Meteorol. Atmos. Phys. 77, 155–166 (2001)

Meteorology and Atmospheric Physics



[1] WG Biometeorology, Institute of Medical Physics and Biostatistics, University of Veterinary Medicine Vienna, Austria
[2] Institute for Meteorology and Geophysics, University of Vienna, Austria

# BALTEX 1/6-degree daily precipitation climatology 1996–1998

**F. Rubel**[1] and **M. Hantel**[2]

With 7 Figures

Received September 27, 2000
Revised February 6, 2001

**Summary**

A precipitation correction and analysis (PCA) model has been designed and tested during the preparation phase of the BALTEX main experiment BRIDGE. The PCA model consists of a dynamical bias correction module and a geostatistical module. The bias correction reduces the systematic undercatch of the rain gauges due to wind-induced, evaporation and wetting losses by taking instrument-specific properties plus additional information from synoptic observations into account; the mean correction factor is maximum in February (1.25–1.50) and minimum in August (1.02–1.05). The geostatistical module is an ordinary block kriging algorithm; it yields gridded daily precipitation values plus error estimates on the 1/6-degree resolution of the mesoscale BALTEX models.

Here we use 3 years (1996–1998) of 4000 rain gauge observations collected by the BALTEX Meteorological Data Centre for a preliminary high-resolution climatology of the BALTEX catchment. It comprises: Time-series of area-averaged daily precipitation; and area distributions of monthly and annual precipitation. Largely independent is the worldwide monthly GPCP data set which includes also satellite data and is available from 1979 on. GPCP yields, for the years 1996–1998, an average of 2.10 mm/day while our evaluation yields 2.01 mm/day. The maximum difference (22%) occurs in January; during the summer months the values are about equal.

## 1. Introduction

The Baltic Sea Experiment (BALTEX) is the European contribution to the Global Energy and Water Cycle Experiment (GEWEX). In this paper we present a new 1/6 degree ( = 18 km; see Rubel, 1996a) daily precipitation climatology analyzed from more than 4000 bias-corrected rain gauges[1] located in the Baltic Sea drainage basin (Fig. 1). Within the framework of BALTEX the main experiment BRIDGE (Oct. 1999–Dec. 2001) has been launched at the end of 1999. BRIDGE (Bengtsson, 1998) is a campaign of international, interdisciplinary field experiments to observe new oceanographical, meteorological and hydrological data sets. These should help to improve our knowledge on the water and energy cycles of the climate system leading to improved developments of numerical weather prediction (NWP) and climate models. Both the field and the numerical experiments have been run in the test mode within the BRIDGE preparation phase (Aug. 1995–Sep. 1999). The results presented here are from this period.

Here we focus on the precipitation input into the continental scale catchment of the Baltic Sea as analyzed from surface observations only. Mesoscale precipitation fields with temporal resolutions of one day or below are highly needed to verify todays model predictions. On the other hand, it is a serious problem to accurately estimate the precipitation distribution over large areas with resolutions pre-defined by actual NWP models (20 km and below).

[1] Following a suggestion of one of the reviewers *precipitation gauge* might be the more appropriate notation.

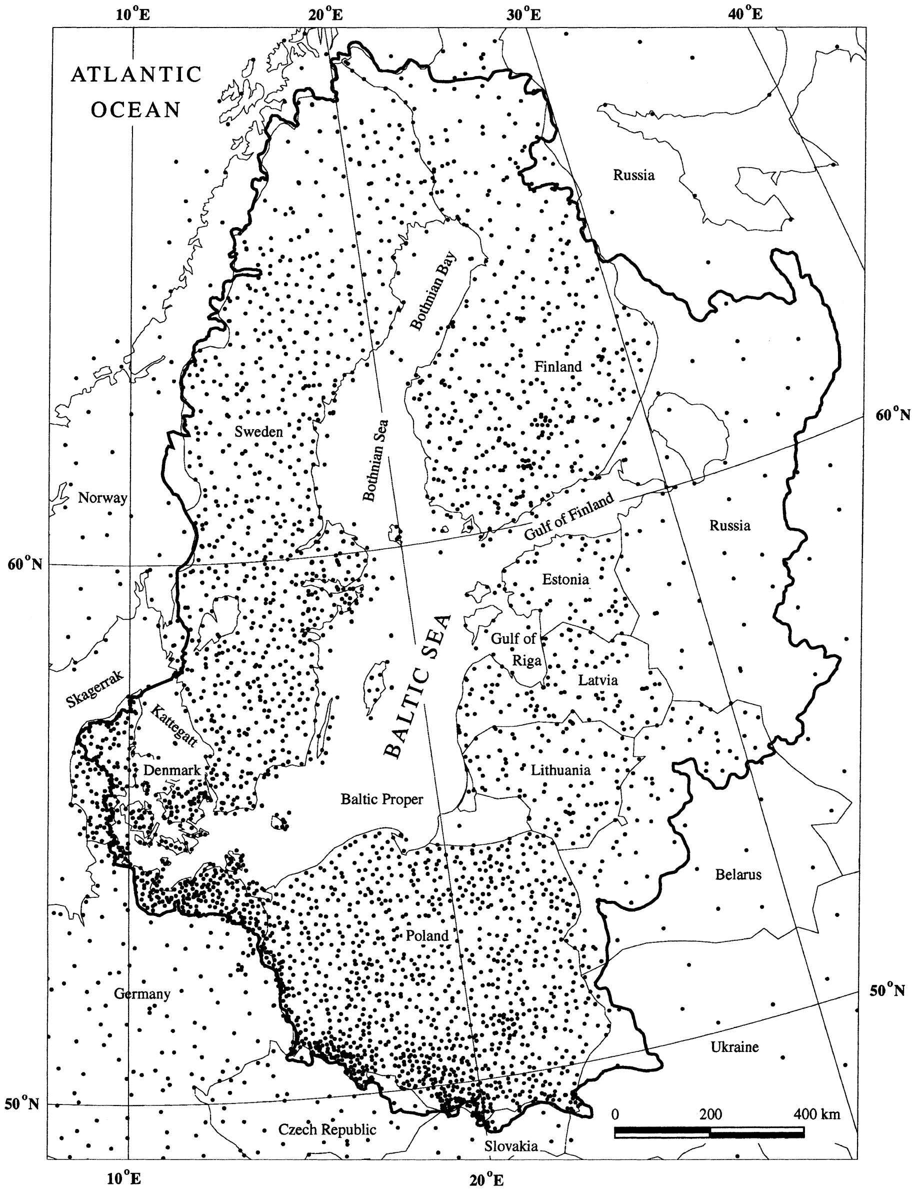



**Fig. 1.** Drainage basin of the Baltic Sea and locations of rain gauges collected by the BMDC and completed with synoptic rain gauges provided by the GPCC

In a cooperative effort of the numerous institutions involved in delivering rain gauge data, PIDCAP (Isemer, 1996), the Pilot Study of Intensive Data Collection and Analysis of Precipitation (Aug.–Oct. 1995) was initiated at the beginning of BALTEX. The BALTEX Meteorological Data Centre (BMDC) started with the collection of the rain gauge data from national climate networks and a quick look atlas based on 12-hourly precipitation accumulations from the standard synoptic data base has been compiled (Rubel, 1996a). The spatial resolution of this first precipitation product was 1/2 degree. These data set serves as reference to select periods of special interests within PIDCAP.

For the final PIDCAP analysis (Rubel, 1998) a thoroughly improved analysis model was developed. We shall refer to it as the *Precipitation Correction and Analysis* (PCA) model. PCA uses the additional data base of about 4000 gauges collected by the BMDC (Lehmann et al., 1999). PCA consists of two components: (1) a module for the reduction of the systematic measurement error of the rain gauges, and (2) a geostatistical module for the analysis of areal precipitation estimates.

Depending on constructive details rain gauges measure systematically too low values. This error has a profound impact upon climatological, hydrological and environmental studies. The correction of these systematic measurement errors is a central point in the statistical precipitation analysis.

According to Sevruk (1986), the components of the systematic measurement error are losses due to wind field deformation above the gauge orifice (2–10% for liquid and 10–50% for solid precipitation), losses from wetting on internal walls of the collector and in the container (2–10%) and losses due to evaporation from the container (0–4%).

An important factor when assessing the accuracy of precipitation measurements is the gauge type used. Gauges with wind shields, on average, measure 20–70% more snow than gauges without wind shield (Yang et al., 1999a). Other sources of errors are splash-out and splash-in. Blowing and drifting snow is important particular in polar regions and may lead to significant overestimation or misinterpretation of measurements. Proposed correction factors or statistical correction models (Sevruk, 1996; Allerup et al., 1997; Yang et al., 1999b) are based on field studies with reference gauges, e.g. the WMO Solid Precipitation Measurement Intercomparison (Goodison et al., 1998), and it is expected that implementation of these corrections to raw rain gauge observations will significantly improve the accuracy and homogeneity of these data. In the PCA model used here, a dynamic correction model for daily precipitation measurements is implemented (Rubel and Hantel, 1999). This correction model, developed following the concepts proposed in the Manual for Operational Correction of Nordic Precipitation Data (Førland et al., 1996), was designed to be applied operationally to the BMDC data base.

The second component of our PCA model concerns the task to compile representative area-averaged precipitation fields. Within the catchment the rain gauge observations are irregularly distributed and also the station density is highly variable (Fig. 1). It is therefore necessary to use a spatial interpolation method to estimate areally averaged precipitation values. Geostatistical methods, also known as kriging, historically introduced by Krige (1962), or optimum interpolation (OI) methods, historically introduced by Gandin (1963), have some advantage over other methods (Creutin and Obled, 1982). Some methods are equivalent; for example, kriging and splines are formally alike even if they are practically quite different (Cressie, 1993).

Splines in precipitation analyses have been used by e.g. Hutchinson (1995), whereas geostatistical methods have been used by e.g. Seo et al. (1990). These methods are the basis for general spatial data analysis as implemented in geographical information systems and a large body of literature exists, summarized in e.g., Cressie (1993).

In the PCA model we use a geostatistical standard method, the so-called ordinary block kriging method. It is a linear, unbiased, least-squares technique based on *Gauss' Theory of Errors* and therefore optimal in a statistical sense. Only primary data, the rain gauge observations, are used in this study. However, kriging could be easily expanded to co-kriging to optimally merge secondary data from different sources, e.g. weather radar data or satellite estimates (Rubel, 1996b).

With the PCA model we have the following strategy: Only rain gauge data are used in the analysis. The temporal resolution is 24 hours as dictated by the observations. The spatial resolution is set to 1/6 degree (about 18 km), consistent with NWP models used in BALTEX. Neither remote sensing data nor information from NWP models are taken as input; only quality checked surface observations, corrected for systematic measurement error, are used. These analyses are known to have the highest accuracy compared to precipitation estimates based on other data sources. Results from the PCA model could therefore be taken as ground truth to verify NWP and climate model predictions (Yang et al., 1998; Graham and Jacob, 2000).

The purpose of this paper is to review the climatological background (next section), the 1996–1998 data base (Sect. 3) and the PCA model (Sect. 4). Main outcome is the application of the PCA model to the BRIDGE preparation phase for preliminary climatological fields (Sect. 5). Some outlook is discussed in Sect. 6.

## 2. Climatological background from GPCP data

The total area of the Baltic Sea drainage basin (Fig. 1) is about 1 732 000 $km^2$, covering 14 countries. Because the dense rain gauge networks shown in Fig. 1 are not available for long time periods, a standard precipitation data set, the GPCP-V2X product, was used to calculate a 20-year time series. This series (1979 to 1998) of monthly precipitation within the Baltic Sea

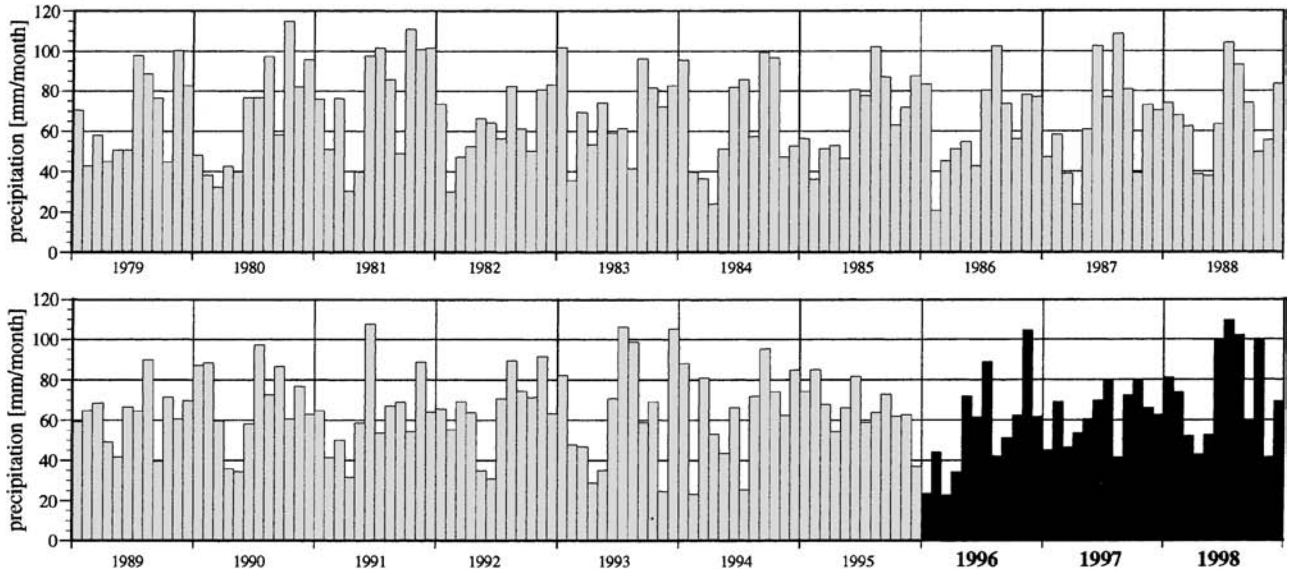



**Fig. 2.** Time series of monthly averaged precipitation within the Baltic Sea drainage basin calculated from GPCP's merged satellite-gauge product. Period: 1979 to 1998, units mm/month. Black part of histogram: BRIDGE preparation phase 1996–1998

drainage basin is shown in Fig. 2. Data basis is the GPCP's merged satellite-gauge product (Huffman et al., 1997; Rudolf et al., 1999) which has become a standard data set for climate model verification.

The evaluation of the present study offers the opportunity to check the accuracy of this widely used monthly GPCP data set. We shall demonstrate this below with our daily corrected analyzed data for the BRIDGE preparation phase. A caveat: The 3 year period 1996–1998 is still not yet long enough for a robust climatological average. However it is well suited for a reference data set for validation.

Figure 3 shows the mean monthly values of the precipitation input into the drainage basin calculated from the 20 years of Fig. 2, together with calculations of independent authors. The estimates of Kuusisto (1995) are preliminary values compiled from various sources; they have been corrected for systematic measurement errors. The estimates of Omstedt et al. (1997) are calculated from uncorrected synoptic rain gauges of the period 1980–1994.

The rough annual estimate of precipitation is about 700 mm/year with maximum in August (about 80 mm/month) and minimum in April (about 40 mm/month). Further, all three curves agree reasonably well with each other from April to September. During the winter months, however,

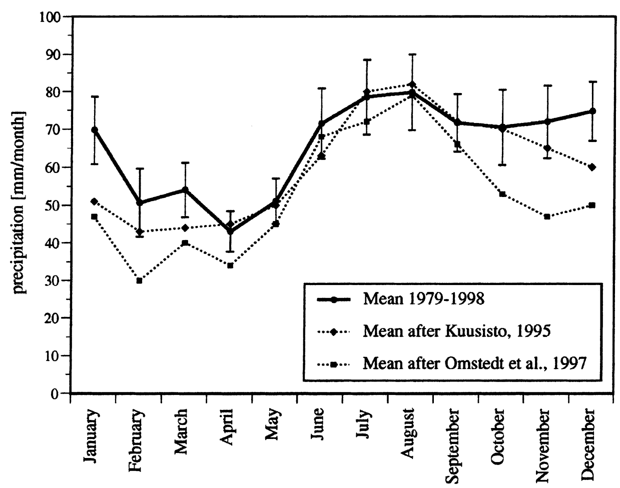



**Fig. 3.** Mean monthly precipitation averaged over the Baltic Sea drainage basin. The mean was calculated from 20 years of GPCP-V2X products of the period 1979–1998 (solid line with dots and 95% confidence intervals). Earlier estimates (dashed lines) from Kuusisto (1995) and Omstedt et al. (1997) are plotted for comparison. Note, that the GPCP estimates as well as the values given by Kuusisto (1995) are based on corrected rain gauge measurements while Omstedt et al. (1997) gives uncorrected values. Note further, that the three curves have been calculated for different time periods and the values given by Omstedt et al. (1997) relate only to sea areas

the GPCP data are generally higher than the Kuusisto (1995) estimates; the major differences occur in January and December. For these months the estimates after Kuusisto (1995) are not within the 95% confidence intervals of the precipitation calculated from GPCP data set. This may be due to different correction algorithms used for snow. The precipitation amounts given by Omstedt et al. (1997) are also significantly lower during winter time; this is to be expected, because of the neglected corrections for solid precipitation in the Omstedt evaluation.

Additional climatologies for parts of the drainage basin, e.g. the Baltic Proper (Isemer and Lindau, 1998; Clemens and Bumke, 2001) have been given by other authors (not shown).

## 3. Database

The first organisational step of this study was the collection of the rain gauge data which are available only in data archives of national services, stored in various different file formats. In the case of the Baltic Sea drainage basin non-synoptic data from 10 countries have been collected by the BMDC, listed in Table 1. Additional synoptic data (transmitted via GTS) have been provided by the Global Precipitation Climatology Centre (GPCC). Figure 1 shows the station density of both types as used in this study. The network of the rain gauges is about 10 times denser within the catchment; outside the catchment only synoptic data are available. The synoptic data base includes data from the Czech Republic, Norway, Slovakia and Ukraine as well as additional data from the countries listed in Table 1. Together with the about 500 gauges from the synoptic network the total number of gauges is 4 400 (during PIDCAP) in 1995 and decreases to about 3 500 in 1998.

**Table 1.** Average number of non-synoptic rain gauge data provided by 10 countries, collected and archived by the BMDC (Lehmann et al., 1999)

| Country | 1995 | 1996 | 1997 | 1998 |
|---|---|---|---|---|
| Belarus | 60 | 60 | 60 | 60 |
| Denmark | 610 | 215 | 215 | 215 |
| Estonia | 80 | 70 | 60 | 60 |
| Finland | 500 | 400 | 450 | 435 |
| Germany | 285 | 285 | 280 | 280 |
| Latvia | 75 | 85 | 95 | 95 |
| Lithuania | 70 | 85 | 95 | 95 |
| Poland | 1260 | 1175 | 1070 | 975 |
| Russia | 150 | 75 | 0 | 0 |
| Sweden | 850 | 750 | 795 | 765 |
| Total | 3940 | 3200 | 3120 | 2980 |

## 4. Precipitation correction and analysis model

The PCA model has been developed in order to calculate high resolution precipitation fields based on dense networks of rain gauges within the Baltic Sea drainage basin. It consists of 2 parts: a dynamic correction model for the reduction of systematic measurement errors and a geostatistical model to estimate spatial averaged precipitation values representative for the grid areas.

### *4.1 Bias correction of measurements*

The dynamic correction model is based on the methods proposed in the *Manual for Operational Correction of Nordic Precipitation Data* (Førland et al., 1996); it was developed and applied to daily precipitation data in the BALTEX model domain (Rubel and Hantel, 1999). Its main purpose is to correct for the wind-induced losses which is the largest error.

The corrected precipitation value $Z$ is estimated as

$$Z = k(Z_m + \Delta Z_w + \Delta Z_e), \tag{1}$$

where $Z_m$ is the measured precipitation value, $\Delta Z_w$ the wetting loss, $\Delta Z_e$ the evaporation loss, and $k$ the aerodynamic correction factor. While the values of the wetting and evaporation losses are generally low (about 0.1 mm/day, for details see Førland et al. (1996)) and are taken from climatology, the aerodynamic correction factor contains actual information on the weather event (wind speed, temperature, rain intensity) as well as specific information on the rain gauge (gauge type, height of the orifice, shielded or unshielded). Figure 4 shows the annual cycles for 1996, 1997 and 1998 of the monthly mean of $k$ calculated from the total data base (Fig. 1). As an example, the mean of the daily correction factors $k$ for February 1996 is 1.40 for all gauges, 1.56 for the unshielded gauges and 1.26 for shielded gauges. These are the highest corrections during the period 1996 to 1998. Due to the distribution of the specific gauge types, which follows the shape of the countries, and due to the high variability of daily rain events, the monthly mean of the correction factor of shielded gauges can exceed those of the unshielded gauges (e.g., March 1997). On average, however, the correction factors for unshielded gauges (e.g., HELLMANN) are 30–50%

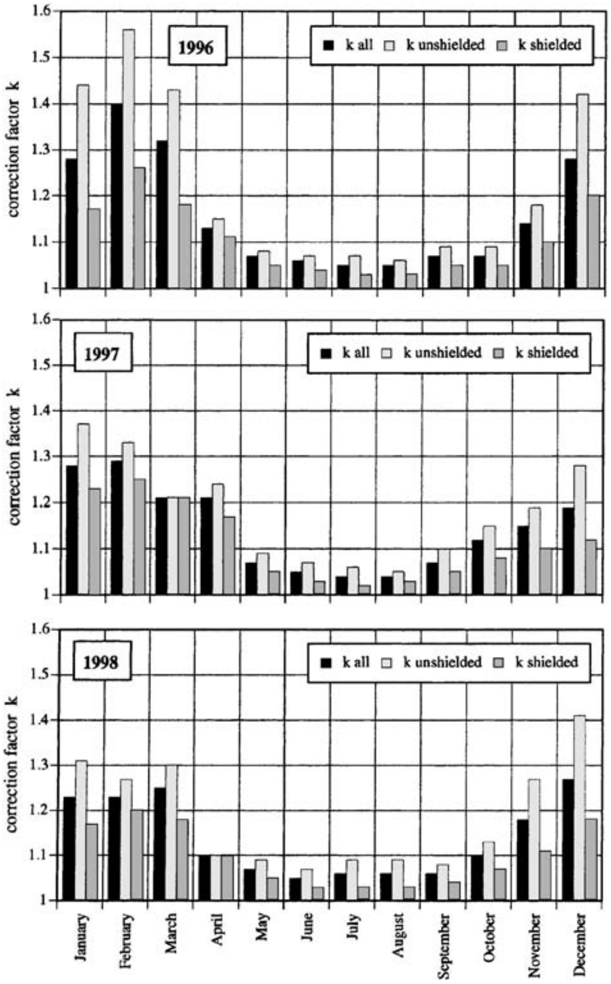



**Fig. 4.** Monthly mean of the daily correction factors $k$ averaged over the BALTEX model domain for 1996, 1997 and 1998

higher than for shielded gauges (e.g. TRETJAKOV, SMHI, H&H-90). The total average aerodynamic correction factor $k$ is about 1.25 during the winter months and 1.05 during the summer months.

### *4.2 Geostatistical analysis*

The irregularly distributed rain gauge data have been analyzed on a meso-scale grid with a spatial resolution of about 18 km. This grid was adapted from the DM and REMO model, the resolution was set to 1/6 degree. Ordinary block-kriging was used for the statistical analysis. This method estimates the areal precipitation $Z_A$:

$$Z_A(\mathbf{u}_o) = \frac{1}{A}\int_A Z(\mathbf{u})dA \qquad (2)$$

from the following linear combination:

$$\hat{Z}(\mathbf{u}_o) = \sum_{i=1}^{n} \lambda_i Z(\mathbf{u}_i), \qquad (3)$$

where $\hat{Z}(\mathbf{u}_o)$ is the estimate of the areal precipitation, the values $Z(\mathbf{u}_i)$ are the corrected point precipitation measurements at locations $\mathbf{u}_i \equiv (x_i, y_i), i = 1, 2, \ldots n$ and $\lambda_i$ are the weighting factors which have to be estimated. The vector $\mathbf{u}_o \equiv (x_o, y_o)$ represents the central point of the grid box considered.

The statistically optimal determination of these weighting factors follows from a linear system of $n+1$ equations written here in terms of the spatial auto-correlation function $\hat{R}$:

$$\sum_{j=1}^{n} \lambda_j \hat{R}(\mathbf{u}_j, \mathbf{u}_i) + \mu = \frac{1}{A}\int_A \hat{R}(\mathbf{u}, \mathbf{u}_i)\mathrm{d}A$$

$$\sum_{i=1}^{n} \lambda_i = 1. \qquad (4)$$

Additionally, for each precipitation field the error variance (normalized estimation variance)

$$\sigma_\epsilon^2(\mathbf{u}_o) = \frac{1}{A^2}\int_A \int_{A'} \hat{R}(\mathbf{u}, \mathbf{u}')\mathrm{d}A\mathrm{d}A' - \sum_{i=1}^{n} \lambda_i \frac{1}{A}\int_A \hat{R}(\mathbf{u}, \mathbf{u}_i)\mathrm{d}A - \mu \qquad (5)$$

was calculated. The error variance is a function of the size of the grid area, the station density and the statistical structure of the precipitation field, which depends on the scale to be resolved.

## 5. Precipitation climatology for the BRIDGE preparation phase

For each day of the BRIDGE preparation phase 1996–1998 the precipitation distribution as well as the corresponding error variance was calculated using the PCA model. For example, Fig. 5 (left) shows one day of the well known Odra flooding event 1997 (Fuchs and Rapp, 1998; Dubicki, 1998), the 7 July 1997. Several days with heavy rain exceeding areal averages of 50 mm/day in the Odra catchment at the boundary of Germany and Poland caused the flooding. Thus, the estimation variance Fig. 5 (right) indicates the high reliability of the precipitation analysis over wide parts of the Baltic Sea drainage basin reflecting the station

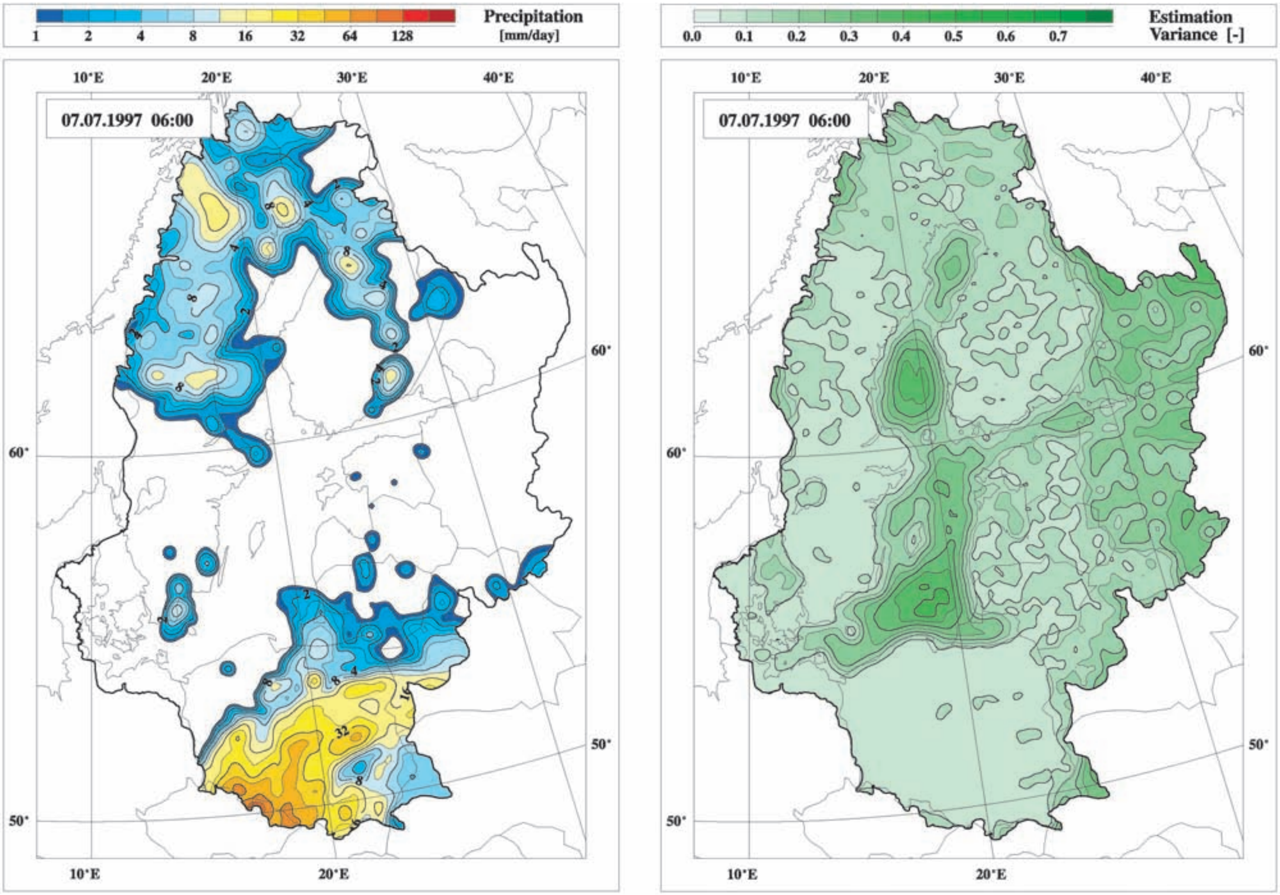



**Fig. 5.** Daily precipitation field for 7 July 1997 (left) and corresponding interpolation error (normalized with respect to the variance, right)

density shown in Fig. 1. The major data gaps are located in the Baltic Proper and in the Bothnian Sea. The precipitation values given for that region have been interpolated from coastal gauges. Also wide parts of Russia have been observed by GTS stations only. Nevertheless, considering the spatial correlation of daily accumulated rain amounts of more than 100 km, these interpolations are acceptable. Further, data users with high demands concerning the data quality could use the error variance to decide which regions have to be eliminated from their studies.

The total daily precipitation input into the Baltic Sea catchment is summarized in the time series in Fig. 6. Both, analyses based on bias-corrected as well as those based on raw rain gauge observations are given to demonstrate the influence of the correction procedure on precipitation climatology.

Monthly results are given in Table 2. The highest precipitation values have been observed during the summer months June to August (1.3 to 3.6 mm/day), the lowest values during spring March to April (0.7 to 1.8 mm/day). This is consistent with the climatology given by (Kuusisto, 1995) or calculated from 20-years of GPCP 2.5 degree precipitation estimates (see Fig. 3).

Going into detail, we find winter precipitations in the GPCP products (Table 3) that are visibly higher than the BALTEX estimates. The difference (referred to as *mean error*) may be due to overestimated snow losses of the gauges introduced by the climatological corrections used in the GPCP analyses compared to the on-event correction of the PCA model. The mean errors are above 10% during the winter months November to February, the maximum error of 22% was found in January. The average annual overestimation of the GPCP products during the BRIDGE preparation phase 1996–1998 is 4.5%.

The daily rain gauge analyses have been accumulated to monthly (not shown) and annual fields

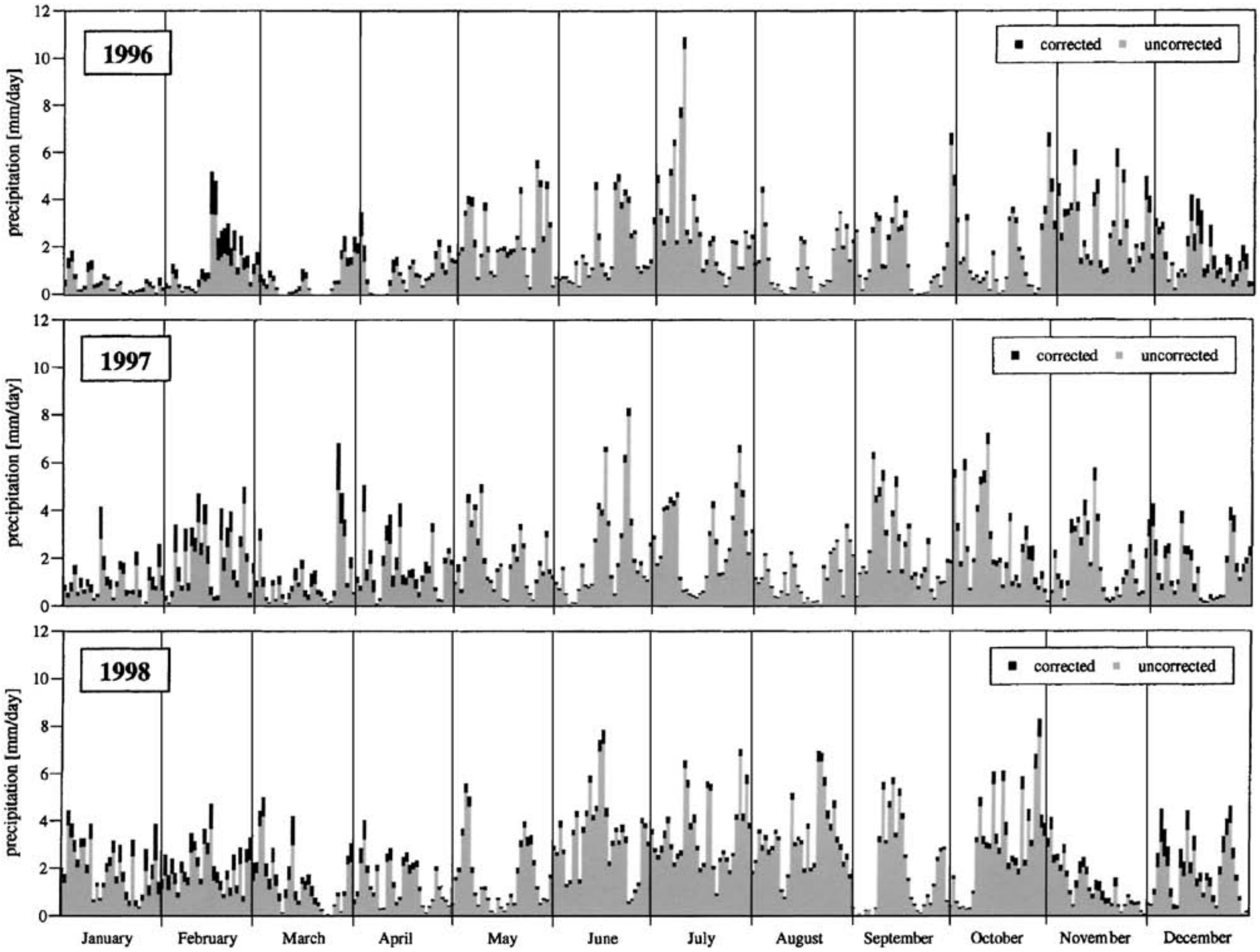



**Fig. 6.** Time series of daily precipitation averages over the Baltic Sea drainage basin based on both uncorrected (grey) as well as corrected (black) rain gauge data. Period 1996–1998, units mm/day

**Table 2.** Monthly and annual precipitation input into the Baltic Sea drainage basin. Units mm/day

| | 1996 | | | 1997 | | | 1998 | | |
|---|---|---|---|---|---|---|---|---|---|
| | Total | Sea | Land | Total | Sea | Land | Total | Sea | Land |
| January | 0.59 | 0.38 | 0.63 | 1.18 | 0.80 | 1.24 | 2.18 | 2.57 | 2.12 |
| February | 1.58 | 1.70 | 1.56 | 2.23 | 2.26 | 2.22 | 2.23 | 2.11 | 2.25 |
| March | 0.71 | 0.67 | 0.72 | 1.33 | 0.96 | 1.39 | 1.58 | 1.54 | 1.59 |
| April | 1.07 | 0.77 | 1.13 | 1.79 | 1.49 | 1.84 | 1.49 | 1.51 | 1.49 |
| May | 2.44 | 2.64 | 2.40 | 1.95 | 1.64 | 2.00 | 1.71 | 1.21 | 1.79 |
| June | 2.01 | 1.38 | 2.12 | 2.24 | 1.66 | 2.33 | 3.43 | 2.93 | 3.52 |
| July | 2.95 | 2.86 | 2.96 | 2.68 | 1.52 | 2.88 | 3.57 | 2.66 | 3.73 |
| August | 1.43 | 1.09 | 1.48 | 1.28 | 0.84 | 1.35 | 3.29 | 2.90 | 3.36 |
| September | 1.84 | 1.80 | 1.85 | 2.40 | 2.50 | 2.39 | 1.87 | 1.52 | 1.93 |
| October | 1.83 | 1.60 | 1.87 | 2.60 | 3.04 | 2.52 | 3.15 | 3.46 | 3.10 |
| November | 3.04 | 3.81 | 2.91 | 1.99 | 1.95 | 2.00 | 1.34 | 1.72 | 1.28 |
| December | 1.75 | 2.10 | 1.69 | 1.72 | 1.72 | 1.73 | 2.00 | 2.24 | 1.96 |
| Annual | 1.77 | 1.73 | 1.78 | 1.95 | 1.70 | 1.99 | 2.32 | 2.20 | 2.34 |

**Table 3.** Comparison of GPCP and BALTEX monthly and annual precipitation input into the Baltic Sea drainage basin in terms of mean error (ME). Period 1996–1998, units mm/day.

| | 1996–1998 | | | |
|---|---|---|---|---|
| | GPCP | BALTEX | ME | % |
| January | 1.61 | 1.32 | 0.29 | 22.2 |
| February | 2.22 | 2.01 | 0.21 | 10.3 |
| March | 1.31 | 1.21 | 0.10 | 8.5 |
| April | 1.46 | 1.45 | 0.01 | 0.6 |
| May | 2.00 | 2.03 | −0.03 | −1.5 |
| June | 2.56 | 2.56 | 0.00 | 0.0 |
| July | 3.00 | 3.07 | −0.07 | −2.2 |
| August | 2.00 | 2.00 | 0.00 | 0.1 |
| September | 2.03 | 2.04 | −0.01 | −0.4 |
| October | 2.61 | 2.53 | 0.08 | 3.3 |
| November | 2.36 | 2.13 | 0.23 | 11.0 |
| December | 2.09 | 1.83 | 0.26 | 14.5 |
| Annual | 2.10 | 2.01 | 0.09 | 4.5 |

(Fig. 7). The effect of the mountain chains of central Scandinavia in the Northwest as well as of Southern Poland, Slovakia and the Czech Republic in the South are well depicted in the precipitation pattern. Monthly and annual totals in units mm/day are given in Table 2. The corresponding annual values are 648 mm/year (1996), 710 mm/year (1997) and 849 mm/year (1998), respectively. For purposes of comparison: The annual precipitation amounts based on uncorrected rain gauge observations are 561 mm/year (1996), 613 mm/year (1997) and 745 mm/year (1998). Thus the average annual deficit (1996–1998) when using uncorrected data is about 13%.

## 6. Conclusions

The *precipitation correction and analysis* model PCA has originally been developed to produce a meso-scale precipitation climatology of the Baltic Sea drainage basin. First application of PCA was made during PIDCAP (Rubel, 1996a, 1998; Rubel and Hantel, 1999). Purpose of the present study has been to implement the most recent version of PCA for application in the upcoming BALTEX main experiment BRIDGE. Preliminary results for BRIDGE have been given by Rubel and Hantel (2001).

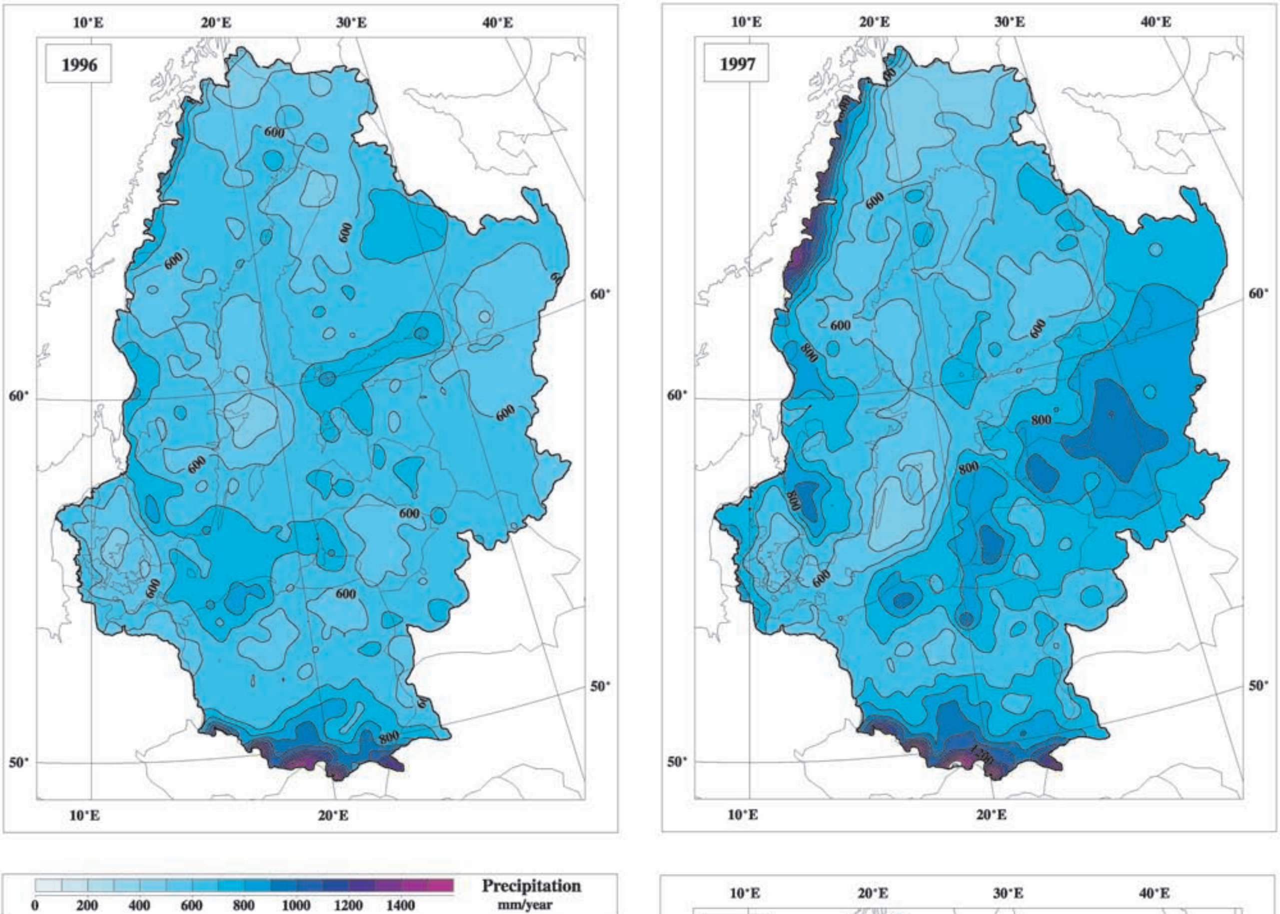
The results presented here are the first of a series of objectively analyzed precipitation fields based on several years of bias corrected rain gauge data from the dense climatological network of 14 countries within the catchment of the Baltic Sea. The analyzed precipitation fields based on corrected rain gauge measurements can be considered an equivalent freshwater input into the Baltic Sea drainage basin. The modification necessary to correct the rain gauge measurements was 13% on average.

The major limitation of the present precipitation analyses is that the fields over the open Baltic Sea are based on coastal and island stations only. Therefore, in order to improve the analyses over the open sea we are planning to include in upcoming applications data from feries (Hasse et al., 1998) running routinely in the Baltic Proper between Lübeck and Helsinki (Clemens and Bumke, 2001).

An approach complementary to the PCA model is the Mesoscale Analysis System (MESAN) developed at the Swedish Meteorological and Hydrological Institute (Häggmark et al., 1997). While PCA needs the complete climatological information and thus runs offline, MESAN is an operationally running online system. It uses the classical OI technique to perform merged radar-gauge precipitation analyses with HIRLAM first guess fields. The power of the MESAN concept becomes evident in nowcasting when precipitation analyses from sparse density online rain gauge networks are filled with information from the weather radar networks. It has been demonstrated for PIDCAP (Michelson et al., 2000) that MESAN gives results similar to the PCA model (but without bias-correction).

Also for PIDCAP, the PCA model results have been used for model intercomparison studies investigating the water budget for BALTEX (Jacob et al., 2001). The importance of an accurate precipitation analysis over the Baltic sea drainage basin has also been demonstrated by climate model verifications. Graham and Jacob (2000) showed that even the annual precipitation cycle could hardly be simulated by climate models.

Another useful application concerns the new 1-degree daily experimental version of GPCP's global satellite precipitation estimates. A preliminary verification of this product with our PCA-generated estimates has recently been done over the BALTEX domain (Rudolf and Rubel, 2000) with the result that a calibration of satellite pro-



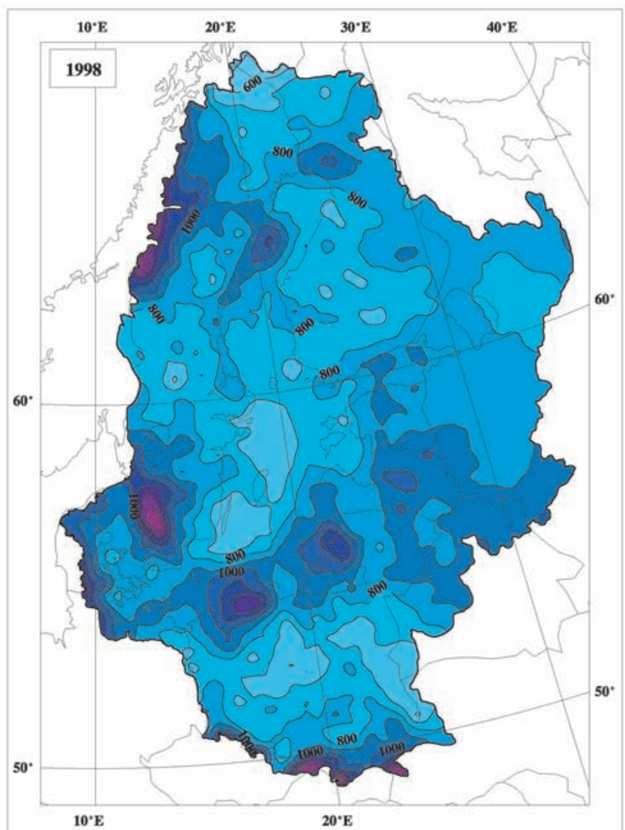




**Fig. 7.** Annual precipitation distribution for 1996, 1997 and 1998 within the Baltic Sea drainage basin calculated from bias-corrected rain gauge measurements. Units mm/year. The corresponding interpolation error (not shown) is available in the complete data set from the equivalent right part of Fig. 5

ducts is indispensable. A further application has been made in diagnostic studies on convection (Hantel and Hamelbeck, 2000).

Finally, it is one goal of GEWEX to transfer developed methodologies to other regions of the globe. Following this concept, the PCA model has been applied to the global synoptic database with special emphasis to the other continental-scale experiments of GEWEX (Ungersböck et al., 2001). Highlight of these evaluations is the conspicuous difference of the correction necessary in the tropics (small) and extratropics (large).

The data base generated for the upcoming BRIDGE-period with the method presented in this study will be archived by BMDC and will be made available to the BALTEX community.

**Acknowledgements**

This research was supported by the EC Environment and Climate Research Programme (NEWBALTIC II, No. ENV4-CT97-0626, Climatology and Natural Hazards). The GPCC, Global Precipitation Climatology Centre (operated by DWD, Offenbach), provided the synoptic data and the BMDC the extended rain gauge data base. Our special thanks are expressed to B. Rudolf and T. Fuchs from GPCC as well as to A. Lehmann, C. Craute and D. Stein from BMDC for excellent cooperation and quick data transfer. E. Raschke and H.-J. Isemer from GKSS laid the foundations for this study with their initiative concerning the data collection for BALTEX/PIDCAP.

**References**

Allerup P, Madsen H, Vejen F (1997) A comprehensive model for correcting point precipitation. Nord Hydrol 28: 1–20

Bengtsson L (1998) Interim memorandum of understanding for the conduct of BRIDGE 1999–2001 in frame of BALTEX. Int. BALTEX Secr., GKSS Forschungszentrum, Geesthacht, Germany, 58 pp

Clemens M, Bumke K (2001) A comparison of precipitation in-situ measurements and model predictions over the Baltic Sea area. Phys Chem Earth (**B**) 26: 437–442

Cressie NAC (1993) Statistics for spatial data. Wiley, New York, 900 pp

Creutin JD, Obled C (1982) Objective analyses and mapping techniques for rainfall fields: an objective comparison. Water Resour Res 18: 413–431

Dubicki A (1998) The Odra flooding event 1997: Characteristics of the process of rising and developement and anti-flood management. In: Raschke E, Isemer H-J (eds) Second study conference on BALTEX, Island of Rügen, Germany, Int. BALTEX Secr., Publ. No. 11, 36–40

Førland EJ (ed), Allerup P, Dahlström B, Elomaa E, Jónsson T, Madsen H, Perälä J, Rissanen P, Vedin H, Vejen F (1996) Manual for operational correction of nordic precipitation data. Norwegian Meteorological Institute, Oslo, 66 pp

Fuchs T, Rapp J (1998) Zwei aussergewöhnlich starke Regenepisoden als Ursache des Oderhochwassers im Juli 1997 (in German). Klimastatusbericht 1997, DWD, Offenbach am Main, 27–30. Online version: http://www.dwd.de/research/klis/ksb/

Gandin LS (1963) Objective analysis of meteorological fields. Gidrometeor. Izdat., Leningrad. Hydromet. Press [Israel Program for Scientific Translation, Jerusalem 1965, 242 pp]

Goodison BE, Louie PYT, Yang D (1998) WMO solid precipitation measurement intercomparison – final report. WMO/TD - No. 872, Instruments and Observing Methods Report no. 67, 212 pp

Graham LP, Jacob D (2000) Using large-scale hydrologic modeling to review runoff generation processes in GCM climate models. Meteorol Z 9: 49–57

Häggmark L, Ivarsson K-I, Olofsson P-O (1997) MESAN-Mesoskalig Analys (in Swedish). RMK 75, SMHI, S-60176, Norrköping, Sweden, 77 pp

Hantel M, Hamelbeck F (2000) Convection in PIDCAP – A descriptive approach. Meteorol Z 9: 77–84

Hasse L, Grossklaus M, Uhlig K, Timm P: A ship rain gauge for use in high wind speeds. J Atm Oceanic Technol 15: 380–386

Huffman GJ, Adler RF, Arkin P, Chang A, Ferraro R, Gruber A, Janowiak J, McNab A, Rudolf B, Schneider U (1997) The global precipitation climatology project (GPCP) combined precipitation dataset. Bull Amer Meteor Soc 78: 5–20

Hutchinson MF (1995) Interpolating mean rainfall using thin plate smoothing splines. Int J Geogr Inf Sys 9: 385–403

Isemer H-J (1996) PIDCAP – Project Description. Int. BALTEX Secr, GKSS Research Centre, 24 pp

Isemer H-J, Lindau R (1998) Climatological estimates of precipitation and evaporation over the Baltic Proper based on COADS. In: Raschke E, Isemer H-J (eds) Second study conference on BALTEX, Island of Rügen, Germany, Int. BALTEX Secr, Publ No 11, 80–81

Jacob D, Andrae U, Graham LP, Karstens U, Koepken Ch, Lindau R, Podzun R, Rockel B, Rubel F, Smith R, Van den Hurk BJJM, Yang X (2001) A comprehensive model intercomparison study investigating the water budget during the BALTEX-PIDCAP period. Meteorol Atmos Phys (this issue)

Krige DG (1962) Statistical applications in mine valuation. J Inst Min Survey S Afr 12(2): 45–84; 12(3): 95–136

Kuusisto E (1995) Hydrology and hydroenergetics of the Baltic drainage. First study conference on BALTEX – conference proceedings, Int BALTEX Secr, Publ No 3, 18–27

Lehmann A, Zimmermann K, Graute C, Stein D (1999) Meteorological data centre for BALTEX – BALTEX MDC – Status Report No. 3, October 1999. Selbstverlag des DWD, Offenbach/M., 106 pp

Michelson DB, Foltescu VL, Häggmark L, Lindgren B (2000) MESAN Mesoscale analysis of precipitation. Meteorol Z 9: 85–96

Omstedt A, Meuller L, Nyberg L (1997) Interannual, seasonal and regional variations of precipitation and evaporation over the Baltic Sea. Ambio 26: 484–492

Rubel F (1996a) PIDCAP – Quick look precipitation atlas. Österreichische Beiträge zu Meteorologie und Geophysik 15: 97 pp

Rubel F (1996b) Scale dependent statistical precipitation analysis. Proceedings of the international conference on water resources & environmental research: Towards the 21st century, Kyoto, Japan, Vol I, 317–324

Rubel F (1998) PIDCAP – Ground truth precipitation atlas. Österreichische Beiträge zu Meteorologie und Geophysik 18: 76 pp

Rubel F, Hantel M (1999) Correction of daily rain gauge measurements in the Baltic Sea drainage basin. Nord Hydrol 30: 191–208

Rubel F, Hantel M (2001) BALTEX precipitation analysis: Results from the BRIDGE preparation phase. Phys Chem Earth (**B**) 26: 397–401

Rudolf B, Gruber A, Adler R, Huffman G, Janowiak J, Xie P-P (1999) GPCP precipitation analyses based on observations as a basis of NWP and climate model verification. Extended abstract, 2nd Int Conf on Re-analyses, Reading UK, August 1999, 4 pp

Rudolf B, Rubel F (2000) Validation of satellite-based global precipitation analyses of the GPCP using bias-corrected rain gauge data of BALTEX as reference. Proceedings of the European Conference on Applied Climatology, Pisa, Italy, 16 to 20 October, 2000

Seo D-J, Krajewski WF, Azimi-Zonooz A, Bowles DS (1990) Stochastic interpolation of rainfall data from rain gages and radar using co-kriging, 2: results. Water Resour Res 26: 915–924

Sevruk B (1986) Correction of precipitation measurements – summary report. In: Sevruk B (ed) Correction of precipitation measurements. Züricher Geographische Schriften 23: 13–23

Sevruk B (1996) Adjustment of tipping-bucket precipitation gauge measurements. Atmos Res 42: 237–246

Ungersböck M, Rubel F, Fuchs T, Rudolf B (2001) Bias correction of global daily rain gauge measurements. Phys Chem Earth (**B**) 26: 411–414

Yang D, Goodison BE, Metcalfe JR, Louie P, Leavesley G, Emerson D, Hanson CL, Golubev VS, Elomaa E, Gunther T, Pangburn T, Kang E, Milkovic J (1999) Quantification of precipitation measurement discontinuity induced by wind shields on national gauges. Water Resour Res 35: 491–508

Yang D, Elomaa E, Goodison B, Gunther Th, Golubev V, Sevruk B, Madsen H, Milkovic J (1999) Wind-induced precipitation undercatch of the Hellmann gauges. Nord Hydrol 30: 57–80

Yang X (ed), Sass BH, Winter T, Karstens U, Windelbrand M, Jakob D, Smith R, Rubel F (1998) Inter-comparison of area averaged daily precipitations. NEWBALTIC Manuscript, Danish Meteorological Institute, Copenhagen, 5 pp

Authors' addresses: F. Rubel, WG Biometeorology, Institute of Medical Physics and Biostatistics, University of Veterinary Medicine, Veterinärplatz 1, A-1210 Wien, Austria; M. Hantel, Institute for Meteorology and Geophysics, University of Vienna, Althanstraße 14, A-1090 Wien, Austria