Rain Estimation in Extratropical Cyclones Using GMS Imagery

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ABSTRACT

A technique is presented which provides estimates of rainfall from extratropical cyclones over an area of 125,000 km² in southeastern Australia in simulated real time conditions. It utilizes a statistical relation between blackbody temperature of cumuliform cloud and 90 minute rainfall totals to determine estimates of rainfall from cumuliform cloud, and approximates the lesser rainfall amounts from the stratiform pre-frontal cloud as a fixed proportion of rain from equivalent cumuliform cloud. It is based on the digitized “HR Fax” imagery received at 3 h intervals from the Japanese Geostationary Meteorological Satellite (GMS). Five case studies are presented, each for a 24 hour period. Rainfall estimates for rainfall districts within the area vary from the observed district averages, which were calculated from daily gage data, by an average of 22%. The mean absolute error for districts is 4.2 mm.

1. Introduction

The ability of geostationary satellites to map large-scale cloud patterns and provide an indication of the cloud top temperature at unrivalled spatial resolution and relatively high temporal frequency has provided considerable stimulus for devising techniques to estimate precipitation. The needs for reliable and timely precipitation estimates are very great, and many schemes have been reported which infer rainfall from satellite imagery. A comprehensive summary of such schemes is given in Barrett and Martin (1981).

Comparatively little has been done with midlatitude rain systems, presumably because these comprise a mixture of cumuliform, middle stratiform, and cirrus types and it has not been easy to isolate the rain bearing cloud. For example, an extratropical cyclone (hereafter ETC) generally contains all cloud types, although there is considerable organization in the distribution of the cloud types which predominate in particular sectors. Hobbs (1978) has examined the mesoscale structure of ETCs in the Pacific Northwest region of the United States and has identified typical cloud types and structures which predominate in certain sectors of ETCs in the northwest Pacific region. Recently, Scofield et al. (1982) have attempted to extend the rain estimation technique, originally developed for deep convective storms, to sectors of ETCs.

This study adopts the approach of considering ETCs in two sectors; one where there is predominantly cumuliform cloud in cold air, called the convective sector, and the other comprising predominantly middle and high level cloud, as in the frontal band, called the upslope sector. These sectors are illustrated with the infrared image of 0000 GMT 27 June 1980 shown in Fig. 1. This is done to utilize an empirical relation established between cloud top temperatures (CTT) of cumuliform cloud and rain totals in the convective sector. For such a system over the Australian continent, the fraction of overall rainfall which falls from middle level cloud is generally quite small, as it is limited to the narrow cold frontal band; warm fronts and occlusions are rarely analyzed over the Australian continent. This is illustrated in Fig. 2 which shows a histogram of normalized 3 h rainfall amounts for the five ETC cases considered in this paper. The plot for \( t = 0 \) corresponds to the interval in which the line of demarcation between the upslope and the convective sectors crossed a station, but it was not possible to partition the rain total during this interval between the two sectors. Excluding this 3 h period, the upslope sector on average contributed only 13% of the total rainfall. Experience shows this sample is typical for the May to September period in southeast Australia, emphasizing the importance of the convective sector's contribution to the total rainfall of the system in the winter months. Recent climatological work, such as Hicks et al. (1984) confirms the predominance of the convective rainfall with frontal passages in southeast Australia.

2. The relation between cloud top temperature and rain totals

a. Physical considerations

Although it is accepted that higher rain rates can be produced by deeper cumuli than by shallow ones, whether they be warm or cold clouds, so many variables are involved in determining the rain rates...
and the rain total at the ground that no simple relationships can be constructed. But if consideration is restricted to cold air masses of maritime origin in the winter months over a fixed region, as in this study, certain assumptions can be made about factors determining the rainfall pattern. The oceanic air mass

![Diagram of Infra-red imagery showing the extratropical cyclone of 0000 GMT 27 June 1980. The cloud is divided into two sectors: the convective sector to the west, where cumuliform cloud predominates, and the upslide sector to the east where middle level stratiform cloud predominates. In the convective sector cloud top temperatures are generally in the 0 to -30°C range.]

![Histogram of the combined normalized 3 h rain totals from the ETC cases. The time is relative to the boundary between the convective and upslide sectors. The ordinate is in mm. Omitting the t = 0 column, only 13% of the rainfall is due to the upslide sector.]

**Fig. 1.** Infra-red imagery showing the extratropical cyclone of 0000 GMT 27 June 1980. The cloud is divided into two sectors: the convective sector to the west, where cumuliform cloud predominates, and the upslide sector to the east where middle level stratiform cloud predominates. In the convective sector cloud top temperatures are generally in the 0 to -30°C range.

**Fig. 2.** Histogram of the combined normalized 3 h rain totals from the ETC cases. The time is relative to the boundary between the convective and upslide sectors. The ordinate is in mm. Omitting the $t = 0$ column, only 13% of the rainfall is due to the upslide sector.
becomes progressively modified after crossing the coast so that the inland penetration of this type of precipitation is generally limited. Since the prevalent aerosol in maritime air is sodium chloride, surveys of the composition of rainwater can describe the extent of the regions wherein this type of airmass and precipitation occur. Such surveys have been made in the United States by Junge and Werbey (1958) which showed precipitation from oceanic air masses extended about 500 km inland. Satellite imagery also clearly shows the inland penetration of the air mass with its characteristic cellular cloud which generally dissipates a few hundred kilometers in from the coast.

This cloud results from the heating of a conditionally unstable air mass by the ocean or a land surface. The depth of the convection layer varies considerably within the cold pool. It may extend to the tropopause with large cumulonimbus clusters, or it may be shallow, capped by stratuscumulus below a subsidence inversion. However, the cloud is predominantly cumuliform with bases at the lifted condensation level, slowly rising with distance inland from the coast. Thus a central assumption in this study is that cloud depth is a significant determinant of the precipitation rate. This is reasonable for such systems because the showers, known to be of ice crystal origin (Mossop et al., 1970), have an intensity determined by the extent of splintering, accretion and coalescence, all of which increase strongly with cloud depth (e.g., see Ludlam, 1980).

The cloud depth is estimated by the cloud top height, which is a monotonic function of cloud top temperature (CTT) in a conditionally unstable layer. Subcloud evaporation effects were observed to be relatively constant, with low level relative humidity everywhere between 60 and 80%. Over elevated terrain convective cloud bases were at lower pressures and temperatures, decreasing the moisture inflow through cloud base, but the subcloud layer was shallower with less evaporation. The major effect of the mountains is believed to be the more vigorous convection resulting from forced uplift releasing convective instability. Consequently, it was assumed that the higher precipitation rates observed over the higher terrain would be explained by the colder CTT values.

Further assumptions are required to enable rain totals at the ground to be expressed in terms of rain rates. These concern the lateral dimensions, speed and spatial distribution of the showers, which may depend upon orography. Over mountainous terrain some convective cloud may become “anchored” by orographic effects, so that modest rain rates may result in larger point totals than over flat terrain. It is assumed here that variations in shower translation speed, both among and within case studies, are insignificant with respect to the time interval of each estimate and the dimensions of the imagery pixel, so that a direct relationship between CTT and rain totals may be assumed. Statistical evidence will be presented which will support these assumptions.

b. The temporal extent of the rain estimate

Since the Geostationary Meteorological Satellite (GMS) infrared data is obtained at three hourly intervals, it is required to examine the maximum time interval over which useful rain estimates can be obtained reliably from one infrared image. This was done empirically as follows. Pluviograph data from over 130 stations in Victoria, (see Fig. 3) were converted to a time series of 6 min rain totals, $R_6$, separately for each station, for a 48 h period in 1979. These were situations when cold fronts and subsequent strong southwesterly streams traversed the region. Cloud top temperature values coincident with each station were then correlated with the $R_6$ values corresponding to the time $T$ of the GMS image. Correlations were calculated separately for $R_6$ values corresponding to times displaced from $T$ by $\pm 6$, $\pm 12$ $\cdot\cdot\cdot \pm 120$ minutes, to examine whether a lagged rainfall total would be better estimated by the imagery. The procedure was then repeated for $R_{12}$, $R_{18} \cdots R_{180}$ to determine the optimum length of rainfall total. An example is shown for $R_{12}$ at Fig. 4a. Although the scatter is large, there is no evidence that any of rain totals, $R_6$, $R_{12}$, etc., when lagged, produce higher correlation coefficients with CTT. Thus rain totals centered on $T$ were used in the remaining work.

The correlation coefficients for $R_{12}$, $R_{24} \cdots R_{180}$ are plotted in Fig. 4b, showing an almost continuous decrease in correlation. These results indicate clearly the requirement for satellite observations to be made at intervals shorter than the 3 h and preferably at intervals of the order of 1 h. An inspection of cloud imagery revealed that much of the decrease in correlation was due to the translation of cloud systems, but development would occasionally contribute appreciably. Thus, rainfall estimates obtained by conversion of 3 h GMS images to rainfall would be unacceptable, with an indicated correlation coefficient of about 0.4.

A solution was devised by the use of interpolated imagery, i.e., estimated CTT maps at times midway between those of the GMS data, providing sequences of 90 min simulated imagery. As shown in Fig. 4b, correlations with $R_{90}$ are significantly higher than with $R_{180}$ and only little below $R_{30}$ or $R_{60}$ values. The intermediate imagery was constructed by averaging consecutive 3 h imagery which had been displaced downstream and upstream by similar amounts. The amounts were determined by tracing the movement of recognizable features, and assuming they progressed uniformly during the period. Thus for a 24 h period the number of images used was increased from 9 to 17, permitting the use of relations between CTT and $R_{90}$. 
c. The relationship between CTT and $R_{90}$

Little suitable published data are available detailing surface rainfall totals produced by midlatitude cumuli, as nearly all studies utilize radar echoes, e.g., Lovejoy and Austin (1979). One of the few is Spillane and Yamaguchi (1962) which collated cloud top temperatures interpreted from radiosonde data with surface 6 h rain totals at Adelaide (34°56'S, 138°35'E) for a period of three years. For cumuliform clouds those results show a clear increase in both rain events and rain totals with decreasing CTT, although the range of CTT does not extend below about $-15^\circ$C because of the increasing response time of the lithium chloride hygriostor used in the radiosonde. DelBeato (1981) examined the relation between 30 min totals and CTT from NOAA-5 infrared imagery in a variety of weather systems over southeast Australia. A clear relationship was found with clouds associated with ETCs which had a high proportion of cumulus. Downey et al. (1980) also examined in detail a severe weather event over southeast Australia, and reported strong indication of a trend between rain totals and CTT of similar cloud.

**FIG. 4:** (a) Correlation coefficients $r$ between cloud top temperature and 12 min rain totals $R_{12}$ displaced by $t$ minutes from the time when the cloud top temperature was observed. Error bars correspond to the 90% confidence limits for $r$. (b) Correlation coefficients $r$ between rain for periods $t$ in length, and cloud top temperature. All totals are for periods centered on the time the cloud top temperature was observed. The broken lines indicate the 90% confidence levels for $r$. 
For this study, a relationship between CTT from GMS, and \( R_{90} \) was determined using pluviograph data in the study area from 11 and 12 May 1979, and 11, 12 and 13 August 1979. A total of 1834 observations were used, and mean totals (including zero values) for each 10°C interval are plotted against CTT in Fig. 5. Also shown are the corresponding \( R_{90} \) values implied by the other studies described here for comparison. Broad agreement is evident, although only the data of this study were known to be relatively free of middle and high level cloud contamination. This contamination is relevant in the colder ranges of CTT, and results in lower rainfall values for a given CTT.

The relation utilized in the following case studies was a simplified fit to the data of May and August 1979, in the form

\[
R_{90} = 0.00025(5 - \text{CTT})^{2.61}, \tag{1}
\]

where CTT is in degrees Centigrade and \( R_{90} \) is in millimeters. This was used to provide estimates of rain totals throughout the study area, which comprised a variety of terrains ranging from sea level to about 900 m in elevation.

3. Case studies

a. Rainfall verification

Verification was done in two ways, both based on daily raingage data. First, isohyetal analyses were manually drawn, with station reports weighted according to spatial density, and subjectively compared with estimated rain patterns. Second, averages were calculated for each of the thirteen operational rainfall districts in the study area (average district size is approximately 10,000 sq km, see Fig. 6) for the estimates and gage data.

Raingages were the standard 203 mm diameter gages and typically over 550 24 h observations from a network of some 700 sites in the area were used, with their spatial density varying considerably as shown in Fig. 6. The verification of rainfall estimates by the use of gage data presents a problem of incompatibility of scales. Each estimate derived from one HR Fax pixel represents a mean averaged depth over an area of about 30 km², while one raingage measures rain over 0.0324 m². Thus the areal estimates were verified against areal data, subjectively drawn isohyets and district average totals, all derived from daily gage data.

Daily gage totals can be taken to be essentially uncorrelated where spatial densities do not exceed about one gage per 1000 km² for rainfall of the cellular convective type (Sharon, 1974). This is a general estimate and may vary considerably with the orography. The gage network used here has an overall density of one per 230 km², although this varies from one per 33 km² in populated parts to one per 1500 km² over mountainous parts. There were ten gages at elevations of 900 m or higher, and 32 above 600
FIG. 7. Isohyetal patterns of the estimated rainfall over the area for 24 h periods in the five cases: (a) 10 May 1979, (b) 10 August 1979, (c) 27 June 1980, (d) 4 August 1980, (e) 17 September 1980. Corresponding verifying analyses based on daily raingage data (f to j). Isohyets are in mm. Stippled areas are for ease of comparison only; heavier shaded areas designate sea.
m. Thus, although the gage data base may be judged adequate for the majority of the study area, the high terrain verifying values, where the rain was heaviest, were considered the least reliable.

b. Estimation procedure

Estimates of rainfall for a 24 h period from 2315 GMT (0915 local time), were produced by summing 17 incremental estimates, each of 90 minute duration. In each incremental estimate, the digitized imagery was geographically located and that part corresponding to the study area or "frame" was stored on a computer. After the extraneous marks embedded in the imagery were identified and replaced by averaging, those parts of the frame which comprised the upslide sector, i.e., the frontal band or other patches of middle level cloud, were identified. This was a relatively straightforward and unambiguous procedure requiring only a basic level of experience in satellite interpretation of cloud type, e.g., see Anderson (1974). The CTT values in the convective sector were then converted to incremental rain estimates by applying (1), and accumulated.

In order to permit comparison with the daily gage data, the rainfall produced from the upslide cloud had to be included, even though no effective technique for estimating it is available. For the purposes of this study, rain from the upslide sector was estimated to be one sixth of the value given by (1), on the basis of the data shown in Fig. 2. If only those days in which no upslide sectors contaminated the study area had been chosen, the number of case studies would have been far fewer, and the rainfall totals much lower since the deepest convective cloud often occurred in the same 24 h period as the upslide sector was present in the study area. In this study every ETC case was used for which a complete set of digitized imagery was available with no discrimination of any kind.

c. Results

The five cases varied considerably in their cloud structure and rainfall yield, ranging from a case with only cumuliform cloud (Case 2) to a case with a preponderance of upslide sector cloud (Case 3). Rainfall yields for the 24 h periods ranged from very light (less than 5 mm) from shallow cumulus (Case 4) to heavy (over 50 mm) from deep cumulonimbus clouds (Case 5). Some basic features of the cases are summarized in Table 1.

The estimated isohyets are shown in Figs. 7a–e for comparison with the verifying analyses (Figs. 7f–j). The estimates have reproduced most of the significant features of the analyses, both quantitatively and qualitatively. However, discrepancies occurred with minor features and with the intensity of some major features. The major discrepancy was that over the higher terrain (see Fig. 3) estimates of the peak values appeared to be too low, particularly in Cases 2 and 4. On average, mean district rainfall was overestimated by 22%, and its mean modular error was 4.2 mm. The average ratio of estimated to observed mean district totals ranged from 0.8 for case 5 to 1.4 for case 1, with the exception of 1.8 for case 3, due to the heavy proportion of upslide cloud (see Table 1). District rainfall in the mountainous districts were estimated better than in other districts even though maximum values were underestimated. The distribution of the district error and ratio of estimated to observed rainfall shown in Figs. 8a, b, respectively. The causes of these discrepancies were varied and not all inherent in the estimation technique. Some examples follow:

1) The "HR Fax" imagery. The low temporal frequency was only partly compensated by interpolation.

2) Verification problem. Difficulty arose in verifying information of comparative resolution to the esti-

<table>
<thead>
<tr>
<th>Case/date</th>
<th>Rain yield* (mm)</th>
<th>Cloud sequence (0000–2400 GMT)</th>
<th>Proportion of upslide sector cloud</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) 10 May 1979</td>
<td>Moderate 19</td>
<td>Cold front band followed by secondary mass of middle level cloud which cleared the area by 1200 GMT; replaced by cumulus.</td>
<td>Moderate</td>
</tr>
<tr>
<td>2) 10 August 1979</td>
<td>Moderate 11</td>
<td>Cumuliform cloud throughout.</td>
<td>Nil</td>
</tr>
<tr>
<td>3) 27 June 1980</td>
<td>Heavy 55</td>
<td>Frontal and post-frontal masses of middle level cloud and interspersed cumulus throughout.</td>
<td>High</td>
</tr>
<tr>
<td>4) 4 August 1980</td>
<td>Light 5</td>
<td>Frontal band over northeast corner of area only; progressively displaced by cumuliform.</td>
<td>Low</td>
</tr>
<tr>
<td>5) 17 Sept. 1980</td>
<td>Moderate 34</td>
<td>Frontal band covering entire area at first, but displaced by Cb and deep Cu.</td>
<td>Moderate</td>
</tr>
</tbody>
</table>

* Rain yield is the maximum district mean for the 24 h from 0900 LST on date shown. For description of upslide sector cloud, see text.
districts, totals were overestimated by 40% compared to an all district result of 22%.

5) **Translation speed.** Omittance in accounting slower translation speed of cloud masses over mountainous terrain, resulting in higher rain totals with identical rain rates. Again this is reflected in an underestimation for mountainous districts.

6) **Estimation inadequacy.** Inadequate estimation of the rain produced in the upslope sector is evidenced by the marked overestimation in Case 3, which contained the most upslope cloud.

4. **Summary**

A technique utilizing only geostationary satellite infrared imagery intended to provide real time rainfall estimates from extra-tropical cyclones over southeastern Australia was described and some results presented. Following previous studies which indicated

![Histogram](image1)

**Fig. 8:** (a) Histogram of the absolute differences between the estimated and observed areal means for the thirteen rainfall districts of the five case studies (described in Table 1). The ordinate is the number of districts. (b) Histogram of the ratios of estimated to observed mean district rainfalls plotted on a nonlinear abscissa. The ordinate is the number of district means.

mates, especially over the rainfall districts because of the low gage densities.

3) **Navigation problem.** Here the geographic location of any imagery frame is in error by 30 km or more (see Appendix). This has the effect of smoothing out some observed maxima, such as those on high terrain, while producing erroneous smaller anomalies.

4) **Cloud base accounting.** Error in accounting for cloud bases being high (smaller cloud depth and greater subcloud evaporation over inland districts of that terrain than in coastal districts). This is apparent from a district analyzing grain totals. Over inland flat

![Histogram](image2)

**Fig. 8. (Continued)**
the prospects for establishing a relation between CTT
and rain totals, coincident observations of CTT and
gage totals were obtained and used, together with
other data to select an empirical relationship. The
data were also used to examine the maximum time
interval and optimal displacement of the rain total
for use with GMS infrared imagery. The optimum
interval length was determined to be 90 min, requiring
a series of simulated 90 min imagery to be prepared
by linear interpolation of the GMS data. The tech-
nique was applied to five independent situations, each
of 24 h duration. These ranged from deep cumulo-
nimbus to shallow cumulus cloud, with rain totals
varying from heavy to light. In order to permit
verification with the network of daily gages in the
area, rain contributed both by convective and up-slope
cloud had to be estimated as each occurred to varying
extents in four out of the five cases. The minor rain
contribution of the prefrontal up-slope cloud was ap-
proximated as a sixth of the rain produced by cu-
muliform cloud of the same CTT.

Results indicated that the technique's estimated
district average falls (for 13 districts of about 10,000
km² average area) differed from those based on daily
gage data by an average of 22%, with a mean modular
error of 4.2 mm. Analysis of limited results suggested
several refinements such as a more comprehensively
based empirical relation between CTT and rainfall
totals, stratified by orographic region. Other limitations
were errors in the geographic location of the infrared
imagery, the 3 h separation of GMS images, and the
problem of estimating rainfall from the up-slope sector.

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APPENDIX

Characteristics of the GMS Imagery

The Geostationary Meteorological Satellite (GMS)
is located above the equator at 140°E. It scans the
earth disc in the infrared window region, approxi-
ately 10.5–12.5 micron, at 0000, 0300, 0600, 0900,
1200, 1600, 1800 and 2100 GMT. A facsimile
transmission ("HR Fax") is received by the Bureau of
Meteorology in Melbourne and the data digitized to
seven bit accuracy, with a temperature resolution of
about 1.8 K. The spatial resolution is approximately
31 km² in the area chosen for this study, which is a
rectangle approximately 500 × 250 km (see Fig. 3).

The facsimile data contain coastline and lat/long
line marks embedded in the data which necessitated
identification and removal before the imagery could
be used as cloud top temperatures. However, these
marks were used to locate the study area within the
imagery transmission as no other location data were
available and recognition of geographic prominences
was not possible with infrared imagery. The marks
are not located accurately in some transmissions, as
their location is based on visible imagery which is
obtained generally only at 0000 and 0600 GMT.
Experience suggests that the location error at other
times is typically about 30 km. Such errors are
inherent in the data used here.

The imagery values were interpreted as temperature
values using a "look-up table" (J.M.S.C., 1980) and
the calibration data included in each transmission.
No explicit corrections for atmospheric absorption,
limb radiance or cloud emissivity were made.

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