Regional Rainfall Climatologies Derived from Special Sensor Microwave Imager (SSM/I) Data

Andrew J. Negri,* Robert F. Adler,* Eric J. Nelkin,† and George J. Huffman‡

Abstract

Climatologies of convective precipitation were derived from passive microwave observations from the Special Sensor Microwave Imager using a scattering-based algorithm of Adler et al. Data were aggregated over periods of 3–5 months using data from 4 to 5 years. Data were also stratified by satellite overpass times (primarily 0600 and 1800 local time). Four regions [Mexico, Amazonia, western Africa, and the western equatorial Pacific Ocean (TOGA COARE area)] were chosen for their meteorological interest and relative paucity of conventional observations.

The strong diurnal variation over Mexico and the southern United States was the most striking aspect of the climatologies. Pronounced morning maxima occurred offshore, often in concavities in the coastline, the result of the increased convergence caused by the coastline shape. The major feature of the evening rain field was a linear-shaped maximum along the western slope of the Sierra Madre Occidental. Topography exerted a strong control on the rainfall in other areas, particularly near the Nicaragua/Honduras border and in Guatemala, where maxima in excess of 700 mm month−1 were located adjacent to local maxima in terrain. The correlation between the estimates and monthly gage data over the southern United States was low (0.45), due mainly to poor temporal sampling in any month and an inadequate sampling of the diurnal cycle.

Over the Amazon Basin the differences in morning versus evening rainfall were complex, with an alternating series of morning/evening maxima aligned southwest to northeast from the Andes to the northeast Brazilian coast. Areal extent of rainfall in Amazonia was slightly higher in the evening, but a maximum in morning precipitation was found on the Amazon River just east of Manaus. Precipitation over the water in the ITCZ north of Brazil was more pronounced in the morning, and a pronounced land-/sea-breeze circulation was found along the northeast coast of Brazil. Inter-comparison of four years revealed 1992 to be the driest over Amazonia, with about a 23% decrease in mean rain rate compared to the 4-year mean estimated rain rate.

The major rain feature of tropical western Africa was found on the west coast—a pronounced overland evening maximum directly between the coast and a high mountain peak, and a morning maximum directly offshore. An intense, localized morning maximum of over 1000 mm month−1 was found at a concavity in the coast at the Bight of Bonny. In the region of the TOGA COARE experiment, precipitation in the ITCZ was greater in November 1989—February 1990, compared to the same period in 1988–1989, notably in the region five degrees either side of the equator from 160°E to the dateline. There was a clear preference in both seasons for morning precipitation over the water. Interesting diurnal effects were found over and offshore of New Guinea and the Solomon Islands. For the eight months studied, averaging both the gauges and Goddard Scattering Algorithm estimates to 2.5° grid boxes yielded a correlation of 0.73, bias of -59.5 mm, and a root-mean-square difference of 131.8 mm—29% and 64%, respectively, of the mean monthly observed rainfall.

1. Introduction

In this study we present climatologies of convective precipitation derived from passive microwave observations from the Special Sensor Microwave Imager (SSM/I). Four regions (see Table 1) are chosen for their meteorological interest and relative paucity of conventional rainfall observations. This work expands the scope of Negri et al. (1993), who presented microwave-estimated precipitation for the southwest United States and northern Mexico during June—August 1988–1990.

Given the assumptions that (a) four to five years compose a representative sample and (b) the microwave technique effectively estimates convective rain, the climatologies reveal important and interesting features of the seasonal rainfall. The specific objectives we wish to accomplish are the following:

- a description of high spatial resolution (0.15°) regional (45° by 30°) climatologies for convective rainfall;
- a documentation of the distinct differences in morning (henceforth AM) versus evening (henceforth PM) rainfall estimates;
- a discussion of the effect of topography and geography (i.e., coastline shape) on the rainfall fields;
- an examination of estimates possible from two satellites (i.e., four observations per day, possible during 1992 only);
- an examination of the interannual variability of precipitation over the Amazon Basin.

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In section 2 we present a brief description of the SSM/I data and of the microwave algorithm used to derive precipitation. Section 3 presents the regional rainfall climatologies. Results are summarized in section 4.

2. Microwave data and algorithm description

The microwave data used in this study come from the SSM/I instrument on board the Defense Meteorological Satellite Program F8, F10, and F11 polar-orbiting satellites. The resolution of the 86- (37) GHz channel is 12.5 (25) km. The F8 (F11) satellites are in sun-synchronous, circular, and nearly polar orbits, with ascending (descending) nodes at approximately 0630 local time (LT). (The F11 satellite replaced the F8 in operational usefulness after the failure of both F8 86-GHz channels in early 1991.) The F10 satellite was launched (erroneously) into a slightly elliptical orbit, causing it to slowly precess through the diurnal cycle. During the summer of 1992 it made overpasses at approximately 0930 and 2130 LT. With a swath width of 1400 km, global coverage from one satellite is incomplete in 24 h. Monthly sampling is about 40 times per month at 30°N or S. A full description of the SSM/I may be found in Hollinger et al. (1987). For displays of multifrequency false-color SSM/I imagery see Negri et al. (1989).

The microwave algorithm is called the Goddard Scattering Algorithm (GSCAT) and is an extension of the technique first described in Adler et al. (1993). The algorithm, which works over both land and water, uses the 86-GHz and 37-GHz (horizontal polarization) channels to eliminate nonraining areas. It uses the 86-GHz (horizontal polarization) brightness temperatures ($T_b$) to define rain intensity in proportion to the amount of scattering by ice and graupel aloft. The microwave 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 and use of the lower-frequency channels to differentiate cold surface and desert from precipitation. This differentiation, necessary when estimates are made globally, is not relevant to this study of warm-season (and overocean) precipitation.

The relationship between 86-GHz brightness temperature and rain rate (RR) is 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 (mm) resulted:

$$RR = \frac{251 - T_b}{4.19}.$$  

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 raingauge data from the western Pacific, Adler et al. (1994) revised the equation for overocean rainfall to

$$RR = \frac{251 - T_b}{2.09},$$

which effectively doubled the derived rain rates over oceanic regions. This relation was applied only to the overocean estimates in the western Pacific region (case 4 in Table 1) due to questions about its general applicability. To effect a smooth transition in rain rate between the ocean and the land, linear interpolation was used.

Instantaneous rain estimates were made for each overpass of the SSM/I over a region and accumulated in 0.15° bins (slightly larger than the 15-km by 13-km resolution of the 86-GHz channel). Rain estimates were accumulated separately for the ascend-

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<th>Table 1. Regions of interest described in this study.</th>
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<td>Geographic area</td>
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<td>Mexico and southern United States</td>
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Fig. 1. Mean rain rate (mm month$^{-1}$) over Mexico and the southern United States derived from the GSCAT microwave algorithm for the 15 months July–September 1987–1990 and 1992. (a) AM (0630 LT) overpasses; (b) PM (1830 LT) overpasses.
ing and descending nodes and then combined for monthly totals.

3. Regional rainfall climatologies

a. Mexico and the southern United States

This section complements and extends the work of Negri et al. (1993), who examined the microwave-estimated rainfall over the northern Mexico region during June–August 1988–1990. In Fig. 1 we present the aggregation of five warm seasons (July–September (JAS) 1987–1990, 1992) of satellite-derived precipitation, stratified into AM (top) and PM (bottom) orbits. The strong diurnal variation in Mexico and Central America is the most striking aspect of the figure; the rainfall fields are virtual mirror images of each other. Pronounced AM maxima occur offshore, the exception being the AM maxima in eastern Kansas and Oklahoma, a feature noted by Wallace (1975). Furthermore, these offshore maxima occur in concavities in the coastline, the result of the increased convergence caused by the coastline shape. Examples of this phenomenon are apparent off the west coast of Mexico from Mazatlan to Puerto Vallarta (20°–25°N along 106°W), in the Bay of Campeche (20°N, 95°W), the Gulf of Honduras (16°N, 88°W), and along the east coast of Central America (12°N, 83°W). A brief theoretical discussion of this phenomenon is provided in the following section. Other AM maxima of note are found in the Gulf of Mexico offshore from Texas to Florida (with a local maximum offshore of Alabama) and offshore of the Carolinas. In a study of tropical convective cloudiness derived from geosynchronous infrared data, Meisner and Arkin (1987) found maxima occurring in June–August convection in late morning over the Gulf of Mexico and Atlantic Ocean off the southeast coast of the United States. Rainfall in the intertropical convergence zone (ITCZ) south of 15°N also demonstrates a slight AM maximum (in areal extent). This feature can become difficult to differentiate from the (land-breeze induced) AM maximum off the west coast of Mexico and Central America.

The major feature of the PM (1830 LT) rain field is the linear-shaped maxima along the western slopes of the Sierra Madre Occidental (SMO). Indeed, the highest PM rain rates of any location in North America...
(save Cuba) are found in this region. Rain rates in excess of 800 mm month\(^{-1}\) are found within this maximum, with an absolute maximum of 1268 near 25°N, 107°W. Other regions of prominent maxima (and their values, mm month\(^{-1}\)) include Cuba (1382), the Florida Peninsula (604), the Front Range of Colorado and New Mexico (413), the Yucatan Peninsula (1083), and the region along the west coast of Central America (1512). Even such regional features as the elevated Mogollon Rim in Arizona (34°N, 112°–114°W) reveal localized maxima (on their slopes). Extremely arid regions include the Gulf of Mexico, eastern Mexico, eastern Texas, and much of the southwestern desert. One should keep in mind that the SSM/I observes close to the time of maximum precipitation (over land), so that estimates produced from these (less than once daily) observations will be severely undersampled and will tend to overestimate the monthly precipitation.

It should be noted that several artifacts of the GSCAT technique appear as precipitation maxima. These are small, inland bodies of water whose cold 86-GHz temperatures are mistakenly identified as precipitation. These generally appear in the AM images and include Mono and Walker Lakes in the United States (near 38°N, 119°W) and Lake Chapala in Mexico (21°N, 103°W). Mixed fields of view along the Baja California coastline can also be misidentified as precipitation.

The effect of topography on rainfall can be gleaned by comparison of the cover figure, the rainfall total from the combined AM and PM overpasses, and Fig. 2, the topography. Note that the rainfall scale in the cover figure is exactly half the scale of Fig. 1, since very few areas have high values of both AM and PM rainfall. Maxima on the order of 400–600 mm month\(^{-1}\) appear along the western SMO, the western coast of Yucatan, central Cuba, and the west coast of Central America. Two intense local maxima are found near the Nicaragua/Honduras border (13°N, 87°W) and in Guatemala (14°N, 92°W), with values of 786 and 730 mm month\(^{-1}\), respectively. Both are located on the coast and have local maxima in terrain within several kilometers. An intense local maximum at Puerto Vallarta, Mexico (20°N, 105°W), may be the result of increased sea-breeze convergence on this small peninsula. (See discussion in the next section.) The western Mexico (SMO) maximum occurs not along the height maxima but rather along the height gradient from 500 to 1500 m. Douglas et al. (1993) discuss in detail the phenomenon of the Mexican monsoon.

The question arises as to how accurate the microwave estimates are. Negri et al. (1993) looked at the observed precipitation for July 1990 over western Mexico and found that the GSCAT had a bias of +41 mm (about 10% of the mean monthly rainfall). In Fig. 3 we compare the GSCAT combined A.M./P.M. estimates with the observed rainfall at first-order U.S. stations south of 40°N by averaging both the estimates and gages to 2.5° grid boxes. Thirteen of the 15 months in our sample had sufficient SSM/I sampling (30–40 observations month\(^{-1}\)) for this purpose; excluded were July 1987 and August 1990. Only grid boxes with two or more observations were included, for a total sample size of 370 boxes. The correlation with the monthly gauge values was low (0.45). The bias was –21.9 mm and the root-mean-square difference (RMSD) was 70.4 mm—respectively, 24% and 77% of the observed monthly mean rainfall of 91.1 mm. Some reasons for this poor correlation are the following:

- any particular location is sampled infrequently (30–40 times month\(^{-1}\)) by the SSM/I;
- the SSM/I overpass is around 06 00/18 00 LT. Many stations in the southeast United States have late evening maxima;
- the GSCAT identifies rainfall associated with convective processes only (warm rain events would be missed);

![Fig. 3. GSCAT monthly estimates for the 13 months July–September 1987–1990, 1992 (except July 1987 and August 1990) vs observed monthly rainfall for first-order U.S. stations south of 40°N. Both the estimates and the gauge values have been averaged to 2.5° boxes, and only those boxes with two or more gauges have been plotted.](image-url)
FIG. 4. Mean rain rate (mm month$^{-1}$) over Mexico and the southern United States derived from the GSCAT microwave algorithm for July–September 1992. (a) DMSP-F11 overpasses near 0630 GMT. (b) DMSP-F10 overpasses near 0930 GMT. (c) DMSP-F11 overpasses near 1830 GMT. (d) DMSP-F10 overpasses near 2130 GMT.

- the use of point gauges to represent areal rainfall (many of the 2.5° boxes contain only two-gauge observations);
- due to the highly skewed nature of rainfall distributions, a monthly average of spatial bins would be expected to have high RMSD.

To summarize, while the patterns expressed by the rainfall estimates have qualitative value, it is important to remember that averaging 6 A.M. and 6 P.M. estimates (even perfect ones) on 15–20 days during the month does not yield a representative daily average.

During 1992 (only) it was possible to make up to four (albeit unevenly spaced) estimates per day from SSM/I's orbiting on two different spacecraft. Figure 5 shows these estimates at 0700 LT (a), 1000 LT (b), 1900 LT (c), and 2200 LT (d). At 2200 LT, convection has diminished with respect to 1900 LT over Cuba, the northern tip of the SMO maximum, Florida, and the Yucatan. Intensification has occurred in extreme southern Mexico (18°N, 94°W), possibly in response to the outflow from the diminishing Yucatan maximum at 1900 LT. The areal extent of the maximum near the border of Nicaragua and Honduras (13°N, 88°W) has increased. The nocturnal High Plains maxima intensifies and moves eastward. At 1000 LT (Fig. 4b), precipitation off the Mexican west coast moves slightly farther offshore (with respect to 0700 LT), and an intense, localized maximum appears on the east coast of Nicaragua (14°N, 84°W). The areal extent of precipitation increases in the Gulf of Mexico, and a well-defined maxima appears to surround the southern tip of the Florida Peninsula. The maximum off Mazatlan (23°N, 107°W) remains well defined. As the 0700 LT maximum off the west Mexico coast weakens by 1000 LT, the true nature of ITCZ precipitation is revealed and is shown to be greater in areal extent than at 1000 LT. To ascertain if the additional observations from the second satellite improve the estimation of monthly
Fig. 5. Mean rain rate (mm month$^{-1}$) over Amazonia and northeast Brazil derived from the GSCAT microwave algorithm for the 20 months January–May 1989–1990 and 1992. (a) AM (0630 LT) overpasses; (b) PM (1830 LT) overpasses.
rainfall, we again averaged the monthly gauge observations and GSCAT estimates (for July–September 1992) to 2.5° grid boxes. Results showed a slight improvement in the correlation from 0.42 to 0.46, an improvement in the RMSD from 71.96 mm to 67.77 mm, and a slight degradation in the bias from −14.1 mm to −16.4 mm as the frequency of satellite estimates is increased.

b. Discussion of concave coastline effects

Many investigators have examined the effects of coastline shape and orientation on the sea-breeze convergence. Arritt (1989) used a nonlinear model to investigate the effect of the radius of coastline and found the sea-breeze front to depend on the geometry of the coastline. For a 1500 LT simulation, subsidence was enhanced for a concave coastline and reduced for a convex one. (Presumably the reverse would be true for the land-breeze-induced morning rainfall maxima observed in this study.) Arritt also found that when the radius of curvature is less than the offshore distance of influence, sea breezes from different parts could interact, distorting the response to the coastal geometry. He further noted that for a given radius of curvature, the offshore effects were a function of latitude. McPherson (1970) used a three-dimensional numerical model to examine the effect of irregular coastlines (bays) on the sea breeze. He found that the asymmetry of the sea breeze with respect to the model bay was due to the Coriolis acceleration acting in concert on one side of the bay and in opposition on the other. This resulted in a relative enhancement of the convergence and vertical motion on one side of the bay. Abbs (1986) observed and modeled the bay and ocean breezes of Port Phillip Bay in Australia. Her results suggest that a vortex was formed by the convergence of the low-level flow, which was itself the result of differential heating. She also found the convergence to be enhanced by the surrounding orography. Meisner and Arkin (1987) examined in detail the diurnal variance over the Gulf of Panama (surrounded on three sides by land). They found a maximum in convective cloudiness over land at 0400–0700 LT, near the center of the area at 0800–1200 LT, and at the western border near 1200 LT, a variation they concluded was consistent with the diurnal movement of land-breeze convergence expected in that area.
c. Amazonia and northeast Brazil

In Fig. 5 we present a four-year (1988–1990, 1992) climatology of estimated warm season (January–May, JFMAM) rainfall over Brazil, stratified into AM (top) and PM (bottom) orbits. A pronounced land-/sea-breeze circulation is found along the northeast coast of Brazil. There is an AM maximum near the mouth of the Amazon River (0°, 50°W) and an elongated PM maximum between the northeast coast and the higher elevations along 2.5°S (see topography, Fig. 6). This elevation gradient is small in comparison to the gradient between the west coast of Mexico and the peak of the SMO (discussed earlier). Rainfall in the ITCZ over the water is more pronounced in the AM data, with a sharp northern boundary along 5°N. The Andes Mountains enter the sector in the lower left corner, where we find an AM maximum on the northeastern slopes.

To answer the question, “Is there a preference for AM or PM rainfall over Amazonia?” it is instructive to compute the difference between the evening and morning estimates. Figure 8 shows such a difference. Beginning in the lower left corner of the grid and extending to the northeast, we find an alternating pattern of PM maxima (yellow–orange–red) and AM maxima (green–blue–violet) across the region, terminating in the PM maxima at the northeast Brazilian coast and AM maxima offshore. This pattern is not aligned with any obvious topographic features and has an average spacing of about 500 km. If we approximate the location of Amazonia by 0°–15°S and 50°–70°W, we find that the mean PM rain rate is 131 mm month⁻¹, while the mean AM rain rate is 121 mm month⁻¹, implying a slight (8%) preference for PM rainfall. This was mainly due to rainfall estimates in 1990, when mean PM rain rate exceeded mean AM rain rate by about 20%. The data do reveal a strong preference for AM precipitation in north-central Amazonia (2.5°S, 57.5°W) coincident with a local minimum in elevation along the Amazon River valley.

There is an interesting AM/PM couplet near 3°N, 67.5°W in a region of strong elevation gradient (the west edge of the Sierra Pacaraima), with a PM maximum along the slopes and an AM maximum in the valley. A similar pairing is found near 11°S, 48°W.

Fig. 7. Evening (PM) minus morning (AM) rainfall difference (mm month⁻¹) over Amazonia and northeast Brazil for the 20 months January–May 1988–1990 and 1992.
along the mountain ridge of the Serra Gera de Golas. In summary, the diurnal character of Amazonia rainfall is complex, forced in some part by mountain/valley circulations, the distribution of land/sea, and possibly by the river itself.

The combined AM and PM estimates are presented in Fig. 8, with the color scale the same as in the cover figure for ease of comparison. A more uniform rain field is evident over northern Brazil than for Mexico/southern United States area. In general, estimated rainfall averages 100–200 mm month\(^{-1}\) over Amazonia. This is low in comparison to the climatology of both Legates (1987), who estimated the mean rain rate of the area (0°–15°S, 50°–70°W) to be 260 mm month\(^{-1}\) during January–May, and Arkin and Meisner (1987), who used satellite IR observations. Rainfall maxima are found inland along the northeast coast (403 mm month\(^{-1}\)), in central Amazonia (293 mm month\(^{-1}\)), along the western foothills of the Sierra Pacaraima (3°N, 68°W), on the Columbia/Venezuela border (308 mm month\(^{-1}\)), and along the northeast slope of the Andes (14°S, 70°W, 474 mm month\(^{-1}\)). Extremely arid regions include far northeastern Brazil and the northern tip of South America. An interesting minimum runs NNW/SSE through central Brazil, separating the effects of the land/sea circulation from the Amazon Basin rainfall. With a longer time series of satellite-estimated rainfall over Amazonia, it might be possible to assess the impact of deforestation on the rainfall. In a model-based study of deforestation, Nobre et al. (1991) found that when tropical forests were replaced by pasture in the model, precipitation was reduced by 25%, and there was a reduction in regional moisture convergence.

An attempt to describe the interannual variability of rainfall is shown in Fig. 9, where we display the seasonal rain (JFMAM) for Brazil for each of the four years 1988–1990 and 1992. We find 1992 to be the driest year over Amazonia. Again, if we use 0°–15°S and 50°–70°W as an approximation to the area of Amazonia, we note a general decrease in the mean rain rate (AM/PM combined) of 135, 144, 125, 97 mm month\(^{-1}\) in 1988, 1989, 1990, and 1992. Note also in 1992 the absence of the previously well-defined rain maximum along the north coast of northeast Brazil and the decrease in offshore precipitation in this

![Fig. 8. Same as Fig. 5 except combined AM and PM overpasses.](Image)
FIG. 9. Mean rain rate (mm month$^{-1}$) over Amazonia and northeast Brazil derived from the GSCAT microwave algorithm for the rainy season, January–May: (a) 1988, (b) 1989, (c) 1990, (d) 1992.

region. The drought-prone region of northeast Brazil was consistently dry throughout this 4-year period.

d. Tropical western Africa

In Fig. 10 we present a 5-year (1987–1990, 1992) climatology of estimated rainfall over equatorial western Africa during July–September, stratified into AM (top) and PM (bottom) orbits. The major diurnal feature of this region is found on the western coast—a pronounced overland PM maximum of 1053 mm month$^{-1}$ near 11$^\circ$N, 14$^\circ$W, directly between the coast and a high mountain peak known as Fouta Djallon (see topography, Fig. 11). Not unlike western Mexico, there is a strong (687 mm month$^{-1}$) elongated maximum off the coast in the AM. Inland over central Africa there is a clear (but not overwhelming) preference for PM rainfall. We find a localized AM maximum of 1238 mm month$^{-1}$ at a concavity in the coast at the Bight of Bonny (5$^\circ$N, 8$^\circ$E). Extending northeast from Bight of Bonny is the Adamawa mountain range, with a broad area of PM rainfall along its northern slope. The Bauchi Plateau in Nigeria (10$^\circ$N, 9$^\circ$E) also has an associated PM maximum. In the valley between these two regions one finds a maximum in AM rainfall (see Fig. 10a, near 8$^\circ$N, 8$^\circ$–14$^\circ$E). Two other noteworthy PM maxima are found in central Africa, both coincident with large gradients in elevation associated with the Marra Mountains (13$^\circ$N, 22$^\circ$E) and Chaine des Mongos (9$^\circ$N, 21$^\circ$E).

The combined AM and PM estimates are presented in Fig. 12, with the color scale the same as in Fig. 8 and the cover figure. There is a sharp boundary to the rain field along 15$^\circ$N and an equally distinct southern boundary along 5$^\circ$N until the continent begins to branch southward. A fairly uniform field of precipitation of 200–300 mm month$^{-1}$ is found in a band between 10$^\circ$ and 15$^\circ$N, with the absolute maximum of 547 mm month$^{-1}$ just inland on the west coast. The aforementioned Bight of Bonny maximum is also apparent. See Nicholson (1986) for an in-depth study of the spatial patterns of rainfall variability over the African continent.

Bulletin of the American Meteorological Society
Fig. 10. Mean rain rate (mm month⁻¹) over tropical western Africa derived from the GSCAT microwave algorithm for the 15 months July–September 1987-1990 and 1992. (a) AM (0630 LT) overpasses; (b) PM (1830 LT) overpasses.
e. Equatorial western Pacific

During November 1992 through February 1993 an experiment known as TOGA COARE (Tropical Ocean Global Atmosphere Coupled Ocean–Atmosphere Response Experiment) took place in the tropical Pacific Ocean northeast of Australia. TOGA COARE was designed to study the coupled ocean–atmosphere system to gain understanding of global climate change (Webster and Lukas 1992). As an example of the type of rainfall information available only from a satellite platform, seasonal (November–February, NDJF) rainfall was estimated by the GSCAT algorithm for two seasons. Figures 13 and 14 compare and contrast the 1988/89 and 1989/90 seasonal precipitation over this region. (Due to increasing noise in, and eventual failure of, the 86-GHz sensors on board the F8 satellite, and due to the archiving of only 40%–50% of the F10 data in 1991, these are the only two seasons, through 1992 for which complete data exist.)

Notable differences between the AM (top) and PM (bottom) estimates can be found in both seasons. There is a pronounced PM maxima over the island of New Guinea, with a nonraining zone extending approximately 200 km around the island. The reverse is true in the AM estimates, with intense rain maxima surrounding New Guinea. Localized maxima in AM precipitation are found in the three major concavities in the coast, two on the south coast and one on the northeast tip of New Guinea. There is a narrow minimum in both AM and PM rainfall running along the chain of the Solomon Islands 3°S, 150°E to 10°S, 163°E, despite their situation in the midst of an otherwise rainy ITCZ. An AM rain minimum can be found in the lee of New Britain (5°S, 152°E).

The most dramatic difference in the two seasons is the magnitude and extent of the precipitation in the ITCZ, with 1989/90 displaying much more precipitation, especially in the region five degrees either side of the equator from 160°E to 180°. There is a clear preference in both years for AM precipitation. For example, in NDJF 1988/89, in the oceanic region 10°N–10°S, 155°E–180°, away from the effects of major landmasses, 51% of the total area was covered by rain 50 mm month\(^{-1}\) in the AM data, compared to 33% of the area in the PM data. Corresponding numbers for NDJF 1989/90 are 87% (AM) and 78%.
(PM), showing both the tendency for AM rainfall and the tremendous increase in rainfall compared to NDJF 1988/89.

Verification of these tropical oceanic estimates was possible using a dataset of atoll and low-island rain-gauges believed to be representative of open ocean rainfall (Morrissey and Greene 1993). For the eight months studied, averaging both the gauges and GSCAT estimates to 2.5° grid boxes yielded a correlation of 0.73, bias of −59.5 mm, and an RMSD of 131.8 mm—respectively, 29% and 64% of the mean monthly observed rainfall. A scatterplot of the data is shown in Fig. 15. Only grid boxes with at least two gauges are plotted, for a total sample size of 61.

4. Conclusions

In this study we have presented climatologies of convective precipitation derived from passive microwave observations from the SSM/I. The technique uses the 86-GHz brightness temperatures to define rain intensity in proportion to the amount of scattering by ice and graupel aloft. Because monthly sampling at the full spatial resolution is poor (about 20 observations per month in the AM or PM), data were aggregated into multimonthly means over several years. Four regions were chosen for their meteorological interest and relative paucity of conventional rainfall observations.

Over Mexico and the southern United States the strong diurnal variation was the most striking aspect of the climatology; over northern Mexico the AM and PM rainfall fields were virtual mirror images of each other. Pronounced AM maxima occurred offshore, the exception being the AM maxima in eastern Kansas and Oklahoma. These offshore maxima were found to occur in concavities in the coastline, the result of the increased convergence caused by the coastline shape. This is well supported by previous observational and theoretical studies. The major feature of the PM rain field was the linear-shaped maximum along the western slopes of the Sierra Madre Occidental. The highest PM rain rates (in excess of 800 mm month$^{-1}$) of any location in North America (save Cuba) are found in this region. It was noted that this maximum occurred not along the height maxima but at the height gradient between 500 and 1500 m. Regional features such as
FIG. 13. Mean rain rate (mm month$^{-1}$) over the equatorial western Pacific (TOGA COARE region) derived from the GSCAT microwave algorithm for the period November 1988–February 1989. (a) AM (0630 LT) overpasses; (b) PM (1830 LT) overpasses.
Fig. 14. Same as Fig. 13 except for the period November 1989–February 1990.
FIG. 15. GSCAT monthly estimates for the 8 months November 1988–February 1989 and November 1989–February 1990 vs observed monthly rainfall for atolls and low island stations in the equatorial west Pacific. Both the estimates and the gauge values have been averaged to 2.5° boxes, and only those boxes with two or more gauges have been plotted.

The elevated Mogollon Rim in Arizona reveal localized maxima (on their slopes). Extremely arid regions included the Gulf of Mexico, eastern Mexico, eastern Texas, and much of the southwestern desert. Topography exerted a strong control on the rainfall, particularly near the Nicaragua/Honduras border and in Guatemala, where maxima of 786 and 730 mm month$^{-1}$ were located adjacent to local maxima in terrain. Correlations between 2.5°-averaged estimates and gauge values for monthly rainfall were poor (0.45), due mostly to undersampling by the SSM/I and incomplete sampling of the diurnal cycle. Additional information on the diurnal cycle was provided by the inclusion of data from a second satellite during 1992. A modest improvement in the RMSD and correlation of monthly estimates was found when this data (1000/2200 LT) was added to the 0700/1900 LT data.

Over Amazonia, estimated rainfall averaged 100–200 mm month$^{-1}$. A pronounced land-/sea-breeze circulation was found along the northeast coast of Brazil. Precipitation in the ITCZ was more pronounced in the AM data, with a sharp northern boundary along 5°N. Extremely arid regions included extreme northeastern Brazil and the northern tip of South America. The Amazon Basin had a complex diurnal signature that included an alternating pattern of AM and PM maxima running southwest to northeast from the Andes to the northeast Brazilian coast. A strong maximum in AM precipitation was found along a narrow portion of the Amazon River itself, just east of Manaus, Brazil. Mountain/valley circulations were evident in the estimated rain fields over the northeastern slopes of the Andes and the western slopes of the Sierra Pacaraima. Amazonia was shown to have its driest year in 1992 (of the four years studied).

The major feature of the region of tropical western Africa was found on the west coast—a pronounced overland PM maximum of 1053 mm month$^{-1}$ near 11°N, 14°W, directly between the coast and a high mountain peak. There was also a large (687 mm month$^{-1}$) elongated maximum off the coast in the AM. Inland over central Africa there was a clear (but not overwhelming) preference for PM rainfall. A localized AM maximum of 1238 mm month$^{-1}$ was found at a concavity in the coast at the Bight of Bonny (5°N, 8°E). Clearly defined northern and southern boundaries to the precipitation were apparent.

The region of the TOGA COARE experiment (the equatorial western Pacific) was an example of a region for which satellite estimates are virtually the only source of rainfall information. When the 1988/89 season was compared to the 1989/90 season (November–February), a dramatic difference was noted. The magnitude and extent of the precipitation in the ITCZ was greater in 1989/90, especially in the region five degrees either side of the equator from 160°E to the date line. There was a clear preference in both years for AM precipitation over the water. Diurnal effects were prominent around New Guinea, with a pronounced PM maximum over the island itself and a nonraining zone extending approximately 200 km around the island. The reverse was true in the AM estimates, with intense rain maxima surrounding New Guinea, particularly in concavities in the coastline. There was a narrow minimum in both AM and PM rainfall running along the chain of the Solomon Islands. Verification against atoll and low-island stations (believed representative of open-ocean rainfall) showed a correlation of 0.73 for 8 months of monthly rainfall, with a bias of −59.5 mm (29% of the mean) and an RMSD of 131.8 mm (64% of the mean).

There is potential use for the SSM/I data in climatic research due to its long (1987 and continuing) period of operation. Even for regional studies as described here, the data have the potential to identify and describe important meso- and smaller-scale features of the convective rainfall pattern, particularly in the effect of coastline and topography and on the differences in AM/P.M. rainfall. To diagnose the diurnal cycle effectively, either more microwave instruments in orbit are needed, or the infrared data must be effectively used to fill in the gaps left by the microwave sampling. Even simple threshold IR techniques like...
the GOES Precipitation Index (Arkin et al. 1994) can be improved by calibration by the microwave rain estimates (Adler et al. 1993; Adler et al. 1994; Negri et al. 1993). The Tropical Rainfall Measuring Mission (Simpson et al. 1988), with a complement of active and passive microwave instruments, as well as visible/IR channels will specifically rely on combined algorithms to estimate the global tropical precipitation.

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