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Grant NAG5-1308

Collection and Analysis of Radar Rainfall and Satellite Data for the Darwin TRMM Experiment

For the Period of

1 December 1990 to 31 May 1991

Submitted by

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I. Introduction

During three of the last four years NASA's Tropical Rain Measuring Mission and the Commonwealth Bureau of Meteorology have sponsored a wet-season rainfall experiment at Darwin, Australia. Darwin's location, twelve degrees south of the equator, gives it a wet season which ordinarily runs from November through March. Although there have been variations from season to season, the underlying theme of these experiments (*e.g.*, Keenan *et al.*, 1988) has been study of the full range of rain systems occurring at a near-equatorial, monsoon site.

To a greater or lesser degree each experiment has been designed around a single C-band (5.3 cm) Doppler radar (in all years the same radar). In acknowledgement of its main institutional sponsors (both American), this has come to be known as the National Oceanic and Atmospheric Administration/Tropical Oceans and Global Atmosphere radar (more briefly written the NOAA/TOGA radar). For convenience we refer to the collective set of experiments as the TRMM/BMRC (for Bureau of Meteorology Research Centre) Darwin Project.

SSEC has played a role in two of these three experiments, 1989-90 and 1989-90. Our interests have been threefold: the collection of data on tropical rain systems; the improvement of satellite techniques for estimating rainfall; and observations at first hand of the near-equatorial rain systems which for the most part we otherwise knew only from instruments in space. In consecutive years the authors of this report each travelled to Darwin to assist in the operation of the NOAA/TOGA radar. These trips —a total of four— were funded under two grants from NASA.

We have reported elsewhere on the first of these grants (Martin and Hinton, 1989). Here we report on the second grant, NAG5-1308.

II. Overview of the Grant

Originally, there were two goals for Grant NAG5-1308. The first —and paramount— goal was to help gather a set of digital radar rainfall data over Australia's Northern Territory. The second goal had five parts: first, test a video "skywatch" cloud camera; second, test a rain version of the Garand (1988) cloud classification algorithm; third, participate in the Global Precipitation Climatology Project algorithm intercomparison; fourth, measure changes in sea-going rain systems; and fifth, assess the contribution of warm clouds to rainfall around Darwin. Including a no-cost extension of six months, the grant ran from 1 December 1990 through 31 May 1991. NASA awarded the University of Wisconsin-Madison $60,000. Because this award was two-thirds of the amount requested, it was not possible to meet all parts of both goals. Instead, we chose to drop parts three, four and five of the second goal.

III. Video Cloud Camera

A. Purpose

Holle (1987) discussed the desirability of "photogrammetry" of storms in association with radar and other field observations. Photogrammetry emphasizes that the images are quantitative data. From sequences of images one can extract measures of cloud growth and decay, evolution of cloud types and cloud motion (*i.e.* wind). From single images one can obtain cloud cover, cloud type(s), cloud organization, the azimuth and elevation of a cloud element.

Our first year at Darwin underscored the relevance of Holle's argument. Physical presence, including visual observations, enhanced our subsequent interpretation of radar data and standard weather products, such as surface charts. To make this sense of immediacy and personal observation permanent we often photographed the sky. Video is more cost effective than silver photography for large volumes of pictures (cheaper to record, and to replicate, and easier to view and handle subsequently). For our second year in Darwin we chose to record sky conditions by means of a video camera, patterned after cinematography often used in previous field programs.

B. Design

Desired features and parameters for consideration in both the equipment and installation included the following:

- Weather resistance
- Good angular resolution
- Pointing
- Level of operator attention
- Ease of data use
- Availability
- Wide field of view
- Time compression
- Navigation (*where* is it pointing?)
- Ease of implementation
- Portability
- Cost

In addition, the design had several constraints. The primary one was cost. Because funds for the deployment were received relatively close to the departure date, time (equipment availability) was also a major constraint.

Three basic system types were considered: (1) robotic or machine vision systems, (2) security systems, (3) consumer-entertainment video systems. Any of these would take advantage of commercially available hardware. Robotic cameras are generally small in size, easily packaged and flexible with regard to frame rates, but require custom engineering for a complete system. Often they have limited resolution and are usually monochrome. Security systems are available with remote pointing and weather resistant enclosures. They are often used with multi-source switching or sequencing recorders, which are also usually monochrome as are the cameras. We elected to base our installation on a consumer-type video camera in a weather resistant enclosure of our own fabrication.

The camera system used (Philips Model-CPK816AV01) had the following features:

- Half inch CCD
- 9-54 mm zoom lens
- 5.4-32.4 mm with ×0.6 aux. lens
- Angular field of view 45° × 34°
- Date and time annotation
- Ambient temperature range 0-40°C
- Humidity range 10-75%
- Useful illumination range 3 lux to full sun
- Duty cycle 1 sec per min.
- Servicing intervals 10 h of real time
- Recording format VHS
- Video format NTSC
- Integral recorder, tape duration five days

The camera was mounted in a metal enclosure as shown in Fig. 1. The enclosure also contained the AC adapter providing conversion of mains power to 12 V DC. The enclosure was painted white to reduce solar heating and lightly insulated inside to reduce thermal conduction between the electronic equipment and the metal shell, which was expected to heat to temperatures exceeding 40°C in full sun. The interior was then ventilated with a small fan. The net result was an interior air temperature 35-37°C midday. Since the interior temperatures were always above ambient, the 75% limitation on humidity appeared not to be a problem. Humidity within the enclosure was never measured, but no malfunctions were observed. On a few occasions, drops of water were seen inside the box after rain, presumably propelled there by the ventilation fan or wind (in spite of complete sealing around the door and window).

The enclosure was mounted on the roof of the northern radar hutch. Fortunately, this convenient roof location very near the radar beam did not seem to be subject to excessive radio frequency interference from the transmitter. The camera was pointed roughly eastward in a fixed direction, except for a brief time. (On 15 January at 1740, Darwin Civil Time, it was pointed NNW (315°). On 16 January at 1823 DCT it was returned to the original orientation.)[1] Our previous observations suggested that most often storms and squall lines, especially in the late afternoon and evening, could be seen approaching from this direction.

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1 Darwin time is 9.5 hours ahead of UTC.

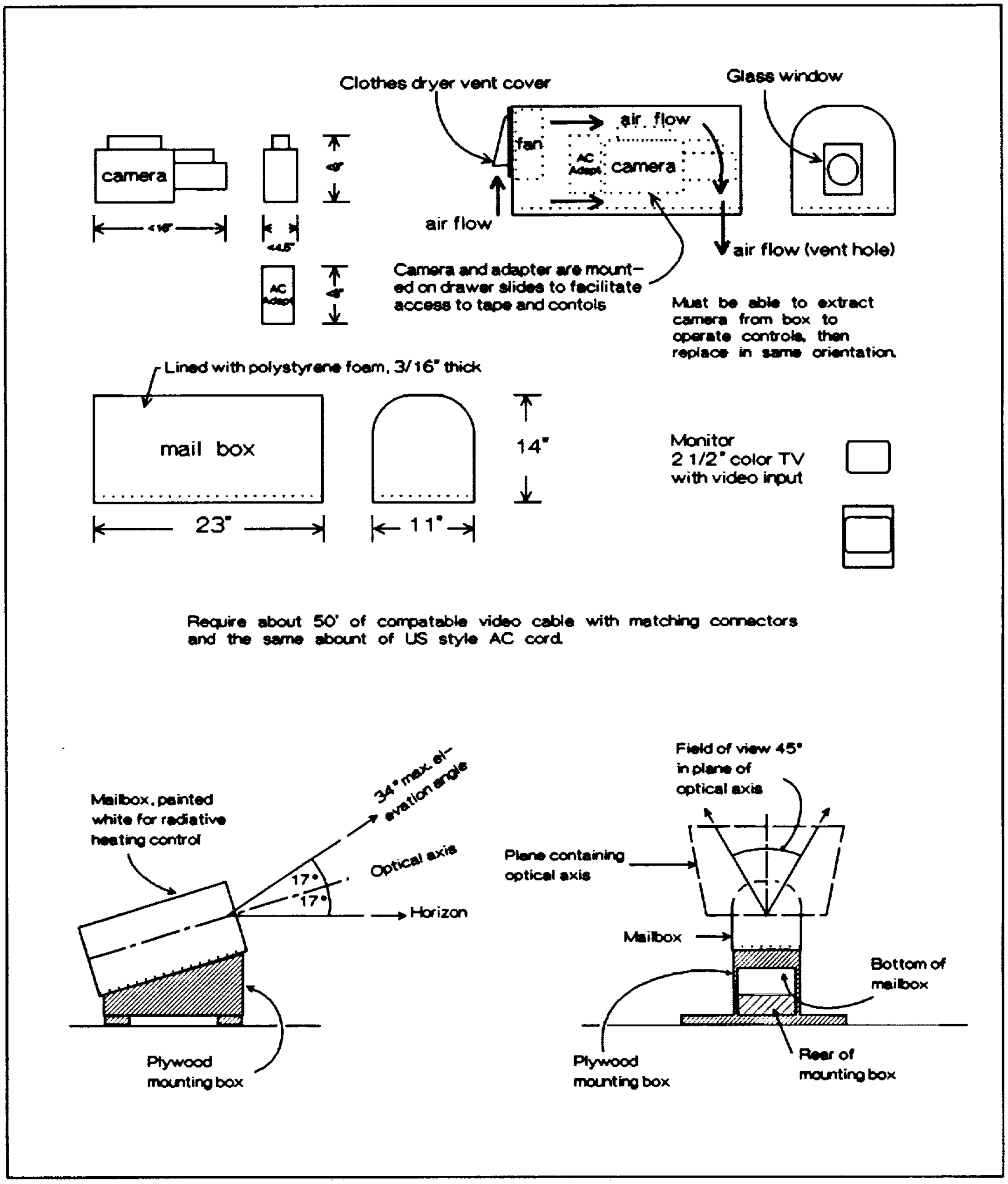

FIG. 1. Enclosure and mounting of video camera

A fixed elevation angle of 17° provided a narrow band of landmarks on the horizon. Elevations from 0 to 34° were thus visible. For a given focal length lens, the time a weather system can be observed is maximized by observation at a low elevation angle (*i.e.* when it's far away).

Power (117 V AC, 50 Hz) was provided by a weather resistant extension cord and video was returned on a parallel coaxial video cable, both passing through a small opening at the bottom of the window in the radar console room. The video signal was visible to the operator on a 2.5" color monitor.

It was surprisingly easy to correlate the cloud images on the horizon with approaching echoes visible on the radar. However, the 45° horizontal field of view was sometimes a disappointing limitation, as storms rather frequently arrived from sectors to the south of our view.

C. Operation

The regimen for operation was generally as follows. Reset the camera into time lapse mode, noting time and tape counter. The latter was both a means of determining that the camera had been operating and anticipating an approaching tape change. Approximately ten hours later, by watch, or absence of image on the monitor, these steps were repeated. The last reset of each day was usually done late enough to insure operation through the night. After about five days, but actually based on the time remaining on the tape at reset as displayed in the view finder, a fresh tape was installed.

D. Data

The camera was operated from approximately 0525 DCT time on 11 January 1990 until midnight 22 February 1990. There are missing data segments. Obviously there are not useful nighttime images. On a few occasions the tape expired or a resetting of time lapse mode was required during intense rain when it was inadvisable to open the camera enclosure. Power interruptions caused the camera to turn off. If an operator were present this would be easily noted on the monitor, but the higher priority tasks of restarting the radars and computer would be completed first. Moreover, restarting required a trip to the roof exposing one to the danger of lightning, which would be an additional cause for delay.

Auxiliary data was required to determine exact pointing directions. Panoramic photographs of the horizon were obtained. A topographic map at 10,000:1 scale, a vertical aerial photograph at about 5,000:1 and data on the location and height of a prominent communications tower were secured. In addition, during the February observations, the camera was usually activated before sunrise to obtain images of astronomical bodies (sun, moon, Venus). The on-tape time annotation in these images and the time differences logged between this clock reading and a standard time signal has been used with ephemeris generating software to determine the orientation of the camera in both azimuth and elevation. Thus, the video images can be used in a quantitative manner to determine the azimuth and elevation of a cloud feature. These can be associated with specific radar echoes which provide range information, with the obvious limitation that nearby clouds may obscure more distant ones.

The data are valuable qualitatively and quantitatively when echoes are not present also. This is especially obvious when viewing the time lapse tapes at normal frame rates. The 60× acceleration makes rates of cloud development, changes in cloud development or type and motion very evident. Unfortunately, we have not succeeded in quantifying much of the information in these images.

The video tapes, as mentioned previously, are easily duplicated for other investigators who may be interested in them as auxiliary information for the radar data. In January 1991 we sent a copy of one tape to Dr. Toshiro Inoue of Japan's Meteorological Research Institute at his request. Dr. Inoue is primarily interested in the interpretation of GMS images.

IV. Special Observing Periods

Each experiment in the TRMM/BMRC Darwin Project consisted of three or four special observing periods (SOP's). Each SOP, in turn, has had a special focus. Depending on the focus, the schedule for operating the NOAA/TOGA radar was altered more or less extensively from surveillance observations (the TRMM mode) toward intensive observations.

Usually the intensive mode has involved a second C-band Doppler radar. This radar belongs to the Massachusetts Institute of Technology. It was situated at Koolpinyah Station, some 28 km east-northeast of the NOAA/TOGA radar. With this configuration of radars, high-quality dual Doppler observations were possible in lobes extending roughly 50 km to the north of the base line between the radars (the sea sector) and 50 km to the south (the land sector).

A. SOP-2

In January 1990 there was an SOP (the second of the 1989-90 experiment) concerned with thunderstorms. The scan schedule adopted for SOP-2 struck a balance between the TRMM mode and a dual Doppler mode. It did this by insuring (in a nominal sense) one NOAA/TOGA base scan every 20 minutes, even during the most intensive dual Doppler operations.

Other instruments also sampled the atmosphere during SOP-2. Apart from routine synoptic observations at Darwin airport (both surface and rawinsonde), the most significant of these were automatic weather stations and a profiler. The weather stations measured some combination of temperature, humidity, pressure, rainfall and wind. The profiler measured vertical velocity.

SOP-2 ran from 0900 on 8 January through 1700 on 29 January. Dr. Tom Keenan managed the SOP. He was assisted by Mr. Graham Bois, Dr. Brad Farrier and the senior author of this report.

Subjectively, we summarize Darwin-area (total) cloud cover, rainfall and lightning for SOP-2 in Fig. 2. In this summary for any of the three variables three states are possible. For rainfall and lightning the states are "nil", "some" and "much". For cloud cover the states are "nil or little", "some" (up to 50%) and "much". States were assigned for each variable on a day-to-day basis through the SOP. They depended as much on eyes and ears as on any of the project instruments.

The SOP began with two days of afternoon and evening thunderstorms. Thereafter, a strong monsoon set in. Cloudy, rainy weather, with occasional squalls (but no lightning), persisted through the rest of the first week. Thunderstorms returned early on the first morning of the second week, when a small cloud cluster formed over and west of Darwin. The three-day dry spell that ensued was broken on Thursday (the 18th) by an intense, southwestward-moving squall line. More thunderstorms, with heavy rain, formed Saturday (the 20th); otherwise, the last part of the second week was relatively dry. The final week of the SOP began spectacularly with a string of three squall lines on successive evenings. The dry spell which followed these squall lines was broken late Sunday (the 28th) by a squall line with tops to 21 km, the highest observed during this SOP.

Through SOP-2 the NOAA/TOGA radar performed nearly flawlessly. Except for two breakdowns during the third week, the MIT radar also performed well.

January 1990

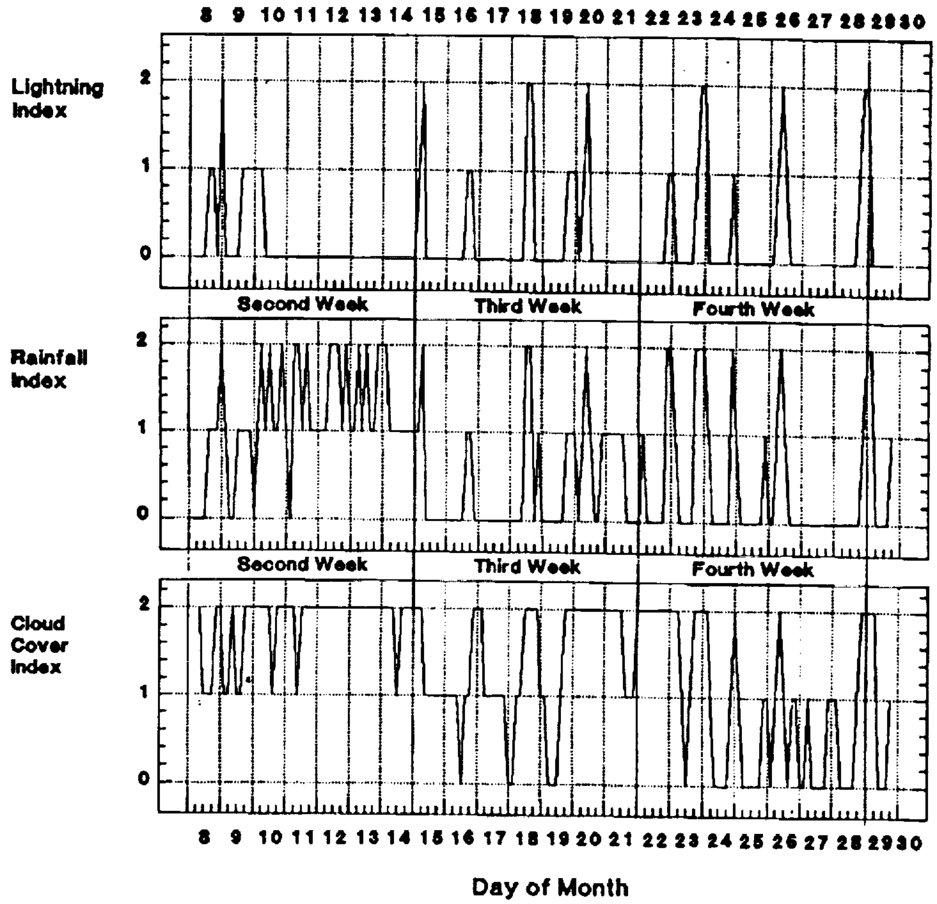

FIG. 2. Summary of lightning, rainfall and cloud cover in the vicinity of Darwin through the period of SOP-2. Eighth-days are 3 h in length. The first corresponds to the period midnight to 3 a.m. DCT on 8 January. Scales of 0, 1 and 2 on the ordinate of each plot correspond to nil, some and much.

During the first day of its operation the camcorder demonstrated a sensitivity sufficient to register nighttime lightning. Because tape was a minor cost and in any case in ample supply, thereafter we tried to maintain observations around the clock. Interruptions were rather frequent the first week, but became fewer as various problems were ironed out. Down time for the SOP was about 15%. The figure is the same whether day or night operation is considered. On two occasions we backed up the skywatch camera with 35 mm photographs taken from a balcony of the Marrakai Apartments in Darwin.

B. SOP 2.5 —An Extension of SOP-2

Because of the scientific staffing noted above for SOP-2, it was decided that project resources could be better spent by extending the period of special observation, rather that having extra staff present for the scheduled SOP. Because of the diurnal cycle of rain near Darwin, a work schedule 0600 to 2200, with a late morning break of 1-2 hours was followed by the second author while in Darwin. This covered most of the interesting cases occurring during the period (1 February through 21 February 1990). One regrettable exception was a nighttime storm which formed unexpectedly over Van Diemen Gulf.

General weather conditions at the beginning of this period included a cold front penetrating unusually far northward (afternoon temperatures in Alice Springs 22-24 °C). This air bore considerable suspended dust, raised as the front passed over the desert regions of south central Australia, and which remained suspended as the front reached north central Australia. This situation seemed, however, to have no direct effect on the character of rain-systems within radar range of Darwin, which continued to be dominated by land-sea breeze effects to the north and solar heating to the south.

The scientist's role is to maximize the observations of the interesting storms, without compromising the standard TRMM PPI and volume scans. This means choosing a promising storm, setting up sector scans, and RHI scans to follow it. These require constant adjustment, so that this role is not a trivial or passive one. The storms which were of particular interest in this case were those which would appear to be approaching the west coast from the east while still well developed. Previously (*i.e.* in 1989) we had observed that the vertical structure of the storms changes with such apparent rapidity near the coast, that great care would be required in applying the results to the interpretation of passive microwave rain retrievals.

Much of the TOGA radar environment in Darwin is quite representative of maritime continent conditions. It is dominated by coastal effects to the north, including land-sea breezes on Melville-Bathurst Islands and Coburg Peninsula as well as various points of land on the mainland (*e.g.* Cape Ford). In addition, Van Diemen Gulf can, at times, act like the enclosed body of large lake with consequent "lake storms."

On the other hand, storms to the south and east initially have no obvious coherent organizing influence, seeming to respond randomly to the intense diurnal heating. Typically echoes first appear around noon and increase in frequency through late afternoon. About 1800, possibly due to the weakening of the sea breeze front, the two types of storms (sea breeze and solar heating) seem to come into collision, with the resultant formation of short lines of cells and squall lines which converge on the Darwin vicinity from the NE to SE sector, often with a great crescendo of electrical activity about 2100. The lines often die rather suddenly as the systems reach the coast, leaving only a mantle of very light "stratiform" rain which then slowly dissipates.

A variation on this theme is illustrated by the RHI scans in Figs. 3a-f. In this case, from 16 February 1990, convection formed on a point of land, or cape, along the coast in the early afternoon. Presumably this was a response to sea breeze induced convergence.

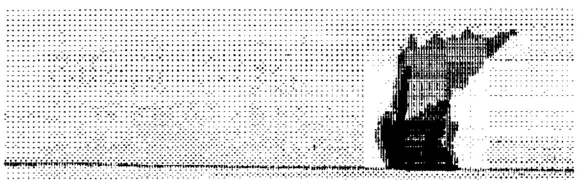

FIG. 3a. Storm of 16 February, 1990 at 1340, azimuth 261°. Darkest shade is 42 dBZ or greater, intermediate shade 18 dBZ or greater, lightest shade is -6 dBZ or greater.

FIG. 3b. Storm at 1430, azimuth 244°.

FIG. 3c. Storm at 1510, azimuth 252°.

FIG. 3d. Storm at 1540, azimuth 258°.

FIG. 3e. Storm at 1610, azimuth 260°.

FIG. 3f. Storm at 1640, azimuth 260°.

The figure suggests that maximum vigor was reached around 1510 Darwin time.

Near the "head" of the storm the Doppler velocity pattern shown by the radar generally indicates two levels of relative forward motion sandwiching a layer of weak (relative) rearward motion, or at some observation times diminished forward motion. The example in Fig. 4 demonstrates that Doppler patterns at a specific time may be quite complex. However, as one would expect, the uppermost layer of cloud is swept rearward quite strongly. Interestingly, for the case illustrated there is low level out flow both to the front and rear.

At earliest times the storm as a whole seemed motionless, but by after 1340 was propagating seaward, though still over land. By 1640 it formed part of a line-form disturbance rapidly losing strength over the Timor Sea. As shown in Fig. 3f, there is a decrease in maximum height and area of echo >40 dBZ. Finally, also as shown in panel f of the figure, there is a brightening in the anvil region (18 dBZ corresponds to rain rates somewhat under 1 mm h^{-1}).

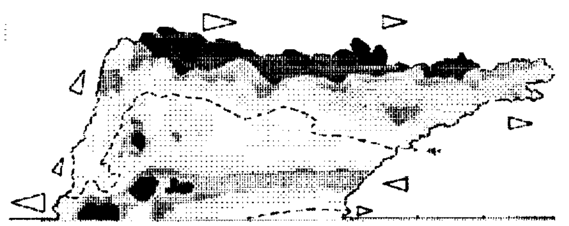

Fig. 4 Doppler velocity pattern in 16 February 1990 storm southwest of Darwin at 1510 local civil time (2340 UTC). The triangles indicate the inferred motion based on the radial component. The dashed line divides "toward" from "away" velocities. Darker shades indicate higher speeds.

On at least five days, cases similar to that outlined above occurred and, with special data sets which were acquired, are suitable for study of the land-sea transition effect. This was one of the priorities of this observing period. In addition, numerous dual Doppler data sets of interest to other investigations were obtained in cooperation with the MIT radar at Koolpinyah.

V. Garand Algorithm

Even though it was designed to recognize clouds, the classification algorithm of Garand (1988) is capable of predicting the point probability of precipitation. In a modified form (Garand, 1989; personal communication, 1991), the algorithm provides not just a probability, but an estimate of rainfall as well.

From a survey of 3 h Geostationary Meteorological Satellite (GMS) image pairs covering the third SOP of the 1988/89 experiment, we chose a day (2 February 1989) upon which to test a Garand rain algorithm. Digital GMS data were on hand. From Goddard Space Flight Center we acquired the NOAA/TOGA radar data matching these GMS data.

Garand's algorithms operate on full-resolution visible and infrared image pairs of the GOES. The code had been written for SSEC's Man-computer Interactive Data Access System (McIDAS) in 1984 and 1985. For the present project it had to be restored to McIDAS and adapted to the GMS satellite. Because of changes to McIDAS subroutines, this task proved to be beyond the resources of the project.

The restoration of Garand's cloud classification algorithm to McIDAS is in progress and will be completed under a separate project. The installation of his rain estimation algorithm on McIDAS is contemplated, also under a separate project. Given either of these algorithms, the test planned for the 2 February case can be run.

As a complement to the GMS images upon which the Garand algorithm was to have operated, we requested LAC data from AVHRR on NOAA 10. (LAC stands for Local Area Coverage; AVHRR, for Advanced Very High Resolution Radiometer.) The National Environmental Satellite, Data, and Information Service recorded a total of 42 scenes during the period 9 January through 27 February 1990. These scenes are listed in the Appendix; the data are available from NESDIS' Satellite Data Services Division. We also requested LAC data for part of the 1990/91 wet season, during which the Bureau of Meteorology operated the NOAA/TOGA radar. From 2 February through 31 March 1991 NESDIS recorded a total of 25 scenes. These also are listed in the Appendix.

VI. Warm Rain

Keenan and Carbone (1989) notwithstanding, in the astonishment of witnessing one of Darwin's twenty-kilometer-tall cumulonimbus clouds, it is easy to overlook lesser forms of convective rain clouds and rain clouds which (although extensive) are not really convective at all. The paper of Keenan and Carbone emphasizes the range of convective modes which exists at Darwin. Forecasters are aware of more or less strictly stratiform modes as well (e.g., see Downey and Ward, 1985). In north Australia, as in West Africa (Omotosho, 1985), these are often referred to as "monsoon" rains (Garden, 1985). A case of such monsoon rain is shown in Figs. 5 and 6.

At 1731 on 14 January 1990 a vertical scan (RHI) of the NOAA/TOGA radar along an azimuth of 315 degrees showed broken precipitation out at least to 110 km (Fig. 5, lower panel). This precipitation was almost entirely confined to the layer below 8 km. Reflectivities were low (mostly less than 35 db); however, echoes were quasi-cellular up to a height of 5 km.

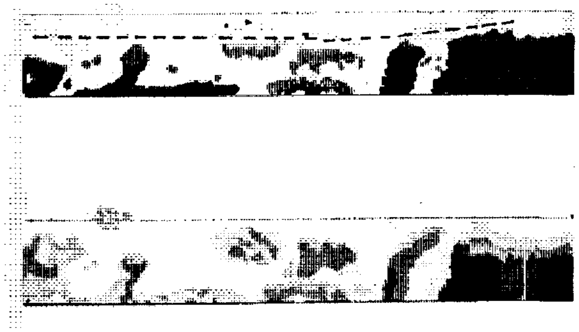

Fig. 5. Range-height indicator (RHI) scan of the NOAA/TOGA radar in Darwin, along an azimuth of 315 degrees. The scan was made at 1731 on 14 January 1990. For each panel the abscissa is range and the ordinate is height. At left is 0 km range, at right 110 km. The vertical scale is exaggerated relative to the horizontal. The thin horizontal lines above the baselines of the velocity (above) and reflectivity panel (below) are at 5 km altitude. In the top panel white is 0 to 1.88 m/s. Progressively darker shades are centered at 3.7, 7.5, 11.2 and 14.5 m/s. The dashed line divides the velocities directed away from the radar in the upper levels of the echo from the velocities directed toward the radar in the lower levels. The bottom panel shows reflectivity, in dBZ. Depending on the choice of Z-R relationship, 30 dBZ corresponds to a rain rate of 1 to 6 mm/h. The darker echoes are mostly 30 dBZ, but a few very dark areas indicate 38 dBZ)

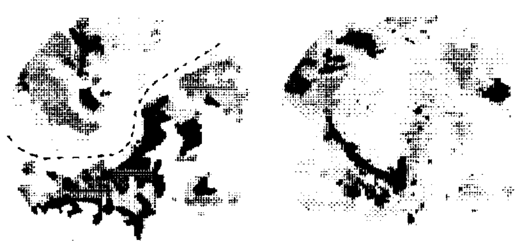

Fig. 6. Plan-position indicator (PPI) scan of the NOAA/TOGA radar at an elevation of 0.8 degrees. The scan was made at 1752 on 14 January 1990. On the left is Doppler velocity; on the right, reflectivity. Coding of the gray scales is the same as Fig. 5. To the left of the dashed line the velocities are toward the radar, to the right away from the radar. The maximum range (bounding circle) is at 112 km. Significant clutter extends outward from the radar a distance of about 15 km.

A horizontal base scan taken 21 minutes later (Fig. 6, right panel) showed some rain along almost every azimuth. Rates were low—of the order of millimeters per hour. However, out to distances of 100 km or more, rain covered a tenth to a half of each quadrant of the radar.

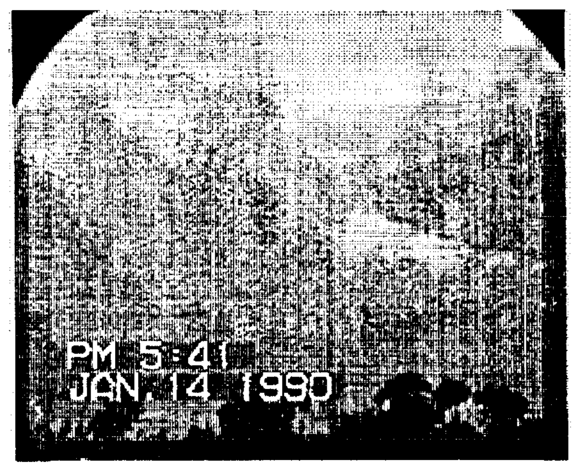

Fig. 7. Print of the scene recorded by the video camera at 1741 DCT on 14 January 1990. The camera was pointed due east at an elevation of 17°.

Through this period, looking east from the radar, the skywatch camera recorded overcast skies (Fig. 7). Both stratus and cumulus types were present (fractostratus, low stratus and altostratus; also, fractocumulus, cumulus and stratocumulus), with stratus types tending to become dominant. Conditions reported at Darwin's airport, a few kilometers to the northwest, were much the same: stratus or fractostratus under altocumulus.

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The Bureau of Meteorology sounding for Darwin at 1930 DCT is shown in Fig. 8. Five kilometers corresponds to the 0°C isotherm. At 8 km the temperature was −18°C. In a 2-km layer centered near 5.5 km the sounding was saturated. Above 7 km the air became progressively drier. For this sounding the lifting condensation level was low and the level of free convection was high (0.6 and 4.5 km, respectively).

In terms of temperature the 1930 DCT sounding was not drastically different from the January mean sounding for Darwin. Four and one-half kilometers was a critical level. Below it the 1930 sounding was cooler than the mean; above, warmer. Significantly, in the mean sounding as well as in the 1930 sounding, there is a stable layer extending upward from the 4.5 km level.

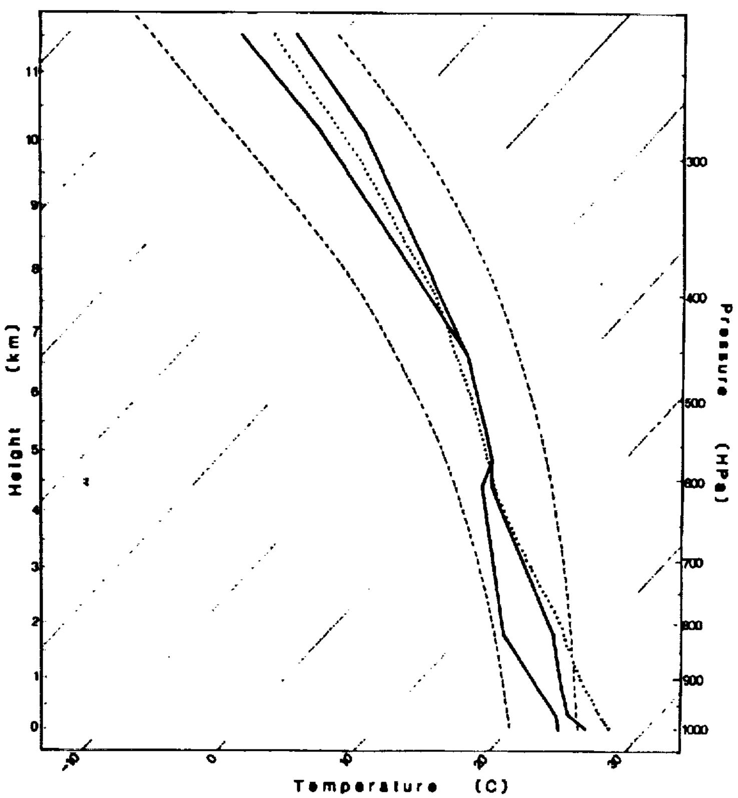

Fig. 8. Sounding of 1930 14 January 1990, plotted as heavy solid lines. Drybulb temperature is on the right; dewpoint temperature on the left. Also shown (as a dotted line) is the January mean temperature sounding for Darwin and (as dashed lines) two moist adiabats.

From the observations we conclude that the clouds of the 14 January rain system existed in a mildly (statically) unstable layer, that they intruded from below on a weak stable layer and that the bulk of each precipitating cloud was warm. From literature reports and the mean sounding we further conclude that at Darwin rain systems of this kind are by no means exceptional.

The following implications, which are based in part on RHI scans not shown here, are of a more speculative nature. First, precipitation in this case was dominated by warm (condensation/coalescence) processes. Second, significant amounts were present. Third, this rain would have been invisible to any infrared technique employing a threshold lower than 253K. Fourth, it would barely have been visible to any passive microwave technique employing scattering. Finally, there is a further implication (which gains credibility not so much from the present set of observations as from historical observations such as those of Sakakibara (1981) and List et al. (1988); also see Houghton (1985), Jameson and Johnson (1990) and the review by Cotton (1982)), namely, near Darwin significant rain may fall from clouds which have no ice phase whatsoever.

VI. Concluding Remarks

SOP-2, from January 1990, featured a remarkable variety of rain systems. Instruments, including the NOAA/TOGA radar, performed well.

We have demonstrated that a commercial video camera can easily be adapted to monitor clouds in a single quadrant of the sky at a radar sited in the tropics. The University of Wisconsin skywatch camera shows promise of filling a gap between the view of rain systems afforded by a ground-based radar and the view afforded by an operational geostationary satellite.

Nothing in our experience prepared us for the sense of discovery which accompanied our stints in Darwin. Coming home our briefcases were stuffed with maps, charts and tables; with notebooks and crude catalogs; with half-finished case studies. For this report we have reviewed the notebooks and polished the catalogs. Regrettably, the case studies remain half-finished.

Acknowledgements

Mr. Jim Arthur and his staff offered us the full resources of the Bureau of Meteorology's Regional Office in Darwin. Drs. Tom Keenan and Brad Ferrier and Mr. Graham Bois braved rain, sandflies, storm and darkness to keep the cloud camera going. Dr. David A. Short and Mr. David B. Wolff loaded certain radar data from the TRMM archive at Goddard Space Flight Center, which Dr. William Olson then copied for our use.

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APPENDIX

Local Area Coverage
Advanced Very High Resolution Radiometer
NOAA/TOGA Radar Domain

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S-B NSS.LHRR.NG.D90009.S2251.E2257.B1720909.WI  CORNERS:   1N,116E   3
SCENE START = 22:51  DURATION =  6 MIN                    20S,110E  24
TAPE NO. = J41082   FILE NO. =   2

S-B NSS.LHRR.NG.D90009.S2252.E2255.B1720909.WI  CORNERS:   3S,115E   7
SCENE START = 22:52  DURATION =  3 MIN                    13S,112E  17
TAPE NO. = J41082   FILE NO. =   3

S-B NSS.LHRR.NG.D90010.S2228.E2234.B1722323.WI  CORNERS:   1N,121E   3
SCENE START = 22:28  DURATION =  6 MIN                    20S,116E  24
TAPE NO. = J41121   FILE NO. =   2

S-B NSS.LHRR.NG.D90010.S2229.E2232.B1722323.WI  CORNERS:   3S,121E   7
SCENE START = 22:29  DURATION =  3 MIN                    13S,118E  17
TAPE NO. = J41120   FILE NO. =   3

S-B NSS.LHRR.NG.D90013.S2301.E2306.B1726666.WI  CORNERS:   1N,113E   3
SCENE START = 23:01  DURATION =  5 MIN                    16S,109E  21
TAPE NO. = J41253   FILE NO. =   2

S-B NSS.LHRR.NG.D90014.S2238.E2244.B1728080.WI  CORNERS:   3S,118E   7
SCENE START = 22:38  DURATION =  5 MIN                    20S,113E  24
TAPE NO. = J41288   FILE NO. =   3

S-B NSS.LHRR.NG.D90015.S2215.E2221.B1729494.WI  CORNERS:   1N,125E   3
SCENE START = 22:15  DURATION =  6 MIN                    20S,119E  24
TAPE NO. = J41318   FILE NO. =   3

S-B NSS.LHRR.NG.D90018.S2248.E2253.B1733737.WI  CORNERS:   1N,117E   3
SCENE START = 22:48  DURATION =  5 MIN                    16S,112E  21
TAPE NO. = J41440   FILE NO. =   2

S-B NSS.LHRR.NG.D90018.S2249.E2251.B1733737.WI  CORNERS:   3S,116E   7
SCENE START = 22:49  DURATION =  2 MIN                    10S,114E  14
TAPE NO. = J41442   FILE NO. =   2

S-B NSS.LHRR.NG.D90019.S2217.E2228.B1735151.WI  CORNERS:   4N,123E   0
SCENE START = 22:24  DURATION =  4 MIN                    10S,120E  14
TAPE NO. = J41484   FILE NO. =   2

S-B NSS.LHRR.NG.D90019.S2226.E2230.B1735151.WI  CORNERS:   3S,121E   7
SCENE START = 22:26  DURATION =  4 MIN                    16S,118E  21
TAPE NO. = J41484   FILE NO. =   3

S-B NSS.LHRR.NG.D90022.S2257.E2303.B1739494.WI  CORNERS:   1N,114E   3
SCENE START = 22:57  DURATION =  6 MIN                    20S,108E  24
TAPE NO. = J41593   FILE NO. =   2
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S-B NSS.LHRR.NG.D90023.S2234.E2240.B1740808.WI  CORNERS:   1N,120E    3
SCENE START = 22:34  DURATION =  6 MIN                    20S,114E   24
TAPE NO. = J41632   FILE NO. =   3

S-B NSS.LHRR.NG.D90023.S2236.E2238.B1740808.WI  CORNERS:   6S,118E   10
SCENE START = 22:36  DURATION =  2 MIN                    13S,116E   17
TAPE NO. = J41635   FILE NO. =   3

S-B NSS.LHRR.NG.D90024.S2211.E2217.B1742222.WI  CORNERS:   1N,126E    3
SCENE START = 22:11  DURATION =  6 MIN                    20S,120E   24
TAPE NO. = J41675   FILE NO. =   2

S-B NSS.LHRR.NG.D90026.S2307.E2313.B1745151.WI  CORNERS:   1N,112E    3
SCENE START = 23:07  DURATION =  6 MIN                    20S,106E   24
TAPE NO. = J41756   FILE NO. =   2

S-B NSS.LHRR.NG.D90027.S2244.E2250.B1746565.WI  CORNERS:   4N,118E    0
SCENE START = 22:44  DURATION =  6 MIN                    16S,113E   21
TAPE NO. = J41796   FILE NO. =   2

S-B NSS.LHRR.NG.D90027.S2245.E2248.B1746565.WI  CORNERS:   1N,117E    3
SCENE START = 22:45  DURATION =  3 MIN                    10S,115E   14
TAPE NO. = J41804   FILE NO. =   2

S-B NSS.LHRR.NG.D90028.S2214.E2225.B1747979.WI  CORNERS:   4N,124E    0
SCENE START = 22:20  DURATION =  5 MIN                    13S,120E   17
TAPE NO. = J41837   FILE NO. =   3

S-B NSS.LHRR.NG.D90028.S2221.E2227.B1747979.WI  CORNERS:   1N,123E    3
SCENE START = 22:21  DURATION =  6 MIN                    20S,117E   24
TAPE NO. = J41836   FILE NO. =   3

S-B NSS.LHRR.NG.D90031.S2254.E2259.B1752222.WI  CORNERS:   1N,115E    3
SCENE START = 22:54  DURATION =  5 MIN                    16S,110E   21
TAPE NO. = J41949   FILE NO. =   2

S-B NSS.LHRR.NG.D90031.S2255.E2258.B1752222.WI  CORNERS:   3S,114E    7
SCENE START = 22:55  DURATION =  3 MIN                    13S,111E   17
TAPE NO. = J41946   FILE NO. =   3

S-B NSS.LHRR.NG.D90032.S2231.E2235.B1753636.WI  CORNERS:   1N,121E    3
SCENE START = 22:31  DURATION =  4 MIN                    13S,117E   17
TAPE NO. = J41994   FILE NO. =   3

S-B NSS.LHRR.NG.D90035.S2303.E2309.B1757979.WI  CORNERS:   3S,112E    7
SCENE START = 23:03  DURATION =  5 MIN                    20S,107E   24
TAPE NO. = J42112   FILE NO. =   3

S-B NSS.LHRR.NG.D90036.S2240.E2246.B1759393.WI  CORNERS:   3S,118E    7
SCENE START = 22:40  DURATION =  5 MIN                    20S,113E   24
TAPE NO. = J42145   FILE NO. =   2

S-B NSS.LHRR.NG.D90036.S2242.E2244.B1759393.WI  CORNERS:  10S,116E   14
SCENE START = 22:42  DURATION =  2 MIN                    16S,114E   21
TAPE NO. = J42145   FILE NO. =   3

S-B NSS.LHRR.NG.D90041.S2227.E2233.B1766464.WI  CORNERS:   3S,121E    7
SCENE START = 22:27  DURATION =  5 MIN                    20S,116E   24
TAPE NO. = J42345   FILE NO. =   2
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S-B NSS.LHRR.NG.D90041.S2228.E2231.B1766464.WI  CORNERS:     6S,120E    10
SCENE START = 22:28  DURATION =  3 MIN                      16S,117E    21
TAPE NO. = J42352    FILE NO. =  3

S-B NSS.LHRR.NG.D90044.S2302.E2305.B1770707.WI  CORNERS:    10S,111E    14
SCENE START = 23:02  DURATION =  3 MIN                      20S,109E    24
TAPE NO. = J42454    FILE NO. =  3

S-B NSS.LHRR.NG.D90045.S2229.E2240.B1772121.WI  CORNERS:     4N,120E     0
SCENE START = 22:35  DURATION =  5 MIN                      13S,116E    17
TAPE NO. = J42495    FILE NO. =  2

S-B NSS.LHRR.NG.D90046.S2213.E2219.B1773535.WI  CORNERS:     4N,126E     0
SCENE START = 22:13  DURATION =  6 MIN                      16S,120E    21
TAPE NO. = J42535    FILE NO. =  3

S-B NSS.LHRR.NG.D90049.S2246.E2251.B1777878.WI  CORNERS:     3S,116E     7
SCENE START = 22:46  DURATION =  5 MIN                      20S,111E    24
TAPE NO. = J42658    FILE NO. =  2

S-B NSS.LHRR.NG.D90049.S2247.E2250.B1777879.WI  CORNERS:     6S,115E    10
SCENE START = 22:47  DURATION =  3 MIN                      16S,112E    21
TAPE NO. = J42656    FILE NO. =  2

S-B NSS.LHRR.NG.D90050.S2223.E2229.B1779292.WI  CORNERS:     1N,123E     3
SCENE START = 22:23  DURATION =  6 MIN                  (XR   20S,117E   24S,1
TAPE NO. = J42693    FILE NO. =  3

S-B NSS.LHRR.NG.D90050.S2224.E2227.B1779292.WI  CORNERS:     3S,122E     7
SCENE START = 22:24  DURATION =  3 MIN                      13S,119E    17
TAPE NO. = J42691    FILE NO. =  2

S-B NSS.LHRR.NG.D90053.S2255.E2301.B1783535.WI  CORNERS:     4N,115E     0
SCENE START = 22:55  DURATION =  6 MIN                      16S,110E    21
TAPE NO. = J42819    FILE NO. =  3

S-B NSS.LHRR.NG.D90053.S2257.E2259.B1783535.WI  CORNERS:     3S,114E     7
SCENE START = 22:57  DURATION =  2 MIN                      10S,112E    14
TAPE NO. = J42822    FILE NO. =  3

S-B NSS.LHRR.NG.D90054.S2225.E2236.B1784949.WI  CORNERS:     4N,121E     0
SCENE START = 22:32  DURATION =  4 MIN                      10S,117E    14
TAPE NO. = J42867    FILE NO. =  2

S-B NSS.LHRR.NG.D90054.S2232.E2238.B1784949.WI  CORNERS:     4N,121E     0
SCENE START = 22:32  DURATION =  6 MIN                      16S,115E    21
TAPE NO. = J42867    FILE NO. =  3

S-B NSS.LHRR.NG.D90057.S2306.E2311.B1789292.WI  CORNERS:     3S,111E     7
SCENE START = 23:06  DURATION =  5 MIN                      20S,106E    24
TAPE NO. = J42982    FILE NO. =  3

S-B NSS.LHRR.NG.D90058.S2235.E2246.B1790606.WI  CORNERS:     4N,118E     0
SCENE START = 22:41  DURATION =  5 MIN                      13S,114E    17
TAPE NO. = J43020    FILE NO. =  3

S-B NSS.LHRR.NG.D90058.S2242.E2248.B1790606.WI  CORNERS:     1N,118E     3
SCENE START = 22:42  DURATION =  6 MIN                      20S,112E    24
TAPE NO. = J43020    FILE NO. =  2
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S-B NSS.LHRR.NG.D91038.S2246.E2252.B2281515.WI  CORNERS:    3S,113E    7
SCENE START = 22:46  DURATION =  5 MIN                    20S,108E   24
TAPE NO. = K06888   FILE NO. =  2

S-B NSS.LHRR.NG.D91039.S2223.E2228.B2282929.WI  CORNERS:    3S,119E    7
SCENE START = 22:23  DURATION =  5 MIN                    20S,114E   24
TAPE NO. = K06924   FILE NO. =  1

S-B NSS.LHRR.NG.D91040.S2159.E2205.B2284343.WI  CORNERS:    1N,126E    3
SCENE START = 21:59  DURATION =  6 MIN                    20S,120E   24
TAPE NO. = K06963   FILE NO. =  1

S-B NSS.LHRR.NG.D91043.S2230.E2236.B2288686.WI  CORNERS:    1N,118E    3
SCENE START = 22:30  DURATION =  6 MIN                    20S,112E   24
TAPE NO. = K07067   FILE NO. =  1

S-B NSS.LHRR.NG.D91044.S2207.E2212.B2290000.WI  CORNERS:    3S,123E    7
SCENE START = 22:07  DURATION =  5 MIN                    20S,118E   24
TAPE NO. = K07105   FILE NO. =  1

S-B NSS.LHRR.NG.D91047.S2238.E2244.B2294343.WI  CORNERS:    1N,116E    3
SCENE START = 22:38  DURATION =  6 MIN                    20S,110E   24
TAPE NO. = K07223   FILE NO. =  1

S-B NSS.LHRR.NG.D91051.S2246.E2251.B2300000.WI  CORNERS:    3S,113E    7
SCENE START = 22:46  DURATION =  5 MIN                    20S,108E   24
TAPE NO. = K07364   FILE NO. =  2

S-B NSS.LHRR.NG.D91052.S2222.E2228.B2301414.WI  CORNERS:    1N,120E    3
SCENE START = 22:22  DURATION =  6 MIN                    20S,114E   24
TAPE NO. = K07406   FILE NO. =  1

S-B NSS.LHRR.NG.D91053.S2159.E2205.B2302828.WI  CORNERS:    1N,126E    3
SCENE START = 21:59  DURATION =  6 MIN                    20S,120E   24
TAPE NO. = K07444   FILE NO. =  2

S-B NSS.LHRR.NG.D91057.S2207.E2212.B2308585.WI  CORNERS:    3S,123E    7
SCENE START = 22:07  DURATION =  5 MIN                    20S,118E   24
TAPE NO. = K07600   FILE NO. =  1

S-B NSS.LHRR.NG.D91060.S2238.E2243.B2312828.WI  CORNERS:    3S,115E    7
SCENE START = 22:38  DURATION =  5 MIN                    20S,110E   24
TAPE NO. = K07710   FILE NO. =  2

S-B NSS.LHRR.NG.D91061.S2214.E2220.B2314242.WI  CORNERS:    1N,122E    3
SCENE START = 22:14  DURATION =  6 MIN                    20S,116E   24
TAPE NO. = K07751   FILE NO. =  1

S-B NSS.LHRR.NG.D91064.S2245.E2251.B2318585.WI  CORNERS:    3S,113E    7
SCENE START = 22:45  DURATION =  5 MIN                    20S,108E   24
TAPE NO. = K07868   FILE NO. =  1

S-B NSS.LHRR.NG.D91066.S2158.E2204.B2321313.WI  CORNERS:    6S,124E   10
SCENE START = 21:58  DURATION =  4 MIN                    20S,120E   24
TAPE NO. = K07944   FILE NO. =  1

S-B NSS.LHRR.NG.D91068.S2252.E2258.B2324242.WI  CORNERS:    6S,111E   10
SCENE START = 22:52  DURATION =  4 MIN                    20S,107E   24
TAPE NO. = K08011   FILE NO. =  1
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S-B NSS.LHRR.NG.D91073.S2236.E2242.B2331313.WI  CORNERS:   1N,116E    3
SCENE START = 22:36  DURATION =  6 MIN                    20S,110E   24
TAPE NO. = K08202   FILE NO. =   2

S-B NSS.LHRR.NG.D91074.S2213.E2219.B2332727.WI  CORNERS:   1N,122E    3
SCENE START = 22:13  DURATION =  6 MIN                    20S,116E   24
TAPE NO. = K08243   FILE NO. =   2

S-B NSS.LHRR.NG.D91077.S2244.E2249.B2337070.WI  CORNERS:   3S,113E    7
SCENE START = 22:44  DURATION =  5 MIN                    20S,108E   24
TAPE NO. = K08344   FILE NO. =   2

S-B NSS.LHRR.NG.D91078.S2221.E2226.B2338484.WI  CORNERS:   6S,118E   10
SCENE START = 22:21  DURATION =  4 MIN                    20S,114E   24
TAPE NO. = K08383   FILE NO. =   2

S-B NSS.LHRR.NG.D91079.S2157.E2203.B2339898.WI  CORNERS:   3S,125E    7
SCENE START = 21:57  DURATION =  5 MIN                    20S,120E   24
TAPE NO. = K08424   FILE NO. =   1

S-B NSS.LHRR.NH.D91082.S0906.E1831.B1283541.WI  CORNERS:   2N,123E    2
SCENE START = 17:18  DURATION =  7 MIN                    21S,117E   26
TAPE NO. = K08541   FILE NO. =   1

S-B NSS.LHRR.NG.D91082.S2228.E2234.B2344141.WI  CORNERS:   6S,117E   10
SCENE START = 22:28  DURATION =  4 MIN                    20S,113E   24
TAPE NO. = K08549   FILE NO. =   2

S-B NSS.LHRR.NG.D91086.S2235.E2241.B2349898.WI  CORNERS:   3S,115E    7
SCENE START = 22:35  DURATION =  5 MIN                    20S,111E   24
TAPE NO. = K08697   FILE NO. =   1

S-B NSS.LHRR.NG.D91087.S2212.E2217.B2351212.WI  CORNERS:   6S,121E   10
SCENE START = 22:12  DURATION =  4 MIN                    20S,116E   24
TAPE NO. = K08734   FILE NO. =   1

S-B NSS.LHRR.NG.D91090.S2242.E2248.B2355555.WI  CORNERS:   1N,114E    3
SCENE START = 22:42  DURATION =  6 MIN                    20S,109E   24
TAPE NO. = K08843   FILE NO. =   1
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