Evaluation of Passive Microwave Precipitation Algorithms in Wintertime Midlatitude Situations

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(Manuscript received 7 March 1994, in final form 22 June 1994)

ABSTRACT

The second intercomparison project of the Global Precipitation Climatology Project examined the estimation of midlatitude, cool-season precipitation. As part of that effort, the authors report here on the results of two microwave techniques, the Goddard scattering algorithm and the physical retrieval algorithm of Kummerow. Results from the estimation of instantaneous rain rate for five overpasses of the Special Sensor Microwave/Imager (SSM/I) are presented in a case study mode to illustrate both the strong and weak points of each technique. These five cases represent a sampling of the various types of precipitating systems observed. Results for the complete set of 20 swaths chosen by the United Kingdom Meteorological Office are then categorized by scatterplots and statistics of instantaneous radar versus microwave-estimated rain rate, rain/no-rain contingency tables, and scatterplots of areal coverage of rainfall.

Neither algorithm produced a good statistical correlation with the radar data, yet in general, both did well at determining rainy areas. Two reasons are suggested for the low correlation coefficients between both algorithms and the radar data. Time differences between the SSM/I overpass and the radar observations can occasionally account for some of the differences. The primary reason for the low correlations, however, appears to be the predominance of very light rain in the area of interest during the winter. Both algorithms are in good spatial agreement with the radar when the radar data are restricted to rates above 1 mm h⁻¹. When all rainfall rates are included, the radar areal coverage increases by as much as a factor of 10 in some cases. Because the Kummerow algorithm does not handle such low rain rates over land very well, and because the Goddard scattering algorithm uses 1 mm h⁻¹ as the minimum reliably detectable rain rate, regimes that contain large areas of very light rain present inherent difficulties for these retrieval methods. Therefore, the proliferation of low rain rates observed during the experiment is the main contributor to low correlation coefficients and high root-mean-square differences. Misidentification of cold surface (e.g., snow cover) as precipitation was also a problem in several instances.

1. Introduction

The Global Precipitation Climatology Project (GPCP), under the auspices of the World Climate Re-

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search Program (WCRP), is an effort to provide a 10-yr global precipitation dataset to the climate and modeling community. Part of that effort is an organized intercomparison of infrared (IR) and microwave (MW) satellite rainfall estimation techniques. Three distinct algorithm intercomparison projects (AIP) were proposed. The first experiment (AIP-1) was conducted over Japan and surrounding oceanic regions during June–August 1989. Its goal was to examine both
"baniu," or frontal precipitation, in June and tropical convective precipitation in July and August. Results of this intercomparison may be found in Arkin and Xie (1994). An intercomparison of three IR techniques applied in AIP-1 may be found in Negri and Adler (1993), while descriptions of an MW technique and a combined MW–IR technique were reported in Adler et al. (1993). The second intercomparison (AIP-2), the subject of this study, examined the estimation of midlatitude, cool-season precipitation. The third experiment (AIP-3) was coordinated with the Tropical Ocean Global Atmosphere (TOGA) Coupled Ocean–Atmosphere Response Experiment (COARE) during November 1992–February 1993 over the tropical western Pacific Ocean, with data analysis now in progress. In all three experiments, validation datasets were withheld from participants until submission of their rain estimates.

The goal of the current project (AIP-2) was to produce rain estimates from Meteosat visible and IR data and Special Sensor Microwave/Imager (SSM/I) data in the period from 1 February through 9 April 1991, in an area covering most of the United Kingdom (UK) and northwest Europe. Radar data from the operational network across Europe were compiled and analyzed by the UK Meteorological Office (UKMO). Much like the AIP-1, the objectives of AIP-2 included gaining a better understanding of existing rainfall retrieval algorithms, determining the relative strengths and weaknesses of each one, deciding how best to process ground-truth radar data, and selecting appropriate statistical methods for the intercomparison (Allam et al. 1993). Unlike the first such project, however, this one has been carried out in a winter regime.

In this paper, we report on the results of two MW techniques, the Goddard scattering algorithm (GSCAT) and the physical retrieval algorithm of Kummerow and Giglio (1994, henceforth KU). Results from the estimation of instantaneous rain rate for five SSM/I overpasses are presented in a case study mode to illustrate both the strong and weak points of each technique. These five cases represent a sampling of the various types of precipitating systems observed. Results for the complete set of 20 swaths chosen (a priori) by the UKMO are then categorized by 1) scatterplots and statistics of instantaneous radar versus microwave-estimated rain rate, 2) rain/no-rain contingency tables, and 3) scatterplots of areal coverage of rainfall.

2. Data and algorithm descriptions

The MW data used in this study come from the SSM/I instrument onboard the Defense Meteorological Satellite Program (DMSP) F10 polar-orbiting satellite (Hollinger et al. 1987). The resolution of the 86–(37) GHz channel is 12.5 (25) km. The F10 satellite was erroneously launched into a slightly elliptical orbit, causing it to slowly precess through the diurnal cycle. During the period of the AIP-2 (1 February–9 April 1991) it made overpasses at approximately 0800 and 1900 LT. Monthly estimates were not possible because only about 50% of the data were collected or archived. Twenty individual swaths (approximately 1400 km across) between 40° and 57.5°N and 15°W to 15°E were chosen (prior to the dissemination of the radar ground truth) by the UKMO. For this analysis, the rain estimates were mapped to a grid of resolution 0.15°, slightly larger than the 15 km × 13 km resolution of the 86 GHz.

The radar validation data were composited from two sources, the UKMO’s FRONTIERS (forecasting rain optimized using new techniques of interactively enhanced radar and satellite) system and the European national radar system (COST-73 (Cooperation in Science and Technology)). The UK radar data were recorded every 15 min, while the COST-73 data were recorded hourly. Hence, the composite image was within 7.5 min (30 min) of the SSM/I overpass in the UK (rest of Europe). The resolution of the radar data was 5 km, and only low-level (0.5°–1.5°) scans were used, out to an effective radius of 120 km. Better quality control, calibration, and adjustment to rain gauges were available with the UK data. Further details may be found in Allam et al. (1993). Subsequent analysis revealed that further quality control was necessary. For each of the 20 cases, every pixel within the radar array was flagged as either raining or nonraining, and a cumulative count was maintained. The resulting map of the radar frequency of rain (Fig. 1) revealed several locations with anomalously high frequencies. These included locations near the edge of the radar data in southern France, in the Swiss and French Alps, and in northern France (50°N, 2°E). Based on cursory examination of Fig. 1, we eliminated from the statistics any radar pixel whose aggregate frequency exceeded 45%. Many of the eliminated pixels were located within mountainous terrain where the radars had difficulty accurately depicting precipitation or in the clutter region of the COST-73 radars.

a. Goddard scattering algorithm

The Goddard scattering algorithm is an extension of the MW technique first described in Adler et al. (1994). The algorithm, which works over both land and water, uses a selection of the SSM/I frequencies to first eliminate nonraining areas. It then uses the 86-GHz (horizontal polarization) brightness temperatures to define rain intensity in proportion to the amount of scattering by ice and graupel aloft. The technique is physically and most directly related to in-cloud rain processes when the ice mechanisms are prevalent; that is, the technique cannot detect rain from clouds below the freezing level. Recent modifications to the GSCAT (Adler et al. 1994) include better quality control, ad-
ditional checks based on Grody (1991) to screen out desert and cold surface conditions, and the selection of checks based on the nature of the underlying surface. As Adler et al. (1994) describe, occasional, regionally coherent misclassifications by the Grody (1991) cold surface check led the authors to develop the additional category of "ambiguous" precipitation in which the pixels are assigned a rain rate but are marked as being uncertain. (The ambiguous category corresponds to combinations of channels for which precipitating and cold surface verification can be found.) The authors do not currently have a satisfactory scheme for detecting artifacts from the instantaneous SSM/I data alone, so in this study all of the ambiguous pixels were treated as rain. We will see that, indeed, both precipitation and cold surface are found for ambiguous pixels. We continue to follow Grody (1991) in assigning zero rain rates to cold surface areas, even though it is likely we miss almost all light and moderate snowfall. On longer timescales, say monthly, Adler et al. (1994) found that artifacts were well controlled by the elimination of grid boxes whose aggregate monthly coverage of ambiguous and cold surface pixels exceeded 20% of the total accumulated pixels.

The 86-GHz brightness temperature $T_b$-rain rate relations are based on calculations from a combined cloud–radiative transfer model (Adler et al. 1991). When the 1-km resolution model output was averaged to the resolution of the SSM/I, the following relation for rain rate (RR, in millimeters per hour) resulted:

$$RR = \frac{251.0 - T_b}{4.19}$$

Choosing a rain/no-rain boundary at 1 mm h$^{-1}$ yielded a threshold $T_b$ of 247 K. Based on an analysis of atoll rain gauge data from the western Pacific, Adler et al. (1994) revised the equation for over-ocean rainfall to

$$RR = \frac{251.0 - T_b}{2.09},$$

which effectively doubled the derived rain rates over oceanic regions. Linear interpolation was used between the ocean and land rain-rate coefficients to effect a
smooth transition in rain rate across coasts. Instantaneous rain estimates were made for each overpass of the SSM/I. Limited comparisons with other microwave algorithms, such as in the first Wetnet precipitation intercomparison project (PIP-1, Barrett et al. 1994), show that the GSCAT is competitive with the current state of the art for statistically based passive algorithms applicable over both land and water. The overall procedure for identifying raining pixels is not all that dissimilar to the scattering index of Grody (1991). In fact, in an intercomparison of seven microwave techniques over Japan, Lee et al. (1991) showed that the GSCAT had the highest correlation with the Grody scheme during the convective regime in July–August 1989.

b. Physical retrieval algorithm

The KU algorithm developed by Kummerow et al. (1989) and Kummerow and Giglio (1994) is a profile or deterministic algorithm. The algorithm makes use of inversion techniques based upon theoretically calculated relations between rainfall rates and brightness temperatures. Potential errors introduced into the theoretical calculation by the unknown vertical distribution of hydrometeors are overcome by explicitly accounting for diverse hydrometeor profiles. This is accomplished by using a set of explicit structures derived from observations and cloud dynamical models. The algorithm currently uses 18 convective and 9 stratiform rain structures for every discrete freezing height. Freezing heights range from 2.0 to 4.5 km. For each structure, hydrometeor distributions are specified relative to the surface rainfall rate. The KU algorithm avoids the classical “footprint filling problem” by explicitly assuming nonuniform hydrometeor coverage across an individual satellite pixel. In order to account for the variability within each satellite pixel, the 86-GHz spatial variability is used as a proxy measurement for the true variability. rainfall is then assumed to be logarithmically distributed with a standard deviation that is consistent with the 86-GHz measurements.

Using the cloud structures and the distribution of rainfall rates within a given structure, it is possible to calculate upwelling radiances that a satellite would observe. Standard multichannel reflection techniques are then employed to retrieve parameters that most affect the upwelling radiances. These are the rainfall rate at the surface (which scales with the vertical hydrometeor profile of the associated cloud structure), the fraction of the footprint filled with the raining cloud, and a sea surface roughness as it is affected by the surface wind speed. The retrieved parameters can be reinserted into the cloud structure, and upwelling radiances corresponding to the retrieved parameters may be calculated. By comparing the observed and calculated brightness temperatures at all frequencies and polarizations, the cloud structure producing the smallest brightness temperature root-mean-square deviations is iteratively selected as the most appropriate answer.

The KU algorithm is not without weaknesses. There remain subtleties in the radiative transfer solutions that are not well understood, and the extent to which the cloud dynamical model (responsible for the initial guess fields) may be affecting the results is not fully understood at this time. Both these points may lead to biases. From a practical point of view, repeated radiative transfer calculations make this retrieval computationally expensive. The obvious strength of the KU algorithm, however, is that it fully accounts for all the brightness temperature observations. This has three effects that can be considered very attractive in a retrieval algorithm: 1) consistently poor correlations between calculated and observed radiances can point to problems with radiative transfer calculations or our understanding of cloud properties; 2) the retrieval provides vertical structure information for hydrometeors, which in turn leads to much-needed latent heating information; and 3) because it uses all available channel data, the retrieval is more likely to properly determine rainfall in an individual scene than algorithms using less information.

3. Case studies

Case studies were selected to illustrate the range of precipitating systems observed during the AIP-2 period. In each of Figs. 2–6 we display the GSCAT and KU instantaneous rain estimates, along with the radar ground truth. Data outside the radar coverage or SSM/I overpass are unshaded while nonraining areas are displayed using the lightest gray shade.

a. 16 February 1991 case

The case of 1908 UTC 16 February 1991 (Fig. 2) demonstrates some of the problems the MW techniques can encounter in trying to distinguish cold land surface from areas of precipitation. The techniques are unable to identify the bright (radar-detected) precipitation over central France. Conversely, cold surfaces are mistakenly identified as precipitation over Scotland, easternmost England, and much of northeastern France. The radar data show these areas to be precipitation free. Both techniques have checks that attempt to differentiate cold surface from precipitation (e.g., Grody 1991). Apparently, these regions exhibit combinations of channels that correspond to both precipitating and cold surface verification cases. In Fig. 2d, we show the NOAA (National Oceanic and Atmospheric Administration)/NESDIS (National Environmental Satellite Data and Information Service) analysis of snow cover valid 16 February 1991. It reveals that, indeed, eastern England and northeastern France had snow cover at the time of the SSM/I overpass. We also applied the multispectral algorithms of Harrison and Lucas (1989) and Gesell (1989) to the 1-km resolution
AVHRR (Advanced Very High Resolution Radiometer) data made available to us. This also confirmed that regions of ambiguity in the GSCAT algorithm did, indeed, have the spectral characteristics of snow cover in the AVHRR imagery. Specific application of the microwave algorithms of Grody (1991) and Neale et al. (1990) failed to be completely successful in discriminating snow cover from precipitation during this period.

Both microwave techniques do correctly identify the rain area off the northwest coast of France. Over the water, the GSCAT detects the convective features but overestimates their intensity. The KU algorithm, with a greater sensitivity to low rain rates (0.1 versus 1.0 mm h⁻¹ for the GSCAT), makes a better estimate of light rainfall over the water.

b. 21 February 1991 case

The case of 0837 UTC 21 February 1991 (Fig. 3) represents a fairly narrow but strong convective line over ocean. Both algorithms detect the line. The peak intensity (over the western end of the English Channel) is better captured by GSCAT using the high-resolution (86 GHz) channel. The KU algorithm, which relies more on the emission signal of the lower-resolution channels, spreads out the precipitation and underestimates the strong convection. The precipitation maximum south of Ireland appears as light precipitation in the radar data but is assigned rain rates as high as the strong convective line by each algorithm. The lighter rain assigned by KU agrees better with the radar, but distance from the radar makes these observations less reliable than those of the convective line. Neither algorithm captured the light rain extending east–west over the United Kingdom. More misidentification of cold surface as precipitation appears in both estimates along the eastern boundary of the SSM/I swath. As before, the GSCAT flags these misidentified pixels as ambiguous.
c. 12 March 1991 case

The case of 1852 UTC 12 March 1991 (Fig. 4) is an example of light rain (approximately 1 mm h\(^{-1}\)) over the ocean. In this situation, the KU algorithm does well in detecting both the area and magnitude of the rain. This system does not appear to have sufficient ice to allow GSCAT to properly determine the rain area. This is consistent with results from the KU, which indicates ice content was approximately 30% of liquid water content. The many small cells indicate that the precipitation is near the GSCAT rain/no-rain threshold of 247 K (at 86 GHz). Both the satellite and the radar have problems masking out ground clutter produced by the snow-covered Alps.

d. 20 March 1991 case

The case of 0831 UTC 20 March 1991 (Fig. 5) portrays a rain system across southern Ireland. In the heavier precipitation in the Irish Sea, the GSCAT is able to identify the rain area. It misses the lighter rain to the south. The KU does quite well in estimating both areas and magnitude. The rain over Ireland is identified only by GSCAT, with magnitude that is slightly less than the oceanic precipitation, despite contrary indications from the radar. The KU does not detect this precipitation at all. The small rain feature across the English Channel is better identified by KU, again, because GSCAT appears to have problems over ocean until rain reaches 1–2 mm h\(^{-1}\).

e. 21 March 1991 case

The final case (Fig. 6) contains a significant band of precipitation across northwestern France at 0800 UTC 21 March 1991. Both algorithms capture the intensity of the southern portion of the line quite well. The general intensity of the line determined by GSCAT is higher than observations. It is possible that the decrease in the radar precipitation is due to the increasing elevation of the radar beam. Much of the light (\(\leq 1.0\) mm h\(^{-1}\)) rain rate goes undetected by both algorithms.
The highly irregular coastline of the Netherlands presents occasional problems in the KU algorithm, and the snow-covered Alps are, again, misidentified as rain in both estimates (again, with tagging as ambiguous by GSCAT).

4. Results for all cases

a. Scatterplots and statistics

Statistics were accumulated for all grid points for each of the 20 swaths by averaging the 5-km radar data to the 0.15° resolution of the MW estimates. Statistics included the correlation coefficient (CORR), root-mean-square difference (rmse), mean-estimated minus mean-observed precipitation (bias), mean radar rain rate (RDR), and number of points (TOT). These are displayed in Table 1. Note that all statistics include many points of no-rain estimated, no-rain observed. Scatterplots are shown in Fig. 7 for the 0.15° resolution estimates. For land and ocean combined (Figs. 7a,c), the scatter is large, with CORR = 0.11 and 0.07 for the GSCAT and KU, respectively. There are numerous points along both axes. The rmse of the GSCAT is almost 10 times the mean radar rain rate, and the bias is 20% of the radar mean. Restricting the estimates to ocean only (Figs. 7b,d) improved the correlations to 0.31 (GSCAT) and 0.25 (KU), but the rmse still remained high relative to the mean for both techniques. The KU estimates tended to underestimate in specific instances. This was due primarily to the resolution of the KU (25 km), which fails to capture intense rain at small scales.

For comparison with results from the AIP-1 (Lee et al. 1991), in which rain estimates were evaluated at 1.25°, we spatially averaged the 0.15° estimates over 8 × 8 pixels to produce an estimate at 1.20°. Improvement was shown for the over-ocean estimates of both GSCAT (Fig. 8b) and KU (Fig. 8d), where the correlation increases to 0.46 for both the GSCAT and KU, and the rmse decreases by about 50% for both tech-
niques. Note the small number of samples (98). Correlations for the GSCAT and KU for the total dataset (land and water) are only marginally improved by spatial averaging; however, the rmse improves. Results are, in general, adversely affected by misidentification of cold surface as rainfall in the first three swaths during the coldest portion of the test period.

b. Rain/no-rain contingencies

In Table 2, we use the following standard definitions for rain/no-rain contingency analysis:

- **RR**—number of coincident SSM/I and radar rain points
- **NR**—number of coincident SSM/I no-rain and radar rain points
- **RN**—number of coincident SSM/I rain and radar no-rain points
- **NN**—number of coincident SSM/I and radar no-rain points
- **TOT**—**RR** + **RN** + **NR** + **NN** (total number of points)

We then define the following quantities to characterize the success of the algorithms:

- **probability of detection (POD)** = **RR**/(**RR** + **NR**)
- **false-alarm ratio (FAR)** = **RN**/(**RR** + **RN**)
- **critical success index (CSI)** = **RR**/(**RR** + **RN** + **NR**)
- **percent error (ERR)** = (**NR** + **RN**)/**TOT**

In Table 2, items **RR**, **NR**, **RN**, and **NN** have been normalized by the total number of points (**TOT**) and are, therefore, expressed as percentages. The GSCAT, with a minimum detectable rain rate of 1 mm h⁻¹, has a low POD (0.07) when attempting to estimate all the radar-detected rainfall. The POD increases to 0.22 when the radar threshold is raised to 1 mm h⁻¹. At this higher threshold, percent error (ERR) is low, if only because almost 95% of the area is not raining at this threshold. The CSI, an overall measure of the suc-
cess of a technique, is low for both thresholds (0.07 and 0.10). No appreciable differences are found using the ocean-only dataset, which has approximately an order-of-magnitude fewer points. Better results are found for the KU for both radar thresholds over the water. The POD increases to 0.71 for the 1.0 mm h\(^{-1}\) threshold, but unfortunately the FAR increases also, resulting in low success (0.05). This increase in the number of false alarms is also reflected in the higher percent error of the KU.

![Image showing three maps of rain-rate estimates](image)

**Fig. 6.** Comparison of instantaneous rain-rate estimates made at 0800 UTC 21 March 1991. (a) GSCAT; (b) KU; (c) radar.

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>Land/ocean</th>
<th>Resolution (°)</th>
<th>CORR</th>
<th>rmsd (mm h(^{-1}))</th>
<th>Bias (mm h(^{-1}))</th>
<th>RDR (mm h(^{-1}))</th>
<th>TOT</th>
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<td>0.07</td>
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<td>0.48</td>
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<td>0.053</td>
<td>98</td>
</tr>
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</table>

* Original estimates made at 25-km resolution, remapped to 0.15°.
c. Areal coverage of rainfall

Figure 9 depicts scatterplots of the percentage of the total area of each of the 20 swaths, within the radar coverage area and the SSM/I field of view, identified as rain by either microwave technique and radar. The GSCAT–radar comparison uses a threshold of 1 mm h⁻¹, compared to 0.1 mm h⁻¹ for the KU–radar comparison. Scatterplots are shown for all of the data (Fig. 9a,c), as well as for the ocean-only data (Figs. 9b,d). (Note the difference in scale among the plots.) The statistics presented in this section do not reflect any information about how well the estimated rainfall areas line up with the radar rainfall areas. Instead, they give a general idea of how well the techniques perform at detecting the raining fraction of the total scene.

The correlation between the GSCAT and radar areal coverage values shown in Fig. 9a is −0.02, due largely to the influence of two outlying points where the GSCAT identifies rain over 10%–20% of the overall area, while radar indicates rain over only about 1% of the area. These two points represent the first two cases, 12 and 16 February 1991, in which large areas of snow-covered land (or cold surface) are erroneously flagged as rainfall by the GSCAT (see Fig. 2 for the 16 February case). Elimination of these two points yields a correlation of +0.79 for the remaining 18 cases. This further illustrates the high sensitivity of the technique to areas of snow-covered land. When the scene is free of extensive snow cover, the GSCAT does a fairly good job of identifying areas of precipitation.

Over ocean only, the GSCAT–radar correlation (Fig. 9b) for all 20 cases is 0.57. With snow cover no longer a potential problem, removal of the first two cases is unnecessary. However, for comparison purposes, the
correlation for the last 18 cases is 0.58. Similarly, for the KU estimates (Fig. 9d), the oceanic data have a correlation of 0.67 with the radar for all cases, versus 0.73 for the last 18 cases. In general then, the two retrieval techniques perform capably at delineating the overall proportion of the oceanic area of interest covered by precipitation, although there are still cases in which the techniques over- and underestimate the area as determined by radar.

The correlation between the KU-estimated and radar areal coverage in Fig. 9c, using a threshold of 0.1 mm h\(^{-1}\), is -0.03. When the first two cases, represented by the points with the highest KU-estimated percent coverage, are removed, the correlation improves to 0.31. A comparison of Figs. 9a and 9c reveal that in lowering the threshold from 1 to 0.1 mm h\(^{-1}\), the percentage of the radar field qualifying as precipitation increases from generally less than 5% to values approaching 25%. A similar tendency can be noted in the comparison of Figs. 9b and 9d for the oceanic subset of the data. Taking the dataset of 20 cases as a whole, 82% of all points identified by the radar as raining had rain rates below 1 mm h\(^{-1}\). For the ocean-only data, this value increases to 91%. Therefore, because the GSCAT has a minimum reliably detectable rain rate threshold of 1 mm h\(^{-1}\), it is inherently unlikely to detect much of the light rain falling in the United Kingdom and northwest Europe during the winter months. This is likely due to both the tuning of the GSCAT to tropical rainfall as well as to inherent deficiencies in the ability of the 86-GHz channel to detect light rain over land.
5. Conclusions

The AIP-2 was designed to compare the performances of various rainfall retrieval algorithms over western Europe. The results of two MW techniques, the GSCAT and the KU algorithms, have been presented. Neither algorithm produces a good statistical correlation with the radar data, yet in general, both do well at determining rainy areas. Two reasons are suggested for the low correlation coefficients between both algorithms and the radar data. Time differences between the SSM/I overpass and the radar observations can occasionally account for some of the differences. The primary reason for the low correlations, however, appears to be the predominance of very light rain in the area of interest during the winter. Both algorithms are in good spatial agreement with the radar when the radar data are restricted to rates above 1 mm h\(^{-1}\). When all radar rain rates are included, the radar areal coverage increases by as much as a factor of 10 in some cases. Because the KU algorithm does not handle such low rain rates over land very well and because the GSCAT uses 1 mm h\(^{-1}\) as the minimum reliably detectable rain rate, regimes that contain large areas of very light rain present inherent difficulties for these retrieval methods. Therefore, the proliferation of low rain rates observed during AIP-2 is the main contributor to low correlation coefficients and high root-mean-square differences. Differentiation of cold surface (e.g., snow cover) from precipitation is also a major problem in making instantaneous microwave rainfall
estimates in the cool season. Toward this end, a concerted effort needs to be made to find a scheme for resolving ambiguous pixels in the GSCAT. Work by the authors suggest that some form of scene processing or external information (such as temperature maps) is necessary to correctly categorize these pixels.

Acknowledgments. The research in this article is supported through the Office of Space Science and Applications, Mesoscale Atmospheric Processes Research Program of NASA Headquarters. We thank Drs. Ramesh Kakar and John Theon for their continued support. The authors wish to thank the staff of the UKMO, particularly Gary Holpin, Richard Allam, John Foote, and Giggi Liberti.

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