ON PRECIPITATION CLIMATOLOGY: FROM CONTINENTAL SCALE EXPERIMENT TO GLOBAL APPLICATION

ZUR NIEDERSCHLAGSKLIMATOLOGIE: VOM KONTINENTALSKALIGEN EXPERIMENT ZUR GLOBALEN ANWENDUNG

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SUMMARY

A precipitation correction and analysis (PCA) model has been developed and tested in the framework of the Baltic Sea Experiment (BALTEX). 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 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 meso-scale BALTEX models.

The PCA model was applied to more than 3 years (Aug. 1995 to Dec. 1998) of 4 000 daily rain gauge observations collected by the BALTEX Meteorological Data Centre to compile a meso-scale climatology of the Baltic Sea drainage basin. The climatology comprises time-series of area-averaged daily precipitation as well as area distributions of monthly and annual precipitation. The total annual precipitation amounts for the Baltic Sea drainage basin are 648 mm (1996), 710 mm (1997) and 849 mm (1998), respectively. For purposes of comparison: The annual precipitation amounts based on uncorrected rain gauge observations are 561 mm (1996), 613 mm (1997) and 745 mm (1998). Thus the average annual deficit (1996-1998) when using uncorrected data is about 13 %.

As a contribution to the Global Precipitation Climatology Programme (GPCP) the PCA model has been used to generate 1-degree daily precipitation fields to verify the new global 1-degree satellite-based estimate of daily precipitation, the GPCP-1DD product. Additionally to the BALTEX precipitation analyses, the ground truth is represented by 3 100 daily rain gauge measurements operating during June/July 1997 in the region of the Mesoscale Alpine Programme (MAP). Further, t+6 to t+30 hours model predictions from the European Centre for Medium Range Weather Forecast (ECMWF) have been included in the comparison studies. A major result is that the verification scores of the GPCP-1DD precipitation estimates have shown to be significantly lower than those of the ECMWF forecasts (probability of detection GPCP=0.62; ECMWF= 0.80, false alarm ratio GPCP=0.20; ECMWF=0.17 and true skill statistics GPCP= 0.36; ECMWF=0.54).

It is one goal of the Global Energy and Water Cycle Experiment (GEWEX) to transfer developed methodologies to other regions of the globe. Following this concept, the PCA model, developed during the GEWEX project BALTEX, has been applied to the global synoptic database with special emphasis to the other continental-scale model domains of GEWEX. Highlight of these evaluations is the conspicuous difference of the correction necessary in the tropics (3 - 10 %) and extratropics (10 - 60 %) .

ZUSAMMENFASSUNG

Im Rahmen des Ostsee Experiments (BALTEX) wurde ein Modell zur Korrektur und Analyse des Niederschlags (PCA Modell) entwickelt und getestet. Das PCA Modell besteht aus einem Modul zur dynamischen Korrektur des Bias und einem Modul zur Geostatistik. Die Bias-Korrektur reduziert die systematische Unterschätzung des Niederschlags infolge von Auffangverlusten, bedingt durch Wind, Verdunstung und Benetzung. Dabei werden spezifische Informationen zu den verwendeten Instrumenten sowie zusätzliche Informationen von synoptischen Beobachtungen berücksichtigt. Das geostatistische Modul besteht aus einem *Ordinary Block Kriging* Algorithmus. Es dient dazu, gerasterte tägliche Niederschlagswerte sowie deren Fehlerabschätzungen für die 1/6 Grad Auflösung der mesoskaligen BALTEX Modelle zu berechnen.

Das PCA Modell wurde für mehr als 3 Jahre (Aug. 1995 bis Dez. 1998) auf 4 000 Stationen mit täglichen Niederschlagsmessungen, gesammelt vom Meteorologischen Daten Zentrum für BALTEX, angewandt um eine mesoskalige Klimatologie des Einzugsgebietes der Ostsee zu erstellen. Diese beinhaltet Zeitreihen flächengemittelter täglicher Niederschläge sowie Felder monatlicher und jährlicher Niederschläge. Die totalen Niederschlagseinträge in das Einzugsgebiet der Ostsee sind 648 mm (1996), 710 mm (1997) und 849 mm (1998). Zum Vergleich: die Niederschlagssummen basierend auf nicht korrigierten Messungen sind 561 mm (1996), 613 mm (1997) und 745 mm (1998). Daraus folgt ein mittleres jährliches Defizit (1996-1998) bei Verwendung nicht korrigierter Daten von ca. 13 %.

Als Beitrag zum *Global Precipitation Climatology Programme* (GPCP) wurde das PCA Modell zur Erzeugung von täglichen Niederschlagsfeldern mit einer Auflösung von 1 Grad verwendet. Damit wurde die neuen globalen täglichen Satellitenniederschläge, das GPCP-1DD Produkt, verifiziert. Die Referenz aus Bodenmessungen wurde durch die BALTEX Niederschlagsmessungen und zusätzliche 3 100 Niederschlagsmessungen der Periode Juni/Juli 1997 aus dem Gebiet des *Mesoscale Alpine Programme* (MAP) repräsentiert. Darüber hinaus wurden auch t+6 bis t+30 Stunden Modellvorhersagen des Europäischen Zentrums für Mittelfristige Wettervorhersage (EZMW) zum Vergleich herangezogen. Als wesentliches Ergebnis dieser Studie wurde gezeigt, dass die Verifikationsmaßzahlen für die GPCP-1DD Niederschlagsabschätzungen bedeutend geringer sind als für die EZMW Prognosen (Entdeckungswahrscheinlichkeit GPCP=0.62; ECMWF= 0.80, Rate falschen Alarms GPCP=0.20; ECMWF=0.17 und *True Skill* Statistik GPCP= 0.36; ECMWF=0.54).

Ein Ziel des *Global Energy and Water Cycle Experiment* (GEWEX) ist es, die regional entwickelten Methoden für die Anwendung in anderen Regionen der Welt zu adaptieren. Diesem Konzept folgend wurde das, im Rahmen des GEWEX Projektes BALTEX entwickelte, PCA Modell auf die globale synoptische Datenbasis angewandt. Dabei wurde spezielles Augenmerk auf die kontinentalskaligen GEWEX Modellgebiete gelegt. Wesentliches Merkmal dieser Anwendung ist der auffallende Unterschied der notwendigen Korrekturen in den Tropen (3 - 10 %) und den Aussertropen (10 - 60 %).

ACRONYMS

BALTEX	**BALT**ic Sea **EX**periment
DWD	**D**eutscher **W**etter-**D**ienst
DFIR	**D**ouble **F**ence **I**nternational **R**eference
ECMWF	**E**uropean **C**entre for **M**edium Range **W**eather **F**orecasts
ELDAS	Development of an **E**uropean **L**and **D**ata **A**ssimilation **S**cheme to Predict Floods and Droughts
GAME	**G**EWEX **A**sian **M**onsoon **E**xperiment
GCIP	**G**EWEX **C**ontinental-Scale **I**nternational **P**roject in North America
GCOS	**G**lobal **C**limate **O**bserving **S**ystem
GEWEX	**G**lobal **E**nergy and **W**ater Cycle **EX**periment
GPCC	**G**lobal **P**recipitation **C**limatology **C**entre
GPCP	**G**lobal **P**recipitation **C**limatology **P**roject
GTOS	**G**lobal **T**errestrial **O**bserving **S**ystem
LBA	**L**arge-Scale **B**iosphere-**A**tmosphere Experiment in Amazonia
MAGS	**MA**ckenzie **G**EWEX **S**tudy
MAP	**M**esoscale **A**lpine **P**rogramme
MDC	**M**eteorological **D**ata **C**entre
NASA	**N**ational **A**eronautics and **S**pace **A**dministration
NCEP	**N**ational **C**enter for **E**nvironmental **P**rediction
NEWBALTIC	**N**umerical Studies of the **E**nergy and **W**ater Cycle of the **BALTIC** Region
NWP	**N**umerical **W**eather **P**rediction
PCA	**P**recipitation **C**orrection and **A**nalysis
PIDCAP	**P**ilot Study for **I**ntensive **D**ata **C**ollection and **A**nalysis of **P**recipitation
WCRP	**W**orld **C**limate **R**esearch **P**rogramme
WMO	**W**orld **M**eteorological **O**rganisation

1. Introductory remarks

The *Habilitationsschrift* presented here summarises the contributions of the author to the Baltic Sea Experiment (BALTEX) as well as to the Global Precipitation Climatology Project (GPCP). BALTEX and GPCP are international projects within the framework of the World Climate Research Programmes (WCRP).

The goal of BALTEX is to investigate the energy and water cycles of the Baltic Sea drainage basin to provide solutions for basic problems in climate and environmental research. An overview of the present BALTEX activities is given by Raschke et al. (2001). Here we focus on the main component of the water cycle, the observed precipitation input into the Baltic Sea drainage basin. At the beginning of BALTEX, in a cooperative effort of the institutions involved in delivering rain gauge data, the Pilot Study of Intensive Data Collection and Analysis of Precipitation (Aug. - Oct. 1995), PIDCAP (Isemer, 1996), was initiated. The BALTEX Meteorological Data Centre (BALTEX MDC) started with the collection of the rain gauge data from national climate networks and a quick look atlas based on synoptic precipitation measurements has been compiled (Rubel, 1996a). For the final PIDCAP analysis (Rubel, 1998), compiled within the projects NEWBALTIC I and II (Bengtsson, 1998; Hantel et al., 1998) and the national project *Bestimmung des Frischwassereintrages im Einzugsgebiet der Ostsee aus Boden- und Fernerkundungsdaten* (Rubel et al., 2000a), a thoroughly improved analysis model was developed. This model, the so-called *Precipitation Correction and Analysis* (PCA) model, was applied to the additional data base of about 4 000 gauges collected by the BALTEX MDC (Lehmann et al., 2000). The main result was the first mesoscale precipitation climatology for the Baltic Sea drainage basin (Rubel and Hantel, 2001; chapter 4 this volume).

The GPCP was established by the WCRP in 1986 to investigate the spatial and temporal distribution of precipitation around the globe for advancing our ability to model and predict global long-range weather and climate changes. The new operational precipitation product is the GPCP-V2 product, a 2.5-degree monthly precipitation estimate for the period 1979 to present. It is based on a combined satellite gauge analysis (Huffman et al., 1995; Rudolf et al., 2000). In recent time efforts are made to develope new products with the higher resolution of 1-degree daily. As a first milestone NASA presents its GPCP-1DD product (Huffman et al., 2001), the new experimental version of a global 1-degree daily precipitation estimate. This daily precipitation product is calculated from multi-satellite estimates and adjusted with the monthly GPCP products.

To determine the performance of the GPCP-1DD product the Global Precipitation Climatology Centre[2] (GPCC) initiated the project *Verifizierung der GPCP-Produkte mit BALTEX und MAP-Analysen* (Rubel et al., 1999). In this project the ground truth precipitation fields generated during BALTEX as well as precipitation fields calculated from the Mesoscale Alpine Programme (MAP) data base have been used to verify the GPCP-1DD satellite estimates (Skomorowski et al., 2001; chapter 5 this volume). The verification results indicate that a daily calibration of these satellite products is indispensable. Therefore the GPCC aspires to incorporate the daily available online gauge observations into the GPCP-1DD product to improve its reliability over the land areas.

In a first step the GPCC collected 2 years of global daily precipitation data and initiated a project for the reduction of the systematic measurement errors of these measurements. Within this project, titled as *Einrichtung einer operationellen Methode zur Korrektur der täglichen Niederschlagshöhe bezüglich systematischer*

[2]The GPCC, which is a central component of the GPCP and also operationally monitors global precipitation in the framework of GCOS and GTOS, as well as the BALTEX MDC are located at *Deutscher Wetterdienst* (DWD).

Meßfehler und zur objektiven Analyse am WZN (Rubel and Ungersböck, 1999), the dynamic correction model developed for BALTEX (Rubel and Hantel, 1999; chapter 3 this volume) has been adapted for global application. Result of the global bias corrected daily precipitation measurements for the years 1996-1997 (Ungersböck et al., 2001; chapter 6 this volume) is the conspicuous difference of the correction necessary in the tropics (small) and the extratropics (large). The application of this bias correction method will improve the GPCP rain gauge based global analyses which also enter the combined products from GPCP (Huffman et al., 1997) and NCEP (Xie and Arkin, 1996).

1.1. Uncertainties of precipitation estimation

Operational precipitation estimation on different scales such as the rain gauge measurement at one location, the regional precipitation estimation from rain gauge or weather radar networks as well as the global precipitation estimation from multi-satellite measurements is a problem that has not been sufficiently solved until now. Particular global satellite-based precipitation estimates from different techniques (e.g. infrared sensors, microwave 18 GHz and microwave 85 GHz channel) show very large differences one versus another and compared with surface data (Rudolf et al., 1996). At present exact precipitation amounts could only be determined for point locations using expensive reference gauges operating at selected sites in the framework of special projects.

The *Double Fence International Reference* (DFIR) gauge (Sevruk, 1992a) for example is used in the *WMO Solid Precipitation Measurement Intercomparison* (Goodison et al., 1998). In this project the DFIR gauge serves as reference gauge to determine the systematic measurement errors of the various standard rain gauges used in the national hydrological, meteorological and climatological networks. According to (Sevruk, 1986), the main 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 %). Particular snow measurements (Sevruk, 1992b) are sensitive to wind induced errors; at single stations this error can exceed more than 100 %. Therefore the correction of the systematic measurement errors is important specially at higher latitudes. For example the systematic measurement error averaged over the Baltic region during PIDCAP (Aug. - Oct. 1995) was 5-9 % (Rubel and Hantel, 1999; chapter 3 this volume). The correction of the systematic measurement errors is also important in the connection with the calculation of climatological trends. Førland and Hanssen-Bauer (2000) for example demonstrated, that since the mid 1960s the temperature in the Norwegian Arctic has increased by 0.5^o C, resulting in a reduced fraction of solid precipitation. The measured increase of precipitation in this period was 2.9 %, whereas the true (bias-corrected) precipitation increases only by 1.7 %. Thus, without correction the increase of the Norwegian Arctic precipitation in the last decade due to global warming would have been overestimated by about 70 %.

While the uncertainties in point precipitation estimates are caused by measurement errors and could be reduced using statistical correction models, the uncertainties in areal assessments of precipitation from rain gauge networks could be determined using geostatistical interpolation methods. These methods are known as kriging or optimum interpolation and have some advantage over other methods (Creutin and Obled, 1982) or are equivalent; for example, kriging and splines are formally alike even if they are practically quite different (Cressie, 1993). However, only kriging provides a measure of the interpolation error which depends on the statistical structure of the precipitation

process (Rubel, 1996; chapter 2 this volume), the station density and the size of the area considered (e.g. the size of the grid box). Thus, for a given distribution of rain gauges the accuracy of the areal assessment of precipitation depends on the scale to be resolved. For example, the mean relative error of a synoptic scale precipitation analysis (Rubel, 1996b) with about 1 station within each $55 \cdot 55$ km^2 grid box is 5 % for monthly, 10 % for weekly and 20 % for daily precipitation estimates during winter season. The mean error for the summer season, where the number of stratiform events is lower and the number of small scale convective events is higher, is 7 %, 15 % and 30 % respectively (WMO, 1985; Rudolf, 1995). In practice the stations are irregularly distributed and the station density varies by region. The spatial distribution of the interpolation error is given by the field of the estimation variance provided by the geostatistical analysis methods (see e.g. Rubel, 1998).

Following the description above, the uncertainties in precipitation estimation from rain gauges are significant. Nevertheless, in practice rain gauge analyses are taken as ground truth; remote sensing techniques are based on indirect measurements and must be calibrated with ground measurements before they could be used for quantitative precipitation assessments. Thus, statistical methods for the minimisation of errors in both precipitation measurements and areal precipitation assessments have fundamental impact on climatology.

1.2. Contributions to the Baltic Sea Experiment (BALTEX)

The Baltic Sea Experiment (BALTEX) is one of 5 Continental Scale Experiments (CSE) of the Global Energy and Water Cycle Experiment (GEWEX) a project of the World Climate Research Programme (WCRP). The author's contribution to BALTEX comprises the development of a model for the dynamical correction and statistical analysis of daily rain gauge data as well as the compilation of a meso-scale precipitation climatology for the continental-scale catchment of the Baltic Sea.

1.2.1. Development of the precipitation correction and analysis (PCA) 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 module for the reduction of systematic measurement errors and a geostatistical module to estimate spatial averaged precipitation values representative for the grid areas.

The dynamic correction module 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; chapter 3 this volume). Its main purpose is to correct for the wind-induced losses which is the largest error. Therefore, an aerodynamic correction factor has been defined which 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). Additionally values of the wetting and evaporation losses are considered. These values are generally low (about 0.1 mm/day) and are taken from climatology.

The geostatistical module is used to analyze the irregularly distributed bias-corrected rain gauge data on a meso-scale grid with a spatial resolution of 1/6 degree (about 18 km). This grid was adapted from the NWP models used in BALTEX. The geostatistical interpolation methods are linear or nonlinear, unbiased, least-squares spatial interpolation techniques. They are advanced applications of *Gauss' Theory of Errors* and therefore optimal in a statistical sense. Because of the assumptions of homo-

geneity and isotropy, which have to be made in the practical implementation, they do not necessarily yield optimal results. That is the reason why various assumptions have been proposed in the past, which lead to different, more or less expensive, interpolation methods. Here, for the objective analysis of the areal precipitation assessment, the well known method of ordinary block kriging is used (Rubel, 1996a; Rubel, 1996b chapter 2 in this volume).

1.2.2. Precipitation climatology for the Baltic Sea drainage basin

The total area of the continental scale catchment of the Baltic Sea is about 1 732 000 km^2, covering 14 countries. Recent climatologies for the entire Baltic Sea region are based on monthly synoptic observations (Kuusisto, 1995; Omstedt et al., 1997); a comprehensive precipitation climatology is still outstanding. Rubel and Hantel (2001a, 2001b; chapter 4 this volume) developed two strategies to compile an improved BALTEX precipitation climatology: 1) GPCP's monthly precipitation product (Huffman et al., 1995), a global satellite-gauge merged precipitation estimate, has been used to calculate a 20-years time series which serves as climatological background. 2) The PCA model is applied to the 10 times denser rain gauge data base collected by the BALTEX MDC. Result is the first daily meso-scale precipitation climatology for the entire Baltic Sea drainage basin covering several years. It is currently available for the period Aug. 1995 to Dec. 1999 and will be extended to at least 2005 (see the time-line for the BRIDGE related precipitation analysis in Rubel and Hantel, 1999; chapter 3 in this volume).

The daily rain gauge analyses have been accumulated to monthly and annual fields. In the corresponding precipitation pattern 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. The annual values of the freshwater input into the Baltic Sea drainage basin 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 for the period 1996-1998 when using uncorrected data is about 13 %.

The PCA model results have been used for NWP 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. For example, Graham and Jacob (2000) showed that even the annual precipitation cycle could hardly be simulated by climate models. A further application has been made in diagnostic studies on convection in the free atmosphere (Hantel and Hamelbeck, 2000).

1.3. Contributions to the Global Precipitation Climatology Project (GPCP)

At the beginning of this section the global precipitation climatology is reviewed from a historical point of view. One of the first worldwide precipitation maps has been compiled at the end of the 19th century by Supan (1898a,b). It needed about 50 years until Möller (1951) published his seasonal precipitation maps for the globe. Further 25 years later, as a milestone, Jaeger (1976) published the first global monthly precipitation maps. Although Jaeger compiled his precipitation maps still by hand, he was the first author who provided numerical gridded precipitation values. For that reason Jaeger's precipitation climatology was widely used for a long time. Further 10 years later, as a next milestone, Legates (1987) collected worldwide 25 000 rain gauge measurements from the period 1920-1980. Based on this extensive data set he compiled the first objectively analyzed

global precipitation climatology based on bias-corrected rain gauges.

With the initiation of the Global Precipitation Climatology Projects a new era, those of timeseries of global gridded precipitation estimates, began. In 1993 the GPCP deliveres the first two years of gridded 2.5-degree monthly precipitation estimates calculated from multi-satellite measurements. Today this precipitation climatology, the GPCP's satellite-gauge combined products (Huffman et al., 1995), comprises 21 years (1979-1999) of global monthly precipitation fields. Beside satellite estimates these fields are based on about roughly 7 000 rain gauge observations collected by the GPCC (Rudolf et al., 1992) and corrected for systematic measurement errors (Reiss et al., 1992) using the climatological correction factors given by Legates (1987).

Following the requirements of state-of-the-art climate models efforts are currently undertaken to increase both the spatial as well as the temporal resolution of the GPCP products. The new GPCP-1DD product, recently launched and available from NASA, provides the research community with 1 degree daily precipitation fields exclusively computed from multi-satellite measurements and adjusted on a monthly basis with the monthly GPCP products (Huffman et al., 2001).

As a first contribution to the GPCP the high resolution rain gauge analyses from BALTEX and MAP have been used as reference to prove the reliability of the experimental version of the GPCP-1DD product (Rubel and Rudolf, 2001; Rudolf and Rubel, 2000c). Verification scores customary used for NWP verifications have been implemented to document the current state of the GPCP-1DD product performance giving the possibility to quantify future improvements. As a second contribution to the GPCP the dynamic correction module of the PCA model has been applied to the global synoptic data base of the GPCC. The on-event correction of the systematic measurement errors of daily rain gauge observations is necessary because the climatological corrections used so far are only applicable to monthly precipitation accumulations. The bias-corrected global daily rain gauge data set will be used in future projects to improve the calibration of the GPCP-1DD products. The potential for improvements is considerable as indicated by the verification results.

1.3.1. Verification of global daily precipitation products

To verify the GPCP-1DD products the PCA model developed within the framework of BALTEX was applied to the BALTEX and MAP precipitation data base. The BALTEX verification comprises the complete year of 1997, the first year of GPCP-1DD data. For the verification over the European Alps only 2 month of observations during summer 1997 were available. For both BALTEX and MAP the daily rain gauge observations have been re-analysed on the grid of the GPCP data to compile consistent ground truth fields for the verification.

While the verification results over the BALTEX model domaine have not yet been published in journals, but have been presented at the *European Meteorological Satellite Data Users Conference - EUMETSAT* (Rudolf and Rubel, 2000a) and the *European Conference on Applied Climatology - ECAC* (Rudolf and Rubel, 2000b), the verification results over the Alps have been published by Skomorowski et al. (2001; chapter 5 in this volume) and have been submitted for publication by Rubel and Rudolf (2001). Moreover, for the MAP verification the t+6 to t+30 hours model predictions from the *European Centre for Medium Range Weather Forecast* (ECMWF) have been investigated to answer the question on the performance of the GPCP-1DD products compared to those of model predictions. Thus, here the verification results over the MAP model domain are summarised.

The ground truth is represented by 3 100 daily rain gauge measurements operating dur-

ing June/July 1997 in the region of MAP. These observations have been analysed within the MAP section of the global grid by the statistical interpolation module of the PCA model. Verification results are given in terms of difference fields (mean error GPCP=-0.59 mm/day; ECMWF=-1.13 mm/day), correlation coefficients (mean monthly value GPCP=0.57; ECMWF=0.58) as well as accuracy scores (probability of detection GPCP=0.62; ECMWF=0.80 and false alarm ratio GPCP=0.20; ECMWF=0.17) and skill scores (true skill statistics GPCP=0.36; ECMWF=0.54). These scores indicate that both global datasets have deficits in estimating realistically precipitation amounts. However, the ECMWF predictions have a high performance in forecasting the spatial distribution of the precipitating areas. A major result of this study is also that accuracy and skill of the GPCP-1DD estimates have been shown to be significantly lower than those of the ECMWF forecasts. Particular low precipitation amounts are not well represented in the GPCP-1DD satellite estimates. For example the values of the true skill score for observed precipitation amounts $\leq$ 1 mm/day are: GPCP=0.04 and ECMWF=0.40 (Rubel and Rudolf, 2001). Only the mean error of the GPCP-1DD products is low, due to the calibration with monthly synoptic data.

The verification results indicate that the calibration of the satellite estimates on a monthly basis is not sufficient for quantitative applications. To improve the performance of the GPCP-1DD product the calibration with daily bias-corrected rain gauge observations is absolutely necessary. Therefore, first of all an operational method to correct the online rain gauge data for systematic measurement errors is needed.

1.3.2. On-event bias correction of global daily rain gauge data

Goal of the developed method is to improve the statistical reduction of the systematic measurement errors of rain gauge data used by the GPCC. The correction method currently used at GPCC is based on long-term mean monthly corrections described by Legates (1987), Legates and Willmott (1990) and Reiss et al. (1992). In opposition to this, the new method developed for BALTEX (Rubel and Hantel, 1999; chapter 3 this volume) and adapted for global application (Ungersböck et al., 2001; chapter 6 this volume) was designed to use online weather information. Actual wind speed, temperature, rain intensity (estimated from 6- and 12-hourly observations) and information on the gauge (type, shielded or unshielded, height of the orifice) are regularly implemented into the correction procedure. Since the actual precipitation phase (solid or liquid) is of essential importance for the error size, the on-event correction using synoptic data is a major improvement of the estimation of daily and monthly precipitation totals. Fuchs et al. (2000, 2001) demonstrated some of these improvements, such as the more realistic spatial distribution of the correction factors. For example, gauges located at coasts are affected by higher wind speeds and this becomes visible in the maps of the on-event correction factors.

In accordance with Ungersböck et al. (2001; chapter 6 this volume) the discussion of the results will focus on the regions of the GEWEX continental-scale experiments. These comprise BALTEX, the GEWEX Continental-Scale International Project (GCIP) in North America, the GEWEX Asian Monsoon Experiment (GAME), the Large-Scale Biosphere-Atmosphere Experiment in Amazonia (LBA) and the Mackenzie GEWEX Study (MAGS, not considered here, because the provided snow measurements have been bias-corrected by the Canadian weather service). The largest correction factors have been found for rain gauges in the BALTEX and GCIP domain during the winter months (20 - 60 %). The BALTEX and GCIP correction factors during the summer months are less than 10 %. In the tropical regions of GAME (5 - 10 %) and LBA (3 - 5 %) the corrections are significantly

lower. Further it was generally noticed that the climatological corrections given by Legates are significantly higher in the tropics. In the extratropics the climatological corrections gives results similar to the on-event corrections (but without daily variations).

Currently no corrections have been done for trace and blowing snow, which has been shown to be important for gauge adjustment in polar regions (Yang et al., 1998). For simplifications we use a threshold of wind speed to avoid the influence of blowing snow. Despite these simplifications, necessary to apply the correction model to global data sets, the results have been shown to be similar to those given by other authors (at least on a monthly basis). A detailed comparison with other authors is not possible, because the data sets presented by (Ungersböck et al., 2001; chapter 6 this volume) are the first two years (1996, 1997) of global bias-corrected daily precipitation measurements existing so far.

1.4. Outlook

The BALTEX main experiment BRIDGE is still running and thus the collection of rain gauge data, the bias-correction of these gauge measurements as well as the areal assessment of precipitation will be extended until at least 2005. Independent efforts are made to extend the BALTEX precipitation data base to the entire region of Central Europe. An evaluation of the dynamic correction model over the Alps, particular over Austria, is under development (Rubel et al., 2000b). Further, a project proposal containing a workpackage on precipitation analysis (Rubel, 2001) has been submitted to the European Union. Goal is to compile a 10 year meso-scale precipitation data base for Europe, which should serve as ground truth for NWP model verification as well as to investigate extreme events. Further it is planned to disaggregate the daily high resolution precipitation fields using additional information from the so-called *International Radar Composite* provided by the DWD. Outcome of the disaggregation procedure are 3-hourly precipitation fields to be used for the development of soil moisture assimilation schemes for NWP models.

Finally, a major task will be to improve the GPCP-1DD products by calibrating them with the global bias-corrected rain gauge data provided by the GPCC.

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SCALE DEPENDENT STATISTICAL PRECIPITATION ANALYSIS

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abstract

Areal precipitation is a difficult meteorological element to be analyzed. High quality data of precipitation are necessary for many scientific applications in hydrology, environmental and agricultural meteorology, often in real time or in form of forecasts. Because of the errors involved there is a need for a high quality analysis of precipitation. Therefore, first the statistical structure of precipitation fields on different space and time scales is discussed. Second, a statistical interpolation technique is applied to analyse meso-scale and large-scale precipitation fields over Europe. The data used are from rain gauge and weather radar networks. A comparison with fields from the *European Centre for Medium-Range Weather Forecasts* (ECMWF) shows a good agreement between precipitation fields from analysis and model forecast.

1. INTRODUCTION

For the spatial analysis of irregularly distributed precipitation data many methods have been proposed and applied to rainfall fields. These are the *nearest neighbour method*, the *arithmetic mean*, *spline surface fitting*, *interpolation based on empirical orthogonal functions* and statistical interpolation techniques. The latter are the so-called *optimum interpolation* or *optimal averaging* (Gandin, 1993) and the *kriging methods* (Krige, 1981). These methods have been developed since the early 60s in both meteorology and hydrology. Today statistical interpolation methods are state of the art; objective comparisons have pointed out their advantage with respect to other methods (Creutin and Obled, 1982).

The *optimum interpolation* and *kriging* techniques are based upon the knowledge of the statistical structure function (semivariogram) or the correlation function. Here the correlation function is used. The correlation function of precipitation depends primarily on the considered space-time aggregation and can be characterised by decorrelation distances (Zawadzki, 1973). With the knowledge of the correlation function a scale dependent precipitation analysis was performed for a model domain over Central Europe.

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Correction of Daily Rain Gauge Measurements in the Baltic Sea Drainage Basin

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Within the framework of BALTEX regular measurements made at about 4,200 rain gauge sites have been collected by the BALTEX Meteorological Data Centre. This network of rain gauges is about 10 times denser than the synoptic network; here it is used for the objective analysis of daily precipitation fields on the grids of the mesoscale models developed in the research project NEWBALTIC during the pilot period PIDCAP (August to October 1995). The observations were corrected for systematic measuring errors with the *Dynamic Correction Model*. Its main purpose is to correct for the wind-induced losses which is the largest error. The correction formulae use the synoptic observations of wind speed, temperature and rain intensity at the rain gauge station considered. For non-synoptic stations the values of the closest synoptic station are used as estimates; the mean distance of the synoptic stations within the drainage basin is 30 km. For evaporation and wetting losses, which represent the second largest error of the precipitation measurements, climatological corrections are applied. The formulae in the *Dynamic Correction Model* take instrument-specific properties into account; these comprise HELLMANN UNSHIELDED, SMHI SHIELDED, H&H-90 SHIELDED and TRETJAKOV SHIELDED. The spatial distribution of corrected precipitation values were objectively analysed according to Rubel (1998). They yield daily gridded precipitation fields over the drainage basin which are systematically higher than the uncorrected fields. The corresponding increase of the freshwater input into the Baltic Sea drainage basin is 4.7% in August, 5.8% in September and 9.1% in October 1995. Finally, the perspective for further developments and the generation of a ten-year data base of the BALTEX main intensive observational and modelling period BRIDGE is introduced.

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

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With 7 Figures

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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.

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Verification of GPCP-1DD Global Satellite Precipitation Products Using MAP Surface Observations

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Abstract. Daily satellite precipitation estimates have become available for the first time by the Global Precipitation Climatology Project. The experimental version of the GPCP-1DD product, recently launched and available from NASA, provides the research community with 1 degree daily precipitation fields exclusively computed from satellite measurements. These comprise IR estimates from geostationary satellites and SSM/I data in the tropics as well as TOVS data from polar orbiting satellites at higher latitudes. The purpose of the present study is to verify the TOVS based GPCP-1DD rain rates over Central Europe with the surface precipitation measured with the dense rain gauge network operated during *The Mesoscale Alpine Programme* (MAP). 3 100 high quality daily rain gauge measurements during June/July 1997 have been objectively analyzed on the grid of the GPCP-1DD products. Verification results are given here in terms of difference fields (mean error= -0.59 mm/day) , correlation coefficients (mean monthly value =0.57) as well as accuracy scores (probability of detection=0.6, false alarm ratio=0.2) and skill scores (true skill statistics=0.36). These scores are slightly inferior than those known from NWP model verifications.
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1 Introduction

Continuous global precipitation observation is a challenging task. It can be done only by the use of satellite techniques, because over wide areas of the globe no rain gauge or radar measurements are available. Here our interest is to verify the new experimental precipitation product of the Global Precipitation Climatology Project, the GPCP-1DD (resolution: 1 degree, 1 day) data. These global daily precipitation fields are based on a combination of different satellite estimates. In the 40° N-S belt IR estimates from geostationary satellites calibrated with SSM/I data have been used. Outside this region the rain estimates are based on TOVS data from the polar orbiting satellites NOAA-12 and NOAA-14. These two satellites, with 0130/1330 and 0730/1930 local time equator crossing times, are flying simultaneously and provide global precipitation estimates based on an empirical relationship between rain gauge observations and a function of the cloud-top pressure, fractional cloud cover and relative humidity profile (Susskind et al., 1997). The GPCP 1 degree daily precipitation fields over the verification region of the European Alps (Fig. 1) are therefore mainly based on TOVS-data, expect the calibration with monthly GPCP products (see e.g. Huffman et al. (1997), Rudolf et al. (2000)).

For the verification of this precipitation product regions with very dense rain gauge networks are needed. One such region are the European Alps. The rain gauge data from this region are stored in The Mesoscale Alpine Programme (MAP) data archive and fulfil all requirements to be used as ground truth data for the verification of satellite estimates or model predictions. Further comprehensive information on the precipitation climatology of the Alps is available from Frei and Schär (1998).

To prove the reliability of the GPCP-1DD products, the verification measures commonly used for model verification (Stanski et al., 1989) have been applied. Results in terms of scores are directly comparable with corresponding scores from NWP or climate model verifications.

Over the Alps currently no comprehensive model verifications have been done, but various case studies are documented in the literature. These comprise for example studies on the application of different parametrization schemes of the MM5 model (Cherubini et al., 1999) or on the accuracy of DM forecasts (Kreil and Volkert, 1999).

Nevertheless, comprehensive results from model verifications are available from other regions and give an

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Bias correction of global daily rain gauge measurements

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Abstract. Up to the present global precipitation climatologies based on rain gauges have been corrected for systematic measurement errors using monthly correction factors only. We present results from a statistical correction model for daily measurements. It was developed in the framework of BALTEX and adapted for the Global Precipitation Climatology Centre (GPCC) to correct global daily rain gauge data routinely transmitted via GTS. We focus on regions of the GEWEX continental scale experimets BALTEX (Europe), GAME (Asia), LBA (South-America) and GCIP (North- America). The correction model was applied to 2 years of data (1996, 1997) and compared with the correction factors of the widely used precipitation climatology of Legates (1987). In the BALTEX region our averaged daily correction factor is about equal to the monthly correction given by Legates during the summer months, while Legates estimated higher corrections for snow (up to 50 %). In the regions of GAME and LBA the corrections given by Legates are also generally higher (50 - 100 %) than our corrections. This is opposite to the corrections calculated for GCIP rain gauges, which are not significantly different.

1 Introduction

Goal of this study is to develop an improved statistical method for the reduction of the systematic measurement errors of rain gauge data. The method must routinely be applicable on global scale and be fitted to available meteorological and instrumental meta data.

The correction method currently used by the GPCC is based on long-term mean monthly corrections described by Legates (1987), Legates and Willmott (1990) and Reiss et al. (1992). Since the precipitation phase (solid or liquid) is important for the error size, even a rough on-event correction using synoptic data would be an improvement of the estimation of daily and monthly precipitation totals. The global precipitation analyses of GPCC calculated from corrected rain gauge observations are the basis for the verification of precipitation forecasts from NWP model runs or for the calibration of global satellite estimates (Rudolf et al., 2000). The correction model, based on the results of the WMO Solid Precipitation Measurement Intercomparison (Goodison et al., 1998), was originally developed for BALTEX (Rubel and Hantel, 1999). The Baltic Sea Experiment (BALTEX) is one of 5 continental scale experiments of the Global Energy and Water Cycle Experiment (GEWEX) a project of the World Climate Research Programme (WCRP). Therefore discussing our global results we focus on the GEWEX regions. These comprise BALTEX, the GEWEX Continental-Scale International Project (GCIP), the GEWEX Asian Monsoon Experiment

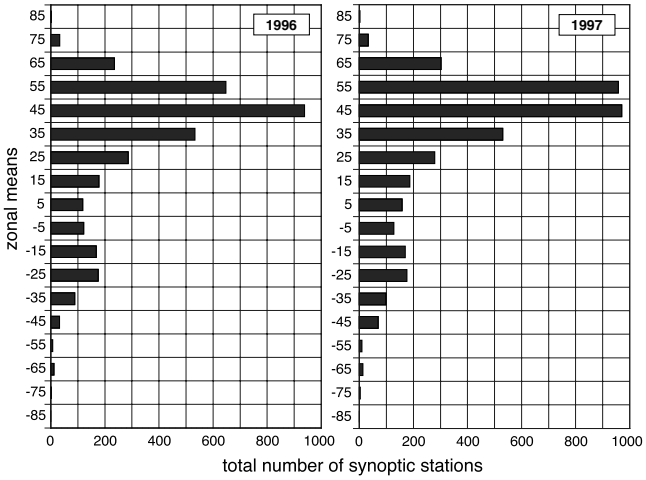


Fig. 1. Zonal distribution of the global synoptic precipitation measurements available for this study. The mean number of daily rain gauge observations increases from 3 700 (1996) to 4 100 (1997).

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Article

Global daily precipitation estimates proved over the European Alps

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Abstract

This paper is a contribution to answer the question on how well do global precipitation fields, often used for climate model verifications, represent reality. Here we focus on the experimental version of the GPCP-1DD product, the daily precipitation estimates based on satellite measurements from the *Global Precipitation Climatology Projects* (GPCP) and t+6 to t+30 hours model predictions from the *European Centre for Medium Range Weather Forecast* (ECMWF). The spatial/temporal resolution of both data sets is 1 degree/daily. The ground truth is represented by 3100 daily rain gauge measurements operating during June/July 1997 in the region of *The Mesoscale Alpine Programme* (MAP). These observations have been analyzed within the MAP section of the global grid by statistical interpolation. Verification results are given in terms of difference fields (mean error GPCP = −0.59 mm/day; ECMWF = −1.13mm/day), rank-order correlation coefficients (mean monthly value GPCP = 0.52; ECMWF = 0.67) as well as accuracy scores (probability of detection GPCP = 0.62; ECMWF = 0.80 and false alarm ratio GPCP = 0.21; ECMWF = 0.18) and skill scores (true skill statistics GPCP = 0.36; ECMWF = 0.54). These scores indicate that both global datasets have deficits in estimating realistically precipitation amounts. However, the ECMWF predictions have a high performance in forecasting the spatial distribution of the precipitating areas. A major result of this study is also that accuracy and skill of the GPCP-1DD estimates have been shown to be significantly lower than those of the ECMWF forecasts. Only the mean error of the GPCP-1DD products is low, due to the calibration with monthly synoptic data.

Zusammenfassung

Diese Arbeit ist ein Beitrag zur Beantwortung der Frage, wie gut globale Niederschlagsfelder, die oft zur Verifikation von Klimamodellen verwendet werden, die Realität abbilden. Untersucht wurden die experimentelle Version der GPCP-1DD Produkte, die täglichen Niederschlagsabschätzungen basierend auf Satellitenmessungen des *Global Precipitation Climatology Projects* (GPCP) und t+6 bis t+30 Stunden Modellvorhersagen des *Europäischen Zentrums für Mittelfristige Wettervorhersage* (EZMW). Die räumliche/zeitliche Auflösung beider Datensätze ist 1 Grad/täglich. Zur Bestimmung der Bodenwahrheit stehen 3100 Ombrometermessungen der Monate Juni/Juli 1997 aus dem Gebiet des *Mesoscale Alpine Programme* (MAP) zu Verfügung. Diese Beobachtungen wurden mittels statistischer Interpolation auf dem MAP-Ausschnitt des globalen Gitters analysiert. Die Verifikationsergebnisse wurden in Form von Differenzfeldern (Mittlerer Fehler GPCP = −0,59 mm/day; EZMW = −1,13 mm/day), Rangkorrelationskoeffizienten (Mittlerer Monatswert GPCP = 0,52; EZMW = 0,67), sowie Genauigkeitsmasszahlen (Entdeckungswahrscheinlichkeit GPCP = 0,62; ECMWF = 0,80 und Rate falschen Alarms GPCP = 0,21; EZMW = 0,18) und Skill Scores (True Skill Statistics GPCP = 0,36, EZMW = 0,54) angegeben. Diese Masszahlen belegen, dass beide globalen Datensätze hinsichtlich der mengenmässigen Erfassung der Niederschläge Defizite aufweisen. Hingegen zeigt die räumliche Erfassung der Niederschlagsgebiete vor allem der EZMW Prognosen eine gute Performance. Als wesentliches Ergebnis dieser Studie wurde gezeigt, dass Genauigkeit und Geschick der GPCP-1DD Abschätzungen deutlich geringer sind als jene der EZMW Prognosen. Einzig der mittlere Fehler der GPCP-1DD Produkte ist zufolge der Kalibrierung mit monatlichen Synopdaten klein.

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