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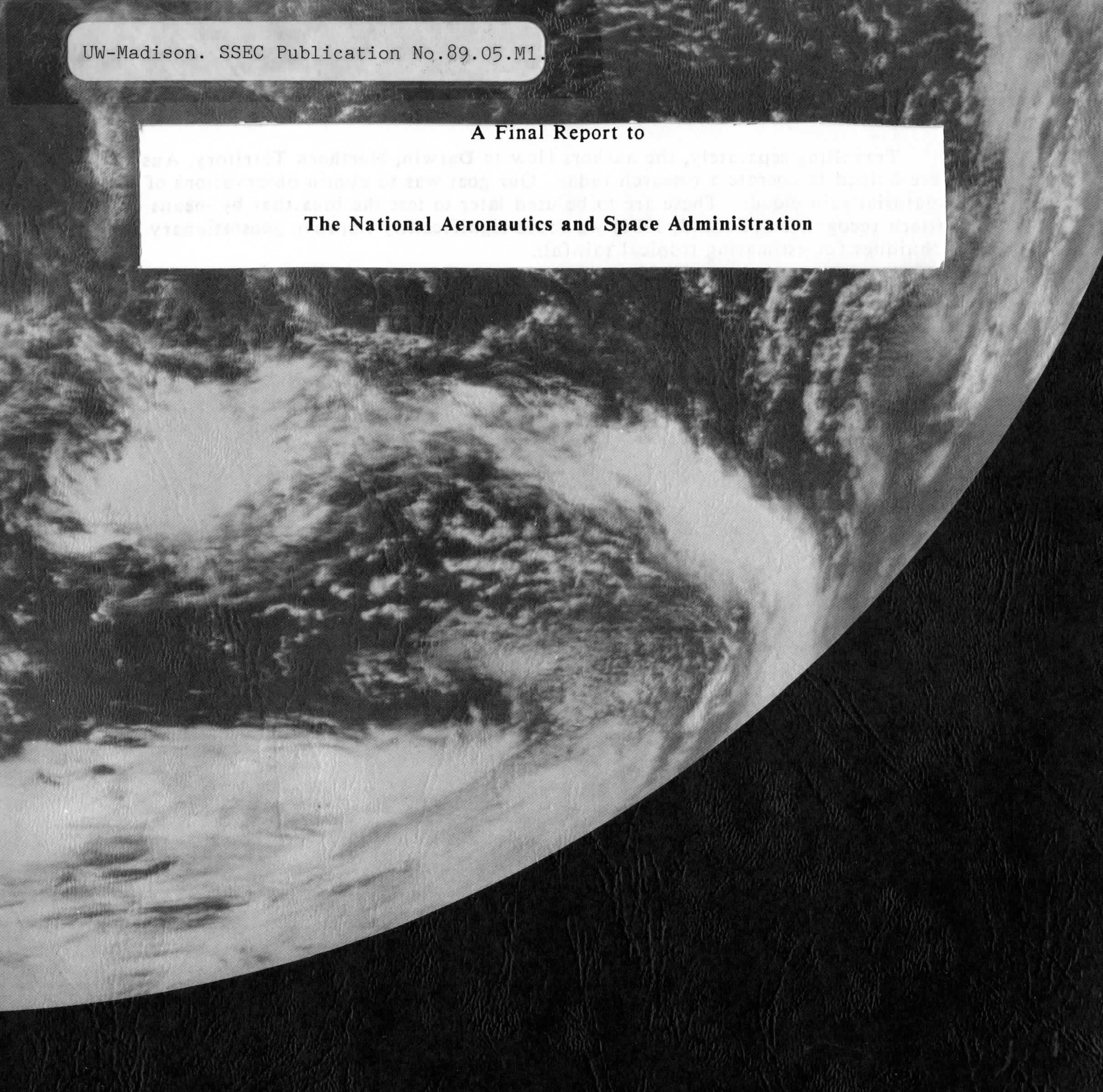
A Final Report to

The National Aeronautics and Space Administration



# A REPORT

from the space science and engineering center
the university of wisconsin-madison
madison, wisconsin

A Final Report to

**The National Aeronautics and Space Administration**

Grant NAG 5-1113

**Darwin Experiment: Collection of Radar Rainfall and Satellite Data**

For the Period of

15 December 1988 through 14 May 1989

Submitted by

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## I. INTRODUCTION

Travelling separately, the authors flew to Darwin, Northern Territory, Australia and there helped to operate a research radar. Our goal was to obtain observations of near-equatorial rain clouds. These are to be used later to test the idea that by means of pattern recognition (Garand, 1986) we could significantly improve geostationary satellite techniques for estimating tropical rainfall.

Each of us has reported elsewhere on our individual trips (Hinton, 1989; Martin, 1989). Drawing on these trip reports, here we report on our joint role in the 1988/89 TOGA/Darwin radar experiment and attempt to provide a more coherent summary of the rain data which we helped to collect.

## II. THE 1988-89 EXPERIMENT

At Darwin during the wet seasons of 1987/88 and 1988/89 NASA and the Commonwealth Bureau of Meteorology sponsored a NOAA radar, which has come to be known as the NOAA TOGA[1] radar.

### RADAR

Originally, this radar was acquired by NOAA and used in GATE. Recently, with NASA cooperation, it has been updated and used in TAMEX and AMEX/EMEX. Subsequently it has remained in Darwin and has most recently been used to investigate island thunderstorms for ITEX as well as to gather climatological data for TRMM.

In Darwin the radar is maintained by personnel from the Darwin office of the Bureau of Meteorology. Personnel of the Bureau's Research Centre in Melbourne attend the radar during designated Special Observing Periods in the transition and wet seasons and act as coordinators for visiting investigators.

The NOAA/TOGA radar is C-Band (5.3 cm). It has a 2.4 m antenna. Beamwidth is 1.65°; gain, 39 db. The radar measures both reflectivity and doppler velocity. It scans in azimuth at a peak rate of 3 RPM, in elevation at a peak rate of 15° $s^{-1}$. In normal operation the radar is controlled by a dedicated computer.

Physically, the radar consists of three main parts: the antenna (and tower) plus two ship cargo containers, or hutches. One hutch serves as an operations center, the second as a utility center. At the site, in addition to the hutches and tower, were a water tank, toilet and gasoline-powered generator. The generator provided power to the site in the event of a failure of the grid power. All facilities were enclosed within a chain link fence[2].

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[1]Acronyms are listed in Table 1.

[2]A more complete description of the radar can be found in the document, "The NOAA/TOGA Radar at Darwin: Operations Plan Summary," which is dated 10 October 1988 and can be obtained from Mr. Otto Thiele, Code 613, NASA/Goddard Space Flight Center. The radar also is described in a paper of Keenan et al. (1989a). Examples of PPI and RHI displays of reflectivity and doppler velocity appear in a second paper of Keenan et al. (1989b). For complete technical descriptions of the radar and its controlling software see the two manuals listed under Sigmet, Inc. in the References at the end of this report.

## Stations

To a user, the radar has several distinct "stations" which may require action or input.

*Radar Console*. Normally, this did not require attention, since the radar function is directed by computer software. However, it was necessary to power-up or -down from this console when switching from main to auxiliary power or vice versa. Also, if the computer should lose control of the radar, this console is used to restore it.

*Computer Panel*. Like the radar console, this only requires attention in case of a problem--usually a power-up -down sequence when changing power sources. The normal interface with the computer is via the operator's terminal.

*Tape Drive*. The tape drive receives a fair amount of use because of the frequent need to archive data when large areas of rain were about. Operation of this drive is similar to most others. Occasionally the read/write heads required cleaning.

*Operator's Terminals*. The main operator's terminal is used to interface with the computer and issue the commands necessary to control the radar function, archiving, and data displays. The line printer with this terminal prints verification information about files which have been archived.

The second terminal, called "watchdog," runs software and displays information on the function currently being performed by the radar and gives timing information about subsequent actions.

*Video Display Monitors*. There are two display monitors, one in each hutch, allowing the scientist on duty to monitor current radar returns while working in either area. Alternatively, by means of the main operator's terminal, he or she could display any radar returns then resident in the computer's disk storage, either singly or in movie loops of up to 20 frames.

## Siting

The radar is sited at 12.4572°S, 130.9253°E, 38 m MSL. This site is approximately 9.5 km, straight line distance, east of downtown Darwin, just off Berrimah Road. The radar sits atop a rounded bluff, which is somewhat rocky and covered with scrub trees 2-4 m tall (mostly pandanus palm) and grass up to 3 m tall. Outward from the site and further down the sides of the hill are larger trees such as paper barks (Fig. 1). There is a nearby ridge to the north, which (from ground level) appears to obstruct the horizon, but may not obstruct the beam from the tower mounted radar at the lowest elevation angle used (0.8°).

The city, especially due to its high rise structures, is probably responsible for some of the clutter usually evident out to 25 km. Rising terrain to the south (Fig. 2) coupled with cooling seems to cause terrain echoes or anomalous propagation at night for the lowest elevation angle. There is a thin "beaded" chain of echoes, in the form of a partial ellipse around the Port Darwin extension of Beagle Gulf to the south and east of Darwin. Power transmission towers, some of which could be seen visually on the horizon, may be contributing to these echoes. Others may be due to side lobe reflections from high-rise buildings in downtown Darwin.

## Large-Scale Geography and Climate

As required for TRMM, a significant fraction of the radar coverage area (Fig. 2) is over water. The Melville-Bathurst Island complex provides almost daily island thunderstorms (Keenan, *et al.*, 1989b). Many also are generated on the Cobourg Peninsula, at the fringe of the observation area.

The northern strip of the mainland sector is hot and humid at the beginning of the monsoon season, with local moisture supplies primed by transition season rainfall and the concentration of moisture by river flow northward and progressive inundation of the northern flood plains. Generally, coastal areas are covered with an open eucalypt forest. The interior vegetation is savannah.

To the south of Darwin, conditions were somewhat drier than the northern coastal flood plains, since the higher areas are better drained, and there is less sea breeze associated rainfall. Nevertheless, in contrast to the extreme aridity of the dry season and the interior still further inland, the region has a good moisture supply.

# AUXILIARY OBSERVATIONS

## Rainfall

Just outside the radar, within the security fence, was a tipping bucket raingauge of the same type used at the outlying calibration sites. This unit, like the others, was fitted with a digital data logger. Data were stored internally until spooled out to a portable microcomputer.

Beside the gauge, on a sound deadening pad was a disdrometer. The output of this instrument was cabled into a dedicated microcomputer in the utility hutch. The micro required a reboot and restart in the event of a power interruption.

## Other

Above ground was a simple crossed dipole pair used for detecting the azimuth to nearby lightning discharges. This was part of a network operated by Dr. Earle Williams. Mounted to the fence was a corona discharge antenna, also belonging to Williams.

There was a Woelfle recording anemometer 30-40 m south of the radar on a short ($\approx$2 m) mast. This instrument was equipped with a strip chart recorder. It was installed toward the end of SOP 2.

During both SOP's, on an on-call basis, the Bureau provided a handful of special radiosondes. These were meant to bracket passage of squall line convective rain bands. The sondes were launched and tracked from the Darwin airport.

Especially during SOP 3, from the Marrakai Apartments in downtown Darwin as well as from the radar site, we photographed rainclouds and storms. In most instances these photographs were documented sufficiently that they can be related to echoes observed by the radar.

## OPERATIONS

### Schedule

Special Observing Period 2 ran 21 days, beginning on the morning of 9 January, a Monday. SOP 3 also ran 21 days. It began on the morning of 6 February, a week after SOP 2 ended. Outside of an SOP the Bureau operated the radar in a background mode, 5 min base scans and 15 min volume scans of reflectivity only.

For each SOP there were three operators, two from the Bureau and either one of us. The five days Monday through Friday were divided into three rotating 8 h shifts shared equally. The weekends were divided into two 12 h shifts. Mr. Ken Glasson served during both SOP's as radar technician and observer. He was joined during SOP 2 by Hinton and Dr. Tom Keenan (and, briefly, by Dr. Jim McBride); during SOP 3 by Martin and Mr. Rod Potts.

### Duties

A considerable fraction of our time was spent simply looking at the current display on the monitors. Of course this was necessary to insure that the radar was functioning--and doing what it was supposed to be doing--even though malfunctions were rather rare. Similarly, messages requiring corrective action appeared a few times on the operator's terminals. Over a period of days, real-time display watching gave considerable insight into consistent patterns of development and motion of storms. This was, itself, scientifically satisfying and worthwhile.

At times, often in the "small hours" of early morning, when weather echoes were infrequent, there were opportunities to replay more interesting data from storage, or for reading the log book.

Periodically we went outside the hutches to make visual observations, some of which were entered in the log book. Particularly noted was rain at the radar site, lightning or thunder, and unusual winds. In addition, using either landmarks or a small compass fitted with a sighting device we were able to associate specific clouds and echoes or identify echoes with lightning producing clouds--often 100 km or more away.

Normally we operated in the TRMM "climatological mode," using the two operations patterns outlined in columns 1 and 2 of Table 2 (with the wait times in the climatology mode row of the table). In a somewhat unfortunate choice of terminology, the software calls a pattern, as one of the columns in this table, a "storm." Hence, in the table the two columns of special interest to TRMM rain estimation are labeled Storm 1 and Storm 2. Because running storms could not be archived, different storms had to be activated when an archive was required. Usually, these would be Storm 11 and Storm 12 which had all parameters the same as 1 and 2--except storm number itself.

However, when stratiform rainfall pervaded an area around the radar high quality VAD scans were possible, so a different set of storms was activated. This set preserved the TRMM requirement for rain estimation by interleaving PPI base scans at five minute intervals.

During stormy periods until the end of the first week of SOP 3 we coordinated schedules with the MIT radar at Koolpinyah Station (28 km ENE; Fig. 2) to produce dual doppler scans. This required running a still different storm set similar to the VAD, but with different timing to allow spaces in the schedule for the unique doppler zone scans (storms numbered in the twenties). In these cases, some of the storms had to be started by hand to avoid interrupting the base PPI scans. Further, communication with the Koolpinyah investigators was necessary to insure that both radars began taking doppler data nearly simultaneously.

Archiving data was usually a routine procedure, requiring special attention only to make sure tapes were labeled properly and tape logs printed on the line printer. However, when dual doppler data sets were being generated, archiving was required more frequently. At the same time the increased work load on the computer (writing data to the disk) slowed the archiving process. This in combination with hand starting scans and phone calls to Koolpinyah increased the work load, at times to the limit of what we could handle.

<u>Gauge Survey</u>

Jim McBride's presence for three days during SOP 2 provided time for visits to recording rain gauge sites. During these visits the gauge data were downloaded onto diskettes using a portable personal computer, and data samples and the equipment were examined for proper function. The flights to remote gauges, which were made in a light plane flying at about 1000 m, provided an opportunity to visually survey vegetation, moisture supply, and terrain over a large portion of the radar's coverage area.

**WEATHER**

Unusually heavy rainfall (the order of twice normal) was reported for the Darwin region in December. However, the beginning of SOP 2 on 9 January occurred after the onset of a protracted break period. Consequently, the weather patterns were similar to the "transition season." This has been described, for example, by Keenan *et al.* (1989a,b). In any case, because this pattern prevailed through February, conditions were not optimum for observing widespread monsoon rains--especially over the ocean sectors.

Figure 3 sketches significant rain from day to day. It is based on the radar log book, personal notes and (for SOP-3) PPI's archived by the RFC. During both SOP's rain fell mostly between noon and midnight. Toward the end of SOP 2 there was a spell of wet days; toward the end of SOP 3, a spell of dry days.

For SOP 3 we have tried to classify 8 h shifts according to one of three weather regimes (Fig. 4). *Squall line convection* propagates a significant distance and has a gust front. *Land/sea breeze convection* parallels coastlines, favoring land during the day and sea during the night. *Monsoon convection* organizes itself without regard for coastlines. For about one-third of the shifts, owing to lack of information, we could not make the classification. Nevertheless a couple of conclusions can be drawn. First, occurrences of the monsoon regime really were rare. Second, during SOP 3, as is the norm (Geoff Garden, RFC, personal communication), squall lines were mainly an early evening phenomenon.

A typical day would begin dry. Around Darwin the rising sun would shine through a veil of cirrostratus and around patches of altostratus and altocumulus. As these layer clouds dissipated cumulus formed, usually in broken lines running east-west or southeast-northwest and mainly over the land.

By early afternoon the sea breeze convergence almost always generated the thunderstorm known as Hector over Bathurst and/or Melville Islands (Keenan, *et al.*, 1989b). Rather than a single persistent storm, this seemed to be a sequence of cells growing to great heights, detaching, collapsing and being supplanted by new cells. Often, but not always, this whole system collapsed terminally by late afternoon.

Occasionally, by early afternoon, showers formed along and in front of a sea breeze moving inland near Darwin. Infrequently thunderstorms erupted from the sea-breeze band of cumulus and on-shore lines (*e.g.*, see Rolestone, 1985). These storms tended to move west. Those which formed along the north coast tended as well to develop some of the attributes of squall lines; *i.e.*, persistence, gust front, trailing anvil.

Toward the middle of the afternoon a few widely separated, very small, moderately intense (approx. 5 km diameter, >40 dbz) cells often appeared in the outer ranges of Storm 1, *i.e.*, at ranges of 170 to 220 km. Through the afternoon single cells and small groups of cells would continue to appear and develop into small storms at decreasing ranges from the radar. Regardless of the large scale situation portrayed on the Bureau's surface charts, the motions of storms tended to follow a pattern--probably influenced locally by land-sea temperature contrasts and by topography (*e.g.*, the 300 m Arnhem Land escarpment). Storms to the south along the west coast moved in northerly or northwesterly directions, while storms along the northern mainland coast moved westward. In effect, there was a confluence of these storms into the "corner" of the mainland near Darwin.

This confluence would sometimes bring storms initially far apart much closer, which seemed to invigorate them, and cause the formation of a N-S oriented line which might propagate westward as a squall line. Lines were also observed to move into the radar area from the east. Borrowing the name of an Arnhem Land mission, Darwin's meteorologists have come to call a storm of this type the Oenpelli Express.

Although remnants might persist for hours, storms most often seemed to begin an immediate decay process upon crossing the coastline. Tops would decrease, as would maximum reflectivity values. It seemed that the likelihood of extensive stratiform rainfall trailing a storm was small in the afternoon but rather greater later in the evening or at night.

The complementary situation to Hector sometimes developed at night in the Van Diemen Gulf when land breeze convergence apparently induced storms. This also sometimes happened in Beagle Gulf between Melville-Bathurst and the mainland (*i.e.*, in Clarence Strait) and off the coast to the southwest of Darwin.

Altostratus and altocumulus clouds were a notable presence. On several occasions we observed such cloud being generated by raining cumulus towers, apparently in the absence of any ice phase. Simultaneous observations of the TOGA radar showed that despite reflectivities of 40 dbz or more, echoes in these clouds did not grow beyond 8 or 9 km. Such observations raise the possibility that a significant amount of Top End rain falls from warm clouds.

## DATA

The radar, we believe, performed very well. Relatively little data--probably less than 5%--were lost. Apart from operator mistakes, losses were due mainly to failure of the grid power and breakdown of equipment. Grid power most often failed due to lightning strikes. However, ordinarily it quickly was restored by means of the stand-by generator. One serious breakdown occurred. Early in the last week of SOP3, the failure of a transformer in the radar resulted in loss of at least two hours of data.

Periodically through both SOP's Ken Glasson ran an electronic calibration of the radar. In addition, once during each SOP (on 29 January and on 26 February) the operating teams ran a sphere calibration.

In addition to the clutter mentioned above, anomalous propagation (AP) sometimes masked signals from rain. AP was most troublesome at the lowest two scan elevations (0.8° and 2.5°). It tended to be most prevalent at night. AP apparently also occurred during the day in the wake of thunderstorms and squall lines.

To supplement the GMS data which the Bureau of Meteorology receives every hour, we asked NESDIS to schedule Local Area Coverage (LAC; *i.e.*, full resolution scans) of the radar domain by the Advanced Very High Resolution Radiometer (AVHRR) on its NOAA series of satellites. NESDIS was able to provide nighttime digital data from NOAA 11 from two weeks in SOP 2 and two weeks in SOP 3. Table 3 lists the LAC orbits.

NOAA/TOGA radar data for the 1989/90 experiment may be acquired through Mr. Otto Thiele at the address given above. AVHRR LAC data may be acquired from Mr. Andy Horvitz, Satellite Data Services Division, 5200 Auth Road, Camp Springs, MD 20746.

## III. CONCLUDING REMARKS

Neither in January nor in February were there significant periods of monsoon rain. Nevertheless over the domain of the radar rain was the rule rather than the exception and it came in almost every imaginable form. Operation of the radar--especially coordinated dual doppler operation--by teams of three over periods of weeks proved to be demanding. That it could be done without significant loss of data is due largely to reliable performance of the radar and material and technical support provided by the Commonwealth Bureau of Meteorology.

Cloud photographs coordinated with radar scans--particularly rhi scans--are proving to be effective ways to put the radar observations into the context of everyday experience of clouds and rain and to document particular events or structures. Ad hoc, on-site measurements of temperature served similar purposes. We suggest that for the 1989/90 experiment dry and wet bulb thermometers be added to the suite of instruments supporting the radar at the Berrimah site. We suggest as well that a recording, remotely controlled video camera be installed atop one of the two hutches. At the very least the radar site should be equipped with a photographic platform which is more accessible than the top of the water tank.

Under a separate project, yet to be funded, we intend to test the power of Garand's (1986) cloud classification algorithm to map tropical rainfall. For this test we will need digital images of the Japanese Geostationary Meteorological Satellite (GMS) as well as radar rainfall maps. As part of this test we also intend to examine the structure of storms passing from land to sea and the role of warm clouds in producing wet season rainfall. These aspects of Top End rain systems bear on our ultimate ability to map rainfall from present geostationary satellites. Finally, under this new project, we would propose to participate in the 1989/90 wet season experiment, as we have in the experiment just ended.

## ACKNOWLEDGMENTS

We thank NASA for funding our work in Darwin. We also acknowledge consistently cordial and supportive working relationships with the staff of the Bureau of Meteorology's Northern Territory Regional Office, with its director, Jim Arthur, and with our partners on the radar--Ken Glasson, Tom Keenan, Jim McBride, and Rod Potts.

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**Table 1. Acronyms**

| | |
|---|---|
| NOAA | National Oceanic and Atmospheric Administration |
| TOGA | Tropical Oceans and Global Atmosphere |
| TAMEX | Taiwan Meteorological Experiment |
| AMEX | Australian Monsoon Experiment |
| EMEX | Equatorial Mesoscale Experiment |
| ITEX | Island Thunderstorm Experiment |
| TRMM | Tropical Rainfall Measuring Mission |
| GATE | GARP Atlantic Tropical Experiment |
| PPI | plan position indicator |
| RHI | range height indicator |
| VAD | volume azimuth display |
| FFT | fast Fourier transform |
| MIT | Massachusetts Institute of Technology |
| RPM | resolutions per minute |
| AVHRR | Advanced Very High Resolution Radiometer |
| NESDIS | National Environmental Satellite, Data, and Information Service |
| RFC | Regional Forecast Center |
| AP | anomalous propagation |

**Table 2. Most used storm formats during the January and February 1989 SOP's in Darwin**

| Storm Number | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| Data Type | Refl | Dopp | Dopp | Dopp | Dopp | Dopp |
| Scan Type | PPI | PPI | PPI | PPI | PPI | Vertical |
| Azimuth Range (°) | 0-360 | 50-50 | 50-50 | 50-50 | 50-50 | 0-360 |
| Resolutionn (°) | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 0.4 |
| Elevation Range (°) | 0.8 | 0.8-25 | 0.8-4 | 30-60 | 0.8-4 | 90 |
| Distance Range (km) | 0-225 | 0-170 | 0-170 | 0-170 | 0-170 | 0-20 |
| Pulse Rep. Rate (Hz) | 400 | 841 | 841 | 841 | 841 | 1200 |
| Pulse Width (ms) | 2.0 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |
| Points in FFT | 32 | 32 | 32 | 32 | 32 | 128 |
| Wait Time (min.) | | | | | | |
| --Climatology Mode | 5 | 5 | --- | --- | --- | --- |
| --VAD Mode | 5 | 15 | 15 | 15 | 15 | 15 |
| --Dual Doppler Modes[1] | 5 | 15 | 30 | 30 | 30 | 30 |

[1]Additional storms (dependent on the region to be studied and not described in this table) are added to fill "blank" intervals.

**Table 3. NOAA II AVHRR (LAC) data at Darwin**

| Day | Time Start | Time End | Corners (degrees S, degrees E) | | | | Orbit | Tape | File |
|---|---|---|---|---|---|---|---|---|---|
| 4 | 1658 | 1700 | 8 116 | 15 114 | 12 143 | 19 141 | 1442 | 27748 | 2 |
| 5 | 1647 | 1650 | 4 119 | 15 116 | 9 146 | 19 144 | 1456 | 27786 | 2 |
| 14 | 1658 | 1701 | 8 116 | 18 113 | 12 143 | 22 141 | 1583 | 28092 | 2 |
| 15 | 1648 | 1650 | 8 118 | 15 116 | 12 145 | 19 144 | 1597 | 28119 | 3 |
| 17 | 1627 | 1630 | 4 124 | 15 121 | 9 151 | 19 149 | 1625 | 28191 | 2 |
| 25 | 1648 | 1651 | 8 118 | 18 115 | 12 145 | 22 143 | 1738 | 28457 | 3 |
| 26 | 1638 | 1640 | 8 121 | 15 119 | 12 148 | 19 147 | 1752 | 28495 | 3 |
| 33 | 1708 | 1711 | 11 113 | 21 109 | 15 140 | 26 138 | 1851 | 28729 | 2 |
| 34 | 1658 | 1700 | 11 115 | 18 113 | 15 143 | 22 141 | 1865 | 28762 | 2 |
| 43 | 1708 | 1711 | 8 113 | 18 110 | 12 140 | 22 139 | 1992 | 29070 | 2 |
| 44 | 1658 | 1700 | 8 116 | 15 114 | 12 143 | 19 142 | 2006 | 29109 | 3 |
| 45 | 1648 | 1650 | 8 119 | 15 117 | 12 145 | 19 144 | 2020 | 29139 | 2 |
| 46 | 1637 | 1640 | 4 122 | 15 119 | 9 149 | 19 147 | 2034 | 29173 | 3 |
| 53 | 1708 | 1710 | 8 114 | 15 112 | 12 140 | 19 139 | 2133 | 29417 | 3 |
| 54 | 1657 | 1700 | 4 117 | 15 114 | 9 144 | 19 142 | 2147 | 29459 | 3 |

**Figure 1.** Site of the TRMM radar observations near Darwin.

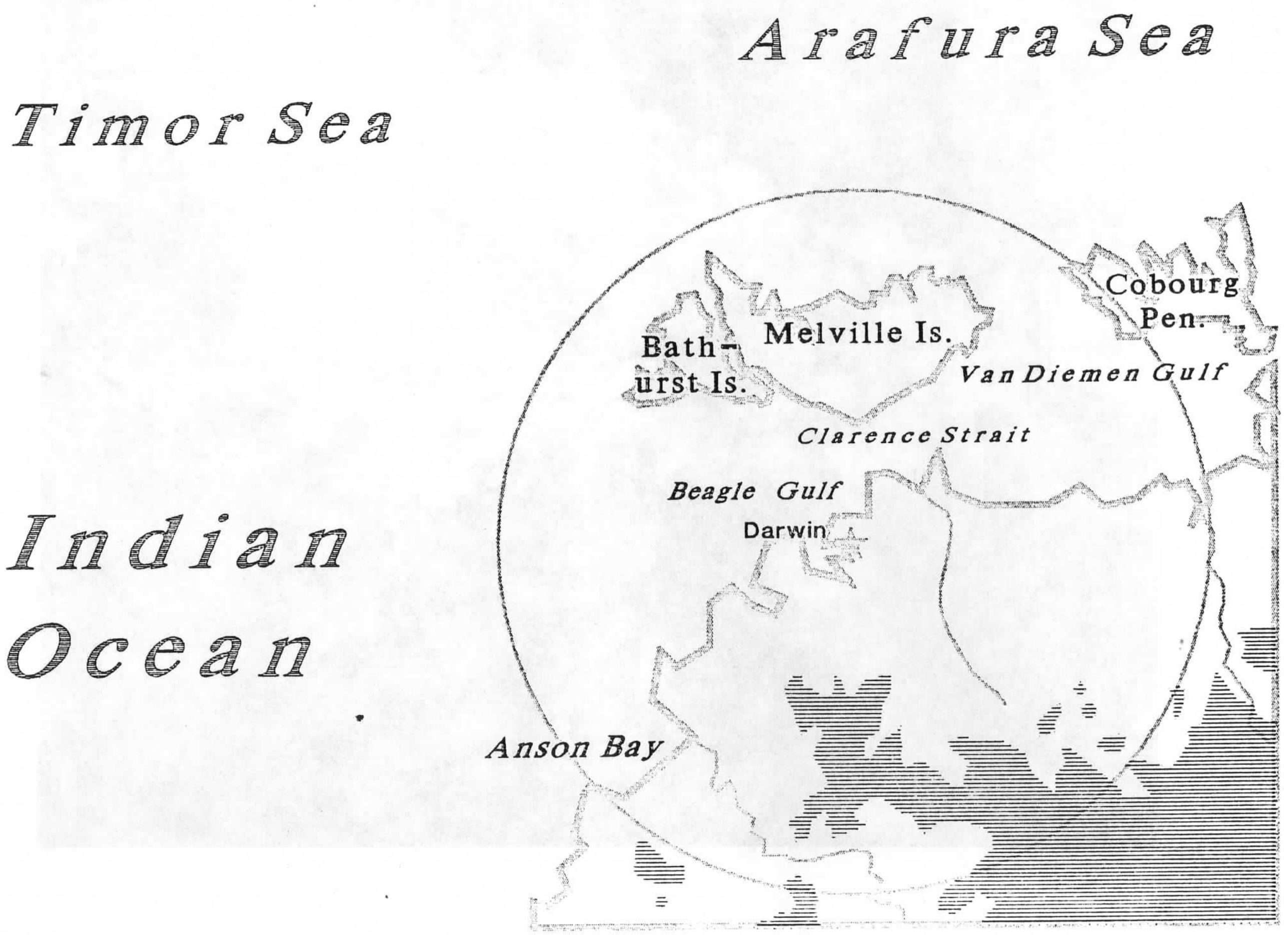


**Figure 2.** Radar coverage area. Shaded area is above 100 m altitude.

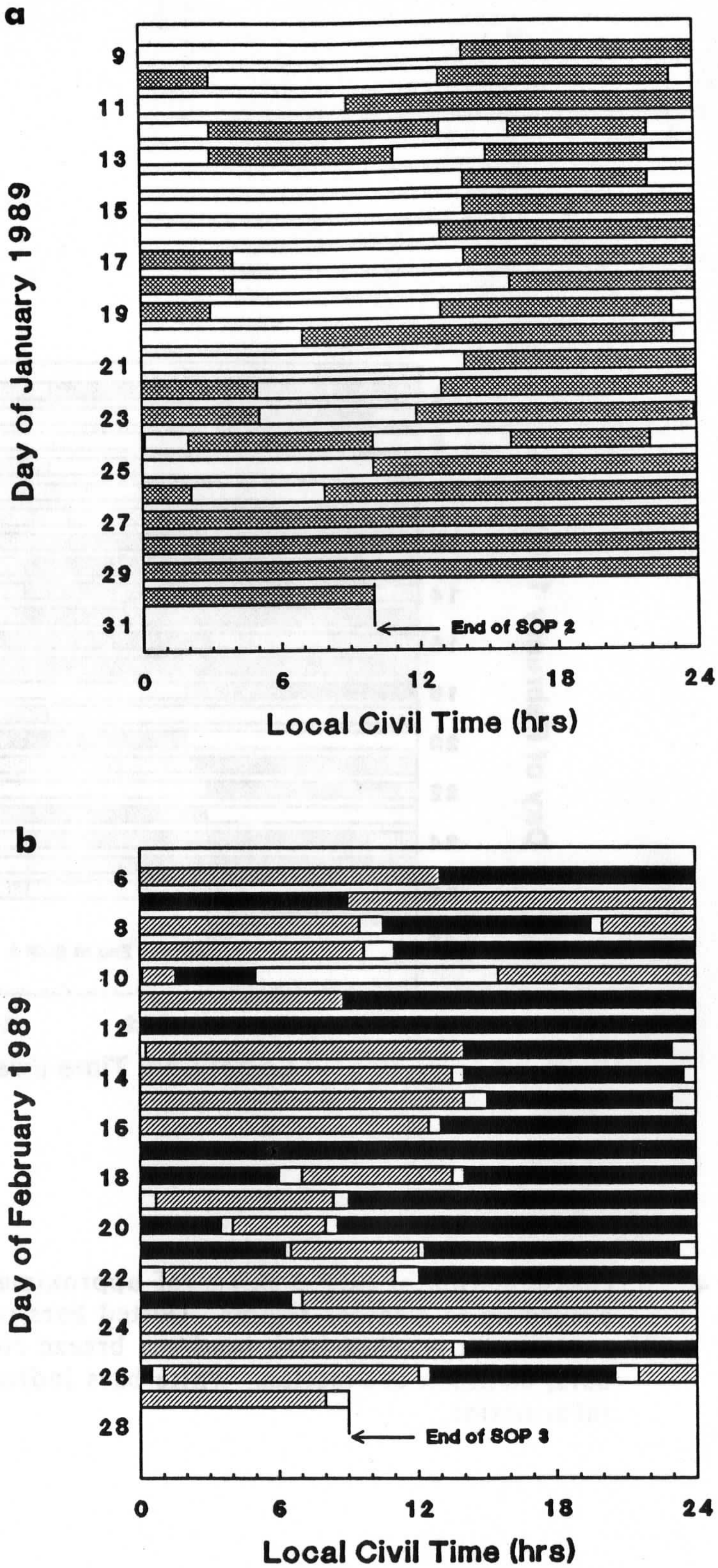


Figure 3. Chronology of wetness over the range of the radar.
a. SOP 2. Significant rain is indicated by cross-hatching.
b. SOP 3. Significant rain is indicated by black bars; its absence, by hatched bars. White bars indicate inadequate information.

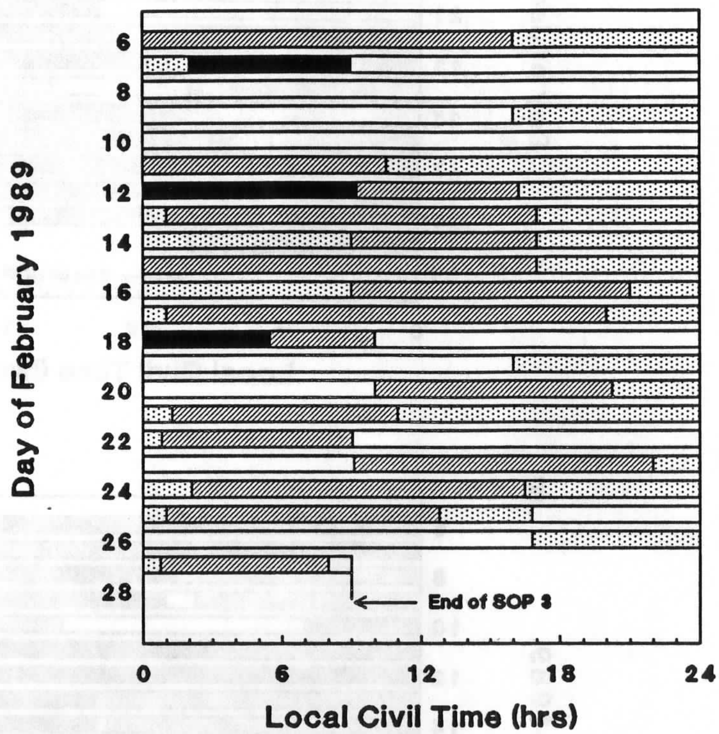


**Figure 4.** Classification of SOP 3 shifts (of approximately 8 h duration) according to weather regime. Dotted bars represent squall line convection; hatched bars, land/sea breeze convection; black bars, monsoon convection. White bars indicate inadequate information.