Chapter 8

The Stormy Weather Group (Canada)

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1 INTRODUCTION

Project Stormy Weather began in 1943. Thirty years later Marshall (1973), reviewing the accomplishments of the Stormy Weather Group in radar meteorology and cloud physics, noted that (in 1973) an estimated 500 scientists around the world were involved in weather radar, the number having increased linearly from a handful in 1943. Quoting Marshall, "Activity of the Stormy Weather Group, continuous for thirty years, represented roughly one-sixth of the whole until, say, 1963, and represents about one-twelfth of the larger activity now (1973)." Thus Marshall and his colleagues in the Group have enjoyed a continuing and significant role in the development of and advances in this (by now) well-established but relatively recent branch of the meteorological sciences.

The author is privileged to have been a member of the Group for about twelve years, beginning in 1954. He remembers well the exciting and stimulating years spent with the Group and attempts here to present a historical review of the Group's activities over a period of about a quarter century.

2 THE BEGINNING: THE 1940s

In one of several historical reviews of the Group, Marshall (1968) has written:

> In 1943, Project Stormy Weather was assigned to Stewart Marshall, of the Canadian Army Operational Research Group. Working (in Ottawa) with him were Walter Palmer, direct from honours physics at McGill, and R.C. Langille, from explosives chemistry. J.T. Wilson as Director of Operational Research, and D.C. Rose . . ., head of the Group, assigned the project, which was to make use of the weather echoes that had appeared, primarily as a nuisance, with the introduction of microwave radar.

The Ottawa group was joined by Guy Eon, and a meteorological connection was provided by L.G. Tibbles of the Meteorological Service of Canada. In 1945 Marshall and Palmer came to McGill, and until 1950 cooperative weather radar researches were in Ottawa and at McGill, supported by the Defence Research Board (DRB) after its inception in 1947. In 1950 the Ottawa work was terminated, and the McGill group carried on as the Stormy Weather Group.

Marshall (1973) recalls that "the first contribution of Project Stormy Weather, within the CAORG, was time-lapse photography of the PPI scope. (By telephoning around the Ottawa Valley, it was established that there was rain where the radar screen glowed, and that rain started at a given point just after the echo moved over that point on the screen.) Viewing these films as movies, one sensed a new approach to storm dynamics and a potential for short-term forecasting. The showing of Stormy Weather films to American scientific meetings did much to stimulate interest in weather radar."

The early radar equipment consisted of a microwave height-finding unit at Ottawa and early warning units at Clinton and Dorval. Differences between continuous and showery precipitation were immediately evident, and the bright band presented its mysteries to the researchers. The group found that the band occurred at or near the 0°C isotherm, suggesting that the precipitation was forming as snow, melting at that height to rain, and that the melting snow was a better radar target than either the snow above or the rain below. Tibbles recalls flights into the bright band in a Beechcraft, and Marshall (1973) describes how Eon sampled the precipitation above, in, and below the bright band by means of a sugar scoop held out from an open cockpit, finding snow, slush, and water respectively—surely a praiseworthy example of an economical research method! These investigations were reported by Marshall and Tibbles (1945), Eon (1945), and Langille et al. (1945).

In 1947 Walter Hitschfeld and K.L.S. Gunn joined the team. As graduate students, their doctoral research was a laboratory and theoretical study of raindrop growth by coalescence (Gunn and Hitschfeld, 1951). By now, Marshall et al. (1947) had laid the basis for quantitative radar rainfall measurement by determining the relationships among rain rate, water content, and reflectivity, introducing both the symbol Z (to this day called "zed" in deference to its Canadian roots) and its nonstandard but durable units of $mm^6\ m^{-3}$. Extensive raindrop sampling had established the celebrated exponential drop-size distribution (Marshall and Palmer, 1948), which has held its own throughout the years as the simplest accurate description of average drop spectra. The radar in use at this time was a TPS-10 located first at Dawson College, later at Dorval. Using stepped gain, Langille and Gunn (1948) produced

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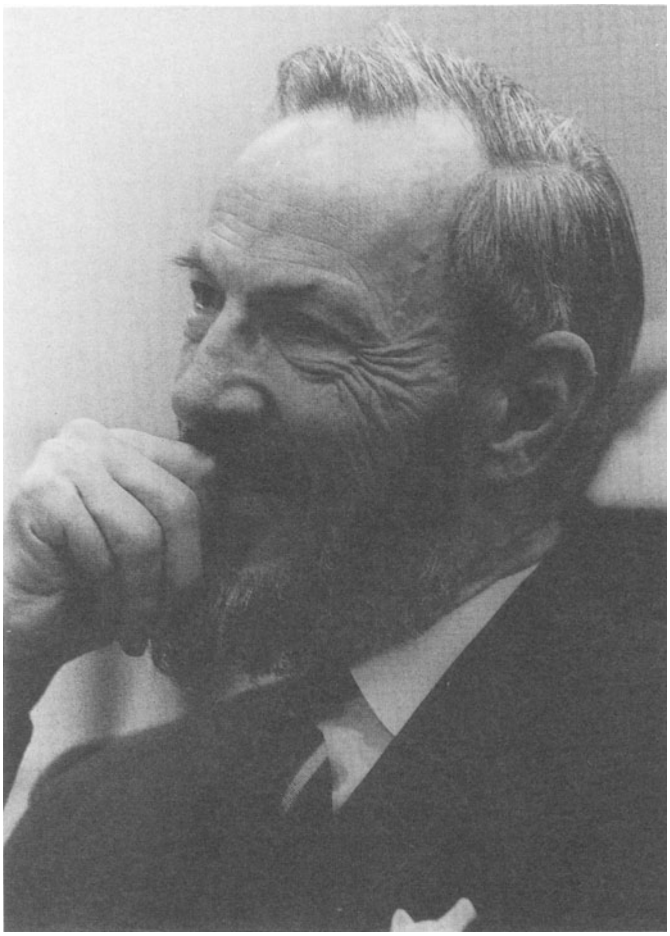

Fig. 1 J. Stewart Marshall (in 1979), founder and Director of McGill's Stormy Weather Research Group.

hand-drawn vertical sections (anticipating the stepped grey scale yet to come) showing the presence, in showers, of intensity maxima aloft, settling with time. At the same time, laboratory and theoretical studies proceeded on such topics as drop coalescence, microwave scattering and attenuation, signal fluctuations, and so forth, leading to a number of important papers that appeared in the early fifties.

3 THE 1950s

The 1950s was a particularly busy and productive decade. New radar equipment with improved antenna programming and display systems was developed and exploited in the study of precipitation processes and storm dynamics. A succession of fundamental contributions extended the understanding of radar reflections from precipitation and the physics of rain, snow, and hail. Radar meteorology as a discipline was defined during this time, and the work at McGill and only a few other centers had a strong influence on shaping the subject.

In 1951 the TPS-10 was relocated at Dorval, with displays accessible to the forecast staff. The author, a forecaster at the time, remembers well the overwhelmingly favorable response of the meteorological staff and of flight crews to this new observing technology, particularly with respect to local convective showers and thunderstorms.

The "mares' tails" patterns of precipitation, as revealed by the RHI display, attracted the attention of the Group (Marshall, 1953), and a generating level for snow was soon identified (Gunn et al., 1954). In 1953 a zenith-pointing radar, with a height–time display, was mounted on the roof of the Physics Building at McGill. This was a Marconi LN27 (3-cm wavelength, 1-deg conical beam), and much of the subsequent work on snow generation was based on its records (e.g., Douglas et al., 1957). By applying snow-trail geometry, fall speeds were determined which were more appropriate to aggregate snowflakes (whose speeds had been measured by Langleben, 1954) than to single crystals. This led to the postulation of a turbulent mechanism in generating cells, driven by the latent heat of sublimation of growing crystals in a moisture-rich environment.

Fig. 2 Walter Hitschfeld, one of the leaders of the Stormy Weather Group. (Deceased, May 1986.)

Fig. 3 Kenrick L.S. Gunn, one of the leaders of the Stormy Weather Group. (Deceased, February 1987.)

Keystone contributions to the theory of weather radar signal fluctuations were the papers of Marshall and Hitschfeld (1953) and Wallace (1953) on first-order signal statistics, including a unique view of what Paul Smith later called the "observer's problem" in radar meteorology (Smith, 1964). Hitschfeld and Dennis (1956) contributed to the understanding of second-order fluctuation statistics, laying the groundwork for Doppler spectral interpretation that was later taken up elsewhere. Gunn and East (1954) assembled their survey of the scattering and attenuating properties of precipitation particles in a paper destined to become the second-most-referenced work of the Stormy Weather Group (after Marshall and Palmer, 1948).

In 1954 the TPS-10 was replaced by the CPS-9, bringing an improvement in resolution and a change in the scanning mode. Hitschfeld and Bordan (1954), in a theoretical derivation unsurpassed for elegance, analyzed the possibility of correcting for attenuation, finding it to be highly sensitive to any error in the radar calibration. The antenna of the new radar was programmed for FASE (Fast Azimuth Slow Elevation) scanning, with a photographic record of the PPI at each elevation angle. The Group now had access to a complete record of the entire volume scanned by the radar; thus began a series of technical developments which were, in time, to fulfill Marshall's concept of weather surveillance radar (Marshall and Ballantyne, 1975).

Increased understanding of precipitation physics kept pace with the improvements in equipment and displays. Melzak and Hitschfeld (1953), in a study that was ahead of its time, formulated the stochastic coalescence equation for cloud droplet growth but were limited to somewhat artificial analytical solutions because digital computers were not yet ready for the task. From radar patterns, Caroline Rigby drew the distinction between the shower process and continuous rain, and she analyzed the evolution of raindrop populations in these two idealized processes. Reported by Rigby et al. (1954), this work laid the foundation for much of the analytical theory of precipitation development that followed.

Activities of the Stormy Weather Group were kept in public view by Marshall, who felt an obligation to communicate the research results of his group and to apply this knowledge to practical problems. In the early years of television, for example, Montreal audiences were shown photographs from the McGill CPS-9 and given short-term forecasts. Later, in the early 1960s, a series of radio lectures by Marshall were broadcast nationwide on the CBC on the topic "Why the Weather?" The Third Conference on Radar Meteorology was held at McGill in 1952, when Marshall introduced the idea of a preprint volume.

The CAPPI (Constant Altitude Plan Position Indicator) was the next technical development, capitalizing on the FASE program. At each elevation angle, the beam would scan some predetermined height over the annular area contained between two appropriate slant ranges. The CAPPI system built up a PPI, at the predetermined height, as a mosaic of these annuli. Langleben and Gaherty (1957) devised an ingenious optical–mechanical system for the synthesis of CAPPI maps, in which the photographic PPI record, at each elevation angle, was scanned and the appropriate annuli extracted to build up a photographic image of the CAPPI. Later, East (1958) devised an electronic technique to develop and display the CAPPI map in real time; in recalling this work, which made use of scan converter tubes, East remarked that "in those days, before memory chips, we used to store data in glass bottles!"

CAPPI was first applied by Langleben (1956) in his investigation of the plan pattern of snow generating cells. The subsequent development of logarithmic amplifiers and then of stepped grey scale (Legg, 1960) added the dimension of quantitative reflectivity to the radar display. This quantitative mapping was widely exploited well into the 1960s, for example, in Hitschfeld's (1959) studies of plumes, Hamilton and Marshall's (1961) estimates of attenuation, Hamilton's (1964) precipitation profiles (with their application to synoptic meteorology), and Carlson

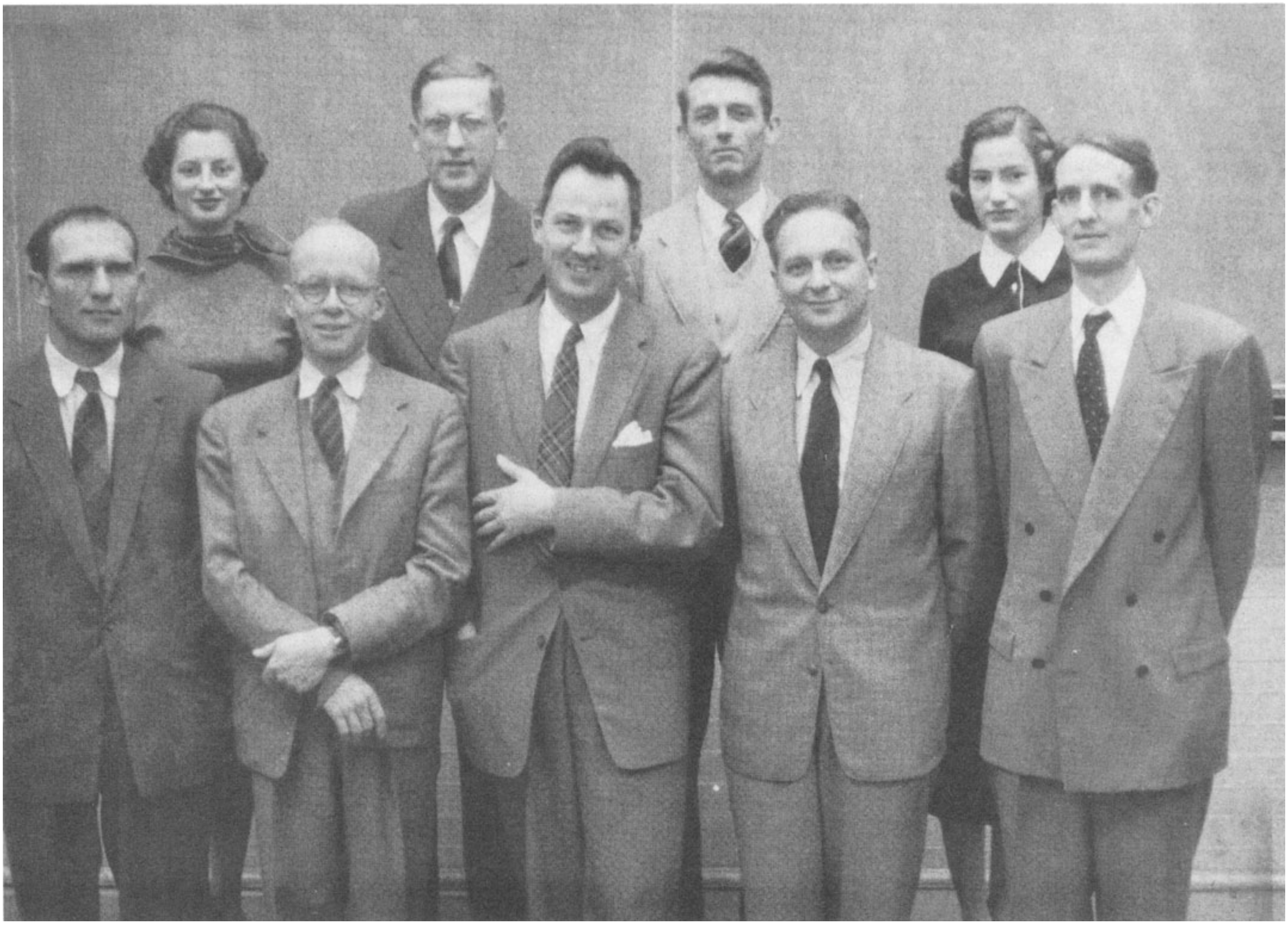

Fig. 4 Stormy Weather Group, ca. 1955. Front row: M.P. Langleben, K.L.S. Gunn, J.S. Marshall, W. Hitschfeld, and T.W.R. East. Back row: J. Bristow (secretary), A.S. Dennis, R.H. Douglas, and R. Huberman (technician).

and Marshall's (1972) mapping of snowfall, with its hydrological implications.

Microphysical studies that complemented the radar research continued, as typified by the definitive work on snowflake-size distributions (Gunn and Marshall, 1958) and preliminary experiments on ice nucleation, which led to the drop-freezing experiments of the next decade (Vali and Stansbury, 1966).

Financial support for all of this research activity was from a combination of Canadian and American sources, with the Air Force Cambridge Research Laboratories often the major source. David Atlas as contract monitor from AFCRL was a frequent visitor to McGill during this time and played a part in influencing the course of the research.

In the mid-1950s an important event occurred that was to have far-reaching consequences for the Group. On the western prairies, following a series of disastrous hail seasons, Alberta farmers approached the provincial government regarding the prospects of hail suppression. This led to an agreement among the Research Council of Alberta, the Meteorological Service of Canada, the National Research Council, and the Stormy Weather Group to plan and implement a hail study program in central Alberta. In the summer of 1956 Douglas (at the time seconded to the Group from the Meteorological Service of Canada) set up a trial hail reporting network and generally surveyed the prospects for a sound field program. In the fall, it was agreed that a full-scale project could and should be mounted, based at RCAF Station Penhold, midway between Edmonton and Calgary, and thus the Alberta Hail Studies (ALHAS) was created. It was agreed at the start that while the ultimate aim was (hopefully) the amelioration, or even complete prevention, of hailstorms, the project must concentrate primarily on an understanding of the storm itself and of the cloud physics involved. Despite occasional pressures, the sponsors and scientists held firmly to this philosophy. When cloud seeding was eventually performed in the late 1960s, it was under carefully controlled and observed circumstances—an experiment rather than a commercial operation.

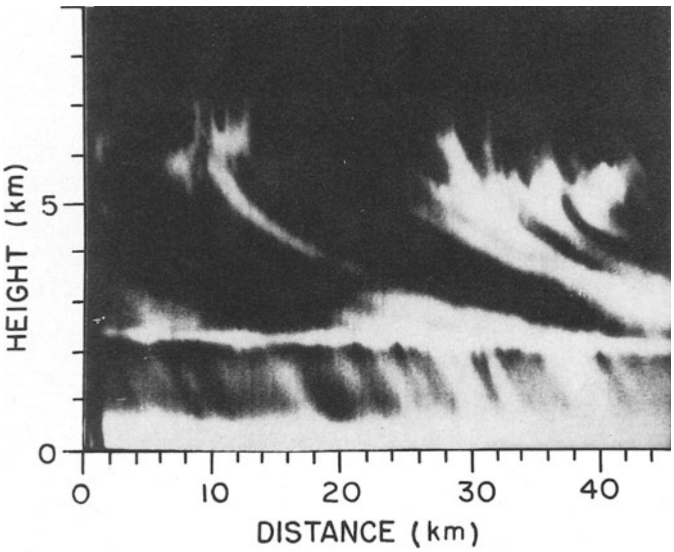

Fig. 5 Generating cells, snow trails, bright band, and rain as displayed on the height–time display of the zenith-pointing radar. The time scale has been converted to distance through the velocity of translation of the cells.

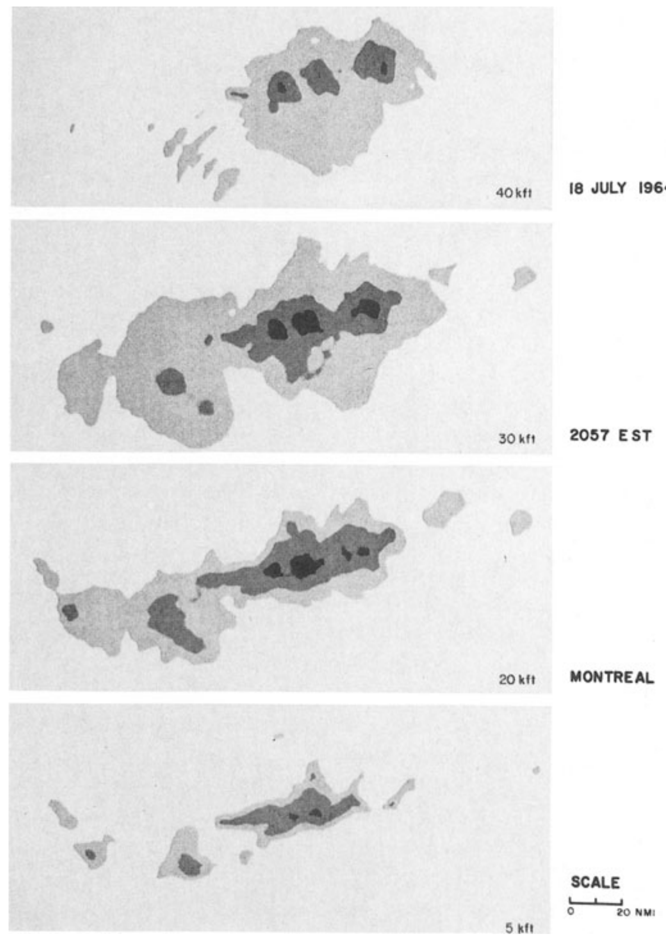

Fig. 6 An example of CAPPI maps of a summer storm, shown at four heights and in three shades of grey, corresponding to rainfall rates of 1.5, 25, and 400 mm h^{-1}.

Once the Group set specifications for a suitable Alberta radar, the National Research Council (NRC) undertook its purchase, modification, installation, and maintenance. The first project radar, in service by the spring of 1957, was a Decca type-41 storm warning radar, with the antenna reoriented to provide a narrow (¾ deg) beam in the vertical and programmed for a FASE scan with a two-minute cycle from which CAPPI maps could be synthesized.

In spite of severe attenuation in the heavier cores of the storms, this radar served the project well. Echoes and their envelopes (the projections of the echoes onto the ground) were mapped and related to the farmers' hail reports (Douglas and Hitschfeld, 1959). Echo-top heights were measured, and a relation was determined between the height and probability of hail (as had been found for New England storms by Donaldson, 1958). It was further observed (Douglas, 1960) that "penetration of the tropopause by the storm top enhances the probability of hail" and, in particular, the production of *large* hail; similar behavior in New England storms was reported by Donaldson et al. (1960). A comparison of the height-probability curve for Alberta storms with those of New England and of Texas revealed important geographical/climatological differences, namely that for a given echo-top height the probability of hail increased latitudinally from Texas to New England to Alberta (Douglas, 1963)—reinforcing the notion of the importance of tropopause penetration. In the field, the height-probability relation was useful, in real time, for alerting the Alberta hail-reporting network by phone and radio, and for providing appropriate warnings to our Air Force hosts at project headquarters.

In subsequent summers, the reporting network became more sophisticated; telephone calls to and from farmers supplemented the mailed-in reports, no-hail reports were solicited from the fringes of storms, and details were sought on the intermittency of hailfall, the rain/hail sequence, the range of stone sizes, and so forth. Automobile surveys were made in some cases. Study of the envelopes and of the intermittency of point hailfall suggested a multicellular structure to the storms. Of importance to subsequent hail-growth models was the finding that, in about 20% of cases examined, hail reached the ground within about 20 minutes of the detection of first echo (Hitschfeld and Douglas, 1963).

By the end of the decade, a large number of hail samples had been collected, their size distribution established (at least tentatively), and Z–R and Z–M relationships determined for hail. The nucleation of the freezing process was being investigated, first by Barklie and Gokhale (1958), later by Vali and Stansbury (1966). These nucleation studies, pursued energetically through the next decade, were to provide a model of freezing that was applied in due time in the various hail-growth models developed by members of the Group.

4 THE 1960s

When the Department of Meteorology was established at McGill in 1959, Marshall was appointed Chairman and Hitschfeld and Douglas were charter members. The other founding members were F.K. Hare, S. Orvig and B.W. Boville, all from what was then called the Arctic Meteorology Group. Gunn remained in the Physics Department. East and Palmer, key members of the Stormy Weather Group in the 1950s, had left McGill. Physics faculty members M.P. Langleben and P.R. Wallace had been part of the Group earlier, but had moved away from atmospheric research by the time the Department was established.

By now two somewhat distinct areas of activity characterized the Group. Some staff members and graduate students did research centered on radar and laboratory studies in Montreal; others were affiliated with the Alberta Hail Project. The Montreal-based research was still supported by contracts with AFCRL, but with an increasing fraction from Canadian sources, mainly the National Research Council and the Canadian Meteorological Service. Many students enrolled under the auspices of the Meteorological Service and were posted when graduating to weather offices or laboratories all across the country. Even as students some had split their time between Montreal in the winter and Alberta in the summer. The Group thus performed an important educational and socializing function for the country, which explains in part the pervasive influence of the Stormy Weather Group, even to the present day, on the practice of meteorology in Canada.

Nourished by a steady stream of good graduate students, research during the sixties expanded on many fronts, with advances in the understanding of atmospheric processes progressing hand in hand with the development of new observing techniques. A few examples give an idea of the scope and diversity of the work:

- The groundwork was prepared for understanding the formation of hail (Douglas and Hitschfeld, 1959; Hitschfeld and Douglas, 1963), leading to a series of contributions by many students that culminated in the monograph by Chisholm and English (1973).
- Holtz (1968) pioneered the use of radar data in the study of thunderstorm water and energy budgets.
- On the theoretical side, Srivastava (1967) analyzed the relation between cloud dynamics and precipitation development in a one-dimensional, time-varying numerical model, initiating what was to become a major area of cloud physics research. His work at McGill was the starting point for a continuous progression of research through Ian Harris, Takao Takeda, J.T. Steiner, and now M.K. Yau and his students.
- Innovative laboratory experiments on freezing nucleation provided insight on hail formation from a microphysical perspective. These techniques, developed further and applied elsewhere, led unexpectedly to the discovery of biogenic ice nuclei and the possibility of reducing frost damage to plants by biological controls (Schnell and Vali, 1976).
- Advanced cloud stereophotography systems were developed for Alberta (Renick, 1966) and Montreal (Shaw, 1969).
- Also in the experimental realm, Zawadzki (1973) designed the hardware for optical (analog) statistical analysis of radar patterns, interpreting his results in ways that have had a continuing influence on hydrology.

Throughout this period, a steady improvement in radar equipment and displays was evident. At the beginning of the decade, the original DC-19 radar was still in operation in Alberta, but attenuation seriously hampered the more detailed radar information now required to mesh with the increasingly sophisticated ground-observing network. Accordingly, an FPS-502 (10-cm wavelength) was acquired, and installed in 1963. This particular model had a broad vertical beamwidth and operated at three tilts. At low tilt, the vertical beam extended from 0°–5°; at medium tilt, from 3°–10°; and at high tilt, from 10°–19°. Pending the acquisition of a more suitable antenna, this system was put into action and remained in use until 1967.

Despite the limitations of the broad vertical beam, the 10-cm unit provided data for several important studies of severe storms and storm cores (Chisholm, 1967). Pell (1969) determined the patterns of columnar water concentration and detected the first hint of an echo-free region on the edge of a storm, later confirmed by Chisholm.

In 1967 the 10-cm radar was fitted with a parabolic antenna with a conical beam of 1.15° width. At this point the Decca was retired. Now, with high resolution and very much less attenuation, the radar was exploited to examine a number of storms in great detail (e.g., Chisholm, 1970a,b), revealing "weak echo regions" which were either "bounded" (BWERs) or "unbounded" (UWERs).

Supporting the radar and the ground network of observers now were mobile observatories, vectored by radio into the vicinity of and under the storms for direct observation as well as for the collection of rain and hail for nucleation studies and for the measurements of hailstone ellipticity, which anticipated later studies of polarization effects. From stereo photography and related analytical techniques the visual cloud structure could be related in some cases to the radar data to build up a more detailed storm model (Warner et al., 1973). On some occasions, serial pilot balloon ascents and additional radiosoundings helped determine the airflow patterns around and near the storms (Thyer, 1970; Ragette, 1973). Additional backup was provided during several summers by instrumented flights of a crew from the University of Wyoming, identifying and locating regions of updraft and downflow. All this, plus several Montreal storms examined with the Dorval radar, provided grist for the "model mill," with English applying the field-deduced storm structure to an increasingly sophisticated hail-growth model (e.g., English, 1969; English et al., 1972).

An outstanding feature of the Alberta radar was its polarization diversity capability. Developed at NRC by Dr. G.C. McCormick and his associates (McCormick, 1968; McCormick and Hendry, 1968, 1970; McCormick et al., 1972), this facility permitted the transmission of a beam of any desired polarization and the reception of two echo components, one polarized as transmitted, the other orthogonal to it. Data obtained in 1969 provided evidence that deformed hail can be distinguished by its depolarization signature. Barge (1970) found good agreement between the observed Circular Depolarization Ratio (CDR) and the value computed from hail samples collected at the ground below, and simultaneous with, the radar observation. In an experiment in 1970, plane-polarized radiation was transmitted and the received signal examined for ellipticity, indicating such large hydrometeors as hail. Preliminary observations suggested that this was indeed the case, so it could be hoped that the polarization facility would provide identification of *large* particles, viz. hail and deformed hail. This work prompted a new wave of research activity in polarization studies in many parts of the world.

The FASE scanning program had been exploited to yield CAPPI displays, but little had been done to extract the vertical sections that are of vital importance in storm studies. In the late sixties, HARPI (Height–Azimuth Range Position Indicator) was developed, as described by Zawadzki and Ballantyne (1970) and Marshall and Ballantyne (1975). HARPI provided a series of vertical cross sections on a rectangular coordinate system wherein the abscissa is azimuth (or circumferential distance) and the ordinate is height. Each cross section corresponds to a different radial distance from the radar. HARPI was first applied with the high-resolution radar in Alberta in 1967 and proved extremely useful operationally with its concise depiction of the complete storm situation.

Inevitably, some of the most advanced and most useful displays came at the end of the analog era, just before inexpensive microcircuits and computers made it possible to record and process the data digitally. A further development of the CAPPI display in Montreal was the addition, around the periphery, of height information, this being dubbed PPHI (Plan Position Height Indicator). A CAPPI map for a height of about 12 kft was displayed to a range of 120 n mi. This map was surrounded by an annular band comprised of ten rings, each representing a height interval of 5 kft, in which are painted the height data from the range interval 20 to 80 n mi. Considerable attention was directed to the problem of attenuation and the resulting deformation of storm cores as displayed on the screen,

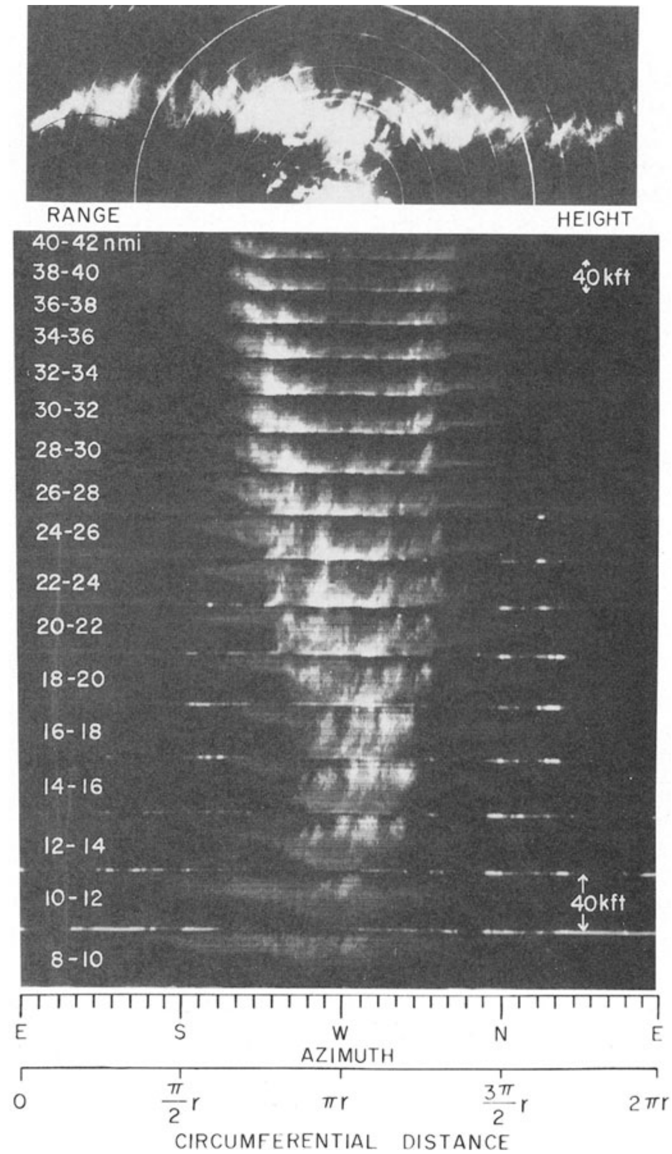

Fig. 7 The HARPI display of a storm in Alberta. Seventeen individual cross sections are displayed, each one for a range interval of 2 n mi and to a height of 40 kft. A low-level CAPPI is shown at the top.

and to the implications of hydrology (e.g., Hamilton and Marshall, 1961; Carlson, 1968). In due time came the development of ADA (Azimuth Display of Attenuation) by Zawadzki and Rogers (1969) wherein the integrated attenuation on each azimuth was displayed on a peripheral scale. AZLOR was a display on rectangular coordinates of Azimuth and Log Range, a conformal map on which the data sites are arrayed uniformly (Marshall and Ballantyne, 1975). The reflectivity data on this display were represented by discrete dots, uniformly spaced in lines parallel to the axes, each dot indicating by its magnitude the target intensity level in the bin it represents.

To round out the decade, an FPS-18 was acquired through the offices of AFGL and installed at a new site on

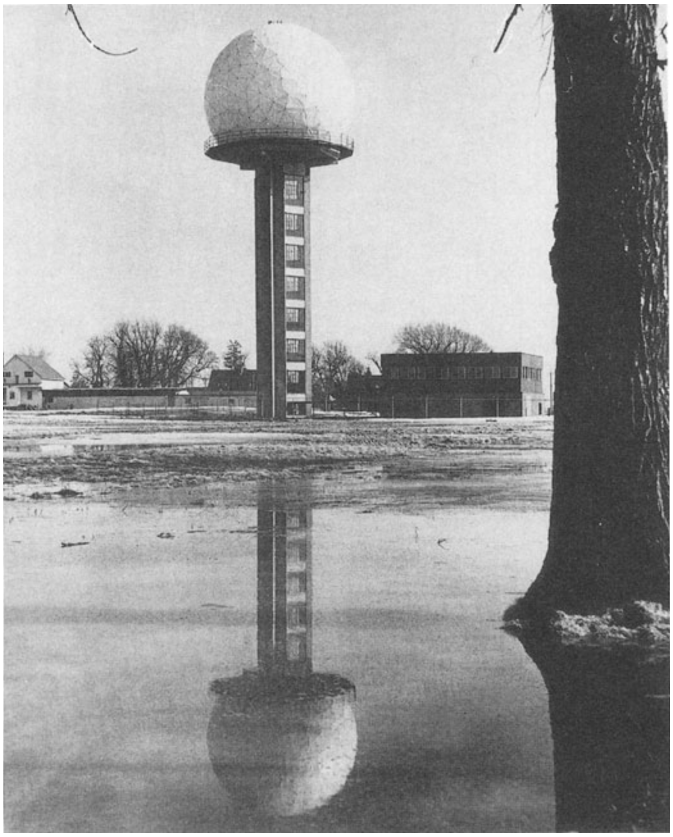

Fig. 8 The CPS-18, located on the premises of McGill's Faculty of Agriculture at Ste. Anne de Bellevue, was formally inaugurated on the occasion of the 13th Radar Meteorology Conference in Montreal in 1968.

the premises of Macdonald College, McGill's Faculty of Agriculture, at Ste. Anne de Bellevue. This installation was formally opened on the occasion of the 13th Weather Radar Conference in Montreal in 1968. This marked a return to 10-cm wavelength and an end to much of the attenuation problem. A few years later the by-now geriatric CPS-9 was retired.

5 CONCLUSION

It is rumored that Stewart Marshall was once accused of (credited with?) wanting to measure everything, everywhere, all the time. Under his energetic and imaginative direction, the Stormy Weather Group undoubtedly worked hard toward the achievement of its goals. While a substantial effort was directed to advancing the techniques of observation and display, the ultimate product was always a furthering of the understanding of cloud dynamics and precipitation microphysics. Technique was applied to answer questions, and unanswered questions suggested fresh technology.

Acknowledgments. The author is indebted to his many colleagues and their writings in the preparation of this brief history. The publications referenced of course represent only a fraction of the total output of the Group. The author's selection is admittedly arbitrary, but the choice is intended to be illustrative (rather than exhaustive) of the many and varied activities of the Group. Particularly helpful have been the several excellent histories and chronologies prepared from time to time by Marshall and Hitschfeld. The assistance of R.R. Rogers, who welcomed the author into the records and libraries of the Department of Meteorology of McGill University, is gratefully acknowledged, as are the personal recollections of L.G. Tibbles and T.W.R. East.

Unfortunately, this review lacks the input that would have been provided by the late Ken Gunn, who was to have been a co-author. The author has also missed the wise counsel and total recall of the late Walter Hitschfeld. To their memory, and to that of Lou Battan, this history is dedicated.