NOTES AND CORRESPONDENCE

Rain Amounts Near and Over North Borneo during Winter MONEX

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ABSTRACT

Radar and rain gauge data are used to determine the precipitation pattern in the vicinity of the north coast of Borneo during Winter MONEX. The results show that separate maxima of rain occurred offshore and inland. Satellite data for other years suggest that this rainfall pattern typifies the winter monsoon in this area.

1. Introduction

One of the objectives of the Global Atmospheric Research Programme's Winter Monsoon Experiment (Winter MONEX) was to determine the rainfall amounts over the South China Sea just north of Borneo. The latent heat released in the heavy rains that occur in this region is an important source of heat for the wintertime planetary-scale circulation (Ramage, 1968). In mapping the rainfall in Winter MONEX, raingauges on three Soviet research vessels were crucial. These gauges effectively extended the Malaysian meteorological service rain gauge network to include the adjacent South China Sea. In addition to rain gauges, the WR-73 weather radar operated by the Massachusetts Institute of Technology (MIT) was used.

The MIT radar was located at Bintulu on the north coast of Borneo so that its area of coverage was partly over land and partly over the sea. Setting up the radar at this location presented a formidable logistical problem, and the final site was less than ideal. Nearby trees and buildings caused some blockage of the beam at most azimuths at the lowest elevation angles. Despite these difficulties, observations were taken successfully for 24 days during December 1978. Comparison of the MIT radar measurements made at Bintulu with data obtained with a quantitative airborne radar indicated that the accuracy of the observations was quite good; the airborne data agreed with the Bintulu observations to within 1–2 dB (Houze *et al.*, 1981a). The Bintulu data were subsequently used to study the diurnal cycle of precipitation over both land and water near the coast (Houze *et al.*, 1981b) and to infer the internal structure of a major precipitating cloud system located off the Borneo coast on 10 December 1978 (Churchill and Houze, 1984a,b).

These previous studies did not attempt to derive surface rainfall maps from the radar data. Such maps have been particularly difficult to derive from the radar data alone because of the blockage of the beam at low elevation angles. However, by devising a correction scheme we were able to improve the radar data enough that they could guide our interpolation between raingauge observations at land and ship stations and thus allow a reasonable estimate of the Winter MONEX rainfall pattern to be constructed. The purpose of this note is to report this pattern. Because of the limitations of the data, the pattern we have obtained is rather crude, but it is probably the best determination yet made of the rain pattern in this area during the winter monsoon.

2. Data

Rain gauge data were in the form of daily rainfall amounts provided by the Malaysian Meteorological Service for several locations in Borneo, and from the Soviet research vessels *Ak. Korolov, Priliv* and *Ak. Shirshov*, that were stationed in the South China Sea for Winter MONEX.

The radar data were obtained with the MIT WR-73 radar, which operates at a wavelength of 5.3 cm, has a 1.45° conical antenna beam and range resolution of 300 m. Minimum detectable signal is approximately −105 dbm, which corresponds to a reflectivity factor of 15 dBZ at 100 km range. Calibration and monitoring of the performance of the radar were carried out as described by Geotis (1975).

3. Correction scheme for the radar data

The Bintulu radar data were collected by running the antenna through a sequence of conical scans. In obtaining the surface rainfall pattern, data were considered in a volume 512 km in diameter, 3 km in depth and centered horizontally on the radar. This region was divided into 4 km × 4 km horizontal grid elements. The value of the average radar reflectivity factor (Z_e) was determined for each grid volume from the low elevation-angle data from that volume. The reflectivity value from each volume was then converted to rainfall rate, multiplied by the appropriate time interval between maps (typically 10 min) and integrated over the entire 24-day period of radar operation (8–31 December 1978).

The reflectivity-rain rate relationship used in these conversions was

$$Z_e = 180R^{1.35},$$

where Z_e is in $\mathrm{mm^6\ m^{-3}}$ and R is in $\mathrm{mm\ h^{-1}}$. This relation was derived by Austin and Geotis (1979) for the eastern equatorial Atlantic Ocean and is similar to others found in the tropics (e.g., Mueller and Sims, 1967).

The first attempt at obtaining a 24-day total rainfall pattern by applying the above method resulted in a pattern with an elongated maximum extending radially to the northwest and southeast, roughly parallel to the runway next to which the radar was installed. Blockage of the beam produced reduced signal at other azimuths. It was not until we had derived this integrated result that it became clear that a correction or adjustment procedure would be necessary if the effects of blocking were to be alleviated. It was not recognized in the field that this correction would be necessary because real maxima of precipitation did, in fact, exist to the northwest and southeast of Bintulu. The existence of these maxima was indicated by visual observations at Bintulu and by reports of Malaysian Airline pilots flying along the north coast of Borneo and is also suggested by satellite data (see Figs. 2 and 3 of Houze *et al.,* 1981b).

A scheme for correcting for the blockage was then devised.[1] In this scheme, data from high elevation angles, for which blockage of the beam was minimal, were compared with low-angle data. A new integrated rainfall pattern was generated using only the higher elevation angles for a representative number of days and an analogous map was obtained for the same days from the lower elevation angles used in the original 24-day total map. The higher elevation angle map was examined at ranges that were sufficiently close to the radar that signal degradation with range was not noticeable. Data obtained at these ranges were compared with data at the same ranges of the low elevation angle map. At some azimuths, the ratio of the high elevation to the low elevation data was almost exactly unity, indicating that at these azimuths there was little or no blockage. At other azimuths, the high elevation angle values exceeded those on the low elevation angle map. At these azimuths, we assumed that the ratio of the high to low elevation values constituted a correction factor for the low-level map. We then applied this azimuthal correction factor to the low-level data at all ranges. The resulting corrected 24-day integrated rainfall pattern derived from the radar data presented a more reasonable pattern. Areas at the longer ranges, where the signal was attenuated beyond detection, could not, of course, be brought back, and unfortunately the entire southwest quadrant was blocked.

4. Analysis of the rainfall pattern

Because of the extent of the adjustments to the low-elevation radar pattern that were necessary, we decided to use the radar data mainly to refine the rain map in areas not adequately covered by rain gauges. Radar measurements in the areas northwest and southeast of Bintulu were least affected by beam blocking and contributed significantly to the delineation of the rain pattern in those directions. Fortunately, the southwest quadrant, for which blocking was most severe, was well covered by rain gauges.

The resultant 24-day rain pattern, drawn subjectively to be consistent with both the station reports and the corrected radar precipitation data, is shown in Fig. 1. (The *Ak. Korolov* changed position in the middle of the experiment; the values plotted assume that the 10-day average rates at each position applied over 24 days). Except for the offshore maximum towards the shore and presence of the sea breeze induced maximum inland that were deduced from the radar measurements, the overall pattern was reasonably well defined by the rain gauge data.

To indicate how the radar data were used to refine the rainfall analysis, the corrected 24-day low-level radar rainfall contours are overlaid on the final rainfall contours in Fig. 2. The radar data are deleted near the radar site (to eliminate ground clutter) and in the entire southwestern region where blocking was most extreme. Note that only one raingauge station was located in the area of radar coverage. The final rainfall contours were positioned within the radar sector to be consistent with the radar data; however, because the ability of the radar to detect rain rate diminishes with range and was further affected in this case by the blocking at low elevation angles, the radar data must be interpreted subjectively. The rainfall contours in the final analysis were influenced by the radar data as follows:

i) The 700 mm contour was extended to near the coast because the corrected radar data indicate values

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[1] In the work of Churchill and Houze (1984a,b), the problem of beam blocking at low levels was largely circumvented by constructing three-dimensional reflectivity analyses and examining precipitation patterns at 3 km altitude. In obtaining the 24-day rain totals for WMONEX, it would have been too laborious to construct full three-dimensional analyses for the ≈3,500 scans included in the totals. The scheme described here is a short cut to allow us to examine the 24-day totals by using the low-elevation angle data and applying correction.

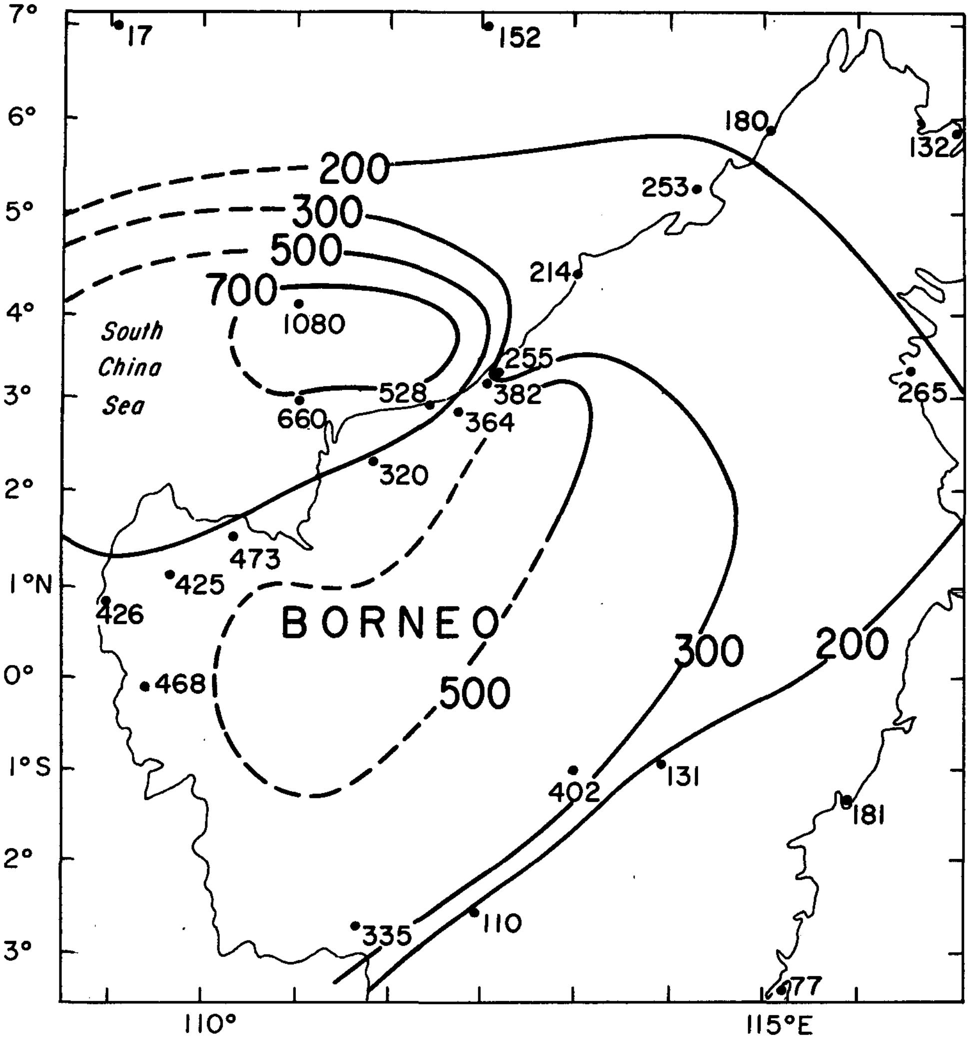

FIG. 1. Final analysis of precipitation pattern based on rain gauges and Bintulu radar data. Contours show 24-day total for rain (in millimeters) for 8–31 December 1978. Stations over the sea are Winter MONEX ships. The ship reports at 3 and 4°N are both from *Ak. Korolov*, which spent 10 days at each site. The 10-day totals are extrapolated to 24-day equivalents for this map. Dashed contour segments are based on satellite observations analyzed in Houze *et al.* (1981b).

this high close to the radar. The drop-off in radar rain intensity to the west and northwest was the result of range and blocking effects. The gauge data at the ships indicate that the 700 mm contour extended as far west as the ships. Since the maximum rain area was produced by mesoscale cloud systems systematically forming near the coast and moving west-northwestward (Houze *et al.*, 1981b), there is no reason to believe that the rain maximum did not extend continuously across the region as shown. Satellite data (Fig. 3a of Houze *et al.*, 1981b) suggest that the rain maximum terminated near 100°E.

ii) The offshore 500 mm contour was drawn close to the 700 mb contour because of the sharp dropoff in radar rain totals in the northern part of the radar area. Blocking of the radar beam was not extreme in this region. Also, the northern coastal and ship gauges as well as the satellite analysis of Houze *et al.* (1981b) indicate a sharp decrease to the north. Note further that the quantitative values of radar rain amount are probably most reliable within 100 km of the radar (inner range circle in Fig. 2), and that within 100 km northwest of the radar, rain values of 500 mm or more were consistently obtained.

iii) The 500 mm contour inland just southeast of the radar site was suggested by the 500 mm radar rain totals found there. The dashed extension of this 500 mm contour to the southwest is consistent with the surrounding rain gauges and the satellite analysis of Houze *et al.* (1981b).

iv) The 300 mm contour was drawn across the northern and eastern parts of the radar area near or

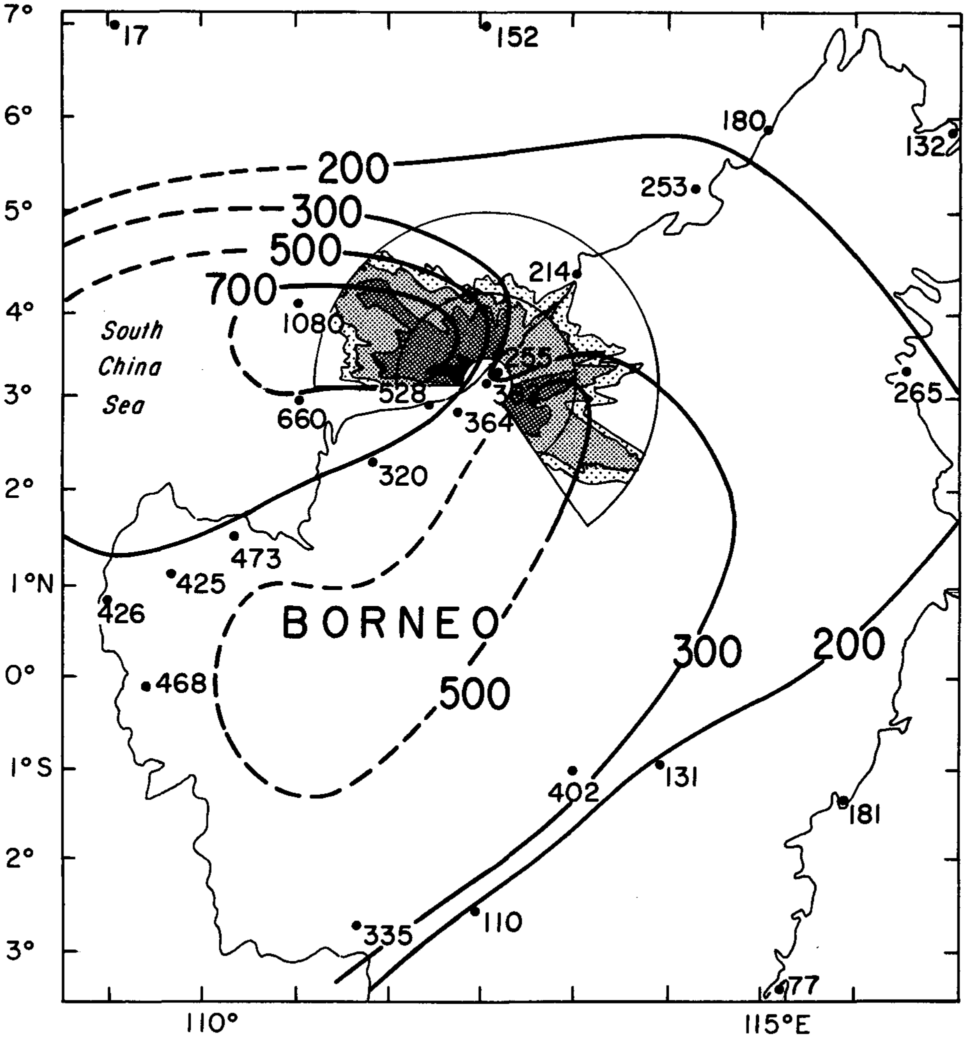

FIG. 2. As in Fig. 1 with rain rate contours derived from low-elevation radar data superposed. Shading thresholds are for 24-day amounts of 10, 100, 500 and 700 mm. Area of Bintulu radar observations is indicated by the circular region. Range marks are shown for 100 and 200 km. The sector to the southwest is omitted because of beam blockage.

just beyond the minimum detectable radar rain amount. This contour location is also consistent with the coastal rain gauge reports.

v) The positioning of the 200 mm contour was not influenced by the radar data.

4. Conclusions

The rainfall pattern in Fig. 1 is striking in several respects. While it has been known for some time that the winter monsoon rains in this area are a major source of energy for the atmosphere, this knowledge has been based primarily on data from land stations. The present analysis indicates that, at least in the case of north Borneo during Winter MONEX, heavy rainfall actually extended over the sea, out to a few hundred kilometers from the coast. That this rainfall is characteristic not just of the year of Winter MONEX, but of other years as well, is suggested by the three-year satellite climatology of Houze *et al.* (1981b).

The maximum of rainfall over the sea and the second maximum inland from the coast (seen in Fig. 1) can be understood in terms of the diurnal cycle of cloud and precipitation development peculiar to north Borneo and described by Houze *et al.* (1981b). The maximum of rainfall over the ocean comes from the cloud clusters that are initiated when convection forms along the coast, near Bintulu, around midnight. These clusters mature and have their maximum areal coverage in the early morning. Concentration of the nocturnally generated rainfall in the region of the offshore maximum is thought to result from the concave coastline and concave mountain range inland, which at night must tend to focus both the land–sea and mountain-drainage winds in the region just offshore from Bintulu (Neumann, 1951). The afternoon maximum of rain seen over land in our Fig. 1 is associated with the sea breeze induced convection that forms inland over Borneo around midday and reaches its maximum areal coverage in the late evening.

Although north Borneo may provide the most dramatic example, the control of precipitation patterns around all the coastlines of the islands and peninsulas of the maritime continent by diurnal land–sea circulations and other topographical peculiarities indicates that intricate precipitation patterns extend well offshore throughout the area. Much work remains to be done to determine these oceanic patterns. The qualitative agreement between the precipitation pattern that we have deduced from radar and raingauge data and the climatology of infrared satellite imagery derived by Houze *et al.* (1981b) suggest that a good approximation to the rainfall patterns in the vicinities of the other coastlines may be determined from infrared satellite data. Passive microwave sensing or radar observations from satellite platforms are further possibilities for future studies directed toward firmly establishing the detailed rainfall patterns in the maritime continent area and over other tropical oceanic regions.

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