An Application of a Geostationary Satellite Rain Estimation Technique to an Extratropical Area

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ABSTRACT

The use of geostationary satellite data for estimating precipitation in non-tropical areas was explored with data taken in Montreal, Canada. The previous studies using geostationary images for rain estimation have concentrated primarily on tropical clouds (Griffith *et al.*, 1978; Stout, *et al.*, 1979). The intent of this study was to evaluate the applicability of using these data and techniques in other geographical areas. The Montreal area provided a wide range of weather situations common to midlatitudes for which the techniques could be tested. Because of the many variables in this area (different cloud types, moisture availability, temperature vertical structure and others) the rain rates of the cloud areas varied. Large differences in rain rates between the days studies in Montreal were found. The Montreal data also had rain rates that were considerably smaller than found in the tropical studies.

To explain these differences the environments of the clouds were investigated using sounding data. By applying a cumulus model (Simpson and Wiggert, 1969) to the soundings most of the daily differences in rain rates were explained. The large differences between the tropical studies and Montreal also were described by the model. It is proposed that future rain estimation schemes combine satellite image with sounding data through a cloud model to form a technique applicable to a wide variety of weather situations and geographical areas.

1. Introduction

The use of satellite data for estimating precipitation has gained attention in recent years because of the need for rainfall information in many areas of the world where weather observations are sparse or nonexistent. Studies of tropical cumulus convection have encouraged the development of techniques using geostationary satellite data (Griffith *et al.*, 1978; Stout *et al.*, 1979; hereafter referred to as Griffith or Stout). Intense efforts using these data were made for the Atlantic Tropical Experiment (GATE, 1974) of the Global Atmospheric Research Program (GARP). Other satellite rain estimation techniques for sampling large oceanic areas have been developed using microwave sensors (Rao and Theon, 1977). Similar precipitation and latent heat release data will be needed on a global scale for the First GARP Global Experiment (FGGE) scheduled for the calendar year 1979.

Outside of the atmospheric research community the need for rainfall information is also very strong. Agricultural grain crop forecasters have sought precipitation data in many of the undeveloped countries of South America and Asia where weather observation networks are very poor (Merritt, 1976). Hydrologists have sought the same information in sparsely populated areas for river basin studies (Barrett, 1976). Many of the needs for satellite-derived precipitation estimates have been in the continental areas of the world and several attempts have been made to satisfy these needs.

Early efforts at estimating precipitation from satellite images have correlated weekly or monthly precipitation to the length of time a station was covered by convective clouds (Follansbee, 1974; Kilonsky and Ramage, 1976). These studies have used polar orbiting satellite images taken twice per day for determining cloud cover and assigned constant rainfall rates to the cloud areas. Refinements to the techniques have used climatological rain rates with the satellite-measured cloud areas for estimating seasonal precipitation accumulations (Follansbee, 1976). Satellite data also have been used to extend coverage between raingages (Barrett, 1976).

Geostationary satellites have provided time sequences of images from which cirrus anvil expansions can be measured as proposed by Sikdar (1972). These measurements have been used by Griffith and Stout on tropical cumulonimbus and by Scofield and Oliver (1977) on air mass thunderstorms over the southern United States. Because of the success of these studies and the needs for rain information in many nontropical areas of the world a test of using geostationary images outside of the tropics was made.

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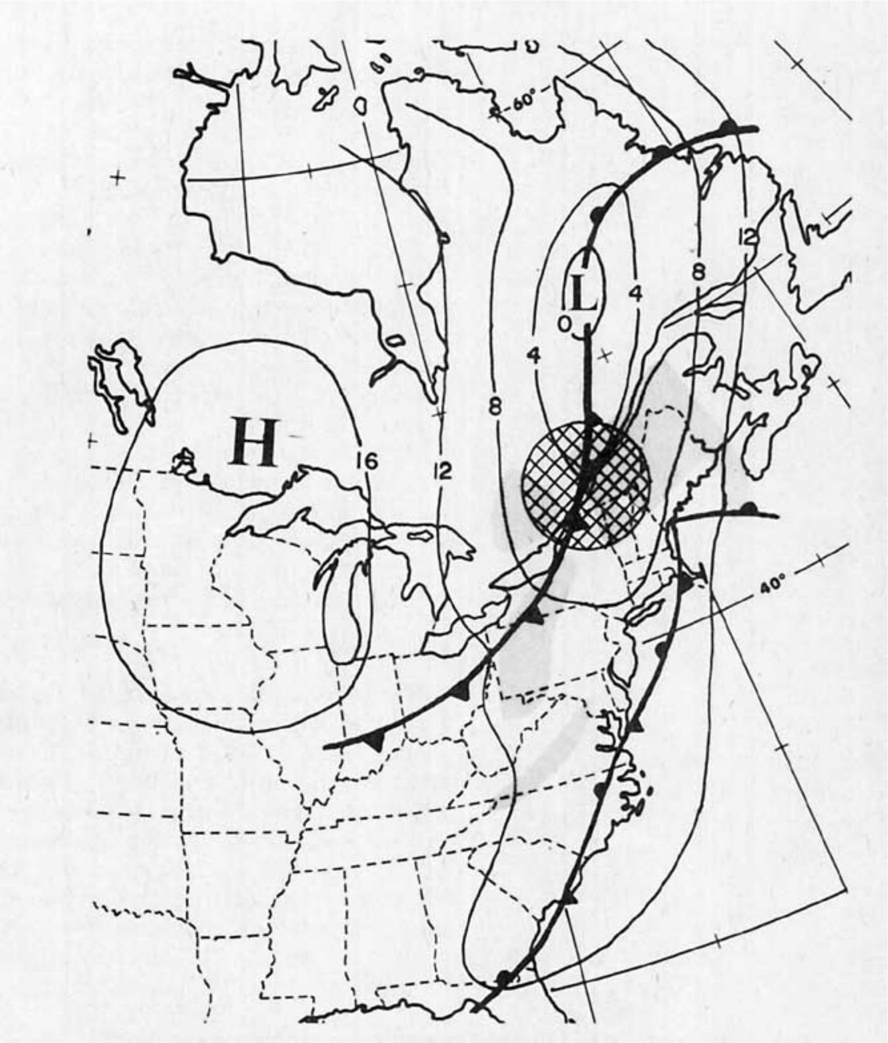

FIG. 1. Surface analysis for 1800 GMT (1300 LST), 2 June 1977, of eastern Canada. Shaded areas indicate precipitation. The circle indicates the area covered by the radar.

This paper will describe the study made on data from Montreal, Quebec, Canada. Images from the Eastern Geostationary Orbiting Satellite (GOES-E) were used for testing the feasibility of estimating rain over a midlatitude continental area. The results obtained in Canada will be compared to the tropical data obtained by Stout, to show the similarities and differences between the application of satellite data to the two different geographical areas.

2. Data used

GOES-E images were archived at one-half hour intervals by the University of Wisconsin-Madison. Visible images (0.7 μm wavelength) and infrared images (11.5 μm) were recorded at spacial resolutions of 2.8 and 5.6 km. The geographical position of the earth in the image was determined from landmark measurements. These satellite images were compared to radar images of the same area.

Rainfall rates under the clouds were measured by the 10.0 cm weather radar of McGill University, Montreal, which covered a 200 km radius circle centered on Montreal (Fig. 1). The method of determining rainfall rate is described by Hodge and Austin (1977). This method basically used a nominal Z-R relationship and then corrected it for bias errors based on the 24 h accumulations of 150 gages in the area. The initial relationship between radar reflectivity (Z, mm^6 m^{-3}) and rain rate (R, mm h^{-1}) of $Z = 200 R^{1.6}$ was used. Radar-derived rain totals over each gage were calculated and compared to the accumulations measured by the gages. The bias errors then were removed by adjusting the Z-R relationship based on the gage totals and recalculating the rainfall rates.

The rainfall rates were averaged over 4 km × 4 km boxes in the horizontal. Scans at multiple altitudes were used to average the rain rates over 1 km in the

TABLE 1. Summary of the data used in the geostationary satellite rain estimation study.

Date	Time period studied (LST)	Satellite data type	Location	Cloud cover (%)
4, 6 Sep 74	0930–1530	Visible	GATE	56
	0330–2000	IR		64
1 Jun 77	1230–1530	Visible	Montreal	44
		IR		33
2 Jun 77	1200–1500	Visible	Montreal	67
		IR		28
29 Jun 77	0800–1330	Visible	Montreal	26
		IR		25
16 Sep 77	1000–1430	Visible	Montreal	60
		IR		98
20 Sep 77	1030–1430	Visible	Montreal	NA*
		IR		51
26 Sep 77	1000–1330	Visible	Montreal	30
		IR		83

* NA, not available.

vertical centered at 3 km above the earth's surface. These data formed a constant altitude projection of rainfall rate which was then remapped to the projection of the satellite image.

3. The types of weather studied

A total of six days when precipitation occurred in Montreal were studied (Table 1). Three of the days in June represented the type of precipitation found in the summer months over eastern Canada. A warm air mass typically covered most of the area, while a cold front advanced from the northwest (Fig. 1). Cumulonimbus clouds (Cb) developed in the warm air and were clearly visible on the satellite images (Fig. 2). East of the front Cb's were easily identified by being isolated or in lines parallel to the low-level wind direction. More widespread cloud cover and precipitation occurred near the cold front making individual cloud identification more difficult. Cirrus from the convective cells also covered the area masking the appearance of the cells on the satellite image.

Three days in September 1977 were studied which represented the type of precipitation found in the fall and winter. On these days the Cb cells were not easily distinguished (Fig. 3). A massive cloud area encompassed most of the radar's viewing area and precipitation was widespread under the cloud cover.

4. The measurement of rainfall rates

The amount of cloud cover in the viewing area of the radar was measured on each of the satellite images taken at one-half hour intervals during the time periods shown in Table 1. Threshold levels of brightness (visible images) and temperature (infrared) were used to define the cloud areas on the digital images. The amount of image area above the threshold brightness or colder than the threshold temperature were digitally summed by the computer.

For comparisons of the cloud cover found in Montreal to the GATE studies it was necessary to

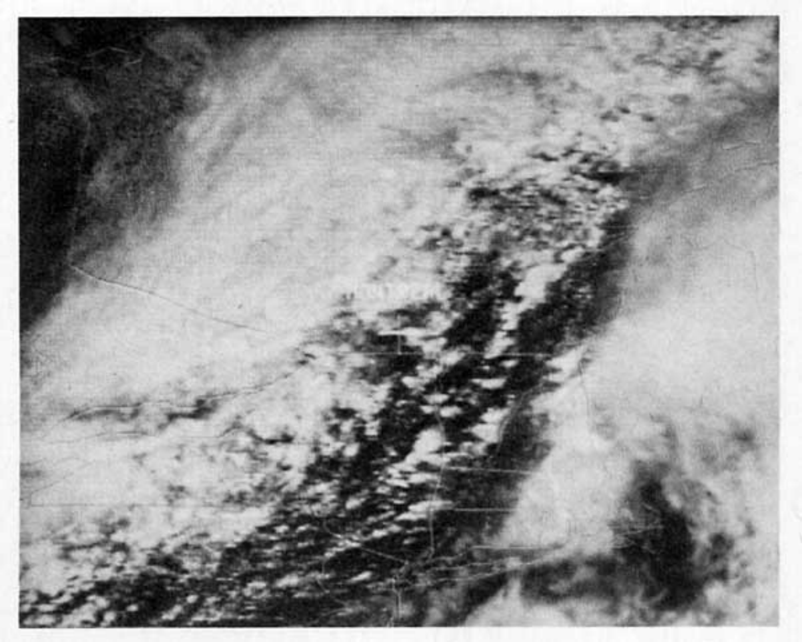

FIG. 2. GOES-E satellite image of eastern Canada, centered on Montreal, 2 June 1977.

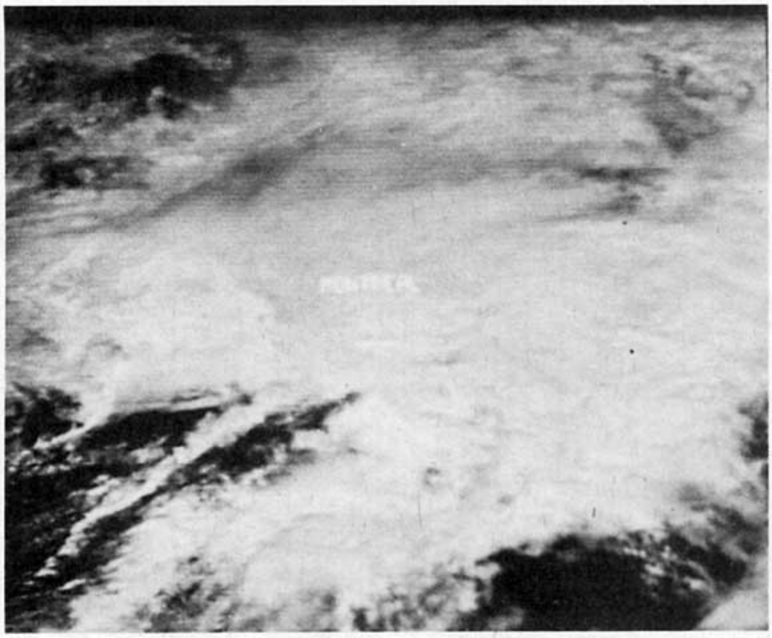

FIG. 3. As in Fig. 2 except for 26 September 1977.

correct the brightness levels of the images. The angle of the sun illuminating the clouds varied both with latitude and the time of day in which each image was taken. A different satellite also was used for the studies of Griffith and Stout. These conditions produced differences in the brightnesses of the clouds between the two geographical areas (GATE and Montreal) and variations in brightnesses between the different days studied in Montreal. These variances were seen only in the visible images. The infrared sensor was routinely calibrated by NOAA as the data were archived and thus did not require any extra processing.

To produce a visible image independent of sun angle and sensor changes, the visible brightness was converted to an optical thickness of the cloud using a plane-parallel, homogenous, multiple-scattering model (Mosher, 1975). The brightest cloud on each image was used as a reference for the radiative scattering model by assuming that this cloud was of a nearly infinite optical thickness. A reference was needed to calibrate the visible sensors on the satellites. All measurements of areas on visible images were made using the threshold levels derived from the multiple-scattering model and the reference calibrations.

To form a statistical basis for estimating rainfall from satellite images, data on the rainfall rates of the clouds were needed. For these data the McGill radar measurements were compared to the satellite images. A rain rate statistic for the cloud areas seen on the satellite images was derived from a combination of radar and satellite data. To form this statistic the total amount of rain falling within 200 km of Montreal was derived by integrating the radar-measured rain rates over the radar's viewing area. This represented a volumetric water flux into the area. The volumetric rain rate then was divided by the amount of cloud cover measured by the satellite over the same area. The cloud-cover measurement was made using the threshold of optical thickness or infrared temperature as previously discussed. This produced a new rain rate statistic that was a function of the threshold used on the satellite image (see Figs. 4 and 5).

The radar-satellite rainfall rates were averaged over the time periods shown in Table 1 for each day. Because satellite images produced cloud areas that were larger than the rain areas seen on the radar, the radar-satellite rainfall rates were smaller than the rainfall rates measured by the radar alone. Lovejoy and Austin (1979) found the satellite cloud areas to be approximately four times larger than the radar rain areas. Thus the combined radar-satellite rain rates were smaller by the same ratio.

The radar-satellite rainfall rates varied with the threshold levels of optical thickness or infrared temperature used because the cloud areas measured were sensitive to the thresholds used. It is intuitively obvious that higher optical thicknesses or colder infrared temperature thresholds would produce smaller cloud area measurements which also was the situation found in these data. The rain rate statistics shown in Figs. 4 and 5 depict this relationship by increasing with increased optical thickness or colder infrared temperature. The volumetric

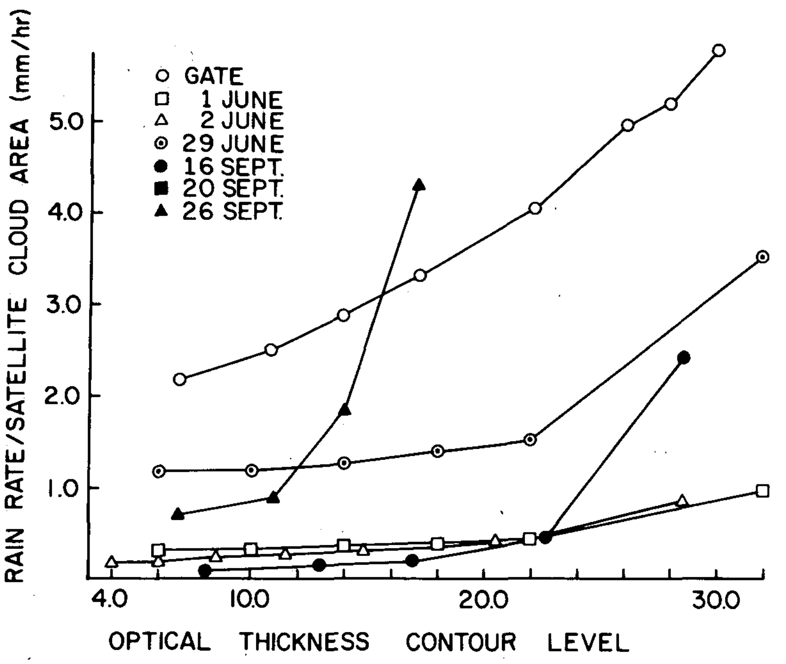

FIG. 4. Rainfall rates for the cloud areas measured on the visible satellite images expressed as a function of the brightness threshold used to define cloud area. Rainfall rates were derived using McGill radar measurements of rain volumes combined with satellite measurements of cloud areas. See text Section 4 for description.

water fluxes into the area were not affected because they were independently measured by the radar and thus the changes shown in Figs. 4 and 5 represent cloud area changes alone.

The objective of any satellite-based rain estimation scheme is to choose threshold levels that define convective cloud areas and eliminate non-convective clouds and land forms. Therefore the higher

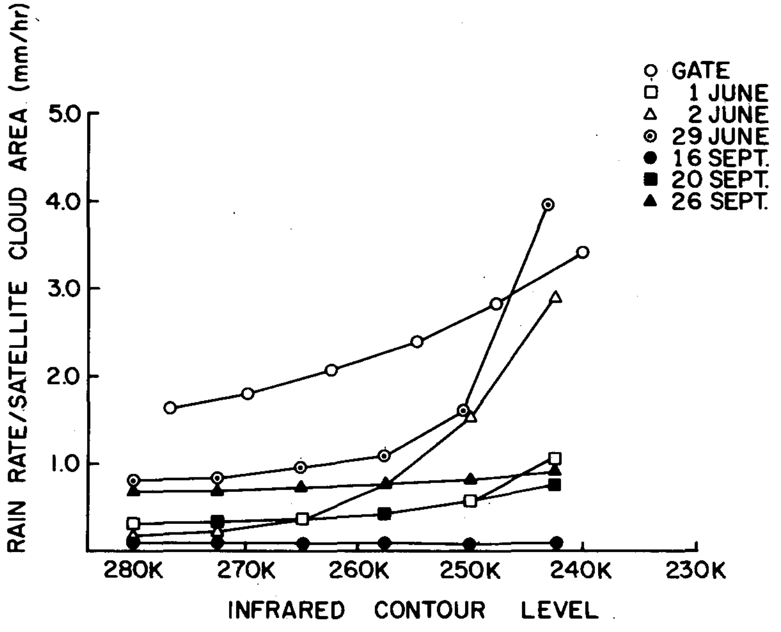

FIG. 5. Rainfall rates for the cloud areas measured on the infrared satellite images expressed as a function of the infrared temperature used to define the cloud areas. Rainfall rates were derived using the combination of McGill radar rain volumes and satellite cloud areas. See text.

optical thickness levels or colder infrared temperatures should be used. However, the data shown in Figs. 4 and 5 indicated that the cloud areas and consequently rain rates were extremely sensitive to the higher (colder) thresholds while at lower (warmer) thresholds the sensitivity was reduced.

The threshold levels used in the GATE study of Stout were an optical thickness of 14 and a temperature of 247 K. The tropical study of Griffith used a similar visible threshold and an infrared threshold of 253 K. These levels were used because the cloud areas measured from them exhibited time variations that closely correlated with the radar-measured rain volumes. In Montreal lower cloud-top heights were found than from the tropical studies and some clouds did not reach the 247 K level. Unrealistically small cloud areas were found using the 247 K threshold. Because of this problem the threshold was increased to a level of 257.5 K where better descriptions of the cloud areas were made.

The locations of the rain areas were compared to the satellite image brightness levels by Lovejoy and Austin (1977) using the same data. For the thresholds used the rain areas were located within an accuracy of 40 km. In all cases the satellite cloud areas defined by the thresholds were larger than the rain areas and the rain areas were contained inside them. for further details on the locations of the rainfall see Lovejoy and Austin (1979).

5. The variability of rainfall rates

The Montreal data were compared to the tropical data used by Stout and Griffith. Rainfall rates were derived for the tropical data in the same manner as done for Montreal. The radar data from the OSS *Oceanographer* taken on 4 and 6 September 1974 in the GATE area were used. These radar data were converted into rainfall units by NOAA (Patterson *et al.*, 1979). Values of the volumetric water flux into the area were obtained by areal integration of the radar data and the radar-satellite rainfall rates were obtained by dividing the volumetric rain rates by the satellite-measured cloud areas. These statistics are also shown in Figs. 4 and 5 for comparison to the Montreal statistics.

The tropical rainfall rates in all cases were larger than any of the days studied in Montreal. In addition, large differences between the days studied in Montreal were also found. The heaviest Montreal precipitation occurred on 29 June from a massive line of convection that moved through the area. Heavy rainfall was also found on 26 September, but it was not concentrated and fell from many Cb's with merged anvils. Unrealistically small cloud areas were measured on the visible images on this day but not on the infrared images. The small cloud areas produced the unrealistically large rainfall rates for the higher optical thicknesses (Fig. 4) while more reasonable rain rates were found for the infrared images (Fig. 5).

TABLE 2. The precipitation rates (mm h^{-1}) of the satellite-measured cloud areas and the precipitable water vapor (mm) measurements from the soundings in the area.

Date	Location	Rain rates over the satellite cloud areas: Visible (τ = 14 μm)	Rain rates over the satellite cloud areas: IR (257.5 K)	Sounding integrated precipitable water
4, 6 Sep 74	GATE	2.8	2.2	54
1 Jun 77	Montreal	0.3	0.4	27
2 Jun 77	Montreal	0.2	0.9	22
29 Jun 77	Montreal	1.2	1.0	38
16 Sep 77	Montreal	0.1	0.1	22
20 Sep 77	Montreal	NA*	0.4	27
26 Sep 77	Montreal	2.4	0.9	27

* NA, not available.

Lighter convective precipitation was found on 1 and 2 June from isolated Cb's in the warm areas ahead of slow moving cold fronts that approached the area on each of the two days. On both days the rapidly expanding anvils from Cb's were seen on the satellite images, but the rainfall rates from these clouds remained small when compared to 29 June and 26 September.

Light precipitation rates also were found on 16 and 20 September. These days were dominated by extensive areas of stratus clouds which yielded very small precipitation amounts.

The large day-to-day variations in rainfall rates found in this study and the large differences between Montreal and the tropics presented a problem to the development of a general rain estimation scheme that could be applied to a range of convection conditions and geographical areas. Attempts were made to estimate rainfall rates from the changes in cloud areas as done by Griffith and Stout. However, these schemes had little success on these data. Bright Cb clouds with expanding anvils were often seen on the satellite images but quantitative measurements of individual anvil areas were difficult. The anvils were often merged into large cloud masses and the extensive stratus cloud cover often obscured the pictures. It became apparent during this study that other data would be needed in addition to the satellite images for estimating the rain rates of the cloud areas.

The sounding data from Maniwaki, Quebec (station 72722) and Albany, New York (station 72518) were inspected for changes between the days studied. The available water vapor measurements for precipitation (precipitable water) were integrated from the 1200 GMT soundings for each of the days studied. The precipitable water vapor measurements are shown in Table 2 along with the rainfall rates derived from the cloud areas. These measurements are compared to the precipitable water vapor

TABLE 3. Comparison between GATE and Montreal rain rates measured from satellite-derived cloud areas, sounding precipitable water vapor and the output of the cumulus model. See text for an explanation of the model.

		Ratio of rain rates Montreal/GATE		Ratio of precipitable water vapor Montreal/GATE	Ratio of model output for 2 km bubble Montreal/GATE
Date	Location	Visible	IR		
4, 6 Sep 74	GATE	1.0	1.0	1.0	1.0
1 Jun 77	Montreal	0.1	0.2	0.5	0.3
2 Jun 77	Montreal	0.1	0.4	0.4	0.3
29 Jun 77	Montreal	0.4	0.5	0.7	0.5
16 Sep 77	Montreal	0.05	0.05	0.4	0.0
20 Sep 77	Montreal	NA*	0.2	0.5	0.0
26 Sep 77	Montreal	0.6	0.4	0.5	0.3

* NA, not available.

measurements made in GATE on the days that the cloud data of Stout were obtained (OSS *Oceanographer* soundings on 4 and 6 September 1974).

The precipitable water vapor measurements in general showed the same differences between the tropics (GATE) and Montreal as the rainfall rates measured from the satellite and radar data. The precipitable water and rain rates measured are shown in Table 3 as ratios of the GATE measurements. The Montreal precipitable water values were from 0.4 to 0.7 of GATE. The highest Montreal values were found on 20 June which also was the day of the highest rainfall rates.

On the days of lighter precipitation (1 and 2 June, 16 and 20 September) the precipitable water measurements did not depict the low rainfall rates. On those days the precipitable water measurements were 0.4–0.5 of GATE while the rainfall rates were smaller (from 0.05 to 0.4 of GATE). Because of this problem it was necessary to consider the stability of the cloud environments in addition to the available water vapor.

6. The use of a cumulus model

The one-dimensional model developed by Simpson and Wiggert (1969) for cloud seeding experiments was applied to the days studied here. The model was run on the morning soundings from Maniwaki, Albany and the *Oceanographer* that were used to measure the precipitable water. The model simulated cloud growth by using an ascending bubble. This model was used here because it included highly detailed descriptions of the cloud physics processes in the development of precipitation.

A convective bubble of 2 km radius was raised in the model for each sounding. The bubbles were started from an altitude where free buoyant ascent could be made. This varied from 50 mb above the surface in the GATE soundings to 200 mb on 26 September in Montreal. The Montreal area soundings were often stable in the lower layers and free ascent did not occur unless the bubbles were started at the top of the convectively stable layer.

The intention of using a model was to interpret the effects of different cloud environments. The precipitation output from the bubble (model output) could not be used as a direct prediction of rainfall rate for cloud areas by itself. This output represented only one bubble ascent while in reality a cloud system is composed of many bubbles and the numbers and rates of generation of the bubbles cannot be predicted from sounding data.

The relative differences in precipitation rates of the clouds between the days studied were estimated by comparing the model output for the bubble ascents made from the soundings. This was done by expressing the model output precipitation as a ratio of the GATE soundings. These ratios are shown in Table 3 for comparison to the daily variations in rainfall rates that were measured using the combined radar and satellite data.

It is apparent that the model more closely approximated the differences between precipitation rates in GATE and in Montreal than the precipitable water. The best results were obtained on the Montreal days where large precipitation rates occurred, 29 June and 26 September. Better predictions of precipitation rates than the precipitable water measurement also were made for the other days. On the lightest precipitation days (16 and 20 September) the model predicted little or no precipitation, although precipitable water amounts were present at the same levels as found on the June days. For the September days the stability of the soundings greatly limited the ascent distance of the model bubble. Convective instability was found only in very shallow layers on the soundings and thus the model indicated no precipitation.

7. Method of estimating rainfall using satellite and soundings

Using the model output and the satellite cloud-cover measurements, estimates of rainfall for the Montreal area were made to demonstrate the feasibility of a combined technique. The rates of precipitation for each of the Montreal days were estimated from the model output and GATE measurements of rain rates for satellite-derived cloud areas. The rainfall rates (R_m) were estimated by multiplying the model output ratios (r) shown in Table 3 by the average GATE rain rates (R_g) shown in Table 2, i.e.,

$$R_m = rR_g. \quad (1)$$

On days where the model predicted no precipitation a minimum rain rate of 0.1 mm h^{-1} was used. The GATE data were used as a baseline because this was part of the data set used by both Griffith and Stout in developing their rain estimation schemes.

The total accumulated precipitation (P_t) for the viewing area of the McGill radar was estimated by applying the rain rates from (1) to the satellite-measured cloud areas (A_c) for each image and summing over the time periods studied (N observations):

$$P_t = R_m A_c. \quad (2)$$

It should be realized that this estimation scheme was made using the GATE data, the satellite cloud area measurements over Montreal, and the cumulus model. This scheme was independent of the Montreal radar data and thus it could be tested using the Montreal radar as the "ground truth" measurement. The accuracies of estimating precipitation have been expressed by Griffith as an error ratio statistic of the measured to the estimated or vice versa. The ratio has been calculated so that it is always greater than unity. A large ratio indicated a large over prediction or underprediction while a ratio of 1.0 indicated a perfect prediction. These error factors were calculated for the estimation scheme and are shown in Table 4.

For the six days studied in Montreal the best estimates of rainfall were made on the June days where summer convective systems were present. The best results were on the day when one large system dominated, 29 June. For the fall days the accuracy of the estimation scheme decreased. The extremely heavy precipitation on 26 September was not predicted accurately because the model estimated a low rainfall rate based on the soundings. On 16 and 20 September the model predicted no rainfall and the nominal rain rate of 0.1 mm h^{-1} had to be assumed. The soundings were stable on those days thus halting the rise of the bubble in the model.

8. Summary and conclusions

The errors shown in Table 4 are slightly larger than the errors reported by Griffith for the tropical applications of a satellite technique. However, it should be realized that the Montreal area presented a wide variety of convective conditions, and rain estimation in this area was considerably more difficult than in the tropics. With the use of sounding data through the model it was possible to build a combined satellite-model technique that showed skill.

To encompass all geographical areas and seasons of the year a more sophisticated model is needed. The model used here was designed for cumulus clouds which occurred in warm air masses, hence reasonable success was obtained for the summer days studied. For the fall days studied the model was not applicable because of the different cloud types and cloud environmental conditions; consequently, rainfall rates had to be assumed. The model also did not consider the dynamics of the wind field or any other mesoscale dynamics which affected the clouds. However the results of this study indicate that a combined satellite-model rain estimation technique could be developed at least for the summer season and the accuracy of such a technique would be approximately an error factor of 2.0 for 3 h rainfall accumulations.

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TABLE 4. The measured and predicted rainfall accumulations for the McGill radar area over the time periods indicated.

Date	Time periods studied (LST)	Radar measured accumulated precipitation (10^7 m^3)	Predicted precipitation (10^7 m^3)		Error ratio	
			Visible	IR	Visible	IR
1 Jun 77	1230–1530	7.4	17.9	10.4	2.4	1.4
2 Jun 77	1200–1500	8.8	27.1	8.9	3.1	1.0
29 Jun 77	0800–1330	26.5	32.1	24.6	1.2	1.1
16 Sep 77	1000–1430	7.2	4.4	7.0	1.6	1.0
20 Sep 77	1030–1430	14.6	NA*	3.2	NA*	4.6
26 Sep 77	1000–1330	40.3	14.1	30.8	2.8	1.3
Average error ratio					2.2	1.7

* NA, not available.

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