PRELIMINARY CLOUD MICROPHYSICS STUDIES FOR TEXAS HIPLEX 1979

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Cloud microphysics studies made in connection with Texas HIPLEX 1979 are described. Any results, however, must be regarded as preliminary and subject to revision based on further work. The objective is to determine important natural precipitation mechanisms in summertime convective clouds in the Big Spring, Texas area. Studies are based on data collected by two instrumented aircraft. Operational procedures used for collecting data are described. Rules used for selecting clouds microphysically suitable for study are listed. A preliminary analysis of a cloud sampled on June 4 reveals a possible example of ice multiplication. Analysis of data collected on July 17 within and beneath a mesoscale convective system shows that when precipitation falls through subcloud air its temperature is decreased and dewpoint increased. From information on the development of ice and precipitation in seven clouds and from estimates of the precipitation from each cloud, a preliminary conclusion is drawn that the ice process is necessary for significant precipitation to occur.

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ABSTRACT

The first cloud microphysics studies made by Texas A&M University in connection with Texas HIPLEX are described. The studies are only beginning, and any results must be regarded as preliminary and subject to revision on the basis of further work. The aim of the studies is to determine the important natural precipitation mechanisms in summertime convective clouds in the Big Spring, Texas area. The studies are based on data collected by two instrumented aircraft in 1979. Operational procedures used for collecting data are described. Rules used for selecting clouds microphysically suitable for study are listed. The selection rules were met in over half the clouds, but for a fraction of the clouds either the top temperature was too low, the initial concentration of ice particles was too high, or precipitation was already underway. A preliminary analysis based on incomplete data of a cloud sampled on 4 June 1979 reveals a possible example of ice multiplication. Analysis of data collected on 17 July 1979 within and beneath a mesoscale convective system shows that when precipitation falls through subcloud air its temperature is decreased and dewpoint increased. This may be an example of the wet-bulb process operating within subcloud air or an example of penetration of potentially cold downdraft air into the subcloud region. From information on the development of ice and precipitation in seven clouds and from estimates of the precipitation from each cloud, a preliminary conclusion is drawn that the ice process is necessary for significant precipitation to occur. This conclusion strictly applies only to the clouds studied.

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1. INTRODUCTION

The overall objectives of the Texas A&M University (TAMU) cloud microphysics studies are:

1) to understand the important natural precipitation mechanisms in convective clouds in the Texas HIPLEX study region, and
2) to formulate and test rain enhancement hypotheses appropriate to these clouds.

Some progress toward Objective 1 is necessary before Objective 2 can be pursued. This report focusses on Objective 1. Progress to date is not sufficient to support a statement on appropriate rain enhancement hypotheses for convective clouds in the Texas HIPLEX study region.

The cloud microphysics studies presented in this report are the first to be made by Texas A&M University in connection with Texas HIPLEX. As such the studies are only a beginning and must be regarded as preliminary. Only a limited amount of the data collected has been studied, and those data which have been studied require more study. Any conclusions in this report with regard to precipitation mechanisms are not final and may be revised after further work.

The cloud microphysics studies presented in this report are centered on data collected in the field in the summer of 1979. Two instrumented aircraft flew from Big Spring Municipal Airport during the experimental period, May 21 to July 20, 1979, and collected data on the thermodynamic, kinematic, and microphysical properties of growing cumulus clouds in the area. These data were recorded in real time on magnetic tape. Subsequent to the field season the data were processed using appropriate computer programs. Some analyses of the data have been made. They are described here. The analyses shed some light on the important natural precipitation mechanisms in the clouds sampled.

Sections 4 and 6 are the most important part of this report. They contain the results of the data analyses. The reader familiar with cloud microphysics studies may wish to read these Sections first. Section 2 introduces the general scientific approach taken in studies of cloud microphysics data. This discussion may be of value to those not familiar with this type of work. Section 3 describes how data were collected in 1979, and Section 5 discusses the processing of the data from the p-Navajo aircraft for which TAMU was responsible. Salient points of this report are summarized in Section 7. Future plans are described in Section 8.

2. SCIENTIFIC APPROACH

The scientific approach of the cloud microphysics studies is now described. A brief review is first presented of the microphysical processes likely to occur in convective clouds in the Texas HIPLEX study area.

The microphysical processes are laid out in Fig. 1. This diagram is similar to one developed by Braham and Squires (1974); however, the present diagram differs in two respects. First, it includes recently acquired knowledge of cloud microphysical processes. Second, it focusses only on those processes likely to occur in the Big Spring, Texas area in the summertime. Represented in Fig. 1 are the Bergeron-Findeisen (ice) process, the warm rain (coalescence) process, and the more recently discovered process of ice multiplication. The items in upper case and/or underlined represent water substance in various forms or else condensation nuclei or ice nuclei. The items in lower case are processes whereby water substance is changed from one form to another. For example, if graupel melts it becomes cold rain. The arrows show the direction of a transformation or else show where particles of a given type come into a process.

The transformation of water substance to rain by the ice process is represented on this diagram by three different routes. Water vapor and condensation nuclei with either a continental or maritime spectrum enter a cloud through its base, and by nucleation and condensation are transformed into either a narrow or a broad spectrum of cloud droplets. As the droplets rise upward through the cloud they may eventually reach temperatures cold enough for a number of contact and/or immersion ice nuclei to be activated. The nuclei lead to heterogeneous freezing of some of the droplets. The frozen droplets then increase in size by diffusional growth from the vapor. Simultaneously, other ice nuclei may act as deposition nuclei and with their aid ice crystals may develop directly from the vapor. These ice crystals will increase in size by diffusional growth from the vapor.

Regardless which of the three processes for producing ice particles is dominant some particles develop in a cloud when the temperature becomes cold enough for ice nuclei to be activated. This may not happen at a temperature

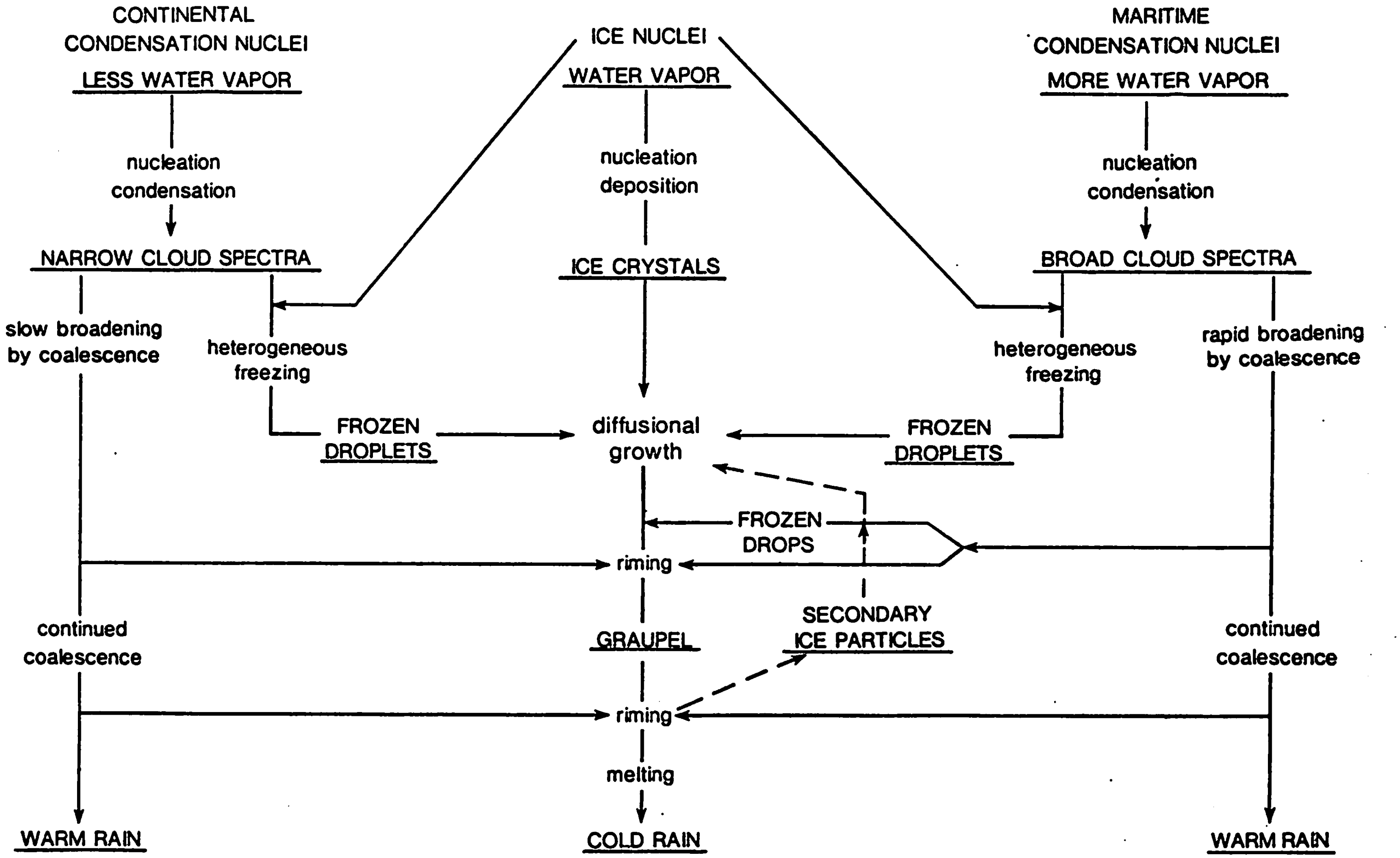

Fig. 1 Flow diagram of the major types of cloud and precipitation elements and of the physical processes through which they originate, grow, and interact. (Similar to diagram of Braham and Squires (1974).) See text for discussion.

as cold as -10C but often happens once the cloud top has reached a temperature of -15C and almost always happens by -20C. Once frozen droplets and/or ice crystals have diffusionally grown to sufficient sizes they may then collect some of the original cloud droplets by riming. Riming will eventually lead to the development of graupel. Graupel can grow further by riming. Once graupel falls below the 0C level it will melt and become rain. It is called "cold" rain because it originates through the ice phase.

The ice process was rather widely accepted for many years as the only mechanism by which precipitation could be produced. The alternative process of coalescence was believed to be too slow to be effective. The calculations made of the rate at which coalescence leads to precipitation were predicated, however, on a rather narrow cloud spectrum. The route to precipitation shown in the left side of Fig. 1 was assumed, and "warm" rain was indeed unlikely to occur.

It is now accepted that warm rain can, in fact, occur. The primary requisite is that there be a broad spectrum of cloud droplets. This spectrum most commonly exists if the distribution of condensation nuclei is what is called "maritime," but a droplet spectrum with a fair number of large droplets may also develop from a more "continental" nucleus spectrum if there is a high water vapor concentration. It is to allow for this latter possibility that the words "more water vapor" and "less water vapor" have been included near the top of Fig. 1. Regardless how an initially broad spectrum of cloud droplets is produced, the important point is that from such a spectrum coalescence by itself can produce rain.

It is important to note, that if there is a broad cloud droplet spectrum the frozen droplets that develop from heterogeneous freezing will tend to be larger than if there is a narrow spectrum. Less diffusional growth will be required of these larger droplets before they can grow by riming. The implication is that the Bergeron-Findeison or ice process may be accelerated if the cloud droplet spectrum is broader and more maritime in character.

In recent years it has become apparent that some clouds, particularly those with broader cloud spectra, contain what are called secondary ice particles (see Fig. 1). These are called secondary particles because their concentrations, of 1 ℓ^{-1} or greater at temperatures of -3C to -8C where they are prevalent, are about 1000 times greater than the average concentration of ice nuclei active at these warm temperatures. The particles apparently are produced by some process other than primary ice nucleation. Considerable effort has been expended in defining the conditions under which secondary ice particles are produced. The evidence suggests the particles are produced when droplets larger than 25μm diameter in concentrations greater than 10 cm^{-3} collide with graupel particles already present at temperatures of -3C to -8C. Although secondary particles are small initially they can grow diffusionally from the vapor (see Fig. 1) and then by riming and lead to more graupel particles. Some of the secondary particles may contact and cause to freeze some of those drops already present in the cloud of sizes large enough immediately to become rimers. Calculations have shown this latter process of graupel reproduction is faster than the process involving diffusional growth of the secondary particles. In either case there is a positive feedback process whereby graupel are rapidly reproduced or "multiplied" in a cloud. Ice multiplication may accelerate the development of significant concentrations of graupel, and it may accelerate the production of rain.

As stated, a minimum concentration of droplets larger than 25μm must be present for ice multiplication to occur. Such a concentration will more likely exist if there is a broad cloud droplet spectrum. It is for this reason that the possibility of secondary ice particles is included only in the right hand side of Fig. 1.

The first task of the TAMU cloud microphysics studies is to establish which of the several precipitation processes, shown in Fig. 1 and just described, operates in convective clouds in the Texas HIPLEX study region. Is the ice process necessary for precipitation in significant amounts, or will the warm rain process suffice? If the ice process turns out to be necessary, are broad spectra of frozen droplets, developed in part by coalescence, often present to accelerate the ice process? Does ice multiplication occur frequently, and what is its effect on the production of rain?

Any study of precipitation processes that is based on field work, such as the TAMU effort, fundamentally is a study of the end products of the precipitation processes, namely, the cloud and precipitation particles themselves. From knowledge gained about the particles inferences about the processes are drawn. Precipitation processes act to increase the overall size of condensed particles of water substance and the number of such particles. The precipitation processes may involve either liquid or solid particles, and the solid particles may have a structure, e.g. shape in the case of ice crystals and density in the case of graupel, that is important for the rate at which precipitation is produced. It is the intention of the TAMU cloud microphysics studies to examine the size, number (or concentration), phase, and structure of condensed particles within a cloud.

Cloud microphysics studies have two basic limitations, even though these studies can provide information on dominant precipitation mechanisms and can lead to precipitation augmentation hypotheses that are capable of being tested. First, cloud microphysics studies are based on a limited sample of data. Ideally, the studies should be based on data on every particle in the cloud, and data should be available at all times. This ideal data sample is not available in practice and probably never will be. Instead, particle information is available only along a few filamentary paths through the cloud, usually spaced several minutes apart in time and usually not successively placed in the same part of the cloud. Data are also limited on particle structure and on the 3-dimensional aspects of particle shape.

A second basic limitation of cloud microphysics studies is the lack of emphasis they usually place on the dynamic environment within the cloud in which the microphysics data are collected. (Information on the larger, mesoscale environment has been and is being collected in Texas HIPLEX and has important uses.) Information on the motions within a cloud is needed to establish, among other things, the dynamic support the cloud gives to particles while they grow and the expected lifetime of the cloud as a turbulent entity. Information on motions could aid in determining whether those natural microphysical processes, which may have been established to be the only ones of potential importance for precipitation, in fact, proceed at a rate fast enough for precipitation likely to occur.

Despite the two basic limitations of cloud microphysics studies just discussed, these studies can still provide much of the fundamental information needed on dominant precipitation processes.

Cloud microphysics (particle) data are more useful for deducing precipitation processes if they are collected at certain times during the life of a cloud and at certain positions within the cloud. General data collection guidelines have been established for Texas HIPLEX, as follows. Data should be collected early in the life of the cloud, when only droplets are present and before precipitation has begun to form, and data should be collected as particles pass through the transient stage between cloud droplet sizes (diameter in 10's of micrometers) and precipitation sizes (diameter in 1000's of micrometers), and finally data should be collected when precipitation has developed. Data should be collected aloft within a cloud, at levels colder than 0C but warmer than about -15C. In Texas HIPLEX those clouds are of marginal interest which never rise above the 0C level. The types of data to be collected at each stage in the life of the cloud are now described in more detail. Examples are given of the deductions to be made from the data.

Data collected early in the lifetime of a cloud, before precipitation has begun to form, include the liquid water content and concentration of cloud droplets, and the distribution (spectrum) of droplet diameters. The cloud droplet size distribution is useful in assessing the importance of the warm rain (coalescence) process in a particular cloud in 1) producing droplets which may eventually act as precipitation embryos, in 2) accelerating the ice process as described earlier, and in 3) providing the droplets necessary for the ice multiplication process. It is noted that the rate at which large droplets are being produced by the coalescence process is better estimated if droplet size distributions are available both from aloft within a cloud and from cloud base. A parameter also of importance early in the lifetime of the cloud is the amount and spatial distribution of liquid water in cloud droplets. Cloud liquid water content is especially important from an operational point of view because it serves as the source of condensed water from which precipitation ultimately has to form. An operational decision to study a cloud further will be based in part on the liquid water in cloud droplets.

Cloud droplet size distribution data can be collected with an optical light scattering probe such as the Particle Measuring Systems (PMS) Axially Scattering Spectrometer Probe (ASSP) or Forward Scattering Spectrometer Probe (FSSP). The Meteorology Research, Inc. (MRI) Navajo carried an ASSP in the 1979 field program. The ASSP detected particles in the 3 to 45µm size (diameter) range. Cloud liquid water content can be obtained by integrating the PMS cloud droplet size distribution or, less expensively, by use of a Johnson-Williams hot wire device (J-W probe). Both the MRI Navajo and the Colorado River Municipal Water District (CRMWD) p-Navajo carried J-W probes in the 1979 field program. It should be noted that the J-W probe does not provide cloud droplet spectra, and thus its data are not sufficient in themselves for a study of the precipitation processes.

Cloud microphysics data should also be collected on intermediate size particles, larger than cloud droplets but smaller than precipitation. Many particles which reach the intermediate size range of about 50 to 500µm will grow little during the remainder of their lifetimes. But an important fraction of these intermediate particles will grow further. They are the embryos for larger precipitation particles (raindrops and graupel). These embryos can be liquid drops growing by coalescence, and ice crystals growing diffusionally from the vapor. The relative concentrations and sizes of both types of embryos are measures of the relative importance and rate of action of the warm rain and ice processes in producing precipitation.

The relative importance of the warm rain and ice processes conceivably also could be determined by photographing or manually dissecting precipitation particles themselves and searching for the embryo. This is a difficult procedure when the precipitation is graupel and impossible when the precipitation is in the liquid form. Thus, there appears to be considerable value in obtaining data on the intermediate size cloud particles themselves prior to the time when some are incorporated as embryos into precipitation particles.

Intermediate particle data can be collected with a PMS Two-Dimensional Optical Array Particle Imaging Probe (2-D probe). The 2-D-C model of this probe provides complete shadowgraph images of particles from 25 to 800 µm diameter, provided they are centered in the field of view, and the probe provides incomplete but often useable images of larger and/or non-centered particles. Less complete data on intermediate particles can be collected with a PMS One-Dimensional Optical Array Particle Probe (1-D 200-X probe) covering the size range 20 to 300 μm. This probe provides information on particle sizes but no information on particle shapes. Particle shape permits deductions as to particle phase and better estimates of particle size distributions and water content. Data from the 1-D 200-X probe are of use despite these limitations. The MRI Navajo carried both a 2-D-C probe and a 1-D 200-X probe in the 1979 field program.

The 2-D probe data, in addition to permitting deductions about the relative importance of the warm rain and ice processes, also can be used to study how ice develops in a cloud. Comparison of ice particle concentrations with measured or climatologically-estimated ice nucleus concentrations should show whether ice multiplication is operating in a cloud. The shape and size of ice crystals can show at what temperature levels the crystals have been growing by diffusion from the vapor and whether they are large enough to grow by riming as well. It is noted that positive evidence of riming to date requires visual examination of ice crystals themselves. Ice crystals can be collected on oil-coated slides exposed in an air-decelerating tube mounted on the outside of the aircraft. Such instrumentation was not available in the Texas HIPLEX 1979 field program.

Cloud microphysical data should also be collected on precipitation particles. Precipitation water content is important as a measure of how much precipitation a cloud will produce. Data from temperatures colder than 0C on the liquid (super-cooled raindrop) or solid (graupel) nature of the precipitation can be direct evidence as to which of the warm rain or ice processes is operating. The validity of the deduction would depend on what evidence is available with regard to recirculation of precipitation through temperatures warmer than 0C and back to colder levels.

Precipitation particle data can be collected with a PMS 2-D-P probe covering the size range 200 to 6400 μm. It is noted that the 2-D-C probe covering the 25 to 800 μm range provides better resolution of the smaller and more irregular precipitation particles. Less complete data on precipitation particles can be collected with a PMS 1-D 200-Y probe covering the size range 300 to 4500 μm. The MRI Navajo carried a 1-D 200-Y probe in the 1979 field program.

The focus of the TAMU cloud microphysics studies is therefore on the condensed elements of water substance. They are the end products of the precipitation processes, and given suitable analysis should serve as evidence of the nature of these processes.

Some indirect evidence can be accumulated in support of the cloud microphysics studies. This evidence includes the following:

(a) cloud base temperature and concentration of droplets,
(b) difference in height between cloud base and freezing level,
(c) cloud-top temperature when significant concentrations of ice first develop,
(d) cloud top temperature when significant precipitation first develops, and
(e) temperature at the height of a first echo.

The first two pieces of evidence are indirect indicators of the size of cloud droplets that can be produced by condensation and coalescence in a cloud and, thus, suggest whether warm rain is likely. The third piece of evidence suggests whether ice multiplication is operating. The last two pieces of evidence suggest whether the ice process is required for precipitation.

The preceding material illustrates the strongly field-experimental approach being taken in the scientific work. This experimental emphasis requires extra care in the collection of data. Data must be collected prior to the formation of any precipitation in a cloud, but for the sake of efficiency in clouds in which precipitation is likely to form. Data must then continue to be collected through the precipitation stage, so that all links in the precipitation chain can be determined. Advanced and reliable measurement systems must be employed.

3. DATA COLLECTION

Cloud microphysics data in 1979 were collected with two instrumented aircraft (MRI Navajo and CRMWD p-Navajo). A third aircraft (CRMWD Aztec) was used for qualitative cloud and precipitation observations. The p-Navajo and the Aztec were able to seed clouds with pyrotechnics. Tables 1 and 2 list the variables measured and recorded by the MRI Navajo and p-Navajo. By virtue of its relatively complete set of instrumentation the MRI Navajo was the primary cloud microphysics data-gathering system in 1979. Data from the instrumented aircraft were recorded on 9-track magnetic tape.

The MRI Navajo made two tapes on each flight. One tape contained PMS 2-D-C probe data exclusively. The second tape contained the other cloud microphysics data as well as meteorological data. MRI Navajo data also included hand-written notes, voice recording by the on-board observer, 35 mm still photographs, and 16 mm movies from a forward-facing camera. All MRI Navajo data should be available through the Water and Power Resources Service in Denver.

The p-Navajo made one tape on each flight. Sometimes a second tape was made if a computer restart was required in flight. Copies of these data tapes should be available from the Water and Power Resources Service. Much of the 9-track p-Navajo data were simultaneously recorded on magnetic tape cassettes for use in post-flight checks of data quality or for quick looks at the data from the tower fly-bys. These cassettes are stored at Texas A&M University. The p-Navajo data also included the hand-written notes and still photographs of the TAMU scientist on board. Responsibility fell to TAMU for post-flight processing of the p-Navajo data. This work is described in Section 4 of this report.

Data from the Aztec consisted of hand-written notes of visual observations of the intensity and areal extent of precipitation and notes of the updraft, downdraft, and ambient air temperature as provided by the standard aircraft flight systems.

One basic flight pattern was used in the 1979 cloud microphysics studies. A single straight-line path was flown back and forth through a chosen cloud or turret. A 90°/270° standard turn was made at the end of each leg to place the aircraft on a reciprocal path. This flight pattern

Table 1. Variables measured and recorded by MRI Navajo in 1979 Texas HIPLEX field program.

Concentration and size distribution of cloud droplets
(PMS ASSP 3μm to 45μm in 3μm intervals)

Concentration and size distribution of intermediate size particles
(PMS 1-D 200-X probe, 20μm to 300μm in 20μm intervals)

Concentration and size distribution of precipitation size particles
(PMS 1-D 200-Y probe, 300μm to 4500μm in 300μm intervals)

Particle images (PMS 2-D-C probe, 25μm to 800μm with 25μm resolution)

Liquid water content in cloud droplets (Johnson-Williams hot wire)

Ice particle concentration (model of Turner-Radke laser device)

Air temperature (Rosemount total temperature probe)

Dewpoint (E.G. & G. hygrometer)

Absolute pressure (Validyne absolute pressure transducer)

True airspeed (Validyne differential pressure transducer)

Vertical air speed (Ball Bros. variometer and pitot-static probe system)

Turbulence (MRI Universal Indicating Turbulence System)

Location (Dual Digital VOR/DME)

Heading (Humphrey gyro compass)

Table 2. Variables measured and recorded by p-Navajo in 1979 Texas HIPLEX field program.

Cloud liquid water content (Johnson-Williams hot wire)

Total liquid water content (copy of Merceret-Schricker hot wire)

Ice particle concentration (CIC/Lawson laser device)

Air temperature (Rosemount total temperature probe and NCAR-type reverse flow probe)

Dewpoint (E.G. & G. hygrometer)

Absolute pressure (Cognition absolute pressure transducer)

True airspeed (Cognition differential pressure transducer)

Location (HT Instruments VOR; aircraft avionics DME) was used in sampling (collecting data on) isolated cumulus congestus clouds (Fig. 2) and growing turrets associated with convective (thunderstorm) complexes (Fig. 3). The isolated clouds had higher priority for study but when they were not available the growing turrets were sampled instead.

Selection of a cloud for sampling was based on information collected on an initial pass through the cloud, made in most cases at the -10C level. The TAMU scientist aboard the p-Navajo selected most clouds. The cloud selection rules are listed in Table 3. These rules were developed at the beginning of the field program to provide quantitative guidelines for cloud selection. Most clouds selected for sampling also were selected for "treatment". Treatment meant seeding or not-seeding a cloud according to instructions. Once a cloud had been selected for treatment the flight became known as a "HIPLEX mission".

Selection of a cloud for treatment was communicated by radio to the other aircraft involved in a HIPLEX mission. The MRI Navajo then made an initial data-gathering pass through the cloud. Also following the decision to treat a cloud, an envelope was opened, by prearrangement by either the pilot of the p-Navajo or by the pilot of the Aztec, and this envelope contained instructions on whether to seed the sampled cloud and, if so, at what rate (number of flares per second). Thirty (30) gram Nuclei Engineering Inc. (NEI) pyrotechnic flares could be dropped into the cloud from the p-Navajo, or twenty (20) gram NEI flares could be burned at cloud base by the Aztec. Following the initial MRI Navajo data-gathering pass the cloud was seeded or not in accordance with the written instructions. All aircraft then commenced to collect data on the cloud as it evolved. Data collection continued until the cloud had dissipated or had become too severe for further penetration. Data collection passes were to be made along the ambient (500 mb) wind direction. The seeding pass was to be in a cross wind direction. Safety was the prime consideration on all flights, and radio contact and, if possible, visual contact between aircraft was maintained so as to ascertain their whereabouts. This contact also helped ensure the aircraft collected data on the same cloud.

A number of flights were made which did not fit the above description and, hence, did not come under the heading "HIPLEX mission". On some flights no clouds were found suitable for microphysics studies. These since have been called "reconnaissance" missions. The "tower fly-by" was employed once early and once late in the season to check the p-Navajo

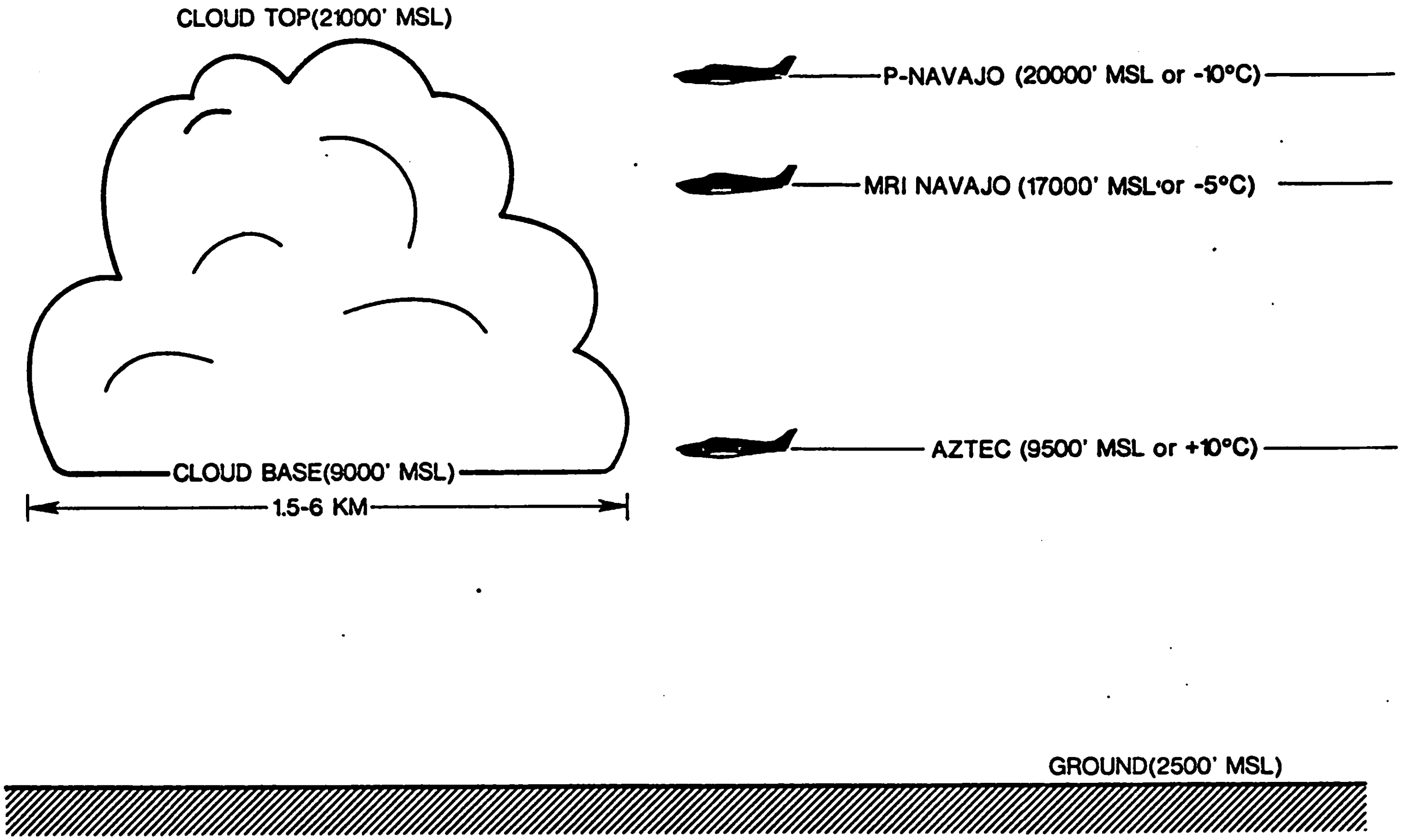

Fig. 2. Flight pattern for sampling an isolated cumulus congestus cloud in 1979 Texas HIPLEX field program. The three aircraft flew back and forth through a cloud along a straight line with reciprocal turns at each end. Temperature levels are those attempted but were not always achieved. See text for discussion.

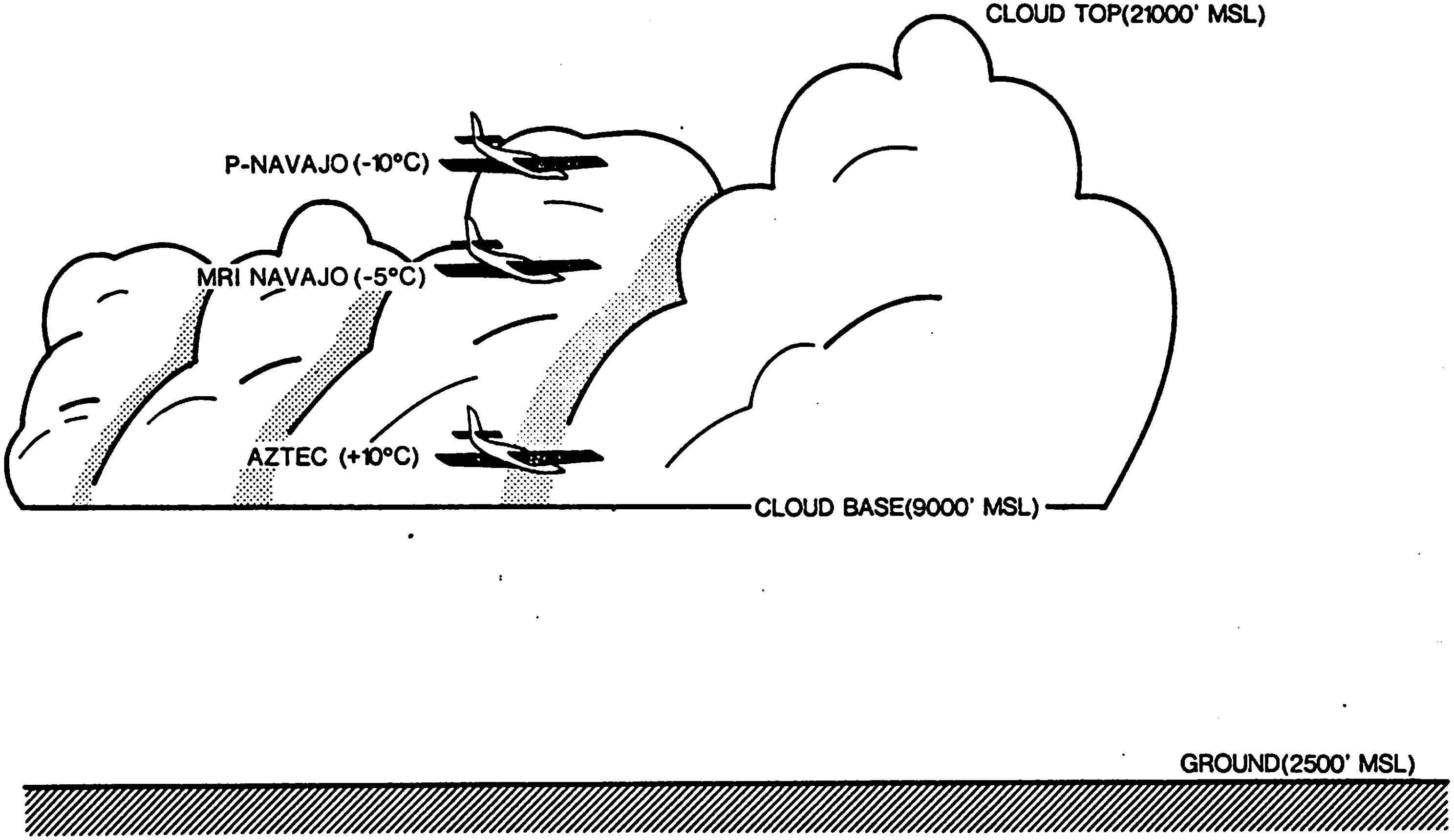

Fig. 3. Flight pattern for sampling a growing turret in a convective complex in 1979 Texas HIPLEX field program. The three aircraft flew back and forth through a turret along a straight line with reciprocal turns at each end. Temperature levels are those attempted but were not always achieved. See text for discussion.

Table 3. Cloud selection rules for 1979 HIPLEX missions

1. Cloud top no colder than about -10C.

2. No precipitation size particles (precipitation water content = 0 g m^{-3}).

3. Peak ice particle concentration no higher than 10 ℓ^{-1} at -10C.

4. Cloud liquid water content of at least 1 g m^{-3} somewhere on the initial pass.

5. Updrafts of at least 2.5 m s^{-1} (500 ft. min^{-1}).

and MRI Navajo measurements of temperature, dewpoint, and absolute pressure. A precision-grade aneroid barometer and an Assmann psychrometer were carried to the top of a tower near the Big Spring Municipal Airport. Their data provided a standard against which to judge the accuracy of aircraft data collected on low-level passes by the tower. "Intercomparison" flights were also used to check instrumentation. The two Navajo aircraft flew in close formation, usually in clear air, and collected simultaneous data on temperature, dewpoint, and absolute pressure. One flight was made in-cloud to obtain comparison data for ice particle concentrations.

In addition to the HIPLEX missions and those directly supporting them just described, other missions were flown to obtain data on 1) the mesoscale temperature, humidity and motion field in the environment around convective clouds, and on 2) the drop size-radar reflectivity (Z-R) relationships applicable for precipitation in the study area. Both Navajo aircraft were involved in the first type of mission. The MRI Navajo was the only aircraft equipped for Z-R studies.

Table 4 summarizes the number of missions and flight hours flown by each aircarft in the 1979 field program. Only those missions are included on which data actually were collected or were intended to be collected. Instrument test missions are excluded. On some flights more than one type of mission was flown, e.g. both mesomapping and Z-R. These missions are counted separately in Table 4, and flight hours are fractionally allocated. Table 4 shows that the HIPLEX mission took up somewhat less than half the flight hours. Reconnaissance missions comprised a significant part of the total. This large fraction of missions unsuccessful in obtaining cloud microphysics data shows it is important to have a large total number of missions so that after unsuccessful missions have been deleted there still remains a useful number of data gathering missions. The total number of flight hours flown in 1979 was only about half that budgeted for the various aircraft. This was mainly due to poor weather. Either no clouds were present at all, or else an NWS severe weather watch or warning was in effect for the study area. In the latter case all aircraft were automatically grounded.

Table 5 provides additional summary information on the cloud microphysics missions conducted in 1979. Included are the 9 HIPLEX missions plus one other mission, on 5 June, on which cloud sampling but no treatment was

Table 4. Summary of aircraft data-gathering missions in 1979 Texas HIPLEX field program

Mission Type	p-Navajo		MRI Navajo		Aztec	
	No. Hrs.	No. Missions	No. Hrs.	No. Missions	No. Hrs.	No. Missions
HIPLEX	14.3	8	12.5	7	10.1	6
Reconnaissance	6.6	6	13.4	8	7.0	5
Tower Fly-by	2.3	2	1.9	2	--	--
Intercomparison	2.0	3	2.0	3	--	--
Meso-mapping	4.5	3	1.7	1	--	--
Z-R	--	--	2.2	3	--	--
	29.7	22	33.7	24	17.1	11

Table 5. Summary of cloud microphysics missions in the 1979 Texas HIPLEX field program.

HIPLEX mission number	Date	Time period of greatest interest (GMT)	Data tape numbers	Comments
1	4 June (1)	1919-2000	MRI904 M2D904 P19155	MRI Navajo sampled two turrets in a line, the first 4 times and the second 3 times. The second turret was selected for treatment. The p-Navajo seeded this turret with 2 flares.
2	4 June (2)	2238-2256	MRI905 M2D905	Isolated towering cumulus on SW side of complex sampled 4 times by p-Navajo and twice by MRI Navajo. Cloud top temperature < -15C. Precipitation process well underway. p-Navajo data system inoperative. MRI data system had problems. Aztec burned 12 flares at cloud base.
—	5 June (1)	2044-2100	MRI906 M2D906 P19156	MRI Navajo sampled an isolated towering cumulus 3 times before it dissipated.
3	25 June	2053-2141	MRI909 M2D909	p-Navajo sampled an isolated towering cumulus 6 times. Cloud top temperature < -15C and graupel present. Precipitation process well underway. p-Navajo also sampled a turret rising from broken altocumulus 4 times. p-Navajo dropped 7 flares into this turret on first pass and 8 flares into it on second pass. IPC had problems. Only p-Navajo data are on tape cassettes.

Table 5. (continued)

HIPLEX mission number	Date	Time period of greatest interest (GMT)	Data tape numbers	Comments
4	3 July (1)	2227-2254	MRI910 M2D910 P191841	One turret in a cluster sampled 4 times by p-Navajo and 3 times by MRI Navajo. p-Navajo data system inoperative on last 2 passes. No seed case.
5	3 July (2)	0108-0207 (on 4 July)	MRI911 M2D911 P191842	Isolated towering cumulus in a line sampled 14 times by p-Navajo and 10 times by MRI Navajo. Aztec made 8 passes below cloud base. p-Navajo dropped 9 flares into cloud top. p-Navajo IPC inoperative. Possibly best case of season.
6	5 July (1)	1856-1922	MRI912 M2D912 P191861	p-Navajo sampled 3 turrets 3 times each in a region of clustered towering cumulus. No seed case.
7	5 July (2)	2014-2042	MRI913 M2D913 P191861	Turret growing from altocumulus sampled 5 times by p-Navajo and 6 times by MRI Navajo. Aztec near cloud base. p-Navajo dropped 4 flares into top of turret. Natural seeding possible from cirrus anvil overhead associated with Cb to northeast. MRI Navajo sampled cloud in IFR conditions using on-board radar for guidance.

Table 5. (continued)

HIPLEX mission number	Date	Time period of greatest interest (GMT)	Data tape numbers	Comments
8	8 July (1)	2122-2202	MRI915 M2D915 P191891 P191892	MRI Navajo sampled 1 turret in a line 5 times. Aztec burned 12 flares at cloud base.
9	15 July	2124-2140	MRI919 M2D919 P191961 P191962	Isolated towering cumulus sampled 5 times by p-Navajo and 3 times by MRI Navajo. Cloud was short-lived due to dry air entrainment. No seed case.

performed. Listed is the period of time containing potentially the most interesting data and the identifying numbers for the p-Navajo and MRI Navajo data tapes. A few descriptive comments on each mission are included. More important data system problems are mentioned.

No more detail on individual missions and other aircraft flights is provided at this point. Reference is instead made to a TAMU Interim Technical Report entitled "Aircraft Operations in the 1979 Texas HIPLEX Field Program" submitted to the Texas Department of Water Resources in August 1979 under TDWR Contract No. 14-90026. The report briefly describes some of the aircraft instrumentation problems and the format of the data collected. The bulk of the report describes in detail each aircraft mission with emphasis placed on cloud observations. The mission descriptions are based mainly on the notes of the various aircraft observers. The intent of that report is to present enough information for others to be able to judge whether to study a given mission in depth.

4. ANALYSIS OF CLOUD SELECTION

Analyses have been made of the HIPLEX missions to determine whether the clouds selected for sampling and treatment were of the correct type and met the selection rules listed in Table 3.

Clouds selected for sampling and treatment were required to be either isolated growing cumulus congestus or growing turrets associated with a convective complex. Table 6 lists the types of clouds actually selected in 1979. Six of the nine missions involved clouds of a correct type, but on HIPLEX missions 3 and 7 turrets growing from altocumulus were sampled, and on HIPLEX mission 4 sampling and treatment was conducted on a short-lived turret building up to the -10C level from amongst a group of such turrets, none of which could have been called a cumulus congestus.

Equally important as the requirement that the cloud be of the correct type was that it meet the selection rules listed in Table 3. It is important to sample and treat a cloud prior to precipitation development, and rules 1, 2, and 3 reduced the chance that at the start of cloud sampling and treatment the ice process had already got underway and precipitation had developed. Rules 4 and 5 helped ensure a good source of liquid water from which precipitation could develop later and helped ensure good dynamic support for particles as they grew. The analysis presented here of how well the clouds sampled and treated in the HIPLEX missions met the selection rules, besides serving as a post facto assessment of how well cloud selection procedures were followed, also provides useful background information on the clouds in support of later analyses in this report.

At the time this report is being written the analysis has been based only on first-pass MRI Navajo data. In basing the analysis on first-pass MRI Navajo data it is important to note that cloud selection in most cases was made on the basis of p-Navajo data, and these data were collected prior to the first MRI Navajo pass through a cloud. It is important then to establish just how much time elapsed until the MRI Navajo made its first pass. It is important also to establish that the MRI Navajo first pass was made prior to any seeding. Table 7 gives the elapsed time from cloud selection to first MRI Navajo pass and to seeding. On average two minutes elapsed to first pass and three minutes to seeding. In every

Table 6. Types of clouds selected in 1979 HIPLEX missions.

HIPLEX mission number	Date	Type of cloud treated
1	4 June (1)*	Growing turret associated with a convective complex
2	4 June (2)	Isolated growing cumulus congestus
3	25 June	Turret growing from altocumulus
4	3 July (1)	One turret in a cluster of short-lived turrets
5	3 July (2)	Isolated growing cumulus congestus
6	5 July (1)	Growing turret associated with a convective complex
7	5 July (2)	Turret growing from altocumulus
8	8 July	Growing turret associated with a convective complex
9	15 July	Isolated growing cumulus congestus

*Parenthetical number denotes whether the mission is the first (1) or second (2) on this date.

Table 7. Elapsed time from cloud selection to first MRI Navajo pass and to cloud seeding.

HIPLEX mission number	Date	Time of first pass of MRI Navajo minus cloud selection time (min)	Time of seeding pass minus cloud selection time (min)
1	4 June (1)	0	3
2	4 June (2)	0	4
3	25 June	no pass by MRI Navajo	0
4	3 July (1)	5	no seed
5	3 July (2)	3	6
6	5 July (1)	no pass by MRI Navajo	no seed
7	5 July (2)	1	2
8	8 July (1)	0	4
9	15 July	4	no seed

relevant case the MRI Navajo made a pass prior to seeding. Thus although the MRI Navajo data are no substitute for the p-Navajo cloud selection data, the MRI Navajo data nevertheless provide a picture of the initial state of the selected clouds from which we can judge whether the selection rules were met.

Table 8 summarizes the initial states of the selected clouds. It is important to note that except on HIPLEX mission 6 only a single cloud was selected on each mission, and Table 8 applies to these single clouds. The MRI Navajo usually penetrated a cloud at a temperature of -1C to -3C. This was warmer than the planned -5C and was directly attributable to the inadequate performance of the heavily instrumented aircraft. Because the cloud selection rules assume a penetration temperature of -10C (the flight level of the p-Navajo) it will be necessary at places in the discussion below to extrapolate some of the data to this colder level.

Most cloud top temperatures in Table 8 were estimated from the height of cloud top above the p-Navajo on its first penetration through the cloud. In mission 8 the MRI Navajo penetrated the cloud at a temperature of about -3C. The cloud top was estimated to be at 7.9 km (26,000 ft) MSL or 3 km (10,000 ft) above flight level. This led to the rough cloud-top temperature estimate of -20C. On most missions the cloud top temperature was near that required. But on mission 2 the cloud top was too cold, and graupel was observed on the initial pass. On mission 8 the cloud top was again too cold, and precipitation was already well underway.

Precipitation water content (WC) in Table 8 includes all particles of 300 μm diameter or larger detected by the PMS 1-D 200-Y probe on the MRI Navajo. In calculating the water content it is assumed that all particles are liquid, but since some particles would have been ice the water contents shown in Table 8 are overestimates. Precipitation was sparse in most clouds. A peak value of 0.20 g m^{-3} was observed in mission 5, but the average value was only 0.04 g m^{-3}. The concentration of precipitation particles reached almost 100 m^{-3} at one point in this cloud. Apparently precipitation had begun to develop. The cloud in mission 8 showed a large amount of precipitation in its initial state. This is consistent with the low cloud-top temperature. In retrospect this cloud should not have been selected.

Table 8. Initial states of selected clouds.

HIPLEX mission number	Date	MRI Navajo cloud penetration temperature (°C)	Estimated cloud top temperature (°C)		Precipitation		Ice Particles Conc. (ℓ^{-1})	Cloud Droplets		Vertical Motion $(m\ s^{-1})$
					WC $(g\ m^{-3})$	Conc. (m^{-3})		LWC $(g\ m^{-3})$	Conc. (cm^{-3})	
1	4 June (1)	-4 to -6	-12	Max.	.01	17	0.5	2.1	900	-9, +10
				Ave.	0	7	0.1	1.0	500	-5, + 8
2	4 June (2)	-1 to -4	-16	Max.	.01	24	5.5	1.2	1500	-3, + 5
				Ave.	0	9	3.4	0.7	900	-2, + 3
3	25 June	—	-10	only p-Navajo data collected; data not yet available for analysis						
4	3 July (1)	-1 to -2	-10	Max.	.01	51	*	1.0	1300	-3, + 0
				Ave.	0	16	*	0.4	550	-2, + 0
5	3 July (2)	-1 to -3	-11	Max.	.20	95	1	2.1	1450	-2, + 8
				Ave.	.04	50	0	1.3	1000	-2, + 4
6	5 July (1)	—	-10	only p-Navajo data collected; data not yet available for analysis						
7	5 July (2)	-1 to -3	-10	Max.	.02	31	53	2.1	1350	-4, + 4
				Ave.	0	7	13	0.8	700	-2, + 2
8	8 July (1)	-1 to -3	-20	Max.	3.15	1500	27	2.1	1300	-7, + 8
				Ave.	0.5	300	5	0.5	400	-3, + 4
9	15 July	+1 to -1	-10	Max.	.04	13	2.5	1.9	1000	-8, +11
				Ave.	.01	4	2.3	1.2	650	-5, + 4

* No useable ice particle concentrations are available due to an apparent malfunction of the MRI Navajo ice particle counter.

Ice particle concentration was less than 10 ℓ^{-1} in most clouds. Note, however, that all concentrations were measured at temperatures warmer than -10C. If ice crystal concentrations are related to ice nucleus concentrations according to the climatological rule (factor of 10 increase in concentration for every 4C decrease in temperature), one would expect greater ice particle concentrations at -10C. In most cases the concentration would have been greater than the permitted 10ℓ^{-1}. Whether the concentrations would have followed this rule will depend on whether ice multiplication was operating in the cloud. If ice multiplication were occurring it would predominate over the temperature effect on crystal concentration. The p-Navajo data when they become available probably will not shed much light on the true ice particle concentration at the -10C level because the data were collected with an ice particle detector with operational problems (susceptibility to electronic noise, production of false data). Because the MRI Navajo ice particle detector was of closely similar design to the p-Navajo detector, data from the MRI instrument must be questioned as well. Prior experience of MRI personnel with the MRI instrument in other projects does lend some credence to its data, however, and they have thus been included in Table 8. The question of ice particle concentration on the initial cloud passes should be deferred at least until the MRI Navajo PMS 2-D-C probe particle images are available.

The liquid water content in cloud droplets (diameters of 3 to 45μm) was at least 1 g m^{-3} somewhere in each selected cloud. The average value was about one-half the maximum or peak value. The average value includes the entire cloud pass and not just those regions where most cloud water was located. In these latter regions the liquid water had close to a "top-hat" profile. All clouds were fairly similar in droplet concentration. It exceeded 1000 cm^{-3} in six of the seven clouds. This high concentration should not be interpreted as implying a highly continental chracter for the droplet distribution. In fact, the liquid water content was fairly high and the volume equivalent droplet diameter was 11 to 12 m in most of the clouds.

Observed vertical motions in the clouds varied from several meters per second upward to several meters per second downward. The upward motions if valid would be adequate to support particles until they had grown to precipitation sizes. The magnitude and even the sign of the derived air motions is in doubt, however, because only a variometer was used. This conclusion is supported by the observation of strong downdrafts in many of the clouds. Such strong downdrafts are usually observed in connection with significant precipitation, and significant precipitation was observed in only one of the clouds at the time the data were collected.

In summary, Table 8 shows that not all the clouds selected for sampling and treatment met the selection rules. In some cases the cloud top was too cold, in other cases precipitation had already begun, and in still other cases the concentration of ice particles was too high.

5. DATA PROCESSING

Data were collected in a variety of forms each requiring its own type of processing. Data from the p-Navajo are discussed here. Data from the other two aircraft did not come under the responsibility of TAMU and are not discussed.

Texas A&M University assumed responsibility for processing the p-Navajo 9-track magnetic data tapes shortly after the conclusion of the 1979 field program. This was an outgrowth of the involvement of TAMU personnel in the data collection operation. Data processing responsibility was assumed due to a shortage of personnel at the Water and Power Resources Service (WPRS) who were originally to do the work. A WPRS computer terminal at Big Spring was brought to College Station November 1, 1979 and processing of the data commenced. This report does not describe all the steps taken in processing the data. Rather it simply lists the computer program developed for processing the data. This program is an outgrowth of one developed by CIC and WPRS personnel prior to the field program. Errors in that program have been removed, logic has been improved, and modifications have been made to allow for hardware problems in recording the data. The p-Navajo data processing program is an indirect access permanent file PNAV79 stored in the WPRS CYBER computer system in Denver. It is accessible with a simple control language routine. The program appears in the Appendix.

6. DATA ANALYSES

Cloud microphysics data can be analyzed in at least two ways. The case study analysis uses all the data for a single cloud and develops a comprehensive and detailed picture of the cloud from the time when it contained only cloud droplets, to when it was precipitating, and finally to when it was dissipating. The primary value of a case study lies in the detail included. This detail increases in proportion to the available data. A weak point of the case study is that it applies only to a single cloud. The conclusions drawn may not be applicable to a population of clouds. Statements about a population must be based on a statistical analysis of cloud properties. This second kind of cloud microphysics analysis brings together the data on a large number of clouds and attempts to identify important similarities and differences in the clouds. Single clouds can then be put in perspective. A statistical analysis of cloud properties increases with the number of clouds included. Thorough analysis of cloud microphysics data includes both the case study and the statistical approaches. This two-pronged effort is being pursued at TAMU. Some preliminary results of both types of analyses are described in this Section.

Exploratory analyses have been made of many of the clouds sampled in the 1979 field program. Graphs have been developed of the MRI Navajo data showing how important cloud microphysical and meteorological parameters vary along each pass through each cloud sampled. Graphs have not yet been developed for clouds sampled on HIPLEX missions 3 and 6 on 25 June 1979 and 5 July (1), respectively. Data on these two missions were collected only by the p-Navajo, and the data are not yet available. Based on the graphs constructed of the MRI Navajo data summary descriptions have been written of each cloud sampled in the 1979 field program, except for those clouds sampled on the two HIPLEX missions just mentioned and on the two HIPLEX missions (4 and 5) conducted on 3 July 1979. These descriptions are not included in this report as they are in preliminary draft form only and for completeness must await the p-Navajo data.

Included in the present report, however, is an extended description based on work to date of the first cloud sampled on 4 June 1979 (1). The two clouds sampled on this mission have been selected for case study by Texas HIPLEX participants. The mesomapping mission on 17 July 1979 was also selected for case study. Results for it obtained to date are also included here. The results presented here for both dates are fragmentary and do not in themselves constitute case studies. The case studies will incorporate data from all sources.

a. 4 June 1979 (1). On this mission significant data were collected on two clouds, A and B. Cloud A was penetrated 4 times by the MRI Navajo from 1920* to 1935 GMT. Cloud B was penetrated 3 times from 1945 to 1959 GMT. Cloud B was selected for treatment as well. The analysis so far has focussed on cloud A (not selected for treatment), and it is the preliminary results of this analysis that are reported here. The analysis is based on the MRI Navajo data alone. The p-Navajo did not arrive on station until about 1935 GMT and sampled only cloud B.

Figure 4 shows the flight track of the MRI Navajo in its four penetrations of cloud A. This track was determined from the recorded range and azimuth of the MRI Navajo relative to the Big Spring VOR/DME. Of the four passes shown in Fig. 4 only passes 2 and 3 were nearly coincident. It is possible to calculate the speed of movement of the central point of each of passes 1, 2, and 3 required for it to lie at the central point of the next successive pass. The required speed is 46 km hr^{-1} between passes 1 and 2, 32 km hr^{-1} between passes 2 and 3, and 50 km hr^{-1} between passes 3 and 4. Evidence from pass 2 presented below of precipitation falling through a region of neutral to positive buoyancy in the cloud suggests little wind shear during the sampling period. Little wind shear is compatible with little translational movement of the cloud and suggests that passes 2 and 3 were made through nearly the same part of the cloud but that passes 1 and 4 were through substantially different regions. Local rawinsonde wind data should shed more light on the movement of cloud A. Figures 5, 6, 7, and 8 display the data collected by the MRI Navajo on passes 1, 2, 3, and 4. These graphs will now be examined.

Pass 1 (see Fig. 5) occurred from 192040 to 192124 GMT along a heading of approximately 265 deg magnetic at a true air speed of approximately 90 m s^{-1}. An extensive region of positive buoyancy (temperature excess)

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*The first two digits are hours, and the second two are minutes. If a third set of digits appears it refers to seconds.

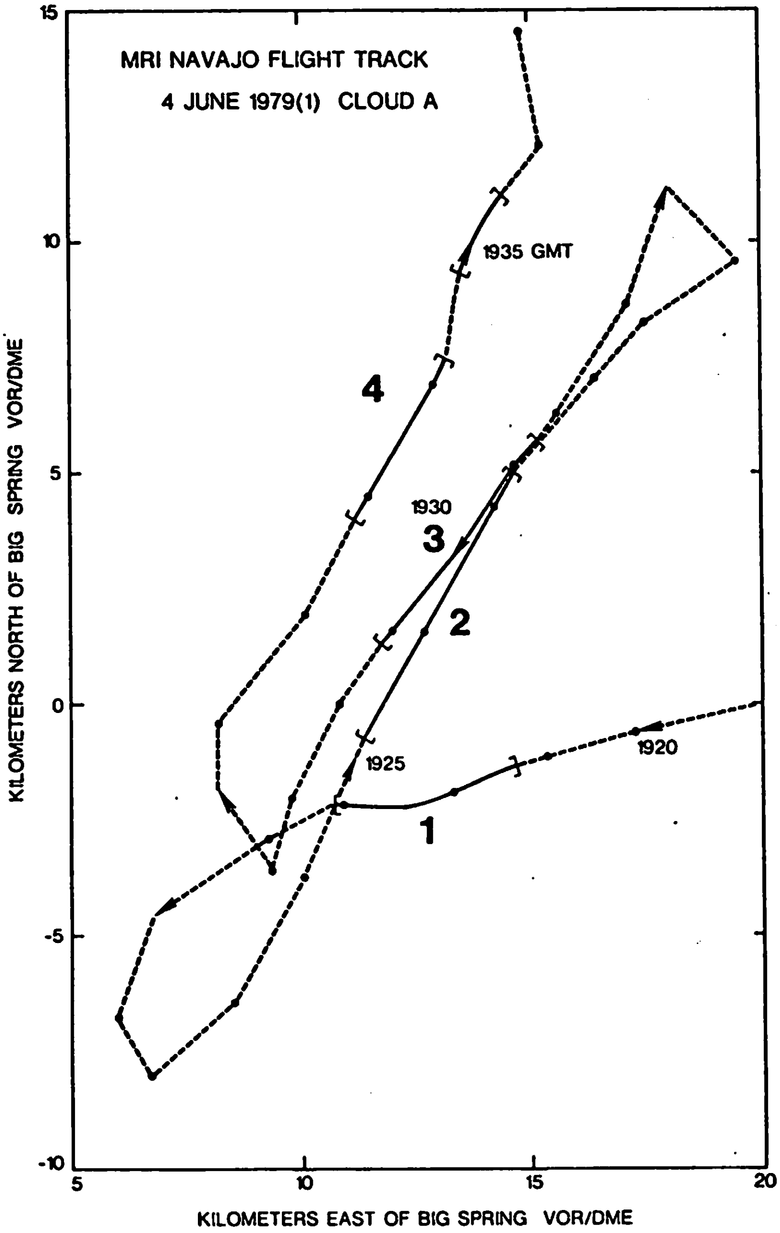

Fig. 4. Flight track of MRI Navajo through cloud A of HIPLEX Mission 1 on 4 June 1979 (1). Solid line shows part of flight track in cloud. Dashed line shows out-of-cloud flight track made up of straight line segments between 30-sec positions of the aircraft.

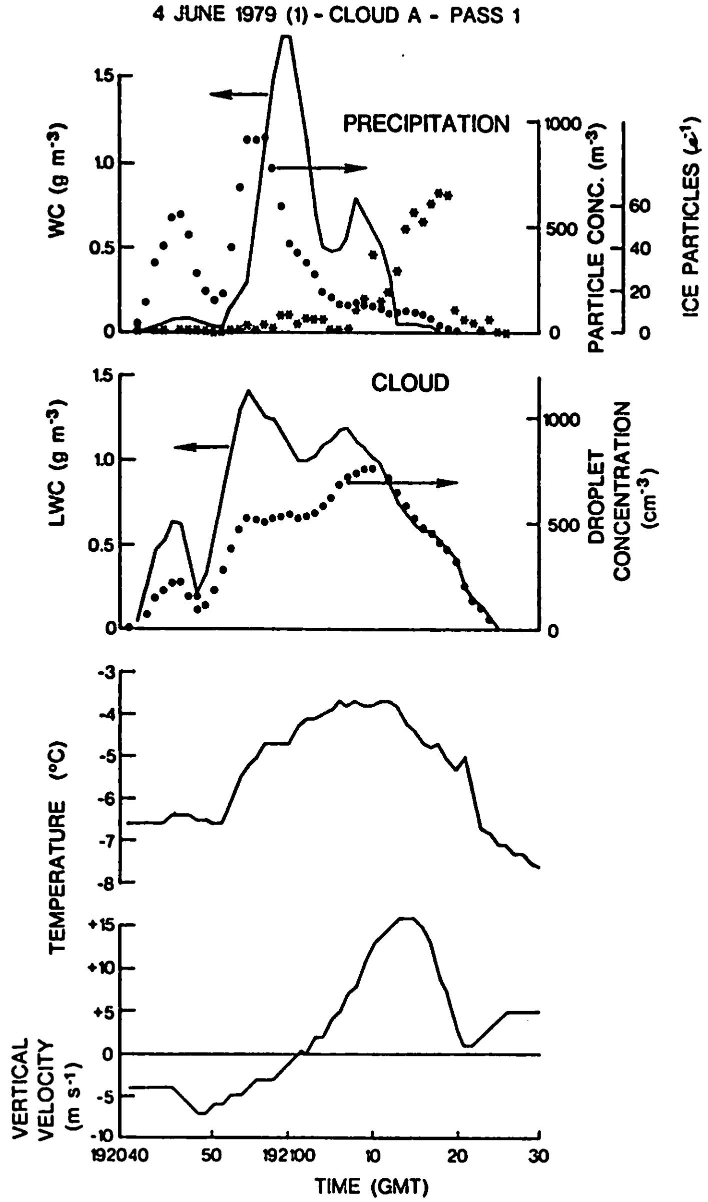

Fig. 5 MRI Navajo data for pass 1 through cloud A of HIPLEX mission 1 on 4 June 1979 (1). One-second values are shown of vertical velocity, ambient air temperature, cloud liquid water content, cloud droplet concentration, precipitation water content, precipitation particle concentration, and ice particle concentration. Time increases from left to right.

was encountered. A very strong (15 m s^{-1}) updraft and a strong (7 m s^{-1}) downdraft were found in the cloud. The existence of the updraft is certain given the observed positive buoyancy, but the downdraft remains unexplained and may be an artifact of the measurement system. The precision of both the updraft and downdraft measurements may be low.

Significant cloud water was observed. (Cloud water is based on all droplets in the 3 to 45 μm diameter range.) The median volume droplet diameter was significantly larger in the eastern one-half of the cloud. Here the graphical line for liquid water content lay well above the dotted line for droplet number concentration.

Precipitation particles (diameters ≥ 0.3 mm) were already present on pass 1. Water contents well over 1 g m^{-3} were found in the central part of the cloud. These contents were calculated from PMS 1-D 200-Y probe data on the assumption all particles were liquid. This assumption appears to have been valid on pass 1 given the lack of correlation between the concentrations of precipitation particles and ice particles. The largest precipitation particles exceeded 2 mm diameter and lay in the central part of the cloud. Smaller, 0.8 mm particles were found in the extreme eastern edge of the cloud. Note the coexistence of precipitation, cloud water, and the region of positive buoyancy.

Ice particles were found in largest concentrations near the outside margins of the updraft and were relatively absent elsewhere. A possible source region for these particles might be located at the same level within the cloud and along the inside margins of the updraft nearer the center of the cloud. The ice particles likely did not come from a lower level inasmuch as they would have been located at the melting (0°C) level perhaps only 1-3 minutes earlier. They likely did not come from above as they could not have fallen against the updraft. (The ice particles must have been smaller than 300 μm since they essentially were undetected by the 1-D 200-Y probe.) This leaves as a possibility lateral entrainment into the sampled region, perhaps by turbulence. According to the MRI Universal Indicating Turbulence System, $\varepsilon^{1/3}$ was as high as 7 $cm^{2/3}$ sec^{-1} throughout much of the region of maximum ice particle concentration. But laterally within the cloud no significant concentration of ice particles is observed. Thus there appears to have been no outside source of the high concentrations actually observed. This suggests these high concentrations developed within the region where they were observed. This development may have been through ice multiplication. The concentration of ice particles is higher than the concentration of ice nuclei ($10^{-3}\ \ell^{-1}$ to $10^{-2}\ \ell^{-1}$) expected to be active at temperatures of -4C to -8C. The temperature is suitable for multiplication. The observed concentration of droplets larger than 24 μm was 6 to 7 cm^{-3} through much of the region of high ice concentration. Confirmation of ice multiplication must await examination of the MRI Navajo PMS 2-D-C probe data. These data may tell whether some few graupel particles were also present in the region as is required in the usual conception of how the multiplication process works. The 2-D-C data should also provide better ice particle concentrations. Reliable ice particle concentrations are, in fact, essential before speculating further on the possibility of ice multiplication.

Pass 2 (see Fig. 6) occurred from 192507 to 192610 GMT along a heading of approximately 42 deg magnetic at a true air speed of approximately 86 m s^{-1}. (In Fig. 6 (and in Fig. 8) time increases from right to left so the data as presented have the same approximate geographical orientation as those in Fig. 5 (and Fig. 7).) Positive buoyancy was significantly smaller than on pass 1. The downdraft observed in the region of greatest buoyancy probably is an artifact. There clearly is difficulty in obtaining reliable vertical velocities with the variometer system installed on the MRI Navajo in 1979. The magnitude and sign of buoyancy is probably a more reliable, if only qualitative, indicator of air motions.

Regions of cloud water and precipitation were rather well separated by this time. Cloud water was confined more to the region of large positive buoyancy and the precipitation to the remainder of the cloud. The cloud water appears to have been rising within an updraft. The precipitation may have been falling through a region of low to neutral buoyancy. The relatively small amount of cloud water in the region of precipitation (between 192533 and 192558 GMT) may be attributed to prior sweepout of cloud water by precipitation falling through levels near the flight level.

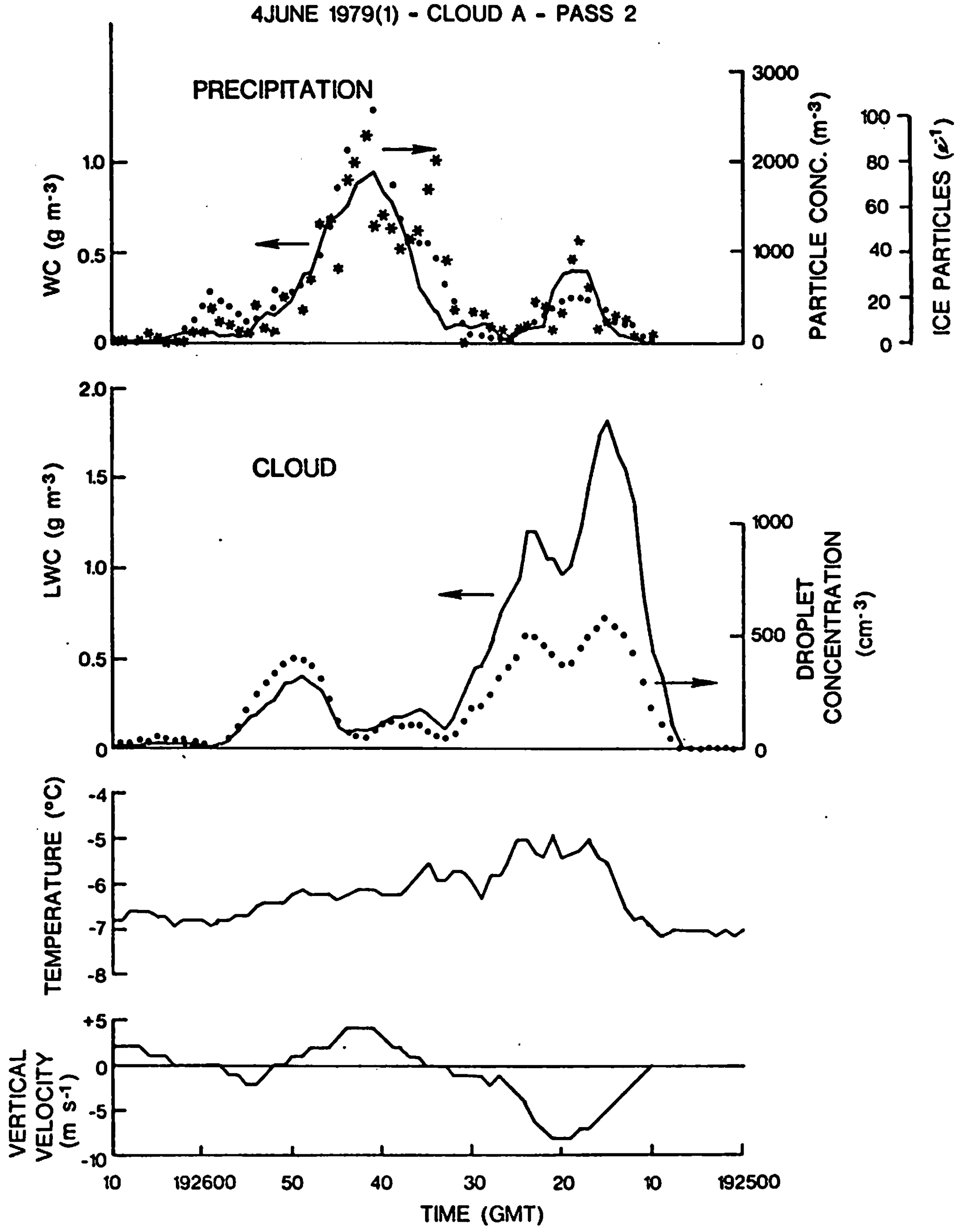

Fig. 6. Same as Fig. 5 but for pass 2. Time increases from right to left so data have same approximate geographical orientation as those in Fig. 5.

The values of precipitation water content in Fig. 6, as in Fig. 5, are based on the assumption the precipitation is liquid. In fact, this may not have been the case. The concentration of precipitation particles is well correlated with the ice particle concentration through most of the cloud. If only 2 to 3% of the ice particles were of precipitation sizes they could account for all the precipitation particles. Future examination of the PMD 2-D-C data will be needed to confirm whether the precipitation was mainly ice. If this is true, a major change in the phase (liquid to solid) of the precipitation occurred from pass 1 to pass 2.

Pass 3 (see Fig. 7) occurred from 192920 to 193030 GMT along a heading of approximately 215 deg magnetic at a true air speed of approximately 87 m s^{-1}. The close juxtaposition of pass 3 and pass 2 (see Fig. 4) supports the conclusion that the data from the two passes apply much to the same part of the cloud. Some evolution of the cloud is evident during the 4½ minute interval between the two passes, but the similarities outweigh the differences. Positive buoyancy still exists through much of the cloud and is about the same magnitude (+1C to +2C). Cloud water is again well-separated from precipitation and by about the same 2 km distance. The small amount of cloud water found earlier in the region of precipitation has now disappeared. Gravitational sweepout by the precipitation passing through the region has apparently been complete. There is evidence similar to that on the previous pass that precipitation is mainly ice. Precipitation water content is larger due to an increase in both particle numbers and particle sizes.

An interesting feature observed on pass 3 is the downdraft in the northeast edge of the cloud in and near the precipitation. Such a downdraft was not observed on the previous pass. Perhaps by this time in the life of the cloud the precipitation had begun to induce a downdraft. This must be regarded as tentative, however, given the uncertainty in the vertical velocity data, but yet is not inconsistent with the observed development of precipitation.

Pass 4 (see Fig. 8) occurred from 193353 to 193450 GMT along a heading varying from 22 to 5 deg magnetic at a true air speed of approximately 87 m s^{-1}. Pass 4 was rather widely separated in space from the

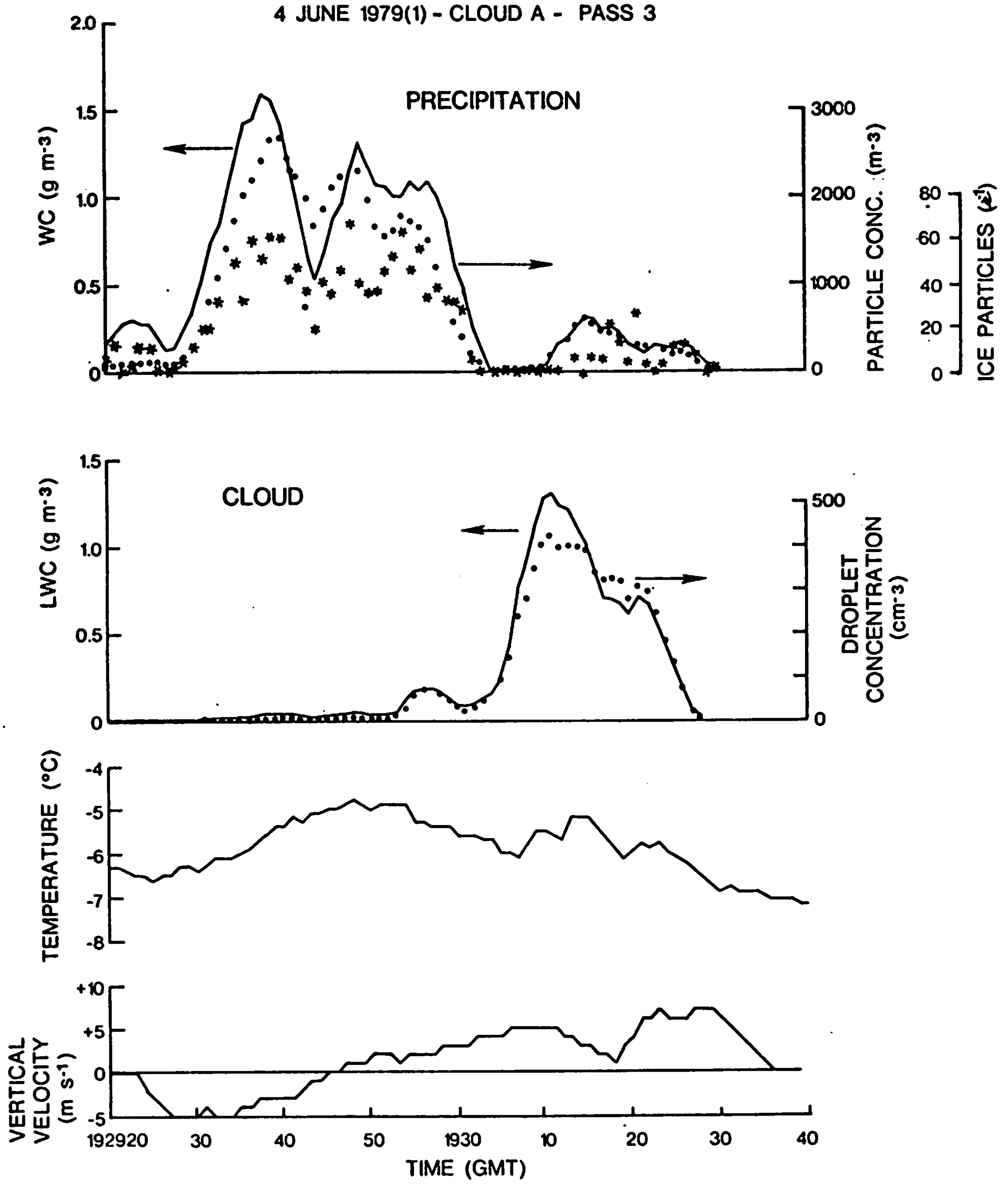

Fig. 7. Same as Fig. 5 but for pass 3. Time increases from left to right so data have same approximate geographical orientation as those in Figs. 5 and 6.

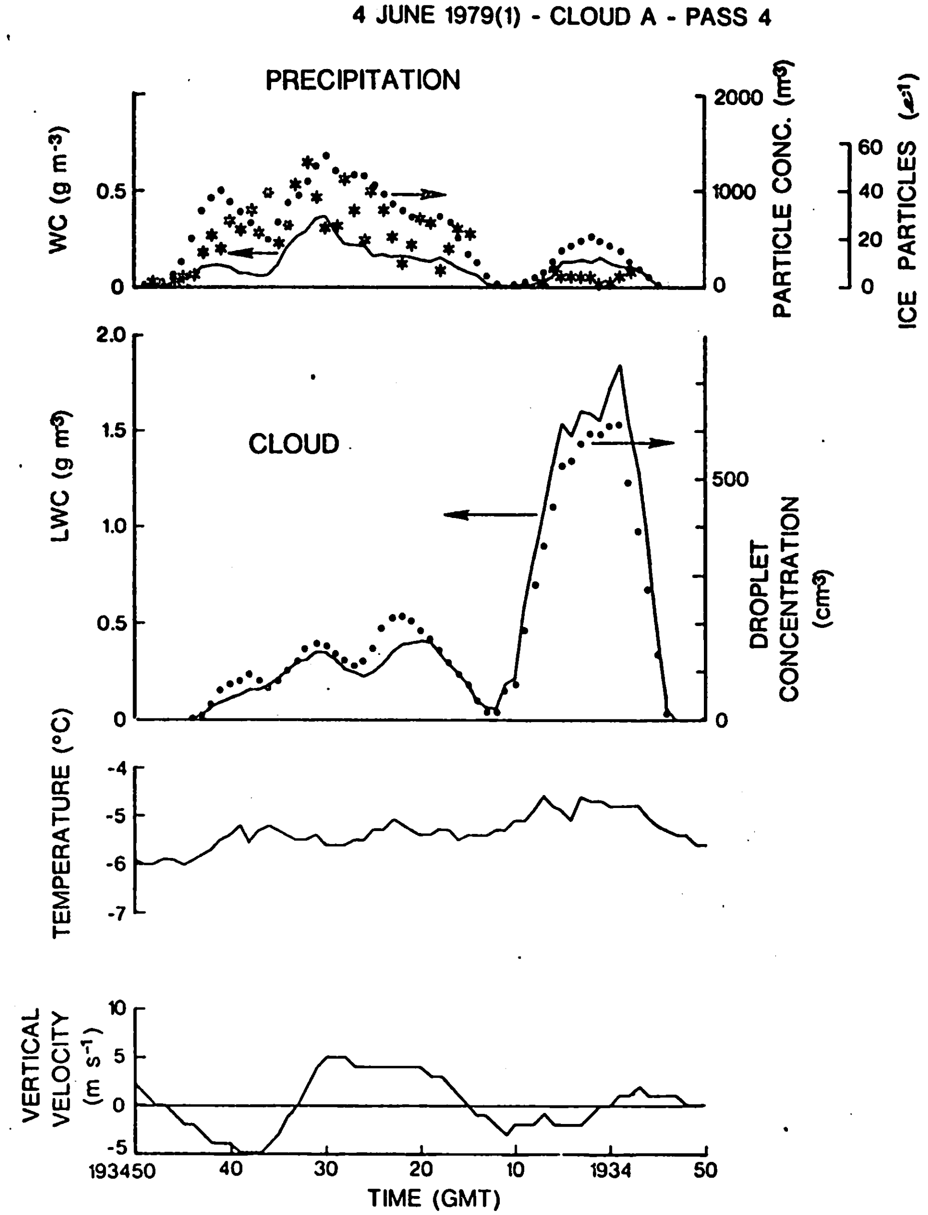

Fig. 8. Same as Fig. 5 but for pass 4. Time increases from right to left so data have same approximate geographical orientation as those in Figs. 5, 6, and 7.

earlier passes and may have been made through a different part of the cloud. Positive buoyancy existed through much of the cloud but was generally smaller than on previous passes. The observed vertical velocities may not be valid in view of their poor correlation with temperature. The bulk of the cloud water is associated with the region of greatest buoyancy and may have been rising within an updraft. Cloud water appears to have returned to the major region of precipitation. Whether this is a real effect is not clear given the difficulty in connecting pass 4 with the same part of the cloud as pass 3. Precipitation particles observed on pass 4 are significantly smaller than those on pass 3. Median volume diameters are now about 1 mm versus 1.5 mm. Precipitation appears still to have been in the form of ice.

The analysis just presented does not provide a comprehensive picture of the precipitation process in cloud A. At least some of the precipitation apparently passed through the ice phase. But the importance of the ice phase for the bulk of the precipitation is not clear since pass 1 showed that a significant amount of precipitation in liquid form could develop. It is noted, however, that the most widespread precipitation, which was observed on pass 3, apparently was in the form of ice particles. The observed spatial extent of the precipitation may, however, have been more a function of the shape of the region of precipitation and of the orientation of the flight track. Since cloud A was not observed prior to the presence of precipitation it does not seem advisable to make any statement as to the processes responsible for precipitation.

The analysis of cloud A presented above is limited in at least three ways. First, although the analysis is based on 4 passes through the cloud, only two of these passes could be identified with some assurance with the same part of the cloud. The only firm statements with regard to cloud evolution came from a comparative study of these two passes. This demonstrates the importance of being able repeatedly to sample the same portion of a cloud. Second, air motions within cloud A were poorly known. This placed reliance on buoyancy (temperature excess) data for information on vertical velocities. Buoyancy information is largely qualitative and cannot support reliable quantitative calculations of particle trajectories within a cloud, and trajectories are an important component of any case study. The third factor limiting the analysis of cloud A was the unavailability of PMS 2-D-C data on particle shapes. These data would have permitted phase discrimination and better estimates of particle size and water content. PMS 2-D-C data from the 1979 field program should be available soon from the WPRS.

b. 17 July 1979. This was a "rapid scan" day in which extra satellite visible and infrared imagery were collected for the continental United States. These data potentially can be used to trace in more detail the mesoscale cloud development in and around the Texas HIPLEX study area. In support of the satellite work, flights were made by the MRI Navajo and CRMWD p-Navajo to collect mesoscale data on the temperature, humidity, and velocity of air in and around individual clouds and groups of clouds identified to be important on the basis of radar data. Information on the location, intensity, and timing of precipitation was also collected by each aircraft. The MRI Navajo flight covered the time period 1955 GMT to 2210 GMT. The first part of the flight from 2012 to 2047 GMT was spent collecting raindrop size distribution data in precipitation shafts below cloud base for use in Z-R studies. From 2103 to 2153 GMT the MRI Navajo was engaged in mesoscale data collection. Its flight altitude for this work was approximately 3.2 km (10,500 ft) MSL. Mesoscale data collection was the sole purpose of the p-Navajo flight. It commenced at 2028 GMT and ended at 2221 GMT. Flight altitude was approximately 1.2 km (4,000 ft) MSL. Reported here are the results of a preliminary examination of the mesoscale data. Study of the Z-R data is left to others. The present discussion is based on a set of maps of the temperature, dewpoint, and precipitation fields measured or observed by the MRI Navajo and the p-Navajo along their flight paths.

Figure 9 shows the temperature and dewpoint measured at 1 minute intervals by the MRI Navajo. The lowest temperatures observed were between 6.5C and 7C at 40 to 50 km east and 25 to 50 km north of the Big Spring VOR/DME. Relatively cold air was also observed approximately 30 km north to north-northwest of the VOR/DME. In both of these regions the recorded dewpoint was within a few-tenths of a Celsius degree of the ambient temperature. The air was evidently close to saturation. (Some recorded dewpoints were even higher than the temperature. This is due to

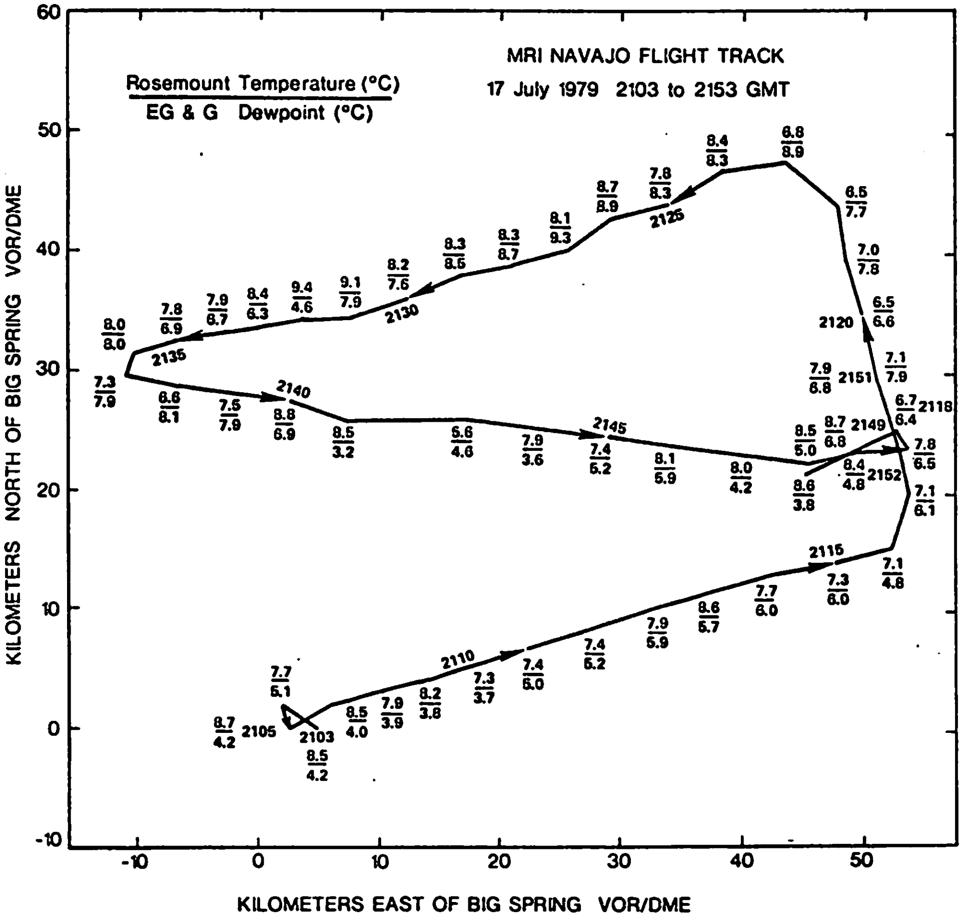

Fig. 9. MRI Navajo flight track for mapping mesoscale temperature, dewpoint, and precipitation fields from 2103 to 2153 GMT on 17 July 1979. Plotted at 1 min intervals are ambient air temperature (upper figure) and dewpoint (lower figure). Flight level was approximately 3.2 km (10,500 ft) MSL.

error in the measurement systems but is another indication of near-saturated conditions.)

Figure 10 shows the precipitation water content measured by the MRI Navajo. Once again water content is calculated from PMS 1-D 200-Y probe particle size data assuming liquid particles. This assumption is a good one given the 7C to 9C temperature at flight level. One-second values are plotted every minute in Fig. 10 rather than 1 minute average water contents. Despite possible short period fluctuations in the data, the instantaneous values show a region of predominantly higher water contents ($\sim$ 1-2 g m^{-3}) 45 to 60 km east and 35 to 50 km north of the VOR/DME. Also found in this region were the lowest temperatures observed around the flight path (see Fig. 9). This cooling may have been induced by evaporation of some of the precipitation falling in this region or else it may be a sign of cool and moist downdrafts in the area. Either process would also explain the near-saturated atmosphere.

Greater vertical velocities appear to have been associated with the precipitation. Figure 11 shows several peaks in vertical velocity from about 212215 to 212545 GMT just when the MRI Navajo was passing through the heaviest precipitation. Although the magnitudes of the velocities are questionable given known deficiencies in the MRI Navajo measurement system, the larger relative velocities, especially downdrafts, which predominate in this time interval, are consistent with general thinking on the effect of precipitation on air motions.

The p-Navajo made three circuits through the same general area in which the MRI Navajo flew. Temperature and dewpoint measurements were recorded every second on magnetic tape and once each minute by hand in the TAMU observer's flight log. The flight log also included observations of rain, updrafts, lightning, and cloud forms in the vicinity of the flight path. The flight log information has been plotted in Figs. 12, 13, and 14.

The flight path shown in Fig. 12 covered the time interval 2035 to 2105 GMT and is known as a "box" pattern. Some rain was observed around the circuit, but generally it was either light in intensity or short in duration. Generally colder temperatures and higher dewpoints were observed where there was rain. This same feature was observed on later circuits by the p-Navajo and on the MRI Navajo flight already described. A prominent

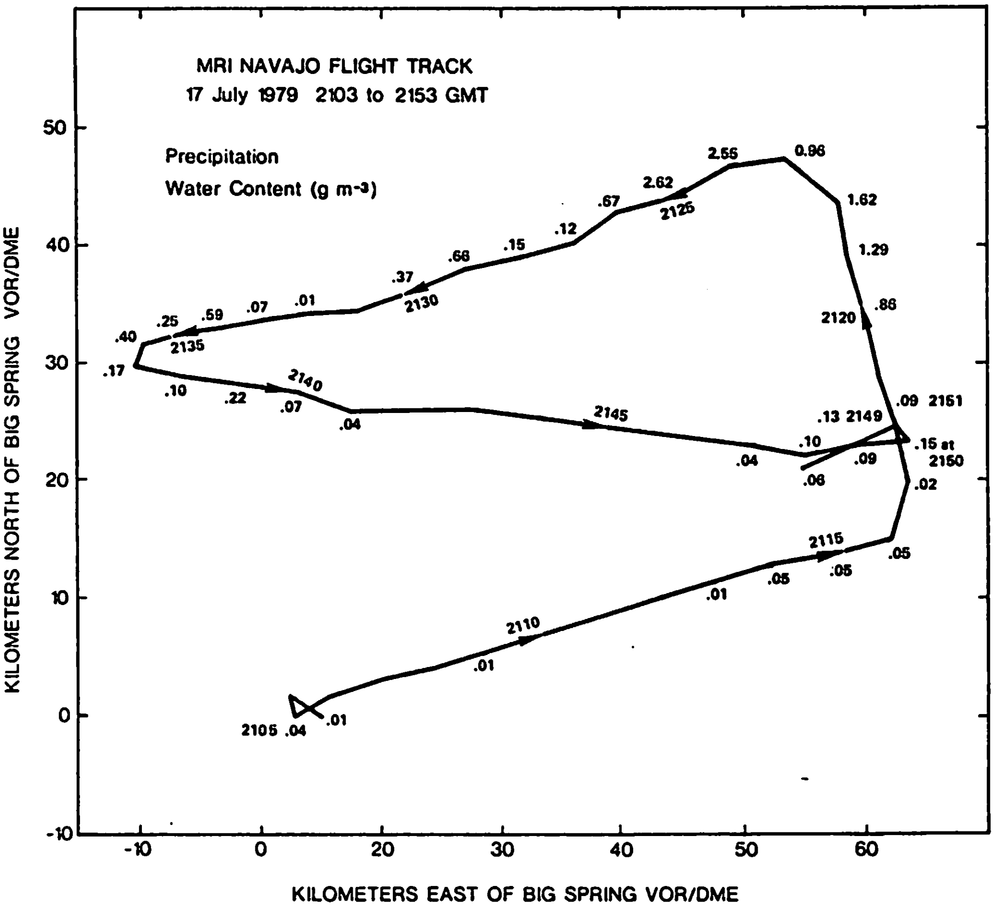

Fig. 10. Same as Fig. 9 except for precipitation water content (g m^{-3}).

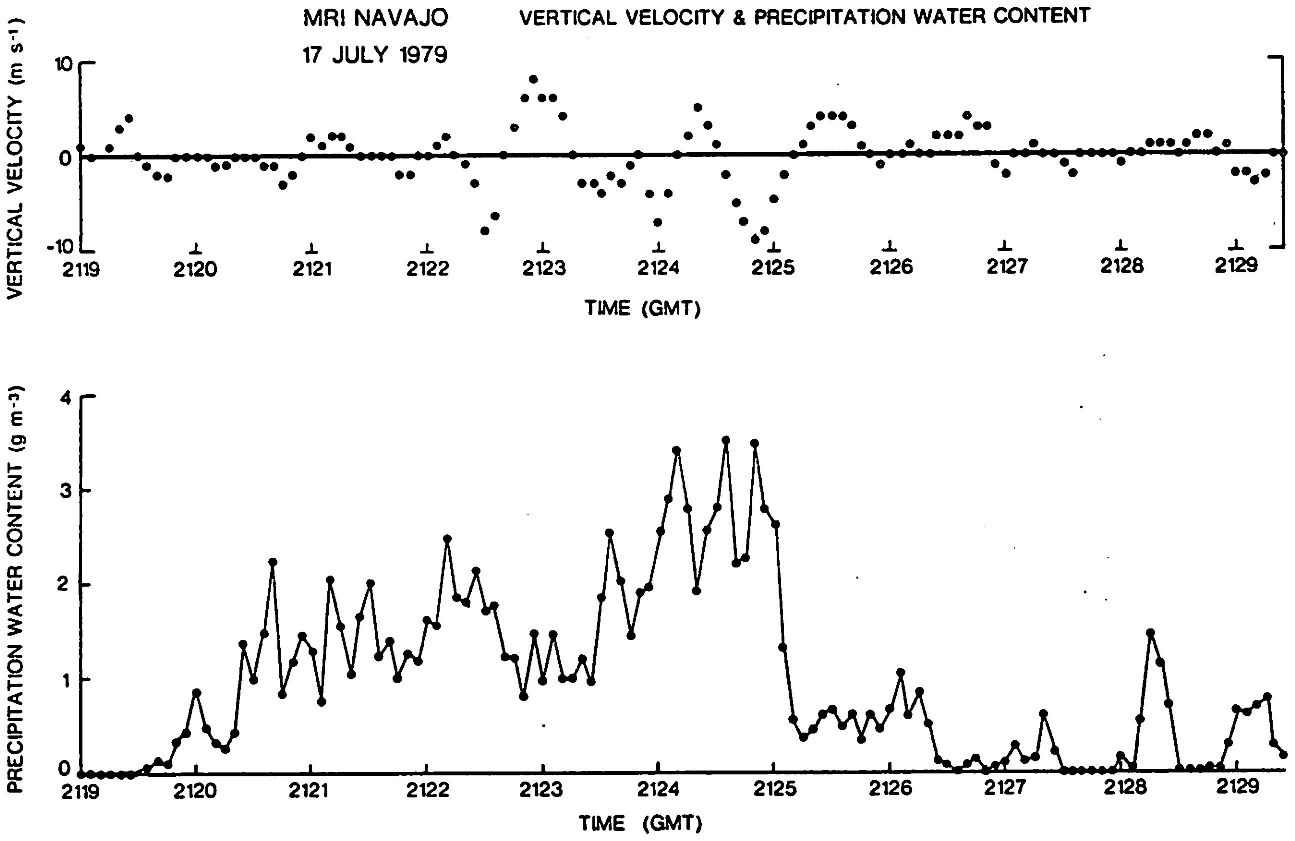

Fig. 11. One-second values of MRI Navajo vertical velocity and precipitation water content, plotted every 5 seconds.

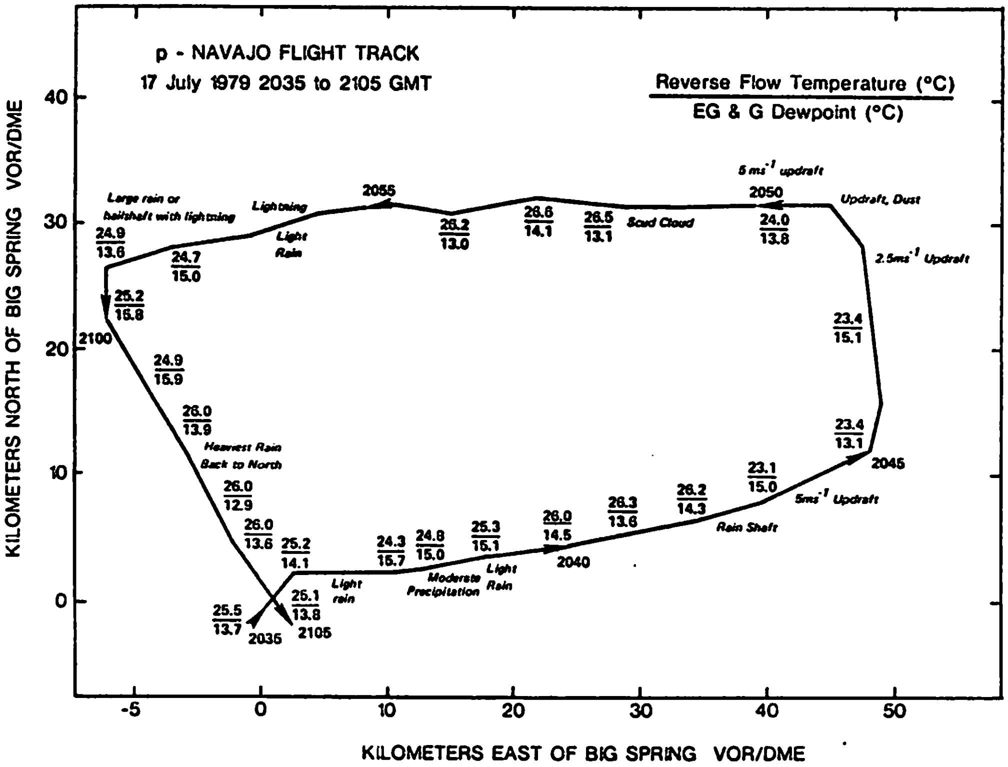

Fig. 12. p-Navajo flight track for mapping of mesoscale temperature and dewpoint fields for 2035 to 2105 GMT on 17 July 1979. Plotted at 1-minute intervals are ambient air temperature (upper figure) and dewpoint (lower figure). Also plotted are comments on vertical velocity, precipitation, and other items as observed and recorded by the TAMU flight observer. Flight level was 1.2 km (4,000 ft) MSL.

feature in Fig. 12 is the set of three observations of updraft 40 to 48 km east and approximately 30 km north of the Big Spring VOR/DME.

The flight path shown in Fig. 13 covered the time interval 2105 to 2148 GMT and is known as a "butterfly" pattern. Fig. 13 corresponds fairly closely in time and space to Figs. 9 and 10 for the MRI Navajo. By this time rain had begun to fall in a number of places where no rain had been observed on the previous circuit. Of special interest is the rain 30 to 35 km east and 35 to 40 km north of the VOR/DME. The pass through this region about 25 min earlier had shown a distinct updraft. Perhaps this updraft had been providing the moist air from which the rain shown in Fig. 13 developed. Heavy rain is also observed in a region 0 to 10 km west and 25 to 30 km north of the VOR/DME. This region of precipitation appears to be the same as that observed by the MRI Navajo about 2135 GMT. Comparison of Figs. 12 and 13 shows ambient air temperatures fell 1 to 2 Celsius degrees and dewpoints rose 1 to 2 Celsius degrees through most of a region 30 to 35 km north of the VOR/DME and extending from 10 to 40 km east. This may have been due to evaporation of precipitation in subcloud air or it may have been a sign of cool, moist downdrafts.

The flight path shown in Fig. 14 covered the time interval from 2148 to 2216 GMT. The circuit has a "triangle" shape but in reality is a butterfly pattern abbreviated by fuel limitations. Rain is the primary feature of Fig. 14. Cooler and more moist sub-cloud air was observed on this circuit than on the previous one (Fig. 13) in the region 0 to 10 km east and 5 to 15 km north of the VOR/DME. Some of the rain showers observed on this mission were rather long lived. Figure 13 showed heavy rain at 2115 GMT at a location 35 km east and north of the VOR/DME. This rain was continuing 45 minutes later (see Fig. 14) and still was heavy.

The maps just discussed provide a graphic picture of the temperature, dewpoint, and precipitation fields in and around the clouds of interest on 17 July 1979. They allow one quickly to relate precipitation to changes in the temperature and dewpoint. Maps could also be developed of vertical velocity, and all data might be plotted more often than once per minute. A more detailed picture of the evolving mesoscale environment would be expected to emerge from such work. Radar data covering the aircraft flight region and times would be especially valuable in this regard.

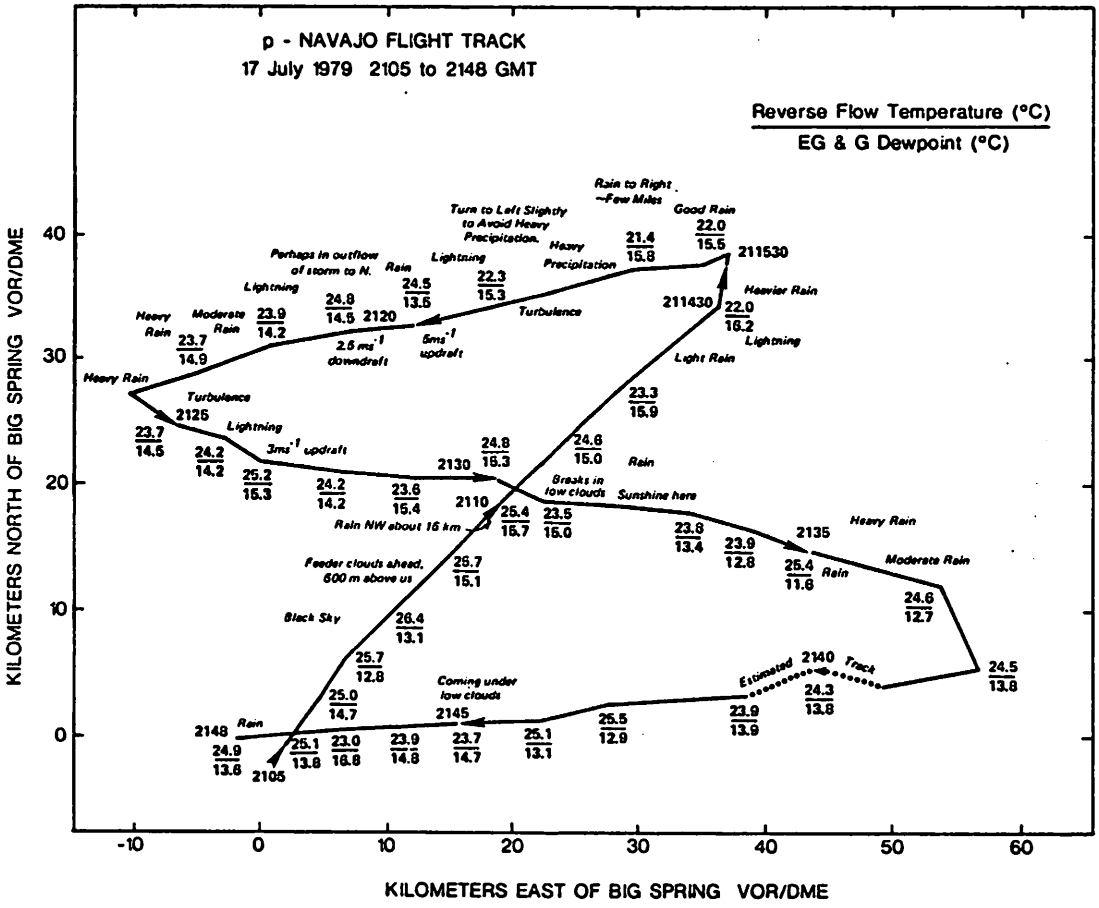

Fig. 13. Same as Fig. 12 but for 2105 to 2148 GMT on 17 July 1979.

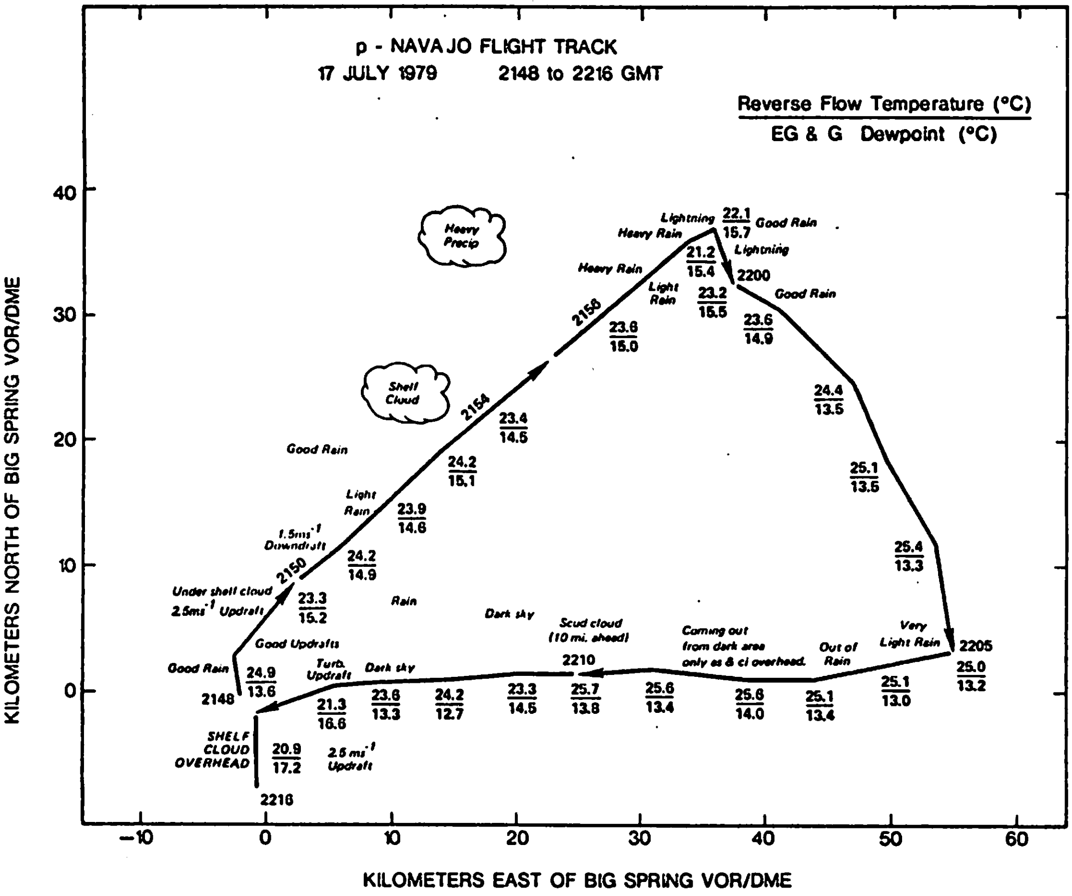

Fig. 14. Same as Fig. 12 but for 2148 to 2216 GMT on 17 July 1979.

c. Precipitation mechanisms. Some preliminary statements can be made regarding the importance of the ice process for precipitation in the clouds sampled and treated in the 1979 HIPLEX missions. Eleven clouds were sampled altogether. HIPLEX mission 6 sampled three clouds, and each of the other missions sampled one cloud. Section 4 has described the initial states of seven of the clouds, prior to any treatment (seeding or no-seeding) that may have occurred. The later development of these seven clouds is now examined in an attempt to assess the importance of the ice process. Reference is made to Table 9. Here are tabulated answers to two questions: Did ice develop in the sampled cloud? Did precipitation develop in the sampled cloud? Also listed is the estimated total precipitation from the sampled cloud for the period of time when the cloud was being sampled.

It is important to state that the analysis now to be presented of the information in Table 9 does not distinguish between those clouds which were seeded and those which were not seeded. All the clouds are lumped together. The number of clouds sampled is too small to permit any separation into seeded and not-seeded groups. Lumping all the clouds together for the purposes of this analysis is not equivalent to assuming a null hypothesis that seeding has no effect on ice or precipitation development, or on precipitation amount. No seeding hypothesis of any form whatsoever is being assumed.

It is important to note that the statements to be made below with regard to the importance of the ice process do not assume that answers to the two questions posed above together with values for total precipitation are all the information needed in establishing the overall precipitation process. This information is insufficient and must be supplemented with information on the size, concentration, phase, and structure of condensed particles within a cloud. This more complete information forms the basis of the scientific approach of the TAMU cloud microphysics studies as outlined in Section 2. This more comprehensive approach is being pursued. But in this report, the first on the TAMU microphysics studies which, indeed, have just begun, the focus is only on whether the ice process is important in Texas HIPLEX convective clouds. At this point it is not possible to say whether the warm rain process is necessary for precipitation

Table 9. Development of and total precipitation for clouds sampled and treated in 1979 HIPLEX missions.

HIPLEX mission number	Date	Did ice develop?	Did precipitation develop?	Total precipitation (kton)
1	4 June (1)	No	Yes	0.7
2	4 June (2)	No, small amount was present initially but decreased	No, not in time of observations	0
3	25 June	(only p-Navajo data collected; data not yet available for analysis)		
4	3 July (1)	??	Yes	0.8
5	3 July (2)	Yes	Yes, and increased with time	210
6	5 July (1)	(only p-Navajo data collected; data not yet available for analysis)		
7	5 July (2)	Yes, but ice was present initially	Yes, and increased with time	1100
8	8 July (1)	Yes, and ice also increased in spatial extent, but ice was present initially	Yes, but precipitation was present initially	3000
9	15 July	No	Yes	25

in significant amounts, whether coalescence accelerates the ice process, or whether ice multiplication occurs frequently. Although these questions must be answered, it seems paramount at this early stage in the work to establish the importance of the ice process in particular, since the Texas HIPLEX project assumes that it is by artificially stimulating the development of ice that precipitation can be augmented.

It was concluded in Table 9 that ice developed in a sampled cloud if the mean concentration of ice particles on a pass through the cloud reached or exceeded 5 ℓ^{-1}. The concentration measured with the MRI Navajo ice particle detector at the flight temperature of about -1C to -3C was used in this determination. The 5 ℓ^{-1} threshold ice concentration is to an extent arbitrarily selected, but it is 1.5 to 50 times higher than that observed initially in four of the six clouds for which initial state information on ice particle concentration is available (see Table 8), and the threshold is at least one-third as large as the ice concentration already observed on the initial pass in HIPLEX missions 7 and 8. If the ice concentration follows the ice nucleus concentration and increases by a factor of 10 for each 4C decrease in temperature, a threshold of 5 ℓ^{-1} at -2C becomes 50 $^{-1}$ at -6C and 500 ℓ^{-1} at -10C. It would not be unreasonable to conclude that ice had developed had these higher concentrations been observed at these colder temperatures. It is not yet known whether such concentrations had developed simultaneously in the sampled cloud at these colder temperatures. An answer must at least await analysis of the p-Navajo data. They should be available in April, 1980. Even then the ice concentration at -10C may remain unknown in view of known malfunctions of the ice particle detector on board the p-Navajo.

Proceeding under these assumptions it has been possible to answer the question of ice development for the clouds for which data are available. Table 9 shows that in three clouds ice developed or was present right from the beginning on the initial pass. In two clouds ice failed to develop, and in one cloud where a threshold concentration existed initially the ice concentration subsequently decreased below the threshold. The verdict is unclear for the cloud on HIPLEX mission 4 because no useable ice particle data are available from the MRI Navajo due to an apparent instrument malfunction.

Precipitation was concluded to have developed in a sampled cloud if the concentration of particles 0.3 mm or larger was at least 100 m^{-3} averaged over a pass. Particles of 0.3 mm diameter are about the smallest which could reach the ground without evaporating in subcloud air of relative humidity 95% or greater. A particle concentration of 100 m^{-3} is often taken to be the minimum needed for detectable precipitation. If all precipitation particles are of 0.3 mm diameter, if particle concentration is 100 m^{-3}, and if precipitation is liquid then the rain rate is about 0.013 mm hr^{-1}. The rain rate would be 0.4 mm hr^{-1} if the particles were twice as large and were present in double the concentration. These comparative rain rates suggest the threshold for precipitation development used in the present analysis may be set somewhat too low, but it will suffice for our present purposes. More comprehensive analyses will consider higher precipitation thresholds.

Proceeding under the above assumptions it has been possible to answer the question of precipitation development for the clouds for which data are available. Table 9 shows that in five clouds precipitation developed and in two of these cases it increased with time. In the cloud sampled on HIPLEX mission 8 precipitation already existed on the initial pass and was approximately steady with time. In one cloud precipitation did not develop, at least not within the time span of the observations.

Comparison of columns 3 and 4 in Table 9 on ice and precipitation development does not permit the conclusion that development of the ice phase in the sampled clouds was a necessary condition for precipitation. Some precipitation could develop without the ice phase (see HIPLEX missions 1 and 9).

The ice phase nevertheless appears important for precipitation amounts. Precipitation amounts can be estimated from aircraft data on precipitation particle concentrations given a few assumptions. Particle concentrations combined with particle masses and terminal velocities permit estimates of the downward flux of water at the aircraft flight level. The flux of water will also depend on the velocity of the air. Air motions have not been taken into account in the present calculations in view of the uncertainty in the vertical air velocity data. Fluxes of water along a linear flight path through a cloud can be used to calculate the flux of water integrated over the entire area of the cloud at flight level if one assumes there is some symmetry to the precipitation structure. A circularly symmetric structure about the center of the flight path was assumed in the present work. Column 5 in Table 9 gives the calculated total precipitation for each cloud for the period of time the cloud was sampled.

The total precipitation varies by more than three orders of magnitude between some of the clouds. Even this small sample of data shows the great natural variability that can occur in convective precipitation. This great natural variability places limits on the minimum size sample of precipitation data needed to show statistically significant precipitation augmentation effects. This will be of importance in designing any future Texas HIPLEX randomized cloud seeding project aimed at precipitation augmentation.

Even with the crude precipitation estimates in Table 9 there seems to be a clear association of greater precipitation with those clouds in which ice developed. Small, negligible, or zero amounts of precipitation fell from clouds in which ice was not observed to develop. Although these conclusions are rather clearly supported by Table 9 it is important to note the very small number of clouds upon which they are based. A great deal more data are needed before firm conclusions can be drawn.

It is worthwhile examining the components making up the total precipitation amounts listed in Table 9. These components are the pass-average precipitation rate, the precipitation duration, and the pass-average spatial extent of precipitation. Table 10 lists these three components for each of the sampled clouds. It is seen that the precipitation rate was about equal for all the clouds (excluding HIPLEX mission 2 in which zero precipitation was observed). Differences among clouds, however, were observed in the duration and spatial extent of precipitation. A comparison of Tables 9 and 10 suggests the development of ice is associated with both a longer duration of precipitation and a generally greater spatial extent of the precipitation.

At the present time it is not possible to state whether the warm rain (coalescence) process was occurring in the sampled clouds to the extent that it produced precipitation itself or accelerated the ice process of precipitation production. A meaningful statement about the

Table 10. Components of total precipitation for sampled clouds.

HIPLEX mission number	Date	Pass-average Precipitation Rate (mm/hr)	Precipitation Duration (min)	Pass-average Precipitation Extent (km)
1	4 June (1)	25	5	0.5
2	4 June (2)	0	0	0
3	25 June	-	-	-
4	3 July (1)	35	5	0.5
5	3 July (2)	35	22	7
6	5 July (1)	-	-	-
7	5 July (2)	30	24	10
8	8 July (1)	35	30	15
9	15 July	35	5	5

effect of the warm rain process on the ice process would in part require making calculations of the heterogeneous freezing rates of those spectra of large drops which develop, by coalescence, from broad and narrow cloud droplet spectra. Calculations would also be needed of the concentrations of large drops, capable of growing by riming, that are needed to accelerate the Bergeron-Findeisen process. The next step would be to place observed spectra of large drops and cloud droplets in the context of these calculations. This work has not been attempted yet. It is more in the way of cloud microphysics modelling than data analysis, but it would be a desirable adjunct to present efforts.

It is important to know whether ice multiplication occurred in the sampled clouds. Ice multiplication was described in Section 2. When ice multiplication occurs it is effective in producing ice in a cloud, and if it also is effective in augmenting precipitation then it may compete with efforts to augment precipitation artificially by seeding. Artificial seeding may then have a negligible or at least smaller effect. It is important therefore to assess the likelihood of ice multiplication.

Evidence for or against ice multiplication usually comes from measurements of the natural ice particle concentration in the tops of clouds which have never been colder than about -10C. Ice concentrations of 1 to 10 ℓ^{-1} or greater at -10C usually will imply ice multiplication. The p-Navajo collected some data on ice particle concentrations. They are not available for study and may be erroneous given known problems in the performance of the ice particle counter. Should the data prove useable they may shed light on the question of ice multiplication.

The possibility of ice multiplication can be investigated using data already available by applying the concept of an ice multiplication boundary as proposed by Mossop (1978). The ice multiplication boundary is expressed as a quantitative relation between cloud base temperature and cloud droplet concentration measured near cloud base (see Fig. 15). Mossop's examination of his evidence on ice multiplication and of the evidence of others suggests ice multiplication will occur if cloud base temperature and droplet concentration lie above the curve in Fig. 15. If the temperature and concentration lie on the lower side of the boundary there will be no ice multiplication. In Fig. 15 are plotted cloud base temperatures observed by the CRMWD Aztec

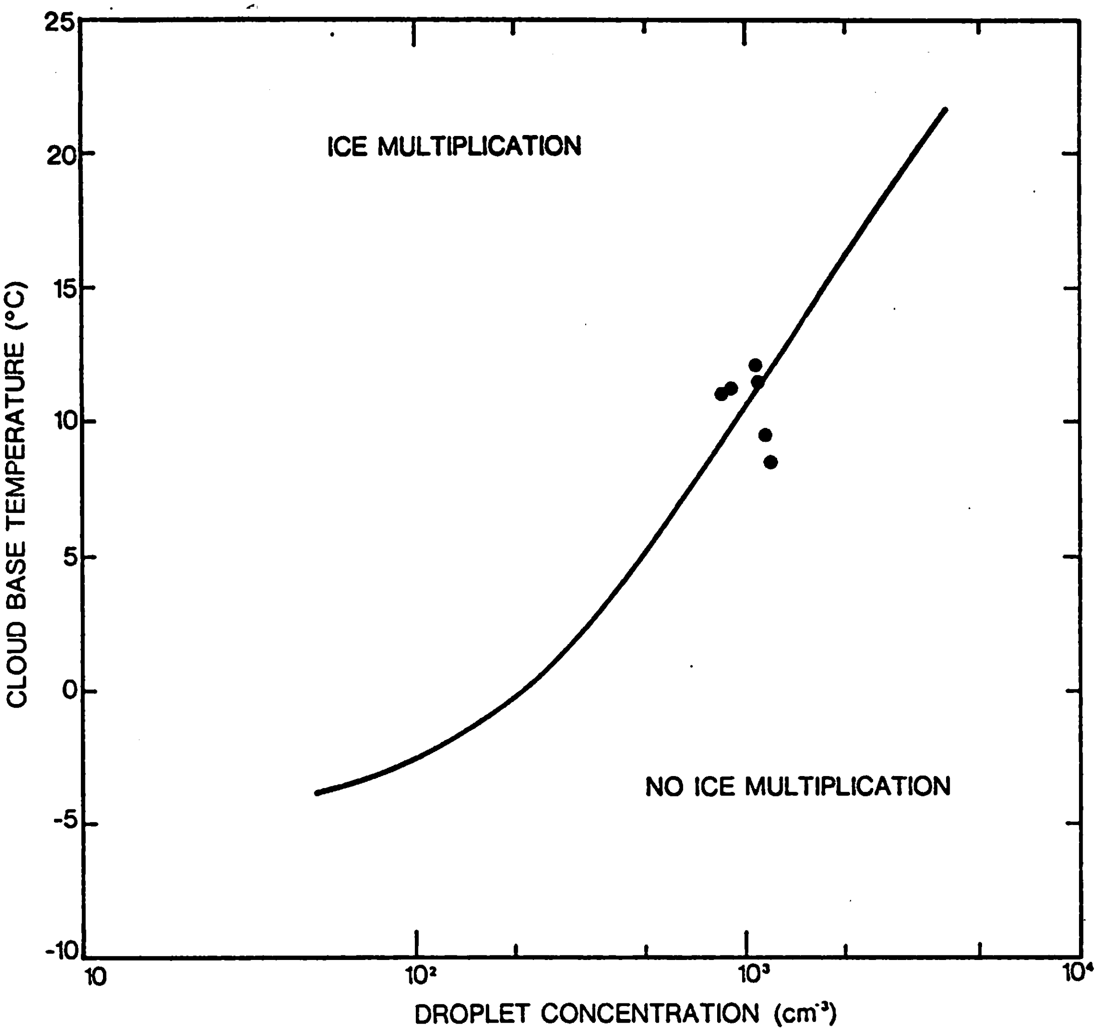

Fig. 15. Ice multiplication boundary as determined by cloud droplet concentration at cloud base and cloud base temperature (after Mossop (1978)).

in six of the clouds from the 1979 field program along with the cloud droplet concentrations observed at the MRI flight level. The droplet concentrations were measured on average at the -2C flight level or about 2 km above cloud base and, hence, are smaller than would be found at cloud base which is where Mossop's boundary applies. If the observed concentrations plotted in Fig. 15 are increased by, perhaps, 50% to allow for coalescence up to the flight level, one finds most of the data points lie below the boundary. From this it appears that ice multiplication was not likely occurring in most of the sampled clouds. It is important to qualify this statement by noting the very small data set and the absence of cloud droplet concentration data from cloud base. Furthermore, the ice multiplication boundary itself (see Mossop (1978)) may not be as sharp as depicted in Fig. 15. Given these qualifications it is best to state that the 1979 data as so far analyzed are not strongly supportive for or against ice multiplication in the sampled clouds.

The most important point of this subsection on precipitation mechanisms is that there appears to be, at least for the sampled clouds as so far analyzed, a clear association of greater precipitation with those clouds in which ice developed. There is also the suggestion that the development of ice is associated with both a longer duration of precipitation and a generally greater spatial extent of the precipitation.

7. SUMMARY

The TAMU cloud microphysics studies are strongly field-experimental. The studies seek to establish the microphysical processes leading to precipitation in growing cumulus clouds in the Texas HIPLEX study region. The work focusses on the end products of the microphysical processes, namely, the cloud and precipitation particles themselves. Inferences about the processes are to be drawn from knowledge about the particles.

This report in Section 2 has identified and discussed the cloud and precipitation particles and the growth and interaction processes of potential importance for growing cumulus clouds in the Texas HIPLEX region. A discussion has been given of the important kinds of data to be collected on cloud particles (diameters ~ 5 to 50 μm), on intermediate-size particles (~ 50 to 500 μm), and on precipitation particles ($\gtrsim$ 500 μm). Examples have been given of the kinds of deductions that can be made from the data. Specific mention has been made of the best instruments available for use in cloud microphysics studies.

Texas A&M University was responsible in the 1979 field program for making decisions as to which clouds would be sampled by aircraft. All aspects of the aircraft data collection effort have been described in Section 3 of this report, including aircraft instrumentation, flight patterns, and operational procedures for selecting clouds. Cloud selection rules, as distinct from operational procedures, were developed by TAMU for use in the 1979 field program. These rules center around certain microphysical parameters of a cloud which had to be observed on an initial pass through a cloud before further sampling would be conducted. Section 4 examines the extent to which each cloud sampled met the selection rules. Not all clouds met the rules. In some cases the cloud top was too cold, in other cases the initial concentration of ice particles was too high, and in at least one case precipitation had already begun.

Texas A&M University was responsible for processing 1979 p-Navajo data. This responsibility grew out of involvement of TAMU personnel in collecting the data. A complete listing of the computer program for processing the data has been provided in the Appendix.

Section 6 presented preliminary results of data analyses made to date. Results have been presented of studies of aircraft data collected on 4 June 1979 and 17 July 1979. The analysis of cloud A on 4 June revealed a possible example of ice multiplication. The analysis of 17 July 1979 examined temperature, humidity, and precipitation measurements made along several aircraft traverses within and beneath a mesoscale convective system. The analysis showed that when precipitation fell through the subcloud air its temperature is decreased and dewpoint increased. This effect may have been an example of the wet-bulb process operating within subcloud air, or it may have been an example of penetration of potentially cold downdraft air into the subcloud region.

Section 6 concluded with an examination of the precipitation mechanisms in a large fraction of the clouds sampled in 1979. From information on whether ice and precipitation developed in each cloud, and from estimates of the precipitation from each cloud, it was concluded that the ice process is necessary for significant precipitation to occur. This conclusion applied only to the clouds studied, was preliminary in nature, and is not to be interpreted as generally true for all convective clouds in the Texas HIPLEX region. More work is required to establish its range of validity.

8. FUTURE PLANS

Future plans in the area of cloud microphysics include completion of data analyses begun in 1979, execution of the 1980 program of field studies, and commencement of new analyses of data collected in 1979 and 1980.

Efforts will be focussed on completing the already identified case studies for 1979, namely 4 June (1) and 17 July. Case studies of 1979 data to be initiated will include 3 July (2), and possibly 5 July (2) and 8 July (1). When the p-Navajo data become available they will be used to expand the case studies. The p-Navajo data will also be incorporated into a study of precipitation mechanisms similar to but more comprehensive than that described in Section 6 of this report.

An important goal of the effort in 1980 will be to collect additional microphysical data on growing cumulus clouds in the Texas HIPLEX study area. Texas A&M University will provide an observer on the CRMWD p-Navajo and will provide in-flight direction and co-ordination of this aircraft and the NCAR Queen Air.

The overall goal will be maintained of determining the predominant precipitation mechanisms in clouds in the Texas HIPLEX study region and of determining methods for enhancing rain from these clouds. Emphasis will be placed on determining for Texas HIPLEX clouds 1) the importance of the warm rain process in accelerating the ice process, and 2) the importance of the ice multiplication process.

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Braham, R.R., Jr., and P. Squires, 1974: Cloud physics - 1974. Bull. Amer. Meteor. Soc., 55, 543-556.

Mossop, S.C., 1978: Some factors governing ice particle multiplication in cumulus clouds. J. Atmos. Sci., 35, 2033-2037.

APPENDIX

Computer program for processing p-Navajo data

```
OLD,PNAV79
/LIST
      PROGRAM ZTXIN(INPUT,OUTPUT,TAPE1,TAPE7)
      DIMENSION IDATA(256)
      DIMENSION IBUF(128),CBUF(35),BUF(8),JBUF(128),ITEST(32)
      EQUIVALENCE (PR,BUF(1)),(AS,BUF(2)),(TEMP,BUF(3)),(RFT,BUF(4)),
     $(DEW,BUF(5)),(WC,BUF(6)),(TWC,BUF(7)),(DME,BUF(8))
C$    ARRAYS
C----------------------------------------------------------------------
C
C                         CONSTANTS USED
C
C----------------------------------------------------------------------
C
C
C UNIVERSAL GAS CONSTANT, ERG/(MOLE-K)
      R=8.31436E7
C MOLECULAR WEIGHT OF DRY AIR
      AMDRY=28.966
C SPECIFIC HEAT OF DRY AIR, ERG/(MOLE-K)
      CPBYMA=0.240*4.18684E7
      CP=CPBYMA*AMDRY
C RATIO OF R TO CP
      RBYCP=R/CP
C REFERENCE POINT FOR ICAO STANDARD ATMOSPHERE
      TSTP=288.15
      PSTP=1013.250
C T AT 0C
      TZERO=273.15
C RECOVERY FACTOR FOR TEMPERATURE PROBES
      ALFRM=0.92
      ALFRF=0.63
```

```
C MOLECULAR WEIGHT OF WATER
      AMWATR=18.0160
C RATIO OF MOLECULAR WEIGHTS OF DRY AIR TO WATER
      RMWDAW=AMDRY/AMWATR
C LATENT HEAT OF VAPORIZATION PER GRAM WATER, AT 0C
      ALHV=597.3*4.18684E7
C RATIO OF LATENT HEAT TO SPECIFIC HEAT
      ALHVCP=ALHV/CPBYMA
C CONVERSION FACTORS
C TO MB FROM PSI
      CMBPSI=68.9476
C TO RADIANS FROM DEGREES
      CRADEG=3.1415926535/180.
C TO KNOTS FROM CM/SEC
      CKTCMS=0.01/0.514444
C
C-----------------------------------------------------------------------
C
C                  COLUMN HEADINGS FOR PROCESSED DATA
C
C-----------------------------------------------------------------------
      WRITE(7,5010)
 5010 FORMAT(1H1,25X,'CRMWD/HIPLEX DATA COLLECTED FROM CIC REAL TIME DAT
     $A SYSTEM ON P-NAVAJO N7335L')
      WRITE(7,5015)
 5015 FORMAT(1H )
      WRITE(7,5020)
 5020 FORMAT(1H ,3X,'DATE',5X,'TIME',4X,'PRS',3X,'ALT',3X,'VOR',3X,'DME'
     $,3X,'IAS',3X,'TAS',1X,'ROSET',2X,'REVT',3X,'DEW',5X,'Q',1X,'THETA'
     $,2X,'THE',1X,'JWLWC',2X,'TWC',5X,'IPC',1X,'FLR',2X,'EVNT')
C
```

```
C-----------------------------------------------------------------------
C
C                            READ IN DATA
C
C-----------------------------------------------------------------------
C
C-----READ IN 256 BYTE(128 WORD) DATA RECORD.
C
    1 NBITS=16
      BUFFER IN(1,0) (CBUF(1),CBUF(35))
      CALL SETB(CBUF(1),59,NBITS)
C-----CHECK MAG TAPE STATUS.
C
      IF(UNIT(1).GE.0) STOP
      CALL GETB(IBUF(1),128)
C
C
C-----INVERT DATA BUFFER.
C
      DO 2 I=1,128
    2 IBUF(I)=.NOT.IBUF(I)
C
C-----LOOP THRU 8 SECONDS OF DATA PER 128 WORD RECORD
C
      DO 100 IT=1,113,16
      IT1=IT+1
      IT15=IT+15
      ITST=AND(IBUF(IT+1),377B)
      IF(ITST.NE.79) 3,6
C
C-----SHIFT DATA BUFFER EIGHT BITS TO RIGHT
C
    3 JBUF(IT)=AND(SHIFT(IBUF(IT),-8),377B)
      DO 4 ITT=IT1,IT15
    4 JBUF(ITT)=AND(IBUF(ITT-1),377B)*256+AND(SHIFT(IBUF(ITT),-8),377B)
      DO 5 ITT=IT,IT15
    5 IBUF(ITT)=JBUF(ITT)
    6 CONTINUE
```

```
C
C-----TEST DATA BUFFER FOR INCORRECT BITS
C
      ITEST(4)=AND(IBUF(IT+1),377B)
      IF(ITEST(4).EQ.79) 7,100
    7 ITEST(1)=AND(SHIFT(IBUF(IT),-8),377B)
      ITEST(30)=AND(IBUF(IT+14),377B)
      ITEST(31)=AND(SHIFT(IBUF(IT+15),-8),377B)
      ITEST(32)=AND(IBUF(IT+15),377B)
      IF(ITEST(1).EQ.0.AND.ITEST(30).EQ.0.AND.ITEST(31).EQ.0.AND.ITEST(3
     $2).EQ.0) 8,100
    8 ITEST(2)=AND(IBUF(IT),340B)
      ITEST(3)=AND(SHIFT(IBUF(IT+1),-8),370B)
      ITEST(5)=AND(SHIFT(IBUF(IT+2),-8),340B)
      ITEST(6)=AND(IBUF(IT+2),300B)
      ITEST(7)=AND(SHIFT(IBUF(IT+3),-8),300B)
      IF(ITEST(2).EQ.0.AND.ITEST(3).EQ.0.AND.ITEST(5).EQ.0.AND.ITEST(6).
     $EQ.0.AND.ITEST(7).EQ.0) 9,100
    9 DO 10 IJT=9,23,2
      IJT2=IJT/2
      ITEST(IJT)=AND(SHIFT(IBUF(IT+IJT2),-8),360B)
   10 CONTINUE
      IF(ITEST(9).EQ.0.AND.ITEST(11).EQ.0.AND.ITEST(13).EQ.0.AND.ITEST(1
     $5).EQ.0.AND.ITEST(17).EQ.0.AND.ITEST(19).EQ.0.AND.ITEST(21).EQ.0.A
     $ND.ITEST(23).EQ.0) 11,100
   11 ITEST(25)=AND(SHIFT(IBUF(IT+12),-8),374B)
      IF(ITEST(25).EQ.0) 12,100
   12 CONTINUE
      JJ=IT-1
C
C-----UNPACK DAY
C
      IDAY=AND(IBUF(1+JJ),377B)
C
C-----UNPACK MONTH.
C
      MON=AND(SHIFT(IBUF(2+JJ),-8),377B)
C
```

```
C-----UNPACK YEAR.
C
      IYR=AND(IBUF(2+JJ),377B)
C
C-----UNPACK HOUR.
C
      IHR=AND(SHIFT(IBUF(3+JJ),-8),377B)
C
C-----UNPACK MINUTE.
C
      MIN=AND(IBUF(3+JJ),377B)
C
C-----UNPACK SECOND.
C
      ISEC=AND(SHIFT(IBUF(4+JJ),-8),377B)
C
C-----UNPACK NEXT 8 PARAMETERS(PR,AS,TEMP,RFT,DEW,WC,TWC,DME)
C
      DO 50 I=1,8
      BUF(I)=FLOAT(AND(IBUF(3+I+JJ),377B)
     $+AND(IBUF(4+I+JJ),177400B))
   50 CONTINUE
C
C-----UNPACK VOR(BCD).
C
      IBCD1=AND(IBUF(12+JJ),17B)
      IBCD2=AND(SHIFT(IBUF(12+JJ),-4),17B)
      IBCD3=AND(SHIFT(IBUF(13+JJ),-8),17B)
      IBIN=IBCD1+10*IBCD2+100*IBCD3
      VOR=FLOAT(IBIN)
C
C-----UNPACK COUNTS FROM ICE PARTICLE PROBE.
C
      PIC=FLOAT(AND(IBUF(13+JJ),377B)+AND(IBUF(14+JJ),177400B))
C
C-----UNPACK FLARE COUNT.
C
      IFLR=AND(IBUF(14+JJ),3B)
C
```

```
C-----UNPACK EVENTS.
C
      IEV1=AND(SHIFT(IBUF(14+JJ),-2),1)
      IF(IEV1.EQ.0) IEVNT=3
      IEV2=AND(SHIFT(IBUF(14+JJ),-3),1)
      IF(IEV2.EQ.0) IEVNT=4
      IEV3=AND(SHIFT(IBUF(14+JJ),-4),1)
      IF(IEV3.EQ.0) IEVNT=5
      IEV4=AND(SHIFT(IBUF(14+JJ),-5),1)
      IF(IEV4.EQ.0) IEVNT=6
      IEV5=AND(SHIFT(IBUF(14+JJ),-6),1)
      IF(IEV5.EQ.0) IEVNT=7
      IEV6=AND(SHIFT(IBUF(14+JJ),-7),1)
      IF(IEV6.EQ.0) IEVNT=8
      IEV7=AND(SHIFT(IBUF(15+JJ),-8),1)
      IF(IEV7.EQ.0) IEVNT=9
      IEV8=AND(SHIFT(IBUF(15+JJ),-9),1)
      IF(IEV8.EQ.0) IEVNT=10
      IEV9=AND(SHIFT(IBUF(15+JJ),-10),1)
      IF(IEV9.EQ.0) IEVNT=11
      IEV10=AND(SHIFT(IBUF(15+JJ),-11),1)
      IF(IEV10.EQ.0) IEVNT=12
      IEV11=AND(SHIFT(IBUF(15+JJ),-12),1)
      IF(IEV11.EQ.0) IEVNT=13
      IEV12=AND(SHIFT(IBUF(15+JJ),-13),1)
      IF(IEV12.EQ.0) IEVNT=14
      IEV13=AND(SHIFT(IBUF(15+JJ),-14),1)
      IF(IEV13.EQ.0) IEVNT=15
      IEV14=AND(SHIFT(IBUF(15+JJ),-15),1)
      IF(IEV14.EQ.0) IEVNT=16
```

```
C-----------------------------------------------------------------------
C
C      CONVERT DATA TO ENGINEERING UNITS
C
C-----------------------------------------------------------------------
C
C-----CALCULATE PRESSURE.
C
      P=6.105E-3*(PR-1638.)
      PMB=P*CMBPSI+17.5
      IF(PMB.LE.0) PMB=1000.
      IPMB= IFIX(PMB)
C
C-----CALCULATE DIFFERENTIAL PRESSURE AND IAS.
C
      DELP=2.442E-4*CMBPSI*AS
      IF(DELP.LT.0.)  DELP=0.
      AIAS2=2.*CPBYMA*TSTP*((1.+DELP/PSTP)**RBYCP-1.)
C THIS INDICATED AIRSPEED IS IN (CM/SEC)**2
C THE FOLLOWING IS FOR PROTECTION ONLY, AND SHOULD NOT BE NEEDED EXC
C IN CASE OF BAD RECORDS
      AIAS=0.01
      IF(AIAS2.GT.0.) AIAS=SQRT(AIAS2)
      AIAS= AIAS*CKTCMS+7.
C
C MUST CORRECT SENSOR FOR HEATING, DEPENDENT ON TAS
C HOWEVER, MUST HAVE TEMPERATURE TO GET TAS FROM IAS
C SO, MUST SOLVE EQUATIONS SIMULTANEOUSLY
C
C CO"PUTE ROSEMOUNT TEMPERATURE
C
      TRM=(4.884E-2*(TEMP-1023.75)+TZERO)
     $  /(1.+ALFRM*((1.+DELP/PMB)**RBYCP-1.))
      TRM=TRM-3.5
      TRMC=TRM-TZERO
C
C COMPUTE REVERSE FLOW TEMPERATURE
C
      TRF=(2.442E-2*(RFT-2087.5)+TZERO)
     $/(1+ALFRF*((1.+DELP/PMB)**RBYCP-1.))
      TRFC= TRF-TZERO
```

```
C NOW GET TAS
      TAS2=2.*CPBYMA*TRF*((1.+DELP/PMB)**RBYCP-1.)
C PROTECTION.  0.01 IN TAS WHEN DONE WILL INDICATE TROUBLE.
      TAS=0.01
      IF(TAS2.GT.0.) TAS=SQRT(TAS2)
C     CONVERT FROM CM/S TO M/S
      TAS=.01*TAS
C-----CALCULATE DEW POINT TEMPERATURE.
C
      TFP=2.442E-2*(DEW-2047.5)
C IF FROST POINT > 0, TDP =TFP, OTHERWISE FOLLOWING INEQUALITIES HOLD
C
      IF(TFP.LT.-30.) GO TO 4000
      IF(TFP.LE.-20.) GO TO 4001
      IF(TFP.LE.-10.) GO TO 4002
      IF(TFP.LE.0.)   GO TO 4003
      IF(TFP.GT.0.)   GO TO 4004
4000  DEW=1.06*TFP-1.24
      GO TO 4010
4001  DEW=1.07*TFP-0.94
      GO TO 4010
4002  DEW=1.11*TFP-0.14
      GO TO 4010
4003  DEW=1.124*TFP
      GO TO 4010
4004  DEW=TFP
4010  CONTINUE
C
C
C-----CALCULATE LWC FROM J-W.
C
      WC=1.4652E-3*WC
C
C-----RAW VALUE OF TOTAL WATER CONTENT.
      ITWC=IFIX(TWC)
C
```

```
C
C ICE PARTICLE CONCENTRATION FROM CROSS POLARIZED PROBE WITH
C ASSUMED EFFICIENCY OF 100 PERCENT.
C
      PIC=PIC*10/(0.175*TAS)
C
C-----DME IN KILOMETERS.
C
      DME=.05657045*DME
C
C
C----------------------------------------------------------------------
C
C                 DERIVED PARAMETERS
C
C----------------------------------------------------------------------
C THETA - USES DRY ADIABATIC
      THETA=TRF*(1000./PMB)**RBYCP
C VAPOR PRESSURE IN MB
      E=VAPOR(TFP)
C MIXING RATIO
      IF(PMB.GT.E) GO TO 332
C THIS IS ONLY FOR BAD INPUT,AS PROTECTION. SHOULD NEVER BE NEEDED
      PMB=E+1000.
  332 W=E/(PMB-E)/RMWDAW
C SPECIFIC HUMIDITY Q IN G/KG
      Q=W/(1.+W)*1.E3
C VIRTUAL TEMPERATURE
      TV=((1.+RMWDAW*W)/(1.+W))*TRF
C VIRTUAL POTENTIAL TEMPERATURE
      THV=((1.+RMWDAW*W)/(1.+W))*THETA
C EQUIVALENT POTENTIAL TEMPERATURE
      TL=DEW-(0.212+0.001571*DEW-0.000436*TRFC)*(TRFC-DEW)+TZERO
      THETAD=TRF*(1000./(PMB-E))**RBYCP
      THETAE=THETAD*EXP(ALHVCP*W/TL)
C ALTITUDE CALCULATION, ICAO STANDARD ATMOSPHERE
      EX=8.31432E7*6.5E-5/(AMDRY*980.665)
      Z=(1.-(PMB/PSTP)**EX)*TSTP/6.5E-5
C CONVERT FROM CM TO METERS
      Z=.01*Z
      IZ=IFIX(Z)
```

```
C-----------------------------------------------------------------------
C
C     OUTPUT
C
C-----------------------------------------------------------------------
      WRITE(7,5000)IYR,MON,IDAY,IHR,MIN,ISEC,IPMB,IZ,VOR,DME,AIAS,TAS,TR
     $MC,TRFC,DEW,Q,THETA,THETAE,WC,ITWC,PIC,IFLR,IEVNT
 5000 FORMAT(1H ,1X,6(I2,1X),I4,1X,I5,1X,8(F5.1,1X),9X,3(F5.1,1X),I4,1X,
     $F7.1,1X,I3,2X,I4)
      IEVNT=0
  100 CONTINUE
      GO TO 1
      END
C----------------------------------------------------------------------
C
C  FUNCTION TO CALCULATE VAPOR PRESSURE:
C
C-----------------------------------------------------------------------
      FUNCTION VAPOR(TFP)
C INPUT IS IN DEGREES C.  IF GT 0, ASSUMED TO BE DEW POINT.  IF
C LESS THAN 0, ASSUMED TO BE FROST POINT.
C ROUTINE CODES GOFF-GRATCH FORMULA
      TVAP=273.16+TFP
      IF(TFP.GT.0.) GO TO 1
C THIS IS ICE SATURATION VAPOR PRESSURE
      E=-9.09718*(273.16/TVAP-1.)-3.56654*ALOG10(273.16/TVAP)
     $  +0.876793*(1.-TVAP/273.16)
      VAPOR=6.1071*10.**E
      RETURN
 1    CONTINUE
C THIS IS WATER SATURATION VAPOR PRESSURE
      E=-7.90298*(373.16/TVAP-1.)+5.02808*ALOG10(373.16/TVAP)
     $  -1.3816E-7*(10.**(11.344*(1.-TVAP/373.16))-1.)
     $  +8.1328E-3*(10.**(3.49149*(1-373.16/TVAP))-1)
      VAPOR=1013.246*10.**E
      RETURN
      END
      END$
```