Rainfall Measurement on Ship Revisited: The 1997 PACS TEPPS Cruise

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ABSTRACT

Fifteen rain measurement instruments were deployed on the National Oceanic and Atmospheric Administration Ship *Ronald H. Brown* during the 1997 Pan American Climate Studies (PACS) Tropical Eastern Pacific Process Study (TEPPS). To examine differences in rainfall catchment related to instrument design, three types of disdrometers, an optical rain gauge, a ship rain gauge, and a siphon gauge were clustered in one location to ensure similar exposure. To address exposure effects, eight siphon rain gauges were deployed on different sides of the ship and on several different levels.

Cross-ship differences in hourly rainfall accumulation were negligible when relative wind speeds were less than 3 m s^{-1} and became significant at greater than 5 m s^{-1}, especially when the relative wind direction was 20° or greater from the bow. Instruments with both horizontal and vertical catchment surfaces yielded a measurable collection advantage over instruments with only horizontal catchment surfaces.

Analysis of data collected during TEPPS using a multiple-instrument, multiple-location approach yields the following recommendations for reducing uncertainty in rain measurement at sea. The first two of the four recommendations apply to rain measurements on buoys as well as on ships. 1) Deploy experimental rain measurement instrumentation paired with a baseline minimum siphon gauge or other trusted instrument. Comparison of the rain-rate time series between the baseline gauge measurements and the experimental instrument data permits detection of erratic behavior and bias. 2) Apply an appropriate wind correction. To do this step properly, both a wind correction formula derived for the specific gauge type and a nearby measurement of relative wind are needed. These features are already incorporated into the ship rain gauge. 3) Locate gauges where distortion of the airflow by the ship is locally minimized and relative wind speeds are as low as possible. This analysis confirms previous recommendations for placement of rain instrumentation at lower locations as long as the location is protected against direct spray from the sea without being shadowed by higher objects. 4) Place instrumentation on both sides of ship and along centerline. Airflow distortion by the ship itself can induce significant differences between port and starboard accumulations at high wind speeds and high angle of wind attack to the bow. Multiple locations aid in constraining error, because relative wind direction and speed vary during a cruise and there is no one perfect location on ship for rain instrumentation.

1. Introduction

Ocean-going ships provide an important platform for collection of surface rainfall data over the open ocean where such measurements are otherwise scarce. Minimization of uncertainties in ship-based rain measurements is important for global precipitation datasets used in modeling and validation of satellite-derived precipitation. The goal of the ship-based rain measurement is to estimate the precipitation falling at the ocean surface. However, several factors contribute to differences between the ship-based rain measurement and a theoretical measurement at the sea surface (Roll 1958):

- disturbance of the ambient air currents by the ship;
- disturbance of the ambient air currents by the instrument;
- movement of the instrument from pitch, roll, and vibration of the ship; and
- intrusion of sea spray.

When an object sitting above the surface interacts with the ambient airflow, the airflow deviates around the object, yielding a pattern of turbulence and accelerated and decelerated flow (Oke 1987). The divergence of the flow acts to divert smaller (lighter) rain drops away from the object's top, which decreases the rain falling on the object in comparison with what it would be at the surface if the object were not present (Robinson and Rodda 1969; Allerup and Madsen 1980; Sevruk 1982; Folland 1988; Nešpor and Sevruk 1999). Additionally, the portion of the airflow that is directed upward on the windward side of the object may have an upward velocity of sufficient magnitude to exceed the terminal velocity of the smaller drops (Robinson and Rodda 1969; Folland 1988). Distortion of the airflow occurs both at the scale of the ship and the scale of the instrument (Austin and Geotis 1980; Hasse et al. 1998).

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The combined effects of the airflow divergence on raindrop trajectories at *both* the ship and instrument scales yields a net decrease in rain catch for gauges on ship as compared with those at the sea surface (Skaar 1955). The percentage reduction in rain catch increases with both increasing wind speed and increasing fraction of small drops (e.g., decreasing rain rate) and varies among different gauges (Jevons 1861; Symons 1864; Sevruk 1982; Groisman and Legates 1994; Strangeways 1996; Folland 1988; Nešpor and Sevruk 1999) and ship geometries (Hasse et al. 1998).

Roll (1958) found an average −8.1% difference in monthly rain catch between gauges on a stationary ship and on a nearby island. In their analysis of data from six rain gauges mounted in several locations on the R/V *Gillis* during the Global Atmospheric Research Program Atlantic Tropical Experiment (GATE; Kuettner et al. 1974), Austin and Geotis (1980) showed that the amount of rain measured on ship is dependent upon the location and exposure of the measuring instrument and tends to decrease with increasing height. Previously, Skaar's (1955) multiple gauge deployment on a Norwegian weather ship had yielded similar results and had also showed that mounting a gauge on gimbals to keep it parallel to the sea surface was not important.

The Pan American Climate Studies (PACS) Tropical Eastern Pacific Process Study (TEPPS) cruise on the National Oceanic and Atmospheric Administration (NOAA) Ship *Ronald H. Brown* from 28 July to 6 September 1997 had as its main focus the collection of surface-based C-band radar measurements to document the three-dimensional structure of precipitation in the eastern Pacific ITCZ where a large discrepancy between satellite passive microwave and infrared precipitation estimates exists (Yuter and Houze 2000). As a piggyback experiment, the location of the ship within the ITCZ provided the opportunity to examine the field performance of several new rain gauge types and both to confirm and to amplify upon the body of work surrounding shipboard measurements of rainfall.

With the assumption that a gauge is calibrated accurately to measure the rainfall it catches, wind effects constitute the main source of rain measurement error on ships (Skaar 1955; Sevruk 1982). In this paper, we examine variation in rain catch for different instruments with the same exposure (design-related differences) and for identical instruments with different exposures to address methods of reducing wind-related uncertainty in rainfall measurement on ship.

2. The measurements

The ship track for the *Brown* during the TEPPS cruise is shown in Fig. 1. Data used in this study were collected from 1 to 28 August 1997 within the eastern Pacific ITCZ on the leg from the Panama Canal to San Diego. Rainfall measurements were obtained for 7 days while the ship was under way[1] and for 11 days while nearly stationary (on station) at 7.8°N, 125°W from 0345 UTC 8 August to 2120 UTC 23 August 1997 under a range of wind conditions (Table 1).

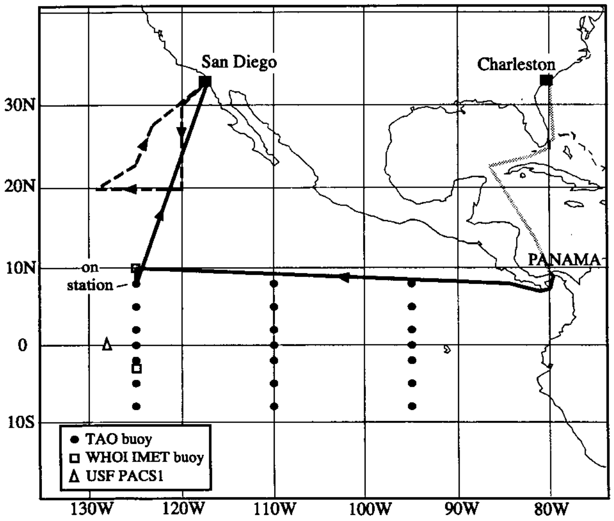

FIG. 1. Ship track of the *Brown* during the TEPPS cruise. Solid track indicates ITCZ portion of track where data were collected for this study. During the stratocumulus portion of the TEPPS cruise (dashed track), drizzle falling on ship was too light to be measured by the rain instrumentation onboard. Gray track indicates transits when data were not collected. [From Yuter and Houze (2000)].

Fifteen rain measurement instruments were aboard ship during PACS TEPPS: a Joss–Waldvogel disdrometer, two piezoelectric disdrometers provided by the National Aeronautics and Space Administration (NASA) Tropical Rainfall Measuring Mission (TRMM) Office, an Institute für Meereskunde (IfM) optical disdrometer, an IfM ship rain gauge, two Scientific Technology, Inc., (STI) optical rain gauges, and eight R. M. Young Company siphon gauges (Table 2, Fig. 2). Instrument performance and the variation of collection efficiency as a function of instrument type in open-sea conditions was studied by clustering three types of rain gauges and three types of disdrometers in one location on the forward port side of the 03 level (designated as the 03P gauge cluster). To address exposure effects, the eight siphon gauges were distributed over the ship in a manner similar to that used in GATE (Fig. 2). Independent wind speed measurements were made with the ''Improved Meteorology'' (IMET) system anemometer (Hosom et al. 1995) on a dedicated mast at the bow and with an IfM-provided anemometer at the 03P gauge cluster (Table 1, Yuter and Houze 2000). Both IfM instruments utilized data from the anemometer at 03P to adjust measured rain rate for wind-related effects. A more detailed description of each type of instrument is presented below.

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[1] On 3 August 1999, the siphon gauges measured trace amounts; thus, the siphon gauges are considered to have only 6 rain days while under way.

TABLE 1. Average daily wind characteristics during the TEPPS cruise measured by instruments on the IMET bow mast and 03P. The true wind speed was derived by subtracting the ship's heading and speed from the measured relative wind speed at the IMET bow mast. A headwind directly toward the bow constitutes a relative wind direction of 0°, winds from the starboard side of the ship are positive, and winds from the port side are negative (see also Fig. 2). The absolute value of the relative wind direction gives the angle of wind attack.

Date	Ship motion	Relative wind direction (°)	True wind speed $(\mathrm{m\ s^{-1}})$	Relative wind speed (IMET)	Relative wind speed (03P)
0801	Under way	−28	3.7	6.2	2.7
0802	Under way	−35	5.5	9.0	10.1
0803	Under way	−49	8.1	10.7	13.2
0804	Under way	−63	10.6	11.6	14.3
0805	Under way	−52	10.4	12.7	14.7
0806	Under way	−67	9.5	10.0	12.3
0807	Under way	−32	5.4	8.9	10.1
0808	Under way	6	3.2	4.0	3.6
0809	On station	72	4.7	4.7	2.6
0810	On station	44	5.5	5.7	4.0
0811	On station	−31	4.7	5.0	4.9
0812	On station	−12	4.9	5.2	4.4
0813	On station	29	4.0	4.1	3.6
0814	On station	−144	3.3	3.3	2.7
0815	On station	−38	2.6	2.7	2.6
0816	On station	108	2.4	2.3	0.8
0817	On station	8	3.4	3.6	2.9
0818	On station	−86	3.5	3.6	2.7
0819	On station	18	3.2	3.5	2.7
0820	On station	58	1.8	1.8	1.7
0821	On station	159	2.2	2.0	0.6
0822	On station	−160	2.0	1.7	1.1
0823	On station	141	2.5	2.7	1.8
0824	Under way	35	5.2	8.5	6.5
0825	Under way	41	8.3	12.0	8.8
0826	Under way	13	5.4	11.7	9.5
0827	Under way	−5	8.6	15.1	11.1
0828	Under way	−31	8.7	13.5	13.8

A disdrometer measures drop size distribution by counting the number of drops within each of several size categories over a time interval. These drop size data can be used to calculate rain rate and equivalent reflectivity and to fit a functional form of a drop size distribution. The design of disdrometers for use at sea is an active area of experimental research (Grossklaus et al. 1988; Nystuen 1998). During the TEPPS cruise, several types of disdrometers were deployed for intercomparison with each other and with nearby rain gauges.

The Joss–Waldvogel disdrometer is an electromechanical device. It transforms the vertical momentum of a raindrop impacting onto a styrofoam cone into an electric pulse in which voltage amplitude is a function of drop diameter (Joss and Waldvogel 1967). The experimental piezoelectric disdrometer outputs voltage produced by resonance created when a raindrop strikes the Delrin cylinder/brass mounting (Nystuen et al. 1994). The peak voltage of the resultant damped sine wave is calibrated to drop size. The experimental IfM optical disdrometer[2] measures drop size using light extinction within a cylindrical active volume held perpendicular to the local flow direction. Each drop passing through the active volume results in a reduction of light received at the end of the path. The depth of the voltage drop is proportional to the drop cross-sectional area (Grossklaus et al. 1998). The STI optical rain gauge measures rainfall rate based on the principle of raindroplet-induced optical scintillation (Wang et al. 1979).

A siphon rain gauge is basically a bucket that can report how much water it contains and can empty itself when it is full. The level of water within the gauge is translated into a voltage using capacitance. When this level exceeds the capacity of the gauge (50 mm depth), the instrument siphons the water out and then fills from near 0 mm. R. M. Young siphon gauges deployed on the *Brown* are designed to measure accumulation. According to the R. M. Young Model 50202 precipitation gauge instructions, the siphon gauges are accurate to the nearest 1 mm. However, further consultation with R. M. Young, Inc., determined that they are typically accurate to within 0.5 mm (J. Campbell 1999, personal communication). For purposes of this study, an accuracy of 0.5 mm will be used.[3] Consequently, for siphon gauge accumulations (or rain rates) to be meaningful, they must be calculated over periods during which the gauge accumulates more than 1 mm. This time period was estimated to be about 1 h for the TEPPS study. In general, such a time period must be chosen on a study-by-study basis, because it is determined by the statistics of rainfall intensity for the regime being studied. The appendix discusses in detail the processing of the siphon gauge data and the selection of a meaningful time period.

The IfM ship rain gauge is a modified siphon gauge with an additional vertical cylindrical collecting surface (Hasse et al. 1998). The water from both surfaces is collected separately and measured by forming and counting drops of a calibrated size. The upper-level collector of the IfM ship rain gauge is a slender cylindrical dish similar to the champagne bowl design recommended by Folland (1988) and is designed to minimize distortion of the ambient wind flow just above the gauge orifice.

The siphon gauges, optical rain gauges, and the IMET

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[2] The IfM disdrometer data collected during TEPPS and used in this study were processed by M. Grossklaus during the cruise. These data are undergoing further analysis at IfM but are adequate for calculation of reflectivity and rain rate (L. Hasse 1998, personal communication).

[3] Analysis of noise in the siphon gauge data on days when no rain occurred indicated that the magnitude of random noise in the data was well below the 0.5-mm threshold. The noise level was well below 0.1 mm for the IMET gauge, which was located on a mast and was subject to greater vibration than the other gauges. The noise level sets a lower limit on the possible accuracy of the gauge. Based on our analysis and on discussion with the manufacturer, the siphon gauge accuracy is between 0.1 and 0.5 mm. We use 0.5 mm for this paper.

TABLE 2. Basic characteristics of rain instrumentation on the *Brown* during the 1997 PACS TEPPS cruise. Both the IfM ship rain gauge and IfM optical disdrometer incorporate data from a collocated anemometer to correct rain rate for instrument-induced wind effects.

Instrument	Type	Collecting surface	Method	Location	Height above waterline (m)
Scientific Technology, Inc., optical rain gauge Model ORG-115-DA (2)	Rain rate	Volume oriented perpendicular to direction mounted	Optical scintillation	Forward 03 Port	12.57
				Winch house top	13.05
IfM ship rain gauge	Rain rate	Horizontal and vertical	Drop forming and counting	Forward 03 port	12.17
Joss–Waldvogel disdrometer	Raindrop distribution	Horizontal	Electromechanical	Top of van on 02 port	11.84
NASA piezoelectric distrometers (2)	Raindrop distribution	Horizontal	Piezoelectric resonance	Top of van on 02 port	11.79
IfM optical disdrometer	Raindrop distribution	Volume oriented perpendicular to wind direction	Light extinction	03 Port	12.95
R. M. Young self-siphoning rain gauge Model 50202 (7)	Rain accumulation	Horizontal	Capacitance	02 starboard	10.31
				02 port	10.31
				03 starboard	12.83
				03 port	12.83
				05 starboard	17.73
				05 port	17.73
				Winch house top	13.31
Woods Hole Oceanographic Institute–modified R. M. Young self-siphoning rain gauge Model 50202	Rain accumulation	Horizontal	Capacitance	IMET mast on bow	13.99

anemometer used the same data logger as the other surface meteorological sensors on ship and were logged at 10-s intervals. The data from the disdrometers, the IfM ship rain gauge, and the 03P anemometer were logged separately at 1-min intervals. The rain instrumentation was calibrated according to manufacturer specifications prior to and, when applicable, during the cruise.

3. Uncertainty associated with intrusion of sea spray

Sea spray is a source of error in ship measurements of rainfall and generally decreases with increasing height of the gauge above the water line (Roll 1958). Quantification of the error requires measurement of the portion of sea spray in the total rain catch, which can be difficult in practice. Skaar (1955) used salinity measurements of the water collected by his gauges to estimate the contribution of sea spray to total rain catch. Roll (1958) criticized this method on the grounds that it will not distinguish actual sea spray from rain that contains dissolved dry salt previously encrusted on the instrument. Verploegh (1957) asserted that sea spray can be neglected when the gauge is located at least 16 m above the water line.

The rain gauges onboard the *Brown* were positioned between 10.31 and 17.73 m above sea level (Table 2). Using a detailed log of rain events during the TEPPS cruise (M. Grossklaus 1997, personal communication), we were able to distinguish time periods when any liquid collected by the gauges was sea spray from those when the gauges collected rain. Over the course of eight nonraining days during both the ITCZ and stratocumulus legs of the cruise (Fig. 1), only two days yielded measurable liquid in any of the gauges. On 27 August 1997, the 02P siphon gauge recorded 3.11 mm, the 02S siphon gauge recorded 1.65 mm, and the IfM ship rain gauge recorded 0.5 mm. On 28 August 1997, the 02P siphon gauge recorded 1.08 mm. These days also experienced some of the largest relative wind speeds recorded during the cruise, 15.1 m s^{-1} for 27 August and 13.5 m s^{-1} for 28 August (Table 1). Because for most of the cruise both relative and true wind speeds were lower, we will assume that the by-catch of sea spray on days with rain was negligible.

4. Assessment of rain instrument performance

The Joss–Waldvogel disdrometer, two piezoelectric disdrometers, the IfM optical disdrometer and ship rain gauge, an STI optical rain gauge, and a siphon gauge were installed on the 03 level port-side area (Fig. 3), close enough to have similar exposure but far enough apart to minimize blockage of one instrument by another. Because a siphon gauge will not catch horizontally windblown rain, a calibrated siphon gauge cannot overestimate rain catch. The siphon gauge data thus provided a lower limit baseline with which to compare the accumulations reported by the other instruments in the cluster. When assessing the instruments clustered on the 03 level on the port side of the ship, accumulations less than the 03P siphon gauge accumulation were taken

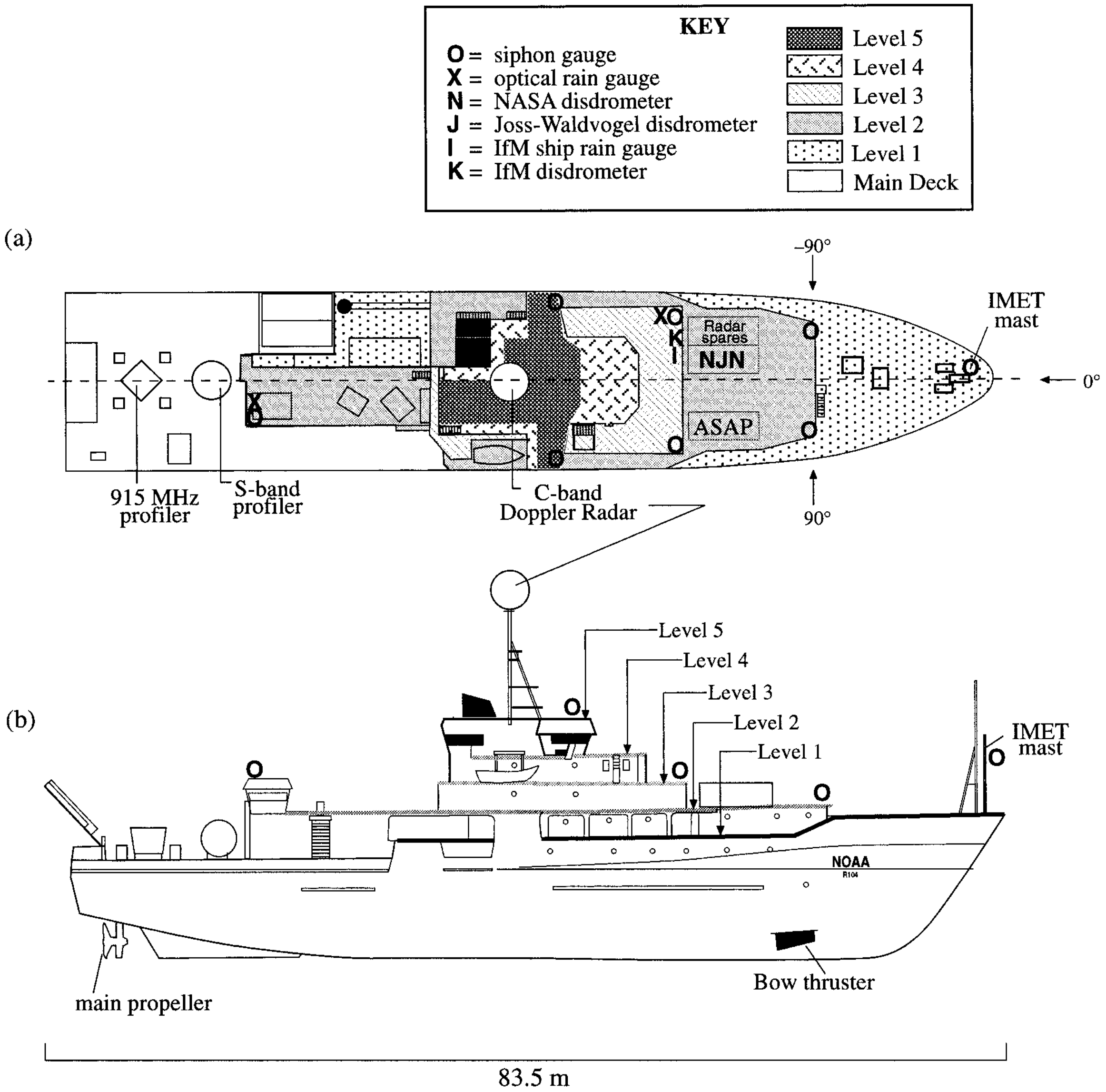

FIG. 2. Positioning of rainfall instrumentation on the *Brown* for PACS TEPPS. (a) Top view and (b) side view. Ship relative wind directions are indicated in (a). [Adapted from Yuter and Houze (2000)].

to indicate either undersensitivity or undercatch.[4] Oversensitivity also was determined by comparison; if an instrument accumulation was several times larger than the accumulations measured by most of the other collocated instruments, then this significant discrepancy was taken to indicate oversensitivity. Table 3 shows the total precipitation accumulations measured by the instruments in the 03P cluster.

The piezoelectric disdrometer data provide good examples of oversensitivity and undersensitivity. The 03P cluster included two experimental piezoelectric disdrometer units, w8 and w20. These disdrometers worked erratically and appeared to have suffered a manufacturing problem in the setting of the threshold below which vibrations are not counted as rain (J. Nystuen 1997, personal communication). Unfortunately, the instrument design precluded user adjustment of instrument sensitivity. Piezoelectric disdrometer w20, the replacement for another piezoelectric disdrometer sent back with other systematic problems, was oversensitive and nearly always reported rainfall, even when tested indoors. When it was raining, the vibrations caused by the drops were sometimes interpreted by w20 as rain rates of several hundred millimeters per hour, resulting in exorbitant accumulations. In addition, there is some evidence that high wind gusts may have triggered w20

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[4] Other instruments with vertical or volumetric catchment may accurately accumulate more precipitation than a collocated siphon gauge.

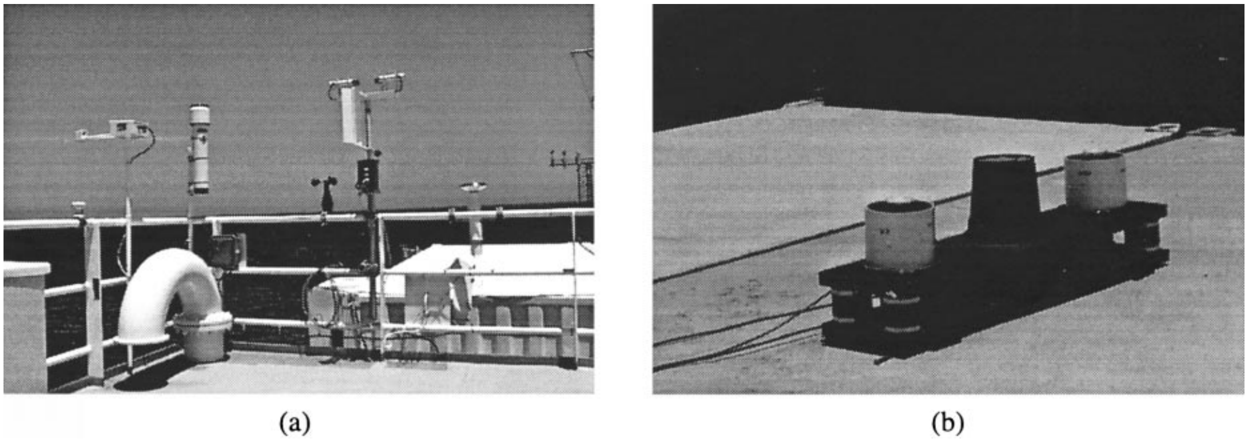

FIG. 3. Cluster of rain instrumentation on 03 port level during PACS TEPPS. (a) Instruments mounted on 03 level port-side railing. From left to right are the STI optical rain gauge, R. M. Young siphon gauge, IfM anemometer, IfM optical disdrometer, and IfM ship rain gauge. The IMET mast on the bow is visible on the middle far right edge of the picture. (b) The disdrometers were placed just to the right and forward of the instruments in (a) on top of the 02 level port inboard van and mounted in foam-lined plastic housings. From left to right are the piezoelectric disdrometer w8, the Joss–Waldvogel disdrometer, and the piezoelectric disdrometer w20.

when it was not raining (e.g., on 6 August, B. E. Furness 1997, personal communication). Over the 1–27 August 1997 TEPPS period, disdrometer w20 accumulated 1592 mm of rain (Table 3), while the other 14 rain collection instruments on the *Brown* accumulated less than 450 mm (Fig. 4a). For this reason, piezoelectric disdrometer w20 was excluded in Fig. 4a and from the analysis that follows. Piezoelectric disdrometer w8, positioned approximately 1 m away from w20, was generally undersensitive, measuring less rainfall than the other instruments. Figure 4a shows that, as a whole, w8 accumulated less than each of the other rain collection

TABLE 3. Daily rainfall accumulation (mm) reported by the instruments in the 03P cluster. The STI optical rain gauge located on the winch house is also included in the table. Abbreviations: IfM ship rain gauge (SR), IfM optical disdrometer (OD), piezoelectric disdrometer w8 (w8), piezoelectric disdrometer w20 (w20), STI optical rain gauge on 03P (ORG-3), siphon gauge (Siphon), Joss–Waldvogel disdrometer (JW), and STI optical rain gauge on winch house (ORG-T). Date is month and day in 1997.

Date	SR	OD	w8	w20	ORG-3	Siphon	JW	ORG-T
0801	6.8	13.5	0.7	38.9	4.5	2.5	1.8	7.4
0802	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0803	0.0	0.1	0.1	19.3	0.1	0.0	0.0	0.3
0804	14.6	20.6	6.1	59.2	19.0	1.5	3.6	62.2
0805	44.9	56.0	38.0	206.9	86.9	20.0	18.1	131.6
0806	7.2	9.8	10.5	41.3	17.6	3.5	2.9	30.8
0807	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0808	1.7	2.4	0.5	9.6	2.0	1.0	1.0	1.8
0809	12.0	12.9	1.1	42.6	9.3	8.0	7.8	9.2
0810	55.7	67.5	5.9	265.4	41.5	40.5	47.5	45.9
0811	11.7	20.2	2.1	77.3	8.6	8.0	13.1	9.8
0812	5.5	5.8	2.5	53.8	4.5	4.0	5.8	5.0
0813	5.6	7.2	0.7	23.6	4.6	4.0	4.3	4.3
0814	0.6	1.3	0.0	25.9	0.6	Tr	0.7	0.8
0815	43.3	54.3	5.8	212.7	37.8	34.0	39.2	33.7
0816	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0817	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0818	22.1	23.9	3.8	88.0	14.9	15.0	13.1	13.0
0819	1.2	2.3	0.1	11.9	0.9	Tr	1.1	0.7
0820	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0821	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0822	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0823	15.4	18.0	0.9	74.1	10.7	12.5	12.9	9.6
0824	58.2	86.6	32.9	237.2	52.0	44.5	21.1	61.6
0825	17.0	26.5	14.3	104.2	16.7	12.5	4.9	25.6
0826	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0827	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Totals	323.5	428.9	126.0	1591.9	332.2	211.5	198.9	453.3

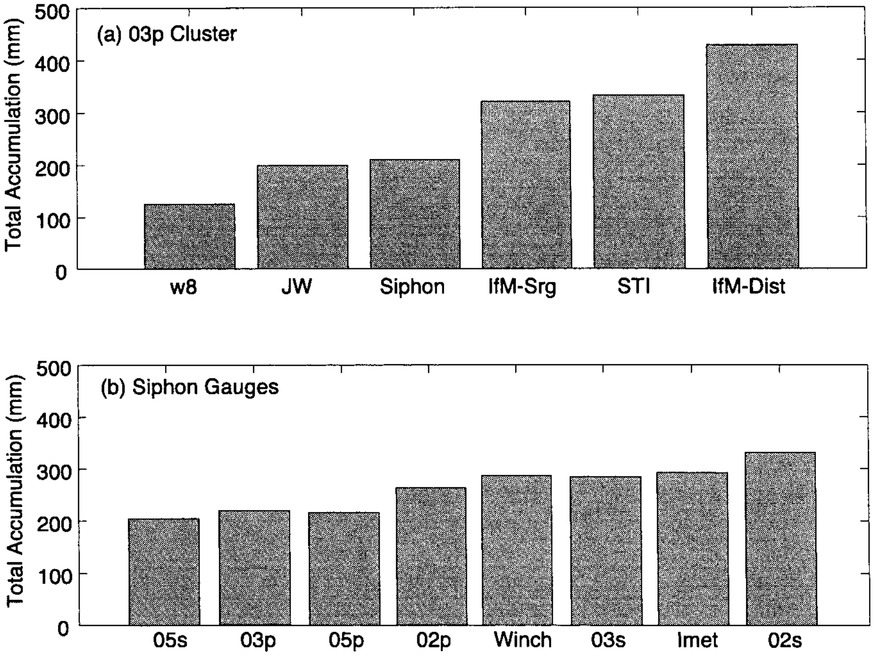

FIG. 4. Precipitation accumulations for 1–27 Aug 1997 reported by the rainfall instruments on the *Brown.* (a) Total accumulations for the 03P cluster instruments. (b) Total accumulations for the siphon gauges.

instruments on the *Brown.* Problems with the sensitivity of these disdrometers were detected prior to the cruise and reported to the instrument supplier. The scheduled ship sailing made it necessary to proceed with the particular instruments on ship.

The Joss–Waldvogel disdrometer has been used extensively on land, and an earlier model was used at sea during GATE. Similar to the findings during GATE (Austin and Geotis 1979), during TEPPS the Joss–Waldvogel disdrometer tended to underestimate rainfall. The underestimation was systematic while under way, when relative wind speeds were higher. For example, when the ship was under way on 6 August 1997, the hourly accumulations reported by the Joss–Waldvogel disdrometer were significantly smaller than those reported by the other collocated instruments, including the IfM instruments (Table 4). When the ship was on station (when relative wind speeds were generally lower), the Joss–Waldvogel disdrometer still tended to be among the instruments that measured the least accumulated precipitation. In contrast to the piezoelectric disdrometer w20 for which vibrations lead to an overestimate of rainfall, ship-induced vibrations increased the noise threshold of the Joss–Waldvogel disdrometer, suppressing measurement of smaller drops (Joss and Gori 1976; Austin and Geotis 1979). Efforts were made to dampen vibrations using upholstery foam, however, neither the piezoelectric nor Joss–Waldvogel disdrometers could be entirely isolated from them.

Both while under way and while on station, the STI optical rain gauge sporadically recorded much higher rain rates than the other collocated instruments. For example, between 0515 and 0525 UTC on 6 August 1997, the STI gauge reported rain rates nearly an order of magnitude larger than those reported by the other instruments in the 03P instrument cluster (Fig. 5).[5] The resulting accumulations for the period shown in Fig. 5 are given in Table 4. Coincidentally, the STI gauge reported a similar hourly accumulation for the time period in Fig. 5 to that of the malfunctioning piezoelectric disdrometer w20. However, over the cruise as a whole, the STI optical rain gauge reported 332.2 mm of rain (Fig. 4, Table 3), a value similar to that reported by the IfM

TABLE 4. Accumulations reported by instruments in the 03P cluster during heavy rain between 0440 and 0540 UTC 6 Aug 1997. During this hour, the ship was under way, and the average wind speed measured by the collocated IfM anemometer was 11.5 m s^{-1}.

Instrument	Accumulation (mm)
R. M. Young siphon gauge	3.0
STI optical rain gauge	24.0
Joss–Waldvogel disdrometer	1.3
IfM ship rain gauge	2.6
IfM optical disdrometer	4.0
Piezoelectric disdrometer w8	7.9
Piezoelectric disdrometer w20	21.8

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[5] The 03P siphon gauge rain rates are included in the plot for qualitative comparison. However, 1 min is too short of a time period over which to calculate *accurate* rain rates from the siphon gauges unless the rain rates are 60 mm h^{-1} (i.e., 1 mm min^{-1}) or higher.

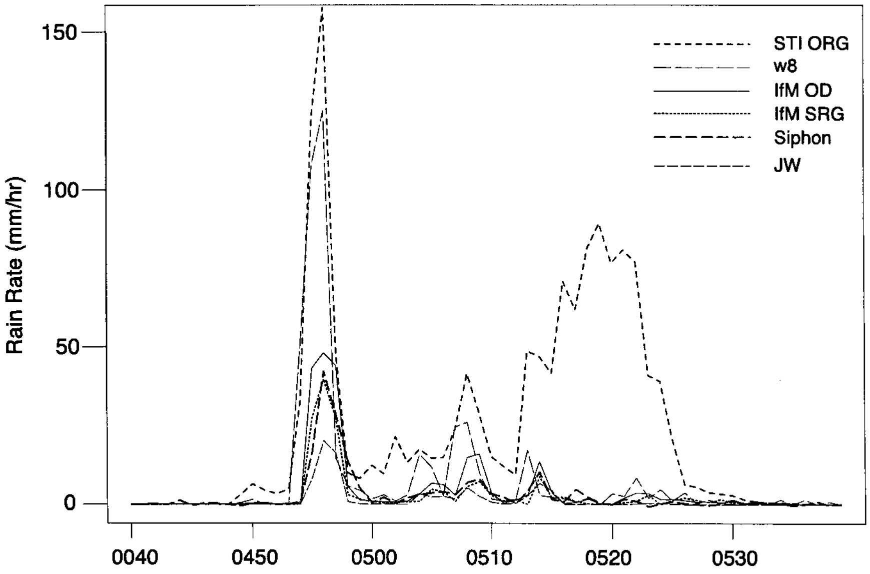

FIG. 5. Example 1-min rain-rate time series for a 1-h period during a heavy rain event on 6 Aug 1997 for rain measurement instruments clustered near 03 level port side: IfM optical disdrometer (OD), IfM ship rain gauge (SRG), STI optical rain gauge (ORG), siphon gauge (Siphon), Joss–Waldvogel disdrometer (JW), and piezoelectric disdrometer w8 (w8). Table 4 contains accumulation values for each instrument for the 1-h period shown.

ship rain gauge. A comparison of accumulations only may not reveal many types of erratic behavior in rain instrumentation. A time series of rain rate at a few-minute interval (e.g., Fig. 5) is a powerful diagnostic tool in assessing instrument performance.

The reasons for the occasional, unrealistic rain rates reported by the STI optical rain gauge remain under investigation. The volumetric collection surface of the STI gauge probably contributed to its reporting a relatively larger amount of precipitation in comparison with the instruments with horizontal-only catchment. However, because it is difficult to correct for the spuriously high STI rain rates, it is also difficult to determine to what extent its accumulation resulted from the effects of design (volumetric collection). Consequently, for purposes of determining the amount of precipitation that actually fell on the *Brown* during the TEPPS study, we choose to exclude the STI optical rain gauges from our consideration.[6]

The IfM optical disdrometer and ship rain gauge performed consistently throughout the cruise. Their rainfall estimates did not indicate large over- or undersensitivity relative to the other collocated instruments. The processing of the IfM instrument data included corrections for wind effects. It is therefore expected that the IfM data would indicate more precipitation than reported by the other collocated instruments, which did not incorporate wind adjustments. Examination of the time series of rain rates from the IfM instruments showed that they tended to agree at lower rain rates but often differed at higher rain rates, with the optical disdrometer usually reporting larger values. The IfM optical disdrometer on average reported 138% of the rain rate reported by the IfM ship rain gauge when the optical distrometer rain rates were >15 mm h^{-1}. The ~ 100 mm difference between IfM ship rain gauge (323.5 mm) and the IfM optical disdrometer (428.9 mm) total accumulations in Table 3 is primarily due to the accumulated differences during heavy rainfall periods. Under higher rain-rate conditions, the optical disdrometer was susceptible to splashing, which could have degraded the functioning of its optics.

The IfM ship rain gauge data were corrected for wind effects using a relatively simple algorithm (Hasse et al. 1998), making it possible to remove the wind corrections for the purpose of separating the relative contributions of design and wind-correction effects to collection efficiency. Daily IfM ship rain gauge uncorrected and wind-corrected accumulations are given in Table 5, along with the daily accumulations reported by the collocated 03P siphon gauge and the average daily relative wind speed reported by the collocated 03P anemometer. Over the period as a whole, the wind-corrected data

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[6] There were two STI optical rain gauges on the *Brown.* The second gauge, located on top of the winch house near the stern of the ship, also occasionally reported unrealistically high rain rates in comparison with the nearby siphon gauge. The total accumulation reported by the winch house STI optical rain gauge over the 1–27 August TEPPS period is included in the rightmost column of Table 3. As with the 03P STI gauge, the total accumulation it reported is much larger than that reported by the collocated winch-house siphon gauge. Because the second STI gauge sporadically reported unrealistically high rain rates, it is not considered to be a reliable estimate of the actual amount of precipitation. It is mentioned here only because it will not be discussed in later sections of the paper.

Table 5. Accumulations for the 03P siphon gauge and the IfM ship rain gauge with and without wind corrections. Average relative wind speeds for each day as measured by the collocated IfM anemometer are given. Asterisks indicate days during which the average relative wind speed was greater than 9 m s^{-1}. On 24 and 25 Aug, average daily wind speeds were larger than average wind speeds during the hours of heaviest rain.

Date	03P avg wind speed (m s^{-1})	03P accumulated (mm)	SR accumulated without wind correction (mm)	WR wind-corrected accumulated (mm)
0801	2.7	2.5	6.6	6.8
0804*	14.3	1.5	12.8	14.6
0805*	14.7	20.0	38.7	44.9
0806*	12.3	3.5	6.3	7.2
0808	3.6	1.0	1.6	1.7
0809	2.6	8.0	11.2	12.0
0810	4.0	40.5	52.5	55.7
0811	4.9	8.0	10.4	11.7
0812	4.4	4.0	4.5	5.5
0813	3.6	4.0	5.2	5.6
0814	2.7	Trace	0.6	0.6
0815	2.6	34.0	38.9	43.3
0818	2.7	15.0	20.0	22.1
0819	2.7	Trace	1.2	1.2
0823	1.8	12.5	15.0	15.4
0824	6.5	44.5	51.3	58.2
0825	8.8	12.5	14.3	17.0
Total (mm)		211.5	291.1	323.5

indicated 323.5 mm of precipitation, while the uncorrected data indicated only 291.1 mm of precipitation. A loss of about 32 mm of precipitation was attributed to wind effects. The 03P siphon gauge caught only about 73% (211.5 mm) of the uncorrected IfM amount, suggesting that design-related differences resulted in an ~80 mm accumulation difference between the instruments over the period.

Design-related differences can be further broken down into those resulting from the modified champagne-bowl shape of the horizontal collector of the IfM ship rain gauge (Folland 1988; Hasse et al. 1998), and those resulting from the gauge's additional lateral collector. The two collecting surfaces are used to calculate rain rate as follows: when wind speeds are less than 9 m s^{-1}, only drops collected from the horizontal collecting surface are used to calculate rain rate; when wind speeds are greater than 11 m s^{-1}, only drops collected from the additional vertical collecting surface are used to calculate rain rate; when wind speeds are between 9 m s^{-1} and 11 m s^{-1} there is a linear transition in the relative weighting of the rain rates calculated by the two collecting surfaces (Hasse et al. 1998).

On most days during August, the ship was on station and average relative wind speeds were below 9 m s^{-1}. For these days, the IfM ship rain gauge with wind correction removed indicated a total of 233.3 mm of precipitation, while the 03P siphon gauge caught only 80% (186.5 mm) of that amount (Table 5). The 46.8-mm difference in accumulation between the gauges can be attributed to the collection advantage afforded to the IfM ship rain gauge by its modified champagne-bowl-shaped top collector. This 20% accumulation difference for the group of light wind days also is fairly representative of the differences on individual days in the group; on average, the 03P siphon gauge accumulated ~74% ± 15% of the uncorrected daily IfM ship rain gauge accumulation.

From 2 to 6 August 1997, the ship was underway in the vicinity of Hurricane Guillermo (Yuter and Houze 2000). Rain fell on the *Brown* on 4–6 August, and the IfM anemometer aboard the *Brown* measured an average relative wind speed greater than 9 m s^{-1} (dates indicated by asterisks in Table 5). The drops collected by the vertical surface of the IfM ship rain gauge contributed (at least in part) to the calculation of the gauge accumulation, and the IfM gauge caught much more precipitation than did the 03P siphon gauge. Over the 3-day period, the uncorrected IfM ship rain gauge data reported a total of 57.8 mm of precipitation, while the 03P siphon gauge caught only 43% (25 mm) of that amount. This 32.8-mm difference reflects the collection advantage afforded to the IfM ship rain gauge by its additional vertical collector.[7] On average, both the IfM ship rain gauge specially shaped top collector and the additional vertical collector significantly increased collection efficiency. For the IfM disdrometer, it is difficult to separate the effect of the wind correction from the effect of the instrument design because the wind corrections applied to the raw disdrometer data are very complex (Grossklaus et al. 1998).

5. Variation of rain catch with rain gauge location

a. *Cross-ship variation*

Airflow distortion over the ship combined with a lack of a wind correction for the instrument influenced the catch reported by siphon gauges placed on the port and starboard sides of the ship and at different heights (Table 6, Fig. 4b). At a given ship level, the windward gauge often caught less precipitation than did the leeward gauge. If the wind was blowing from the starboard side of the ship, then the starboard gauge tended to catch less precipitation than the port gauge on the same ship level, and vice versa. To some extent, this difference is to be expected, because airflow encountering the side of the ship will be forced upward, reducing rainfall incident on the windward side of the ship deck in comparison with the lee side. An extreme example occurred on 24 August when the winds were moderately strong (8.5 m s^{-1} on average) from the starboard side (ap-

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[7] Although some of the time during these days the wind speeds were less than 11 m s^{-1}, for a majority of the time the wind speeds were greater than 11 m s^{-1}, so the accumulations were determined to a greater extent by the vertical collection than by the top collection.

TABLE 6. Daily rainfall accumulation (mm) reported by the siphon gauges on the *Brown* without any wind correction applied.

Date	Imet	02S	02P	03S	03P	05S	05P	Winch
0801	5.5	7.5	2.5	7.5	2.5	4.5	2.5	5.5
0802	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0803	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0804	9.0	28.0	3.5	21.0	1.5	9.5	3.0	17.0
0805	60.0	105.0	30.0	92.0	20.0	45.0	27.5	76.0
0806	3.5	7.0	7.0	7.0	3.5	4.5	1.5	5.0
0807	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0808	1.0	1.5	1.5	Trace	1.0	Trace	1.0	Trace
0809	6.5	6.5	9.0	5.0	8.0	5.0	8.5	6.0
0810	58.0	49.5	54.0	37.5	40.5	36.0	49.0	41.0
0811	12.0	14.0	9.5	13.0	8.0	10.5	9.5	11.5
0812	5.0	8.0	4.0	7.0	4.0	5.5	4.5	6.5
0813	4.5	3.5	4.0	3.0	4.0	2.0	4.0	4.0
0814	0.0	0.0	Trace	Trace	Trace	0.0	Trace	Trace
0815	39.5	46.5	34.5	45.5	34.0	38.0	33.5	44.5
0816	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0817	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0818	13.0	13.0	15.0	13.0	15.0	10.0	13.0	15.0
0819	1.0	Trace	Trace	1.0	Trace	Trace	Trace	1.0
0820	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0821	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0822	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0823	15.0	14.0	14.0	12.0	12.5	11.5	11.5	13.0
0824	43.0	17.5	53.0	13.5	44.5	15.0	33.0	27.0
0825	11.0	4.0	15.5	3.0	12.5	3.0	9.5	6.0
0826	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0827	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total	287.5	325.5	257.0	281.0	211.5	200.0	211.5	279.0
Height above waterline (m)	13.99	10.31	10.31	12.83	12.83	17.73	17.73	13.31

proximately 45° angle of attack relative to the ship's bow). The port gauges caught 2–3 times as much precipitation as the starboard gauges did (Fig. 6).

Cross-ship differences began to appear at relative wind speeds between 3 and 5 $m\ s^{-1}$ (Fig. 7b) and were most significant at wind speeds greater than 5 $m\ s^{-1}$ (Fig. 7c). When the relative wind speed fell below 3 $m\ s^{-1}$, differences between port and starboard accumulations were small and random (Fig. 7a). For any given wind direction, the maximum accumulation difference tended to increase with increasing wind speed. For any given wind speed, the maximum cross-ship difference usually occurred for port or starboard relative wind directions between 20° and 80° (Fig. 7c). Figure 7c shows that hourly accumulation differences greater than 5 mm occurred several times; in fact, hourly differences of 14.5, 18, and 28 mm were observed on 5 August 1997, when the *Brown* experienced high winds and heavy rainfall in the vicinity of Hurricane Guillermo. The points representing these few large differences are beyond the range of accumulation differences shown in Fig. 7c. Analysis of hourly averaged relative wind direction on days when precipitation fell (Fig. 8) revealed that the relative wind direction was from the port side 60% of the time and from the starboard side only 40% of the time. This distribution of relative wind direction seems consistent with the difference between the total accumulations reported by the starboard and port-side siphon gauges at the same levels (Fig. 4b). Despite the consistent qualitative relationship between the relative wind speed and direction and the port–starboard accumulation differences, we did not attempt to quantify this relationship, given that would be valid only for a specific ship with a specific configuration.

b. *Variation with height with wind correction*

By applying a wind-correction formula to the siphon gauge data we can correct for the reduction of rainfall by wind distortion by the instrument and focus on the effect of the airflow distortion by the ship. Although there is no wind-correction formula currently available for the 14-cm diameter (5.5 in) R. M. Young siphon gauges, there are numerous formulas available for similar gauges. Given the complexity of the wind field over the ship, it is best to place an anemometer at the location of each rain measurement instrument. Because relative wind speed was measured only on the IMET mast and on the 03P-level locations, we only apply an estimated wind correction to the siphon gauge data at these locations. The siphon gauge accumulations in Table 6 were adjusted using the wind-correction formula reported in Yang et al. (1998) for the National Weather Service standard 8 in. nonrecording precipitation gauge. Table 7 gives these adjusted precipitation amounts, which should be interpreted as *estimates* of the actual

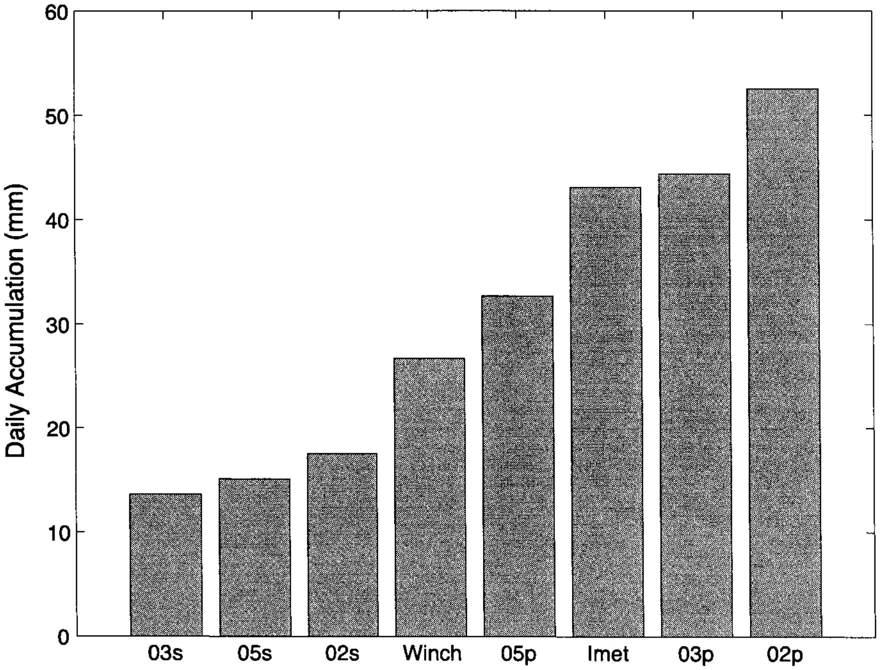

FIG. 6. Daily accumulation reported by siphon gauges on 24 Aug 1997. During precipitating periods, the average wind angle of attack relative to the ship's bow was approximately 45°, and the average wind speed was ~8.5 m s^{-1}.

amount of precipitation received by the gauges. Our assumption in applying this correction is that using an approximate wind correction yields more accurate estimates of rainfall than do uncorrected gauge readings known to be underestimates. With the wind correction supplied by Yang et al. (1998), the total corrected accumulations reported by the 03P (250.0 mm) and IMET (349.0 mm) are closer to the accumulations reported by the wind-corrected IfM ship rain gauge (323.5 mm).

Most of the difference between the IMET and the 03P siphon gauge wind-corrected accumulations occurred on 4–5 August when wind speeds were greater than 10 m s^{-1} and the relative wind direction was more than 50° off the bow (Tables 1 and 7). Under wind conditions such as seen under way, particularly when the angle of attack of the wind to the bow is large, the differences between wind-corrected accumulations at two locations at nearly the same height indicate a difference in incident rainfall between these locations.

6. Conclusions

For weather and climate purposes, the intention of rain measurement from ship is to estimate the amount of rain falling at the sea surface as if the ship was not there. Calibration of the rainfall amount, rate, or spectra caught by a rain gauge or disdrometer in a controlled windless environment, such as a rain tower, only addresses part of the error associated with rain measurement on platforms such as ships. Previous studies (Skaar 1955; Roll 1958; World Meteorological Organization 1962; Austin and Geotis 1980; Hasse et al. 1998) have shown that wind-related errors associated with instrument exposure and instrument design strongly contribute to rain measurement uncertainty. Wind corrections determined empirically or via numerical simulation typically only account for the distortion of the flow around the instrument (Sevruk 1982; Hasse et al. 1998; Yang et al. 1998; Nešpor and Sevruk 1999) and hence correct to the incident rainfall at the location of the measurement; they will *not* always correct fully to the amount one would have obtained had the ship not been there. The effect of wind distortion by the ship itself on rain catch is more likely to be significant for a moving ship (WMO 1962) than a stationary ship (Roll 1958; Austin and Geotis 1980).

When the relative wind speed is high and the angle of attack to the bow is large, the superstructure of the ship can yield a sufficient distortion of wind flow to reduce the rainfall *incident* at the location of the rain measurement (section 5). At wind speeds greater than 3 m s^{-1}, and particularly at speeds greater than 5 m s^{-1}, the cross-ship differences in hourly accumulations between identical instruments located on the port and starboard sides of the *Brown* at the same height became significant.

At a given height above the water line, the windward siphon gauge usually caught less precipitation than the leeward gauge (Fig. 7). For a given wind direction, the cross-ship differences in accumulation tended to increase in magnitude with increasing wind speed. Head-

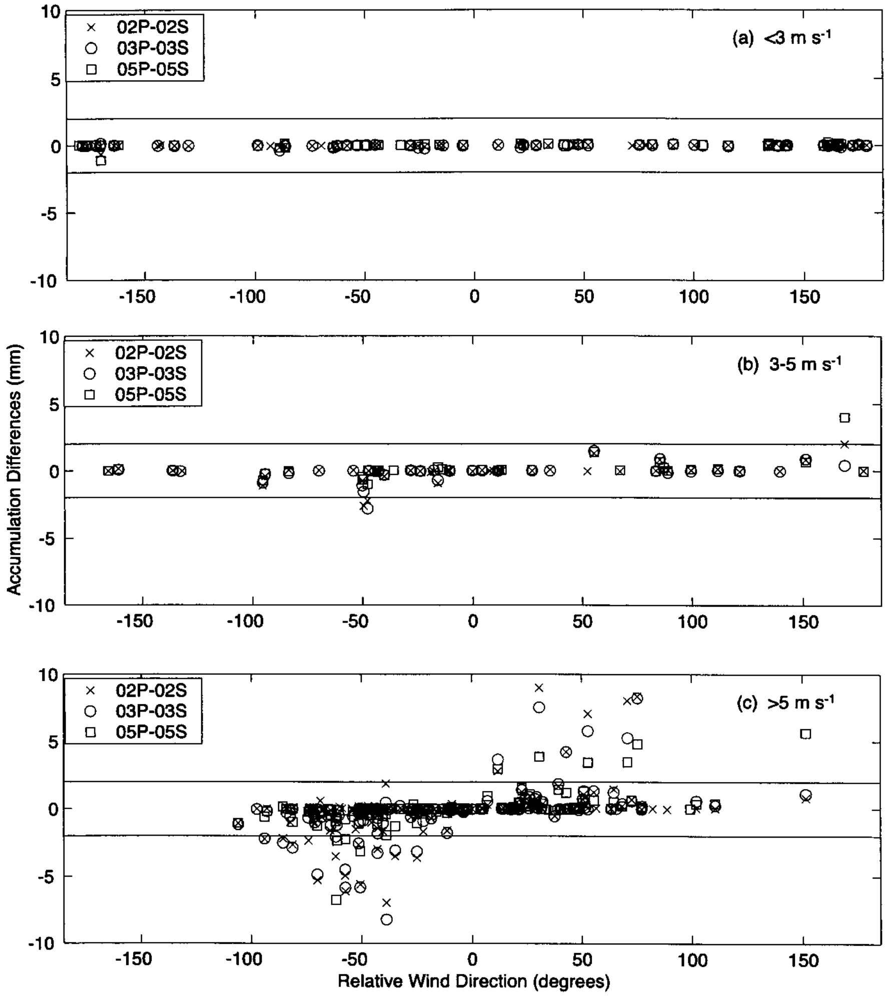

FIG. 7. Port–starboard hourly accumulation differences for the siphon for 1–27 Aug 1997. Differences in (a)–(c) were calculated by subtracting the starboard hourly rain accumulation at a given level from the port accumulation for the same level (e.g., 03P − 03S). Four points out of range for (c) are excluded but are discussed in the text. Differences in port–starboard hourly accumulations for wind speeds (a) less than 3 m s^{-1}, (b) between 3 and 5 m s^{-1}, and (c) greater than 5 m s^{-1}.

winds (0° angle of wind attack) produced the least difference between gauge accumulations on different sides of the ship, independent of wind speed. Once the angle of wind attack exceeded 20° relative to the bow, however, hourly accumulation differences larger than 5 mm were observed on several occasions. An extreme example occurred on 4–5 August 1997 during the TEPPS cruise when wind-corrected siphon gauge accumulations at similar heights but different locations on ship varied by 62 mm during conditions when the relative wind speed was greater than 10 m s^{-1} and the wind angle of attack relative to the bow was greater than 50°.

Both proper placement of the instrument (such that flow distortion by the ship superstructure itself is locally minimized) and a wind correction for the instrument are needed to estimate rainfall at the sea surface accurately from ship. Sea spray also adds uncertainty to the measurement but had a negligible effect on the data obtained in this study. In general, when the ship is pointed into the wind, a bow mast location will usually experience the least air flow distortion caused by the ship and be most representative of undisturbed conditions in the vicinity of the ship (Fairall et al. 1997). However, typical ship operational constraints make it difficult to point the ship continuously into the wind, and thus there is no *single* superior gauge location.[8] Instead, as was found in GATE, we conclude that multiple locations outfitted with identical instruments are needed to constrain rain gauge errors. Preferred locations reduce susceptibility to sea spray and shadowing from above and minimize distortion of the wind field by the ship. We concur with Skaar (1955) and Austin and Geotis (1980) that loca-

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[8] Numerical modeling of the flow around the ship would be useful in qualitatively assessing minimums in flow distortion at various wind speeds and directions but is usually not available.

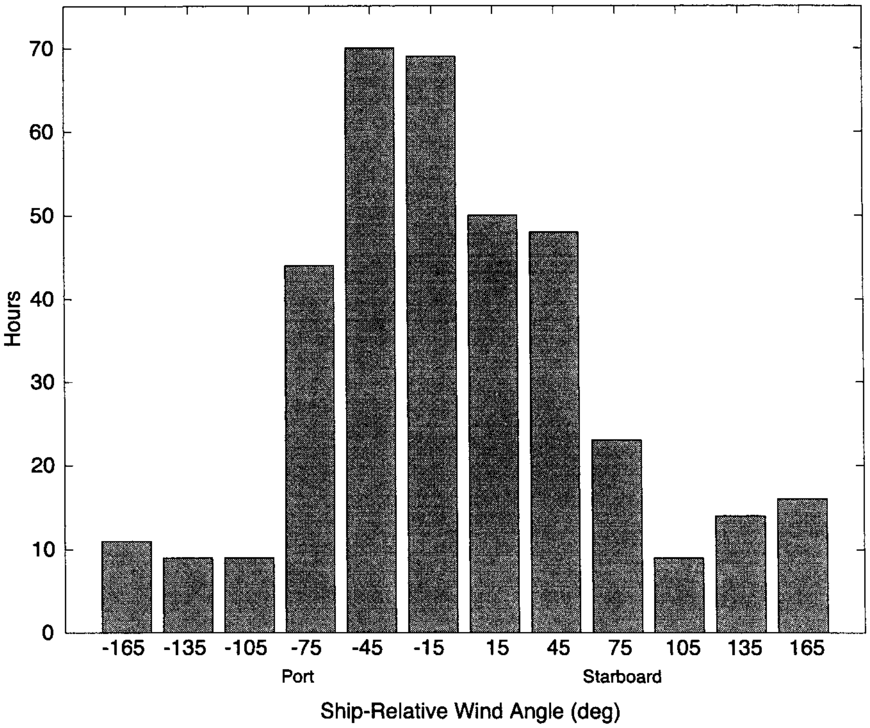

FIG. 8. Distribution of hourly averaged relative wind direction relative to the ship's bow on rainy days over the PACS TEPPS period of 1–27 Aug 1997. Histogram bin interval is 30° centered on the value below the bar.

TABLE 7. Daily accumulation (mm) reported by the IMET and 03P siphon gauges on the *Brown* with Yang et al. (1998) wind correction applied. Data from Table 3 for the IfM ship rain gauge (SR) and optical disdrometer (OD) are repeated to facilitate comparison.

Date	IMET	03P	SR	OD
0801	6.5	2.5	6.8	13.5
0802	0.0	0.0	0.0	0.0
0803	0.0	0.0	0.0	0.1
0804	12.0	1.5	14.6	20.6
0805	78.5	27.0	44.9	56.0
0806	4.0	4.5	7.2	9.8
0807	0.0	0.0	0.0	0.0
0808	1.0	1.5	1.7	2.4
0809	7.5	9.0	12.0	12.9
0810	69.0	46.5	55.7	67.5
0811	14.0	9.0	11.7	20.2
0812	6.0	4.5	5.5	5.8
0813	5.0	4.5	5.6	7.2
0814	Trace	Trace	0.6	1.3
0815	44.5	38.0	43.3	54.3
0816	0.0	0.0	0.0	0.0
0817	0.0	0.0	0.0	0.0
0818	15.0	16.5	22.1	23.9
0819	1.0	Trace	1.2	2.3
0820	0.0	0.0	0.0	0.0
0821	0.0	0.0	0.0	0.0
0822	0.0	0.0	0.0	0.0
0823	17.0	14.0	15.4	18.0
0824	53.5	55.5	58.2	86.6
0825	14.5	15.5	17.0	26.5
0826	0.0	0.0	0.0	0.0
0827	0.0	0.0	0.0	0.0
Total	349.0	250.0	323.5	428.9

tions with lower relative wind speeds (usually lower on the ship rather than on top of a mast) are preferable. The quest to improve rain gauge design to minimize wind cross section (Folland 1988; Hasse et al. 1998) has the same underlying assumption: it is better to reduce the wind effect than to correct for it.

Because the *Brown* typically makes rain measurements both while under way and on station, placement of identical IfM ship rain gauges is recommended at three locations: on the bow mast at a height[9] that jointly minimizes both strong vibration and sea spray and on the port and starboard sides of the 02 level. For the 17 rain days considered, one of these three locations caught as much or more precipitation than each of the seven remaining locations (Table 6).

Several of the newer instruments deployed during the TEPPS cruise behaved erratically. Data from the piezoelectric disdrometers supplied by the NASA TRMM Office and the STI optical rain gauges appeared to be reasonable until compared with other collocated instruments. The errors may have been the result of problems associated with the specific instruments on the ship or with systematic problems in design and manufacture. Some STI units have been reported to yield highly accurate time series of rainfall (F. Bradley 1999, personal

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[9] The sensitivity of the IfM ship rain gauge drop counting mechanism to vibration makes it unsuitable for placement at the top of a mast (L. Loewen 1999, personal communication).

communication), but the two units on the *Brown* during TEPPS did not. It is important to verify that *each* unit is working properly. The factory calibrations on both the piezoelectric disdrometers and STI optical rain gauges were not correct, and neither of these instruments as currently designed can have their calibration adjusted by the user. Given their current design, it is highly recommended that these instruments be deployed in clusters that include baseline instruments such as siphon gauges that yield consistent results. The data from the experimental instruments should be discarded if a comparison of the time series of their measurements and baseline gauge measurements reveals significant differences (e.g., Fig. 5).

The IfM ship rain gauge (Hasse et al. 1998) represents a significant improvement over siphon gauges for rain measurement in windy conditions. The design features of the IfM ship rain gauge, a modified-champagne-bowl horizontal collector (Folland 1988) and cylindrical vertical collector, yielded a measurable collection advantage over the R. M. Young siphon gauge. The IfM instruments also correct for wind effects using input from a collocated anemometer (Grossklaus et al. 1998; Hasse et al. 1998). Since the TEPPS cruise, an IfM ship rain gauge has been added as part of the permanent instrumentation on the *Brown.* However, during the TEPPS cruise, the 03P location experienced sufficient flow distortion by the ship during higher wind conditions to reduce its rain catch when compared with a more preferable location.

Based on our analysis, it is recommended that rainfall measurements made using siphon gauges, currently the most commonly deployed instrument on volunteer-observing ships, be utilized as minimums rather than ‘‘true’’ values until wind corrections can be applied routinely to these data. Without a wind correction, a calibrated, well-placed siphon gauge will systematically tend to underestimate the accumulation of precipitation-sized drops falling on ship.

The catchment variation with exposure among instruments such as the IfM ship rain gauge that have horizontal and vertical catchment surfaces and built-in wind corrections needs to be studied. It is anticipated that such differences will be less than for the horizontal-only catchment of the siphon gauges examined in this study, but further investigation is needed.

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APPENDIX

Processing the PACS TEPPS Siphon Gauge Data

A meaningful accumulation period was determined for the siphon gauges based on their accumulation accuracy of 0.5 mm. In examining subday-scale accumulations, care was taken to select a timescale that would allow for most of the precipitation to be captured in meaningful accumulations (i.e., greater than 1 mm). Various time periods were considered (e.g., 1 min, 5 min, 1 h, 6 h), and eventually a period of 1 h was chosen on the following basis. Accumulations for each hour during which some rain occurred were examined. It was found that, even though only about 35% of these clock hours had accumulations greater than 1 mm, this 35% accounted for about 90% of the total precipitation measured by the gauges over the period. We considered the 90% accounted for by 1-h accumulations to be adequate for our purposes; in general, the adequate threshold will be determined on a study-by-study basis based on the precipitation climate data of the region being sampled.

The processing of the PACS TEPPS siphon rain gauge data from raw recorded gauge readings to hourly and daily accumulations was undertaken using the following steps:

1) When the accumulation in a siphon rain gauge reached approximately 50 mm, the gauge would siphon and thereby return to a near-zero reading (Fig. A1a). These siphon events were removed from the data so that the gauge readings continued beyond 50 mm, rather than dropping to near zero (Fig. A1b). This was accomplished by adding the last presiphon reading to all readings following the siphon event.
2) The siphon-removed data contained some spurious fluctuations. The most common kind of spurious fluctuation was a sharp rise in gauge accumulation quickly followed by a return to the prerise value (e.g., Fig. A1c, between 0100–0400 UTC). These fluctuations were filtered according to the following method. For each gauge accumulation, later values were examined, up to 90 10-s time steps ahead. If any of these subsequent values was found to be lower than the current one, then the current reading was

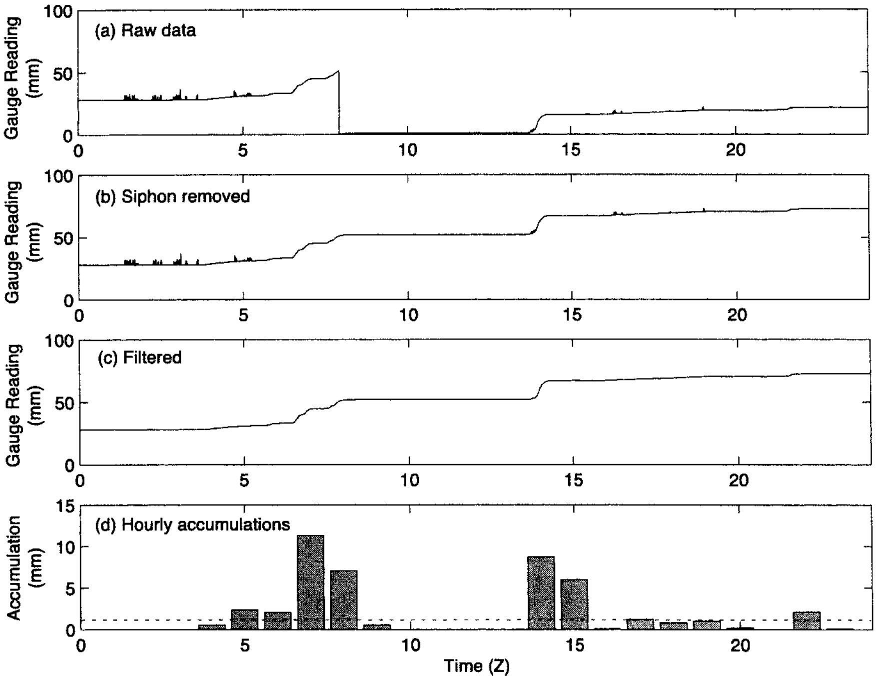

FIG. A1. Steps in the processing of the 03P siphon rain gauge data for 24 Aug 1997. (a) Time series of 10-s data as recorded by ship's computer system, (b) 10-s data after siphon at 0755 UTC was removed, (c) 10-s data after filtering step was applied, and (d) hourly accumulations derived from filtered 10-s data. Dashed line indicates 1-mm accumulation.

set to the lowest of the subsequent values. However, if this lowest value was lower than the previous gauge reading (the reading just before the current one), then the current gauge reading was assigned the value of the previous gauge reading. This filter method was developed on the premise that, on timescales too short for significant evaporation, the true accumulation can only stay the same or increase, and on the observation that gauge readings often jumped spuriously but rarely, if ever, fell spuriously. The result of the filtering is shown in Fig. A1c.

3) The hourly rain accumulations were calculated from the filtered, siphon-removed data by subtracting the final gauge reading during an hour from the first gauge reading during that hour (Fig. A1d). Hourly accumulations less than 1 mm were recorded, but it should be kept in mind that such accumulations cannot be distinguished from noise. The dotted line in Fig. A1d indicates the 1-mm accumulation threshold; accumulations below this line are indistinguishable from noise.
4) Daily accumulations (Table 6) were similarly calculated by subtracting the first siphon gauge reading for the day from the last siphon gauge reading for the day.

REFERENCES

Allerup, P., and H. Madsen, 1980: Accuracy of point precipitation measurement. *Nord. Hydrol.,* **11,** 57–70.

Austin, P. M., and S. G. Geotis, 1979: Raindrop sizes and related parameters for GATE. *J. Appl. Meteor.,* **18,** 569–575.

——, and ——, 1980: Precipitation measurements over the ocean. *Air–Sea Interaction,* F. Dobson, L. Hasse, and R. Davis, Eds., Plenum Publishing, 523–541.

Fairall, C. W., A. B. White, J. B. Edson, and J. E. Hare, 1997: Integrated shipboard measurements of the marine boundary layer. *J. Atmos. Oceanic Technol.,* **14,** 338–359.

Folland, C. K., 1988: Numerical models of the raingauge exposure problem, field experiments and an improved collector design. *Quart. J. Roy. Meteor. Soc.,* **114,** 1485–1516.

Groisman, P. V., and D. R. Legates, 1994: The accuracy of United States precipitation data. *Bull. Amer. Meteor. Soc.,* **75,** 215–227.

Grossklaus, M., K. Uhlig, and L. Hasse, 1998: An optical disdrometer for use in high wind speeds. *J. Atmos. Oceanic Technol.,* **15,** 1051–1059.

Hasse, L., M. Grossklaus, K. Uhlig, and P. Timm, 1998: A ship rain gauge for use in high wind speeds. *J. Atmos. Oceanic Technol.,* **15,** 380–386.

Hosom, D., R. A. Weller, R. E. Payne, and K. E. Prada, 1995: The IMET (Improved Meteorology) ship and buoy systems. *J. Atmos. Oceanic Technol.,* **12,** 527–540.

Jevons, W. S., 1861: On the deficiency of rain in an elevated rain gauge as caused by wind. *Philos. Mag.,* **22,** 421–433.

Joss, J., and A. Waldvogel, 1967: Ein Spektrograph für Niederschlagstropfen mit automatischer Auswertung. *Pure Appl. Geophys.,* **68,** 240–246.

——, and E. G. Gori, 1976: The parameterization of raindrop size distributions. *Riv. Ital. Geofis.,* **3,** 275–283.

Kuettner, J. P., D. E. Parker, D. R. Rodenhuis, H. Hoefer, H. Kraus, and G. Philander, 1974: GATE final international scientific plans. *Bull. Amer. Meteor. Soc.,* **55,** 711–744.

Nešpor, V., and B. Sevruk, 1999: Estimation of wind-induced error of rainfall gauge measurements using a numerical simulation. *J. Atmos. Oceanic Technol.,* **16,** 450–464.

Nystuen, J. A., 1998: Temporal sampling requirements for automatic rain gauges. *J. Atmos. Oceanic Technol.,* **15,** 1253–1260.

——, J. R. Proni, C. A. Lauter Jr., J. Bufkin, U. Rivero, M. Borland, and J. Wilkerson, 1994: APL disdrometer evaluation. NOAA Tech. Memo. ERL AOML-83, Atlantic Oceanographic and Meteorological Laboratory, Miami, FL, 48 pp. [Available from National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161.]

Oke, T. R., 1987: *Boundary Layer Climates.* Cambridge University Press, 435 pp.

Robinson, A. C., and J. C. Rodda, 1969: Rain, wind, and the aerodynamic characteristics of rain-gauges. *Meteor. Mag.,* **98,** 113–120.

Roll, H. U., 1958: Zur Niederschlagmessung auf See: Ergebnisse von Vergleichsmessungen auf Feuerschiffen und benachbarten Inseln. Deutscher Wetterdienst, Seewetteramt Hamburg, Einzelver, **16,** 15 pp.

Sevruk, B., 1982: Methods of correction for systematic error in point precipitation measurement for operational use. Operational Hydrology Rep. 21, WMO No. 589, Secretariat of the WMO, Geneva, Switzerland, 35 pp.

Skaar, J., 1955: On the measurement of precipitation at sea. *Geofys. Publ.,* **19,** 1–32.

Strangeways, I. C., 1996: Back to basics: The ''met. enclosure.'' Part 2(b): Rain gauges, their errors. *Weather,* **51,** 298–303.

Symons, G. J., 1864: Rain gauges and hints on observing them. *Br. Rainfall,* 8–13.

Verploegh, G., 1957: Rainfall measurements aboard the Netherlands Ocean Weather Ships ''Cirrus'' and ''Cumulus.'' K. Ned. Met. Inst. Wetenschappelijk, Rapport 57-003 (IV-014). [Available from Het Koninklijk Nederlands Meteorologisch Instituut, Postbus 201, 3730 AE De Bilt, Netherlands.]

Wang, T., K. B. Earnshaw, and R. S. Lawrence, 1979: Path-averaged measurements of rain rate and raindrop size distribution using a fast-response optical sensor. *J. Appl. Meteor.,* **18,** 654–660.

World Meteorological Organization, 1962: Precipitation measurements at sea. Tech. Note No. 47, WMO No. 124.TP.55, Secretariat of the WMO, Geneva, Switzerland, 18 pp.

Yang, D., B. E. Goodison, J. R. Metcalfe, V. S. Golubev, R. Bates, T. Pangburn, and C. L. Hanson, 1998: Accuracy of NWS 8″ standard nonrecording precipitation gauge: Results and application of WMO intercomparison. *J. Atmos. Oceanic Technol.,* **15,** 54–68.

Yuter, S. E., and R. A. Houze Jr., 2000: The 1997 Pan American Climate Studies Tropical Eastern Pacific Process Study. Part I: ITCZ region. *Bull. Amer. Meteor. Soc.,* **81,** 451–481.