A Ship Rain Gauge for Use in High Wind Speeds

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ABSTRACT

A ship rain gauge has been developed that can be used under high wind speeds such as those experienced by ships at sea. The instrument has an improved aerodynamic design and an additional lateral collecting surface, which is effective especially with high wind speeds. The ship rain gauge has been calibrated at sea against a specially designed optical disdrometer. An accuracy of 2%–3% has been obtained for 6-hourly sums. The ship rain gauge has also successfully been tested at a test site of the German Weather Service and presently is used on research vessels and voluntary observing ship.

1. Introduction

The hydrological cycle is intimately linked with almost all aspects of climatic change. Precipitation at sea forms a strong branch of the hydrological cycle. However, undisturbed precipitation measurements at sea, except from a few stations at small islands, are practically nonexistent, and yet these at-sea measurements are an important part of the World Climate Research Programme (WCRP) and the Global Atmospheric Watch (GAW). We hope that future numerical weather forecast models and satellite remote sensing methods will provide improved precipitation estimates for the World Ocean. Precipitation estimates from weather forecast models and satellite remote sensing algorithms, however, urgently need ground truth at sea, as do ground-based remote sensing methods, for example, seaward-looking radars.

The present article deals with a specialized mechanical ship rain gauge that was developed at the Institut fuer Meereskunde, Kiel, to overcome the difficulties in obtaining rain measurements at sea from moving ships (Hasse et al. 1992; Hasse et al. 1993; and Hasse et al. 1994). We believe that now, after a number of years of tests and improvements (Grossklaus 1996) and after several years of routine use, the ship rain gauge can reliably be used on running ships. We believe the time has come to introduce ship rain gauges worldwide to provide sea truth for indirect methods.

Conventional rain-collecting instruments fail when used on buoys or ships. The problem stems from the often rather high flow velocities around rain gauges on ships, which may result from the addition of wind and ship velocities. This yields the following two sources of biases.

1) The flow around the ship's superstructure may induce spurious vertical velocities and enhanced or reduced speeds at the location of the equipment, leading to under- or overcatch.
2) The flow around the rain gauge for most conventional types of rain gauges tends to carry the rain above the orifice of the gauge, leading to a wind-speed-dependent undercatch.

Because of the difficult flow pattern around ships, many believe that it is impossible to measure rain on them. The flow around a ship's superstructure is different from ship to ship and, even for a given ship, changes with the angle of attack of the relative wind. However, there are some general features of the flow around obstacles that we can expect to also hold for ships and their superstructures. Hence, it should be possible to find sites on a ship where the flow is nearly horizontal (although faster than in the free air). Here, measurements are feasible, provided the collection efficiency of the rain gauge is independent of flow velocity or can be corrected. Typically, on a mast above the bridge house and slightly aft from its leading edge, the flow might be expected to be nearly horizontal. This rule is in agreement with results of simultaneous measurements with several rain gauges distributed over a ship by Austin and Geotis (1980) and Ruprecht (1993).

It can be concluded that the flow distortion of ships is not the main problem for rain measurements at sea. The problem rests with the rain gauge itself. Conventional cylindrical rain gauges are not well suited for use in high wind speeds. It is the intent of this article to report on a specialized rain gauge that can work under

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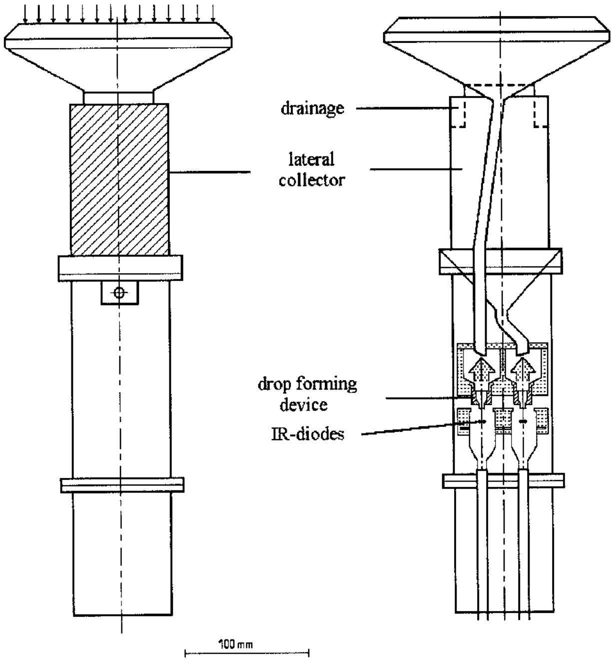

FIG. 1. Side view (left) and vertical cross section (right) of the ship rain gauge. Rain is collected at the horizontal orifice (arrows) and at the lateral collector (shaded). There are five vertical T-bars at the circumference of the lateral collector that hinder rainwater from wandering around the cylinder and being blown off in lee (not shown in the diagram). Horizontal sampling area is 200 cm^2, and the lateral sampling cross section is 106.6 cm^2. Total length is 48.5 cm and weight is 4.0 kg.

high wind speed conditions and is less susceptible to local up or downdrafts.

2. Rain gauge design

Our ship rain gauge has been designed to enable rainfall measurements from a moving ship where conventional cylindrical rain gauges would be ineffective. Standard cylindrical rain gauges form a three-dimensional obstacle that induces updrafts on its upwind side (Sevruk 1989; Folland 1988). The error induced by flow around rain gauges has been known for some time already and corrections have been suggested. Such corrections are unsatisfactory for rainfall measurements from a moving ship where relative wind speeds of 10–20 m s^{-1} are common. For example, the corrections (Allerup and Madsen 1979) for a standard cylindrical gauge would already reach 50% of the measured rain rate at 11 m s^{-1} wind speed and a factor of 2 at roughly 15 m s^{-1}.

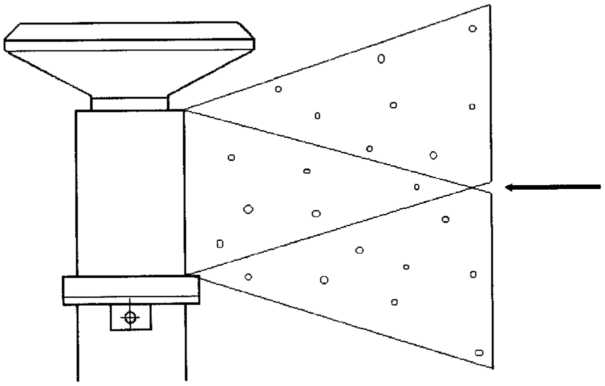

FIG. 2. Sketch of volume of air that reaches the lateral collector with different vertical velocity components and given horizontal wind speed. The arrow indicates the general direction of flow.

The high relative flow velocities may carry the rain almost horizontally over the ship. It is a logical step to use a ship rain gauge that amends the design of a conventional rain gauge by a second collector that measures the water amount driven against the side of the gauge. Based on the water amounts collected from the top and the side and considering the local wind speed near the instrument, it is possible to calculate the true rainfall.

A sketch of the ship rain gauge is given in Fig. 1. To mitigate the wind speed effect, we have reduced the upper-level collector to a slender conical disk, which roughly corresponds to the champagne bowl design recommended by Folland (1988) but has a lower cross section and less wind resistance. A unique feature of the instrument is its lateral collector. This measures liquid water content (LWC) in the volume of air that is formed by the cross section of the lateral collecting surface and the local relative wind speed. This volume is independent of the inclination of the flow (see Fig. 2). The lateral collector is fitted with a set of five vertically running T-bars to hinder the intercepted water to run around the instrument and be blown off before recording. To better define the lateral collecting surface, a drainage has been provided between it and the upper conical funnel. This drainage empties below the lateral collector (not shown in Fig. 1).

The water amounts intercepted at the top and at the side are collected separately, and each is measured by forming calibrated drops in a droplet-forming device that is called a dropper. These drops are counted when they pass through a light barrier. The water amounts are thus converted to electronic counts for recording. The counts, together with the output of a nearby cup anemometer, are fed to a data logger or automatic weather station. The basic time unit for evaluation is typically 8 min. For this time, rainfall rates are calculated by an algorithm for the top and the side separately, and a corrected rainfall rate is obtained as a wind-speed-dependent weighted average (see below).

The sensitive part of the dropper is the nozzle, which forms drops of 0.1 g each. Droppers manufactured by W. Thiess of Goettingen, Germany, are used. These are based on laboratory experiments by Attmannnspacher and Riedl (1993). Droppers are calibrated individually; an example is given in Fig. 3. It is found that drop rates vary fairly linearly with water amount up to a flow rate

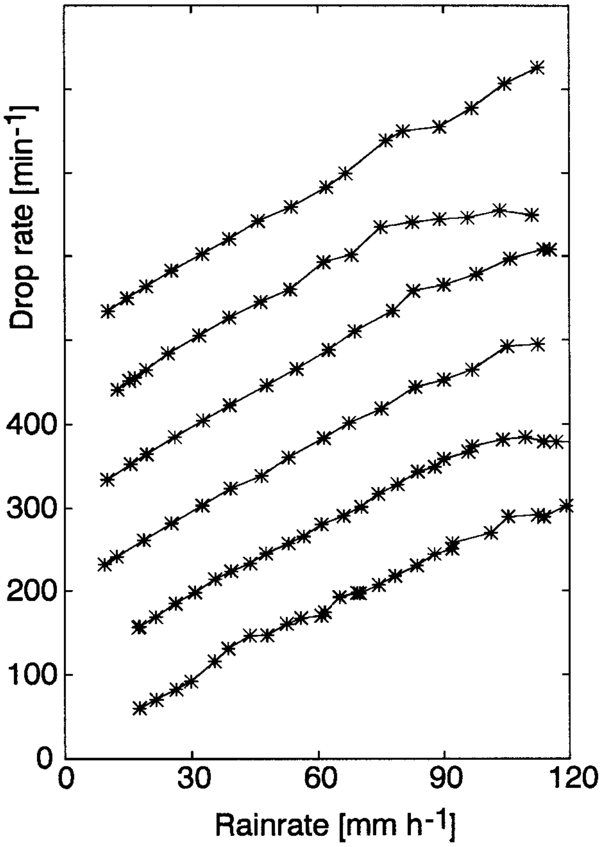

FIG. 3. Calibration of dropper. Abscissa is water amount fed to the rain gauge by peristaltic pump. Ordinate is flow rate measured in terms of counted drops. Calibrations of six droppers are shown. For better reading, ordinate is shifted by 100 counts per minute between curves.

of 20 $cm^3\ min^{-1}$ (corresponding to a rain rate of 60 mm h^{-1} at a 200-cm^2 collecting surface as is used for the upper collector of the gauge). Different droppers usually agree well up to this limit. Above 20 $cm^3\ min^{-1}$ we found some individual variations, but a calibration is still possible up to about 25 $cm^3\ min^{-1}$ (or 80 mm h^{-1}). At higher rates the water starts to flow through the dropper. The lateral collector has a smaller cross section. Rain rates up to 140 mm h^{-1} have been recorded from a moving ship (verified by simultaneous measurements with an optical disdrometer). For buoys or stationary ships in the tropical rainfall, a reduction by a factor of 2 is suggested for the area of the upper collector.

Measurement of LWC at the side is independent of local up- or downdrafts (see Fig. 2). However, with strong updrafts, as are experienced on the windward side of a bulky structure, part of the intercepted rainwater is blown over the upper rim of the lateral collector without being measured. The catch by the upper collector can be influenced by local up or downdrafts, depending on the dropsize distribution. These effects require placement of the instrument above the superstructure of the ship in order to minimize influence of local ship-induced velocities. To compensate for ship roll motions in a sea state, the instrument is suspended to swing freely in the ship's athwartship plane.

The ship rain gauge was designed to collect rain, although the upper collector will also catch solid precipitation. The lateral collector evidently is not built to collect solid precipitation. However, for operations at temperatures near freezing, a heating option may be provided that heats the upper collector and the internal droplet forming and counting unit separately. Temperature sensors switch heating on and off to maintain a temperature slightly above freezing. In situations of wet fog the lateral collector measures an LWC that is not—or only partially—precipitated. In the beginning, we had removed these cases by an algorithm. It appears that such a device is not warranted since the rain amounts are small.

3. The rain algorithm

The efficiency of the ship rain gauge depends on the flow around the instrument. Even with an improved aerodynamic design, some wind influence on the catch from the top collecting surface is expected (e.g., Allerup and Madsen 1979; Sevruk 1985). We determine this aerodynamic effect by comparing it to an unbiased reference instrument as a function of local flow velocity. To this purpose an optical disdrometer was developed (Grossklaus 1996; Grossklaus et al. 1998). The wind speed correction for the upper collector is empirically decribed by the power law

$$\mathrm{RR}_{\mathrm{corrected}} = \mathrm{RR}_{\mathrm{raw}}(1 + 8.5 \times 10^{-3} \times U^{1.7}), \quad (1)$$

where $\mathrm{RR}_{\mathrm{raw}}$ is the rain rate without and $\mathrm{RR}_{\mathrm{corrected}}$ is with the correction for wind influence, and the numerical coefficient applies to relative wind speeds measured in meters per second.

The lateral collecting surface does not measure rainfall but rather the amount of raindrops carried with the air. The catch is inter alia proportional to the local flow velocity and to the cross section seen by the flow. Hence, we divide by the flow velocity and the cross-sectional area to obtain the LWC in a unit volume of air. The geometric cross section of the lateral collecting surface can easily be determined from its geometry. However, the air flows around the instrument and may carry some part of the LWC with it. The collection efficiency at the side of the instrument is determined empirically against an unbiased reference instrument as a function of local flow velocity U (m s^{-1}):

$$\mathrm{LWC}_{\mathrm{corrected}} = \mathrm{LWC}_{\mathrm{raw}}(1 + 4 \times 10^{-4} \times U^2). \quad (2)$$

Here, $\mathrm{LWC}_{\mathrm{raw}}$ is the measured LWC and $\mathrm{LWC}_{\mathrm{corrected}}$ is LWC corrected for wind-speed–dependent efficiency.

From the LWC of the air, we can estimate the rain rate assuming a relation between LWC and rain rate RR. A relation originally was derived by integration of the Marshall–Palmer (MP) dropsize distribution (Marshall

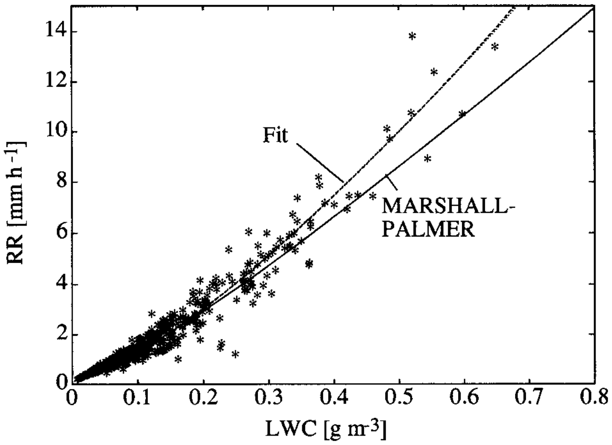

FIG. 4. Rain rate (ordinate) vs liquid water content (abscissa). The full curve is obtained using exponential dropsize distributions and the dashed curve is the empirical fit according to Eq. (3). Stars indicate measurements of rain rate determined with an optical disdrometer and LWC as measured from the lateral collector of the ship rain gauge (Grossklaus 1996).

and Palmer 1948), more exactly, using a family of exponential dropsize distributions with a variable number density N_0 as parameter, as a generalization of the MP distribution. An improved fit (see Fig. 4) was obtained by comparison of LWC to the independent rain rate measurements, obtained with an optical disdrometer (Grossklaus et al. 1998):

$$\mathrm{RR} = 24.6 \times \mathrm{LWC}^{1.3}. \qquad (3)$$

The numerical factor applies to LWC measured in grams per cubic meter and RR in millimeters per hour. This empirical relation gives a slightly higher rain rate for a higher LWC than obtained from the exponential dropsize distributions, corresponding to higher probability of larger drops. Gamma distributions can be seen as a generalization of the exponential distribution. Thus, we fitted the parameters of a gamma distribution to our data and upon integration obtained a relation between RR and LWC. It appeared that (3) is a good fit to the derived gamma distribution, which is preferred for practical reasons (Grossklaus 1996).

Calibration measurements were obtained on R/V *ALKOR* in the Baltic Sea and the Skagerrak–Kattegat area of the North Sea from 1992 to 1994. While these are measurements from different seasons in the temperate zones, we have also obtained more recent comparisons of ship rain gauge versus optical disdrometer in the ITCZ (intertropical convergence zone), which showed no systematic deviations from (3) for tropical rainfalls.

For low speeds, where the rain falls nearly vertically, collection at the top gives a good measure of the rain rate with little correction needed; at the same time, the sampling at the side is unsatisfactory (under low horizontal velocities, for larger drops with high fall velocities, parts of the lateral collector are sheltered by the upper collector). At high flow velocities, sampling at the side leads to a good estimate of rainfall, while measurement at the top would need extensive correction. Hence, our algorithm accepts the corrected rain rates from the upper or the lateral collecting surfaces depending on wind speed with a linear transition between 9 and 11 m s^{-1}.

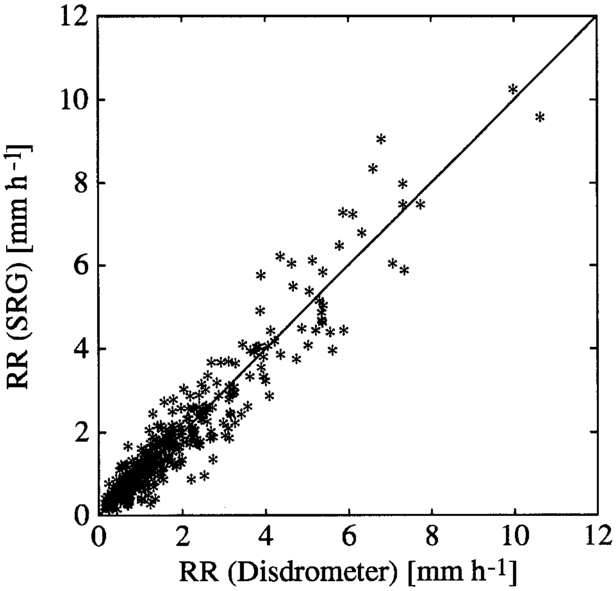

FIG. 5. Calibration of ship rain gauge (ordinate) against optical disdrometer (abscissa) from cruises with R/V *ALKOR.* Stars represent 8-min averages. Full line is the 1:1 relationship. The scatter is mainly due to sampling characteristics of the optical disdrometer and reduces with longer averaging times.

We calibrate the ship rain gauge at sea by simultaneous measurements with an optical disdrometer on a moving ship. Results derived with (1)–(3) are depicted in Fig. 5. The correlation appears to be good (correlation coefficient equals 0.96, rms error from the best-fitting line 0.48 mm h^{-1}). Figure 5 is based on the same data as used to derive (3). Since this is based on 436 observations, and only five empirical coefficients have been used, the result is still meaningful. There is some inevitable scatter due to the spatial difference of position of instruments and due to different sampling characteristics. According to our experience, the scatter is mainly due to the sampling variability of the optical disdrometer. Its active cross section is smaller by a factor of 4 than that of the ship rain gauge. Assuming the unexplained error variance to be distributed 4:1 between disdrometer and ship rain gauge, we determine a sampling error of the ship rain gauge to be roughly 7% for 8-min averages. This error corresponds to 2.4% for hourly means; 6-hourly or daily totals will be considerably more stable. Some statistical variation in this type of calibration is inevitable. The ship rain gauge and the disdrometer do not sample the same volume of air and, since the distribution of raindrops in the air shows a natural variation, part of this variation is reflected in the calibration runs. Also, with the optical disdrometer, each

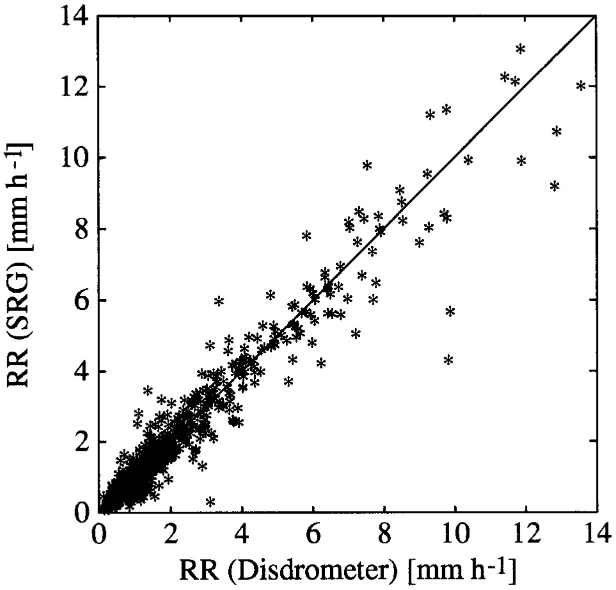

FIG. 6. Test of calibration of ship rain gauge (ordinate) against disdrometer measurements (abscissa), obtained on the rooftop of Institut fuer Meereskunde, Kiel. Stars represent 8-min sums.

raindrop is measured instantaneously, while in the mechanical ship rain gauge water is collected until it reaches 0.1 g and is measured.

4. Verification and results

The field calibration runs also allowed us to check the performance of the upper and lateral collectors against each other. After the wind-speed–dependent corrections have been applied, rain amounts from the upper and lateral collectors agreed well in a surprisingly large range. The aerodynamic calibration of a ship rain gauge against an optical disdrometer has also been tested with help of an independend dataset that was obtained on the rooftop of the institute (Fig. 6). Another pair of instruments of the same type was used. The agreement is remarkably good (correlation coefficient 0.96, rms error, measured as deviation from the best-fitting line 0.58 mm h^{-1}). In this comparison over the course of a few years, we experienced some high wind speed situations but few instances of high winds with rain. Figure 6, therefore, can be seen as a verfication predominantly of the corrections for the upper collector.

The ship rain gauge has also been compared on land against standard meteorological rain gauges. Intercomparisons have been made for several years at the test site of the Deutscher Wetterdienst at Harzgerode. The ship rain gauge was mounted with the upper orifice at 1.15 m above the ground. The same height was used with a standard cylindrical rain gauge of the Hellmann type from the weather service. (The Hellmann cylindrical rain gauge has a 45° rim, identical to the one used with the ship rain gauge; see Fig. 1.) Additionally, a Hellmann rain gauge in a pit, with its orifice level with the surrounding ground, was available. It is anticipated that under windy conditions the standing Hellmann will experience some undercatch as a result of flow distortion and that the measurements in the pit can be used as a reference. The ship rain gauge was deployed in a field of several rain gauges and was situated at about a 5-m distance to the pit rain gauge. The results of the intercomparison at Harzgerode are given in Table 1. Days

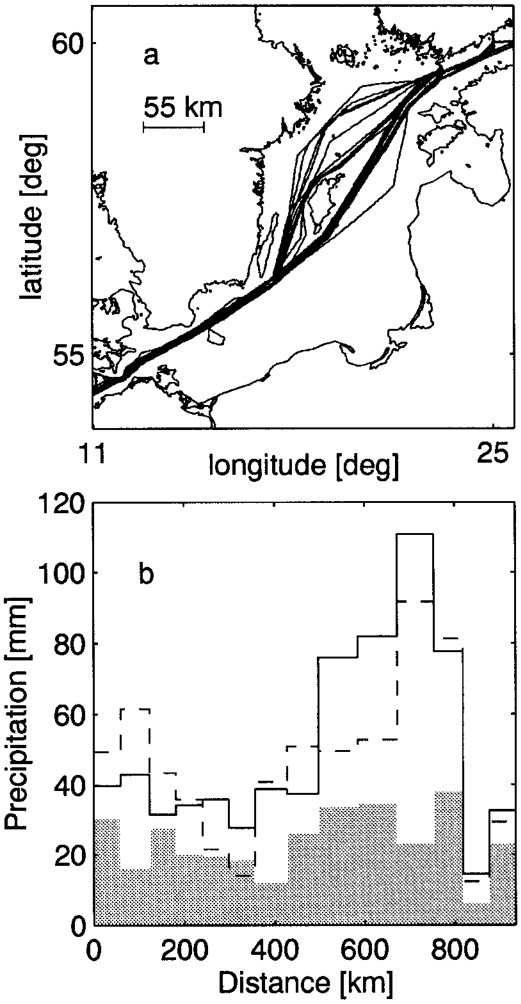

FIG. 7. Intercomparison between measurements and model predictions. (a) Tracks of rain measuring ferries in the Baltic Sea. (b) Precipitation measured in situ on four ferries running between Luebeck and Helsinki (shaded), compared to precipitation predicted by the German Weather Service (Europa model, solid line) and by a regional model (REMO, dashed line) of the Max Planck Institut für Meteorologie, Hamburg. As the ferries continuously change positions, the predictions have been interpolated in space and time to the ship locations. Amounts are compared when either the ship or the model indicated rain. Rain amounts have not been extrapolated to areal averages, only the comparison between model and in situ measurements is meaningful. The graph is organized for measurements on the route between Luebeck (left) and Helsinki (right). Since interpolation was done in the grid of the model, the distance intervals depend on the orientation of the ships track compared to the axes.

TABLE 1. Comparison of rain gauges at the precipitation test site of Deutscher Wetterdienst at Harzgerode, January 1993 through October 1996. The intercomparison is based on daily averages; cases with solid precipitation are excluded. Since during rain events the mean wind speeds measured at 1.15-m height rarely exceeded 5 m s^{-1}, only the measurements from the upper, horizontal orifice contribute.

Year	Wind velocity 1.15 m	Ship rain gauge 1.15 m	Conventional gauge 1.15 m	Total precipitation pit
1992	<5 m s^{-1}	96.0%	91.6%	100% = 486 mm
	>5 m s^{-1}	99.9%	84.9%	100% = 81 mm
1993	<6.5 m s^{-1}	99.2%	92.2%	100% = 498 mm
1994	<6.4 m s^{-1}	99.3%	90.9%	100% = 573 mm
	<5 m s^{-1}	99.0%	91.3%	100% = 552 mm
	>5 m s^{-1}	106.0%	80.8%	100% = 21 mm
1995	<5.7 m s^{-1}	99.6%	92.1%	100% = 422 mm
	<5 m s^{-1}	99.8%	93.0%	100% = 382 mm
	>5 m s^{-1}	98.3%	82.8%	100% = 40 mm
1996	<6.0 m s^{-1}	97.7%	90.9%	100% = 452 mm

with solid precipitation are excluded. It shows that the ship rain gauge compares well with the pit measured rain amount—better than the standard Hellmann does (measurements with the standard Hellmann are not corrected for wind effects). Unfortunately, situations of higher wind speeds with rain were rare, even at the exposed Harzgerode site in the Harz mountains (station height about 440 m). The catch of 106% of the few measurements in 1994 with wind speed exceeding 5 m s^{-1} is taken as accidental, as the total is only 22 mm. Because of the moderate wind speeds, the comparison pertains to the upper collector only.

Ship rain gauge and optical disdrometer have been developed as a contribution to the World Ocean Circulation Experiment. In the beginning, instruments were used in a research mode, for example, for in situ calibration and long-term tests. More recently, the 6-hourly rainfall sums have been included operationally in the ship synop observation transmission via GTS (Global Telecommunication System of the weather services); currently they are transmitted by the R/V *METEOR* and the R/V *GAUSS*. Also for BALTEX [Baltic Sea Experiment, which is a contribution to the Global Energy and Water Cycle Experiment (GEWEX)] recording ship rain gauges are operated at four ferries running between Luebeck and Helsinki through the southwestern and central Baltic Sea. Since ferries move at about 20 kt, rain measurements are predominately from the lateral collector. The rain amount measured at the ships has been compared with the rain amount operationally predicted by the regional forecasting model (Europa model) of the German Weather Service (DWD), interpolated to the same time and location. The same comparison has been obtained with model-derived precipitation of a regional model (REMO, run 71) of the Max Planck Institut für Meteorologie, Hamburg. The results from a BALTEX pilot experiment during August–October 1995 are shown in Fig. 6. The total for the four ships is 297 mm, compared to 638 mm predicted by the Europa model and 427 by REMO for the same time and position. There is a fair agreement considering the notorious variability of rain and the fact that the ship measurements are local in space and time, while the model forecasts are 6-hourly averages for an area of 55-km grid size. Based on experience with additional data we expect that the agreement will improve with increased amount of data available and with advances in models.

This comparison can also be seen as an example for future use. Numerical weather forecast models use parameterizations, and satellite remote sensing techniques use algorithms. Both need sea truth for verification. There are more than 7000 voluntary observing ships that well could be platforms for ship rain gauges. Except for the North Atlantic, the coverage by shipping routes may not be sufficient. However, model and remote sensing products could be calibrated against measurements from shipping routes. The combination of direct measurements, modeling, and remote sensing may finally provide the accuracy desired in GEWEX.

5. Conclusions

We have shown the feasibility of measuring rain on a moving ship with a specialized ship rain gauge that can operate under low and high wind speed conditions. Calibration is obtained at sea by simultaneous measurements with an optical disdrometer on a running ship. An intercomparison on land showed improved performance of the ship rain gauge, as compared to standard rain gauges, due to improved aerodynamic design. The upper part of the instrument is very similar to the shape of a precipitation gauge that independently has been developed by Wiesinger (1993) for alpine use. Hence, our results are perhaps somewhat more general than expected from the title of this paper. The ship rain gauge has now successfully operated at R/V *METEOR* for 5 years. From this and from the results obtained in BALTEX we feel assured that we can recommend this ship rain gauge to WMO for introduction to operational use on ships.

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