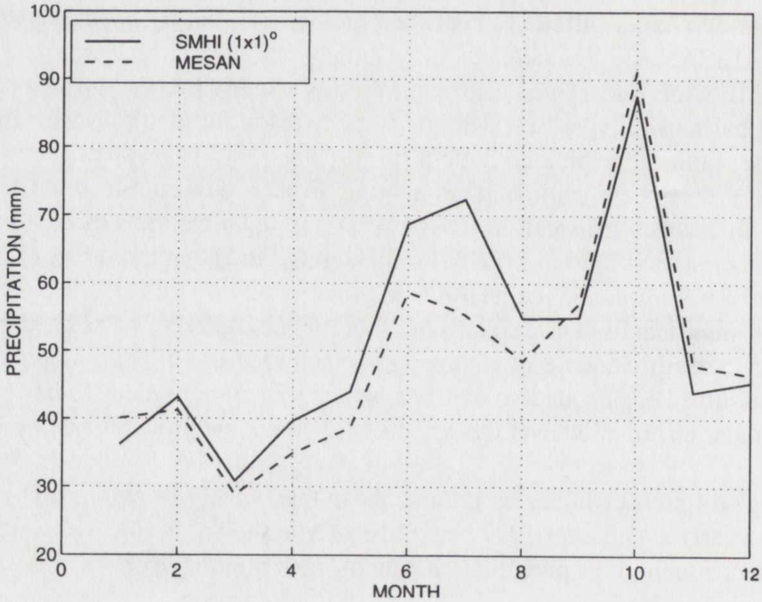


Fig. 8. Monthly precipitation averages for the two year period 1997-1998 for the entire Baltic Sea using SMHI (1×1)° data (solid) and MESAN data (dashed).

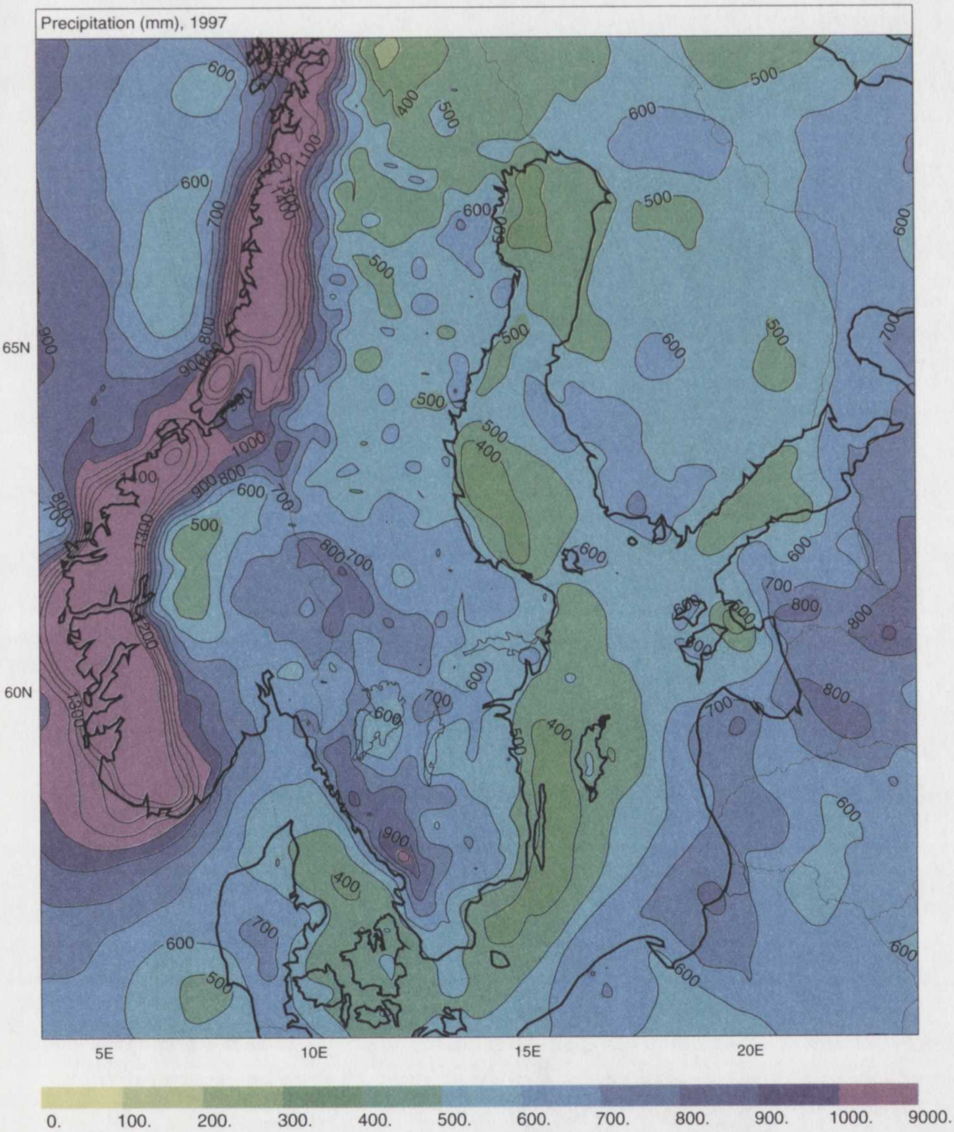


Fig. 9. Accumulated precipitation for one year using the MESAN system. Data are in mm.

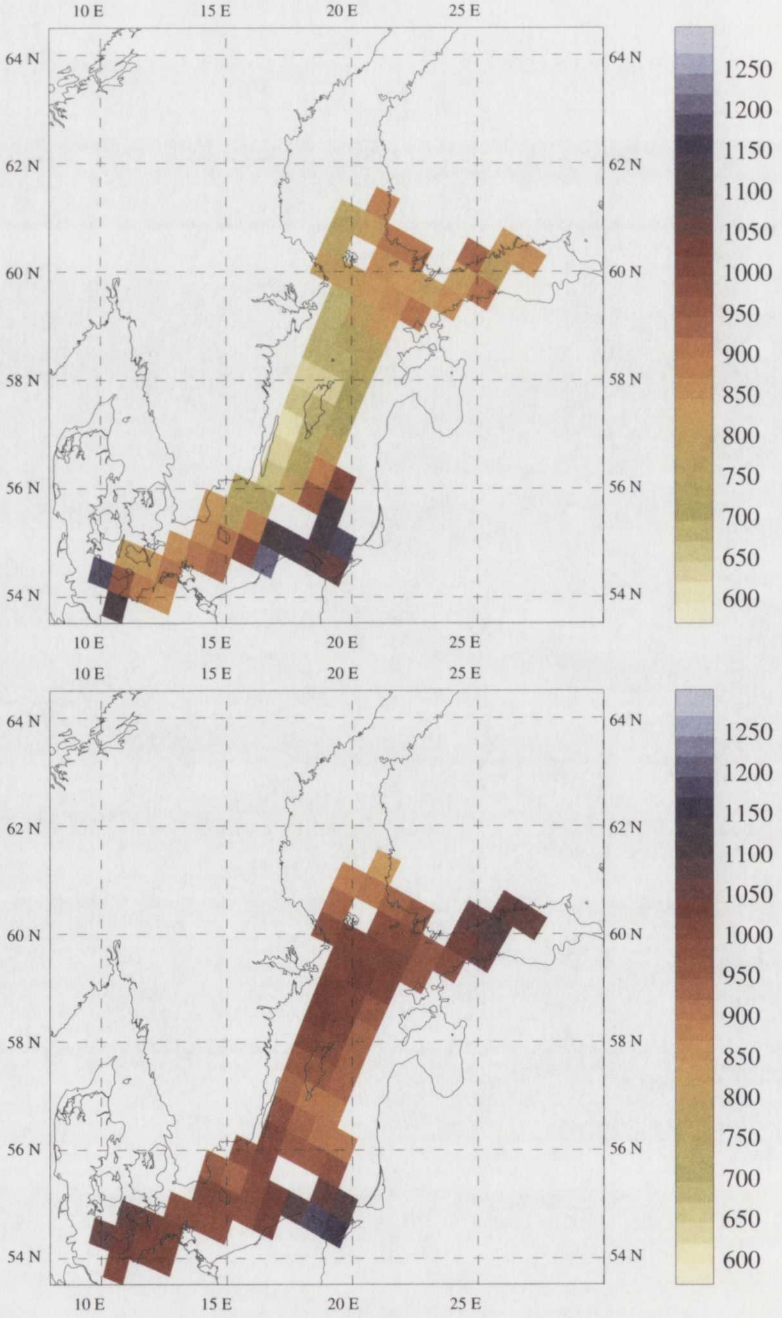


Fig. 10. Accumulated precipitation for April-November 1997 and 1998 using (**A**) MESAN-data and (**B**) direct ship data for 55 km grid resolution. Units are in mm for the 16 months period.

smoothes precipitation maxima from land out over sea. This feature is most clear for small basins with large horizontal gradients, such as Kattegat. For larger basins with smaller gradients, the two methods agree well. The monthly averages in Fig. 8 show larger values for SMHI (1×1)° than MESAN, especially during summer. This is the period when local precipitation systems are strongest, in contrast to late autumn and winter time when the synoptic forcing dominate. In late autumn, SMHI (1×1)° is slightly lower than MESAN. The difference between land and sea can thus be expected to have its maximum during summer, as is also seen in the cloud cover (Karlsson 1994).

The problem with most of the precipitation data over the Baltic Sea is the land influence. Even in MESAN, where orographic effects are taken into consideration, a certain land influence cannot be excluded. Ferry data are not influenced by land, but have other problems such as low coverage in the gulfs and rather low spatial and temporal coverage in general; to get reliable estimates, long time periods are needed.

Averaged over all grid boxes, the precipitation for April to November 1997 and 1998 (16 months) was 997 mm using SRG ship data (standard deviation is 58 mm). For the same grid boxes MESAN gives an average precipitation of 854 mm with a standard deviation of 146 mm. The comparison of MESAN analysis to SRG measurements on ships is given in Figs. 10 and 11. MESAN data are generally more scattered and also on the average lower than the SRG data. The resulting fields in Fig. 10a are for MESAN and in Fig. 10b for the direct ship measurements. From Figs. 10a and 10b there are obvious spatial differences between the precipitation fields. The minimum precipitation in MESAN Northwest of Gotland cannot be seen

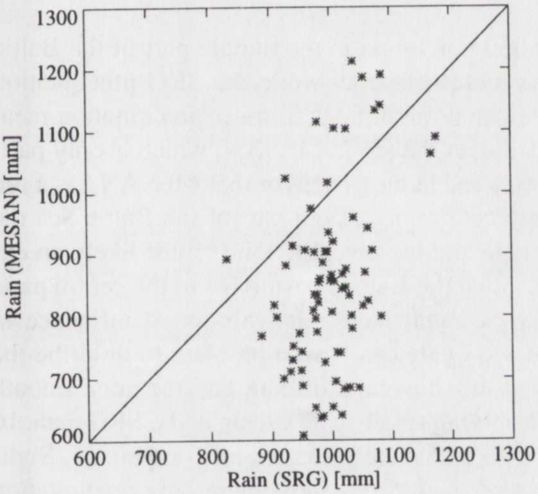


Fig. 11. Direct ship (SRG) data and MESAN data for April to November 1997 and 1998 (a total of 16 months) in mm. Crosses are precipitation comparison, solid line shows the one-to-one relation.

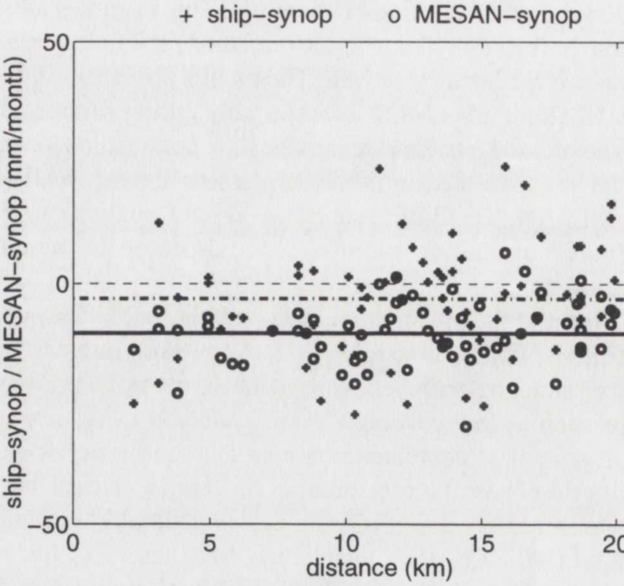


Fig. 12. Comparison between measured precipitation at synoptic stations and the nearest grid box of precipitation fields of MESAN data (circles) and SRG measurements (pluses). Distance means the distance between the synoptic station and the centre of the grid box. The full line shows the mean of the bias of MESAN compared to synoptic observations, the dashed-dotted line the mean bias of SRG measurements compared to synoptic observations. Dashed line shows the zero-line.

in the SRG field, where a small minimum is found in the middle part of the Baltic Proper. The minimum in MESAN is more dramatic, while the SRG precipitation field is smoother. One possible explanation might be that lower precipitation measurements from land were extrapolated over the sea in MESAN, which is only partly modified by the radar measurements used in the system or that MESAN has a too large correction for the orographic effects. In the eastern part of the Baltic Sea the radar data have very low or no coverage and the precipitation is most likely an extrapolation from few coastal stations along the Baltic coast. Also in the centre parts of the Baltic Proper it is likely that the radar have relatively small influence in MESAN (see previous section). The SRG data can have a problem to describe the monthly and spatial variability due to low coverage of data and the very smooth field is an indication of problems of resolving small-scale events in the SRG data. 16 months could be a too short period for a statistically significant comparison. Similarities in the fields can however be seen; both fields show increasing precipitation for the areas south of Sweden and for the Åland Archipelago.

Looking at the SRG measurements in more detail, we find that the maxima of precipitation in the north and south are mainly caused by heavy rain events in the autumn (not shown). These events may originate from convection due to large differences between sea surface temperatures and air temperatures. In spring a precipitation maximum can be found in the central parts of the Baltic Proper – a corresponding maximum is not seen in the MESAN data.

Generally, precipitation rates directly measured on ships are higher than those given by MESAN. The differences are at the upper limit of the corrections described in the Correction Section, which are partly applied on the MESAN data. The averaged difference between the SRG data and MESAN over the Baltic Sea can thus partly be explained by a too small gauge correction for synoptic and climate stations used in MESAN. Another possible explanation is that the interpolation assumption is not quite correct in MESAN.

Data for these two years show large regional variations and strong land influence over sea, which also varies for the seasons; this implies that high-resolution data are needed to gain a better understanding of the processes taking place.

Verification to single synoptic stations has been performed. Analysed fields of MESAN and interpolated fields derived from SRG measurements were compared to measurements at some synoptic stations in the Baltic Sea area. The synoptic stations are corrected according to Rubel and Hantel (1999) for wind speed and evaporation losses. Fig. 12 shows the difference between grid box value of both precipitation fields and the nearest synoptic station within a distance of 20 km between the synoptic station and the centre of the grid box.

MESAN underestimates measured precipitation compared to observations by 10.3 $mm(month)^{-1}$, and SRG measurements by 3.1 $mm(month)^{-1}$. Standard deviations between MESAN and synoptic observations are ±6.6 $mm(month)^{-1}$ and between SRG measurements and synoptic observations ±11.8 $mm(month)^{-1}$. It should be noted that some of the synoptic stations are used for analysis in MESAN, while the precipitation fields estimated from SRG measurements are independent from those data.

Long-term Precipitation Means

To get a good understanding of the precipitation climate, two years are not enough since interannual variations are large (Omstedt *et al.* 1997) and long-term estimates are therefore needed. Table 2 shows estimates from the for SMHI (1×1)° database together with the HELCOM study (HELCOM 1986). Unfortunately the same period is not covered, but the resulting precipitation amounts are within 10% for most of the basins.

It can also be noted that the period 1951-70 is drier than 1931-60, according to the HELCOM study. In Figs. 13 and 14 and Table 3, the SMHI (1×1)° database is compared with the COADS data for the period 1980 to 1995 and for the entire Baltic Sea (Kattegat and Belt Sea are not included).

The yearly cycle in Fig. 13 agree surprisingly well for these two independent data sets, as do the long time averages in Table 3. When looking at the interannual varia-

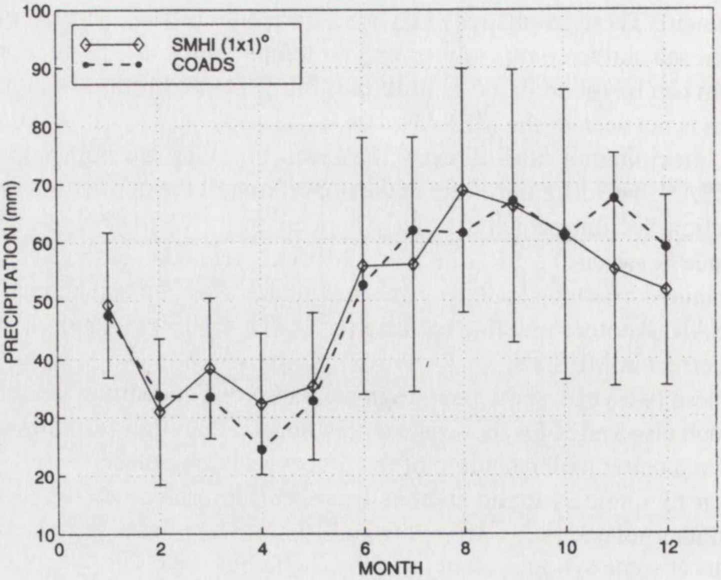


Fig. 13. Monthly precipitation averages of COADS data (circles and dashed) and SMHI (1×1)° data (diamonds and solid) for the entire Baltic Sea, 1980-1995. Vertical bars indicate ±1 standard deviation of the yearly variations of SMHI (1×1)° data; standard deviations for COADS is larger and are presented in Table 3.

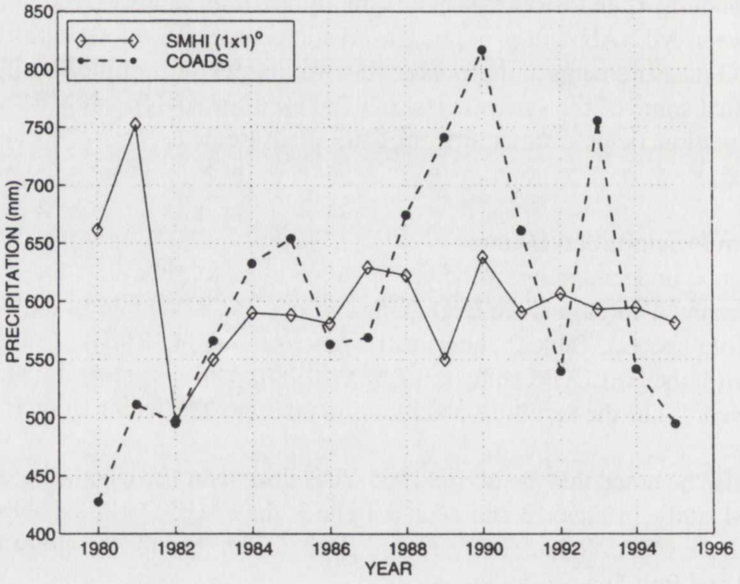


Fig. 14. Yearly precipitation averages of COADS data (circles and dashed) and SMHI (1×1)° data (diamonds and solid) for the Baltic Sea 1980-1995.

Table 2 – Long-term annual averages of precipitation for different basins (Basin 1 to Basin 10). Data are in mm. B is basin, numbers are basin numbers from Fig. 1.

STUDY	B1	B2	B3	B4	B5	B6	B3-6	B7	B8	B9	B10	3-10	1-10
HELCOM													
31-60	684	685	–	–	–	–	655	653	677	598	554	635	640
51-70	701	692	–	–	–	–	628	590	593	572	535	603	612
SMHI (1×1)°													
81-94	715	623	599	575	601	559	584	665	671	607	576	599	606

Table 3 – Long-term annual averages of precipitation (P_{mean}) including standard deviations (P_{std}). The period is 1980-1995 for the Baltic Sea, SMHI (1×1)° and COADS. Data are in mm.

STUDY	P_{mean}	P_{std}
SMHI (1×1)° 80-95	601	56
COADS 80-95	603	108

tions in Fig. 14, the differences between the two methods are large, up to 200 mm for a single year; this can to some extent be explained by the uncertainty of yearly averages in COADS. The standard deviation for the monthly estimates is also larger for COADS. This may indicate that COADS ship data cannot really be used for a single year, and longer measuring periods are needed before reliable statistics can be calculated. However, the long-term annual and seasonal means between the coarse gridded data SMHI (1×1)° and COADS show good agreements. The large interannual variations also indicate that a two-year period, as planned in BRIDGE (BALTEX main experiment), is a too short period for calculating long-term means.

Discussion

This work analyses various methods for estimating precipitation over the Baltic Sea. The methods give slightly different results, which can be explained by several factors. One is the correction of the rain gauges for precipitation losses due to wind and evaporation. The correction at Östergarnsholm is about 25% but this site is extremely exposed to winds. It is likely that the general correction of synoptic gauges in coastal areas is in the order of 5-20%; the correction formulas by Dahlström (1973) and Dahlström *et al.* (1980) appear to agree well with the SRG measurements for the investigated period. It can be argued that it is unnecessary to perform this correction over sea. Gauge based precipitation estimates at sea are generally overestimated since they are mainly based on land-influenced sites which are expected to give higher precipitation (even though orographic effects also can reduce precipitation). The difference between SRG and MESAN, where SRG gave an average of 20-30% higher precipitation, indicates that the correction should be performed nevertheless, at least for methods considering orographic effects like MESAN. In SMHI (1×1)° the increase due to land influence is, to a certain degree in coastal areas, compensating for the error due to uncorrected data. Still the bias in SMHI (1×1)° database is expected to give at least 10% too low precipitation over sea.

Precipitation is difficult to model and measure correctly due to its large temporal and spatial variability. In this study, the time scales are shown to be an important factor. Comparisons for the three-month PIDCAP period give completely opposite signals than longer periods. Comparing SRG with MESAN and SMHI (1×1)° with COADS, both methods using ships give lower values than MESAN and SMHI (1×1)° for the PIDCAP period. For the two years of 1997-98, SRG gives higher values than MESAN, and the long time comparison between COADS and SMHI (1×1)° showed good agreement. To draw any major conclusions, except day by day comparisons, for as short a period as three months is therefore questionable. Climate studies covering one or two years must be considered with care due to the large interannual variability.

The spatial distribution is also an important factor. There is an east/west difference in the distribution of the precipitation over sea in MESAN (Fig. 9). It is more precipitation at the eastern coast of the Baltic Sea due to the predominant westerly flow. Increased evaporation over sea leads to enhanced cloudiness and precipitation in the eastern regions, where there are also orographic effects due to the Baltic land mass. This cannot be seen in the SRG data since the ships do not cover coastal areas (except for areas near harbours). The north/south distribution is more similar between MESAN and SRG with maxima over the Åland Archipelago and south of Sweden, but SRG data shows smaller variations. These maxima are more outspoken for summer and autumn.

The larger variability in MESAN can partly be explained by a certain orographic influence on coastal stations and also by the missing of some major events in the SRG data. For a 16-month period the main features and the averaged value in SRG should be captured. The MESAN data show larger variability, which is mainly caused by the different influences from the coastal areas. The small difference between MESAN and the SMHI (1×1)° database in the large basins indicates that the radar has too low influence in MESAN over sea. The further development of radar data is an important issue, and such work is in focus within the BALTEX project (Michelson *et al.* 2000).

The many uncertainties still existing considering precipitation over the Baltic Sea point towards the need of more data. In order to improve our knowledge of precipitation over the Baltic Sea, more measurements are needed. A denser network of high-quality gauges of the SRG type is suggested, suitable for higher winds on small islands for continuous data series, in combination with ship measurements. More gauge measurements are necessary to obtain new information, together with further development of new methods to improve remote sensing to cover open sea areas.

Conclusions

The purpose of this study was to review various estimates of precipitation over the Baltic Sea and analyse the present state of the art. The main conclusions can be summarised as follows:

- Time scale is an important factor for precipitation investigations. Precipitation is a parameter with large temporal and spatial variations, so three-months and even two-year periods are too short for reliable long-term estimates and comparisons.
- The differences between most of the estimates, when averaged over an extended period and a larger area, are in the order of 10-20%, which is in the same range as the correction of the synoptic gauge measurements.
- It is likely that the MESAN system needs further development over sea. Gauge corrections need to be included to avoid too low precipitation at high wind speeds (presently precipitation in MESAN is probably of the order of 10 to 20% too low over sea). More focus is also needed on the radar data, since it is the only available information of the structure of precipitation over open sea in MESAN. The similarities between MESAN and the SMHI (1×1)° database can be explained by too little consideration of radar data in MESAN.
- For coastal areas with large horizontal precipitation gradients, interpolation methods that don't take orographic effects into account must be considered with care. High-resolution methods (like MESAN) are therefore particularly needed in the transition between land and sea. Due to high frequency of high wind speeds over sea it is important to include wind speed corrections in methods using gauge data. The SMHI (1×1)° database can thus be assumed to underestimate precipitation over sea by at least 10% over sea.
- The direct ship data give the only direct information of precipitation over sea – due to the relatively low coverage it is difficult to get information of the structure on shorter time scales. For extended periods (order of months) and for evaluation of the annual cycle the SRG data gives valuable information.
- For climate estimates (time scales of decades) the only information we have are COADS and synoptic gridded databases like the SMHI (1×1)°. It is in this investigation indicated that the SMHI (1×1)° database is too low due to too small wind correction. This would indicate that also the COADS database is too low during the investigated period, due to the very good agreement between the two sources.

The best way to proceed in the development of precipitation estimates could be to use different kinds of data in combination with models in a MESAN-like system.

This gives the possibility to use the advantage of each method: the better accuracy of gauge data, together with spatial distribution as obtained by remote sensing, and other information such as stratification and humidity in the boundary layer that can be achieved from a model. However, it is clear that more direct measurements over sea (using ship measurements) together with better use of radar data are needed. An intensive measuring period such as the BALTEX main experiment BRIDGE is expected to be valuable to improve data quality and to simultaneously collect different kinds of data that can be used for verification and development of models.

Acknowledgements

This work was performed within the framework of the EU-funded project PEP in BALTEX (contract no ENV4-CT97-0484) and the Deutsche Forschungsgemeinschaft as a part of BALTEX. The SMHI and the Deutscher Wetterdienst kindly provided data of the MESAN and the weather stations. Poseidon Schiffahrt hosts gauges on their ships on their route between Germany and Finland. We thank the meteorology group at Uppsala University, which operates a ship rain gauge on Östergarnsholm. We gratefully acknowledge the help of the crews of all ships who supported our measurements. Franz Rubel provided us with the 'Rubel' data. Lars Meuller is thanked for the preparation of the SMHI (1×1)° database. Daniela Foltescu is thanked for help with the MESAN data and two anonymous reviewers are thanked for valuable comments.

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Received: 1 October, 2000
Revised: 2 January, 2001
Accepted: 4 April, 2001

Appendix A: Main tables

Table I – Precipitation from the MESAN system showing monthly and basin averages of for the PIDCAP period. Data are in mm unless otherwise is noted. B is basin, numbers are basin numbers from Fig.1.

MONTH	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B3-10	B1-10
8	22	35	24	52	56	39	66	42	46	52	48	46
9	99	72	88	88	78	54	52	78	39	39	62	65
10	44	24	26	29	31	28	57	56	38	55	37	37
SUM (mm)	165	131	139	168	165	121	176	176	123	146	147	147
SUM (m^3s^{-1})	463	313	353	824	1845	961	397	653	1222	664	6922	7696

Table II – Precipitation from the SMHI (1×1)° database showing monthly and basin averages for the PIDCAP period. Data are in mm unless otherwise is noted. B is basin, numbers are basin numbers from Fig. 1.

MONTH	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B3-10	B1-10
8	15	29	24	44	59	32	60	51	54	57	49	46
9	109	75	92	98	78	65	47	64	41	33	64	67
10	56	25	27	24	22	26	61	63	35	59	35	35
SUM (mm)	180	129	143	167	159	123	168	178	130	149	148	149
SUM (m^{3}s^{-1})	506	308	364	818	1772	979	378	662	1295	681	6950	7764

Table III – Precipitation from the MESAN system showing monthly and basin averages for 1997-1998. Data are in mm unless otherwise is noted. B is basin, numbers are basin numbers from Fig. 1.

MONTH	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B3-10	B1-10
1	32	36	27	28	46	42	41	47	44	36	41	40
2	40	35	41	38	42	40	45	37	44	45	42	41
3	24	35	34	32	32	24	19	28	29	29	29	29
4	35	45	43	37	41	36	42	36	24	27	34	35
5	42	50	53	49	43	33	40	29	27	43	38	39
6	76	72	71	62	48	48	68	67	60	61	57	59
7	61	66	58	58	51	42	51	59	61	68	54	55
8	47	36	32	39	50	36	55	72	58	53	49	48
9	38	24	48	54	65	54	69	61	62	61	60	57
10	73	81	82	100	131	76	103	88	74	69	93	91
11	37	48	50	49	53	48	34	43	51	43	49	48
12	45	42	49	49	55	53	44	45	42	28	47	47
YEAR (mm)	551	570	589	593	658	530	610	611	574	562	593	589
YEAR (m^{3}s^{-1})	389	342	378	732	1850	1062	346	572	1442	646	7028	7760

Table IV – Precipitation from the SMHI (1×1)° database showing monthly and basin averages for 1997-1998. Data are in mm unless otherwise is noted. B is basin, numbers are basin numbers from Fig.1.

MONTH	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B3-10	B1-10
1	34	36	29	28	32	35	41	50	42	37	36	36
2	55	42	43	47	41	40	46	43	42	44	43	43
3	31	40	36	39	32	23	22	31	28	35	30	31
4	48	50	44	43	45	36	43	41	30	32	39	40
5	46	53	55	56	52	37	52	36	33	39	43	44
6	88	69	74	67	63	61	90	83	69	60	68	69
7	60	77	67	69	72	57	64	74	83	91	73	72
8	58	45	46	50	53	42	60	76	59	64	55	55
9	47	32	46	57	56	50	65	61	60	58	57	55
10	93	94	89	107	112	72	107	85	68	62	87	88
11	37	44	44	48	42	42	36	44	49	44	44	44
12	60	47	47	49	48	52	46	47	44	30	46	45
YEAR (mm)	633	629	620	661	648	548	673	672	607	599	621	622
YEAR (m^3s^{-1})	448	378	398	816	1822	1099	382	628	1526	688	7361	8187

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