A CASE STUDY OF THE APPLICATION OF GMS IMAGERY OVER EXTRATROPICAL AUSTRALIA

W. K. Downey*, R. Del Beato†, R. P. Canterford† and P. J. Meighen†

(Manuscript received July 1979: revised March 1980)

ABSTRACT

A major weather-producing event in September 1978 over southeastern Australia is studied with an emphasis on the use of imagery from the Japanese Geostationary Meteorological Satellite. The synoptic scale is examined using imagery at 12-hourly intervals, and the results suggest that the GMS data base could be used to establish useful variations of the interpretation models pioneered by Guymer (1969, 1978). On the mesoscale, a thunderstorm complex is examined using 'special' once-hourly GMS imagery, and the general problems of interrelating radar imagery, satellite imagery and rainfall rates are addressed. A potentially useful 'cloud top temperature-rainfall rate' relationship is established for convective cloud in a southwesterly stream over Victoria. The hourly GMS imagery highlights the utility of such data for short term warning of damage associated with deep convection, particularly thunderstorms.

INTRODUCTION

A major synoptic scale event in September 1978 over southeastern Australia is examined utilising imagery from the Japanese Geostationary Meteorological Satellite (GMS) supported by the conventional data base. The main objectives of the study are (a) to demonstrate the advantages of temporally frequent imagery, particularly in a thunderstorm-severe weather situation, and (b) to establish those situations where quantitative information from the infrared (IR) imagery could be usefully related to rainfall events detected by radar and the conventional rain gauge network. During the period of the exercise the Japan Meteorological Agency (JMA) provided a number of special GMS observations at one-hourly intervals, supplementary aircraft inflight reports (AIREPS) were requested from aircraft, and a number of additional radiosondes were released from selected Bureau field stations. The RC 33 radar at the University of Melbourne and the WF 44 radar at Laverton were also operative at selected intervals during the experiment (for details refer Fig. 1(a) and Table 1).

* Australian Numerical Meteorology Research Centre, Melbourne
† Head Office, Bureau of Meteorology, Melbourne
<table>
<thead>
<tr>
<th>DATE</th>
<th>SEPT 25</th>
<th>SEPT 26</th>
<th>TYPE OF IMAGERY</th>
</tr>
</thead>
<tbody>
<tr>
<td>HOUR</td>
<td>03 06 09 12 16 18 19 20 21</td>
<td>00 01 02 03 06 07 08 09 12 16 18 19 20 21</td>
<td>00 01 03</td>
</tr>
<tr>
<td></td>
<td>x x x x x x</td>
<td>x x x x x x</td>
<td>full disc imagery infrared</td>
</tr>
<tr>
<td></td>
<td>x x</td>
<td>x x x x x x</td>
<td>special imagery infrared</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>special imagery visible</td>
</tr>
</tbody>
</table>

Special radiosonde releases at Moree, Wagga and Charleville around 26 0600 GMT

Special radiosonde release at Mount Gambier around 26 1600 GMT

Special radiosonde releases at Bowes Avenue 26 0400, 26 0600, 27 0100 and 27 0400 GMT

Table 1 Summary of GMS Imagery received and details of special radiosonde releases.
While the main results of the exercise are examined under the headings of 'Mesoscale Analysis' and 'Cloud Parameters and Rainfall Analysis', a section on broadscale analysis is also included. The latter section provides a synoptic scale framework for the mesoscale events and is also relevant to the long-standing reliance on the interpretation of satellite imagery for synoptic scale analysis in the Australian region. The mesoscale analysis section examines the evolution of a thunderstorm complex in the Broken Hill-Mildura area, as revealed by the special hourly observations from the GMS. The problems of interrelating radar, satellite imagery and rainfall rates in situations of convective and non-convective precipitation are treated in the section on cloud parameters and rainfall analysis.

**BROADSCALE ANALYSIS**

The mean sea level (MSL) pressure charts for the period 23 to 28 September are shown in Fig. 1(b). The main synoptic scale feature of interest is the cut-off low which formed off Western Australia and moved east-southeast, ultimately affecting all of the eastern states. Associated with the cut-off low there were a number of significant cloud bands, the most dominant being a band bowing out to the east-northeast of the centre of the cut-off low and then reverting to a northwest-southeast orientation over central Australia (details appear in a following sub-section). Before examining the evolutionary and mesoscale details of such features it is useful to first identify some of the macroscale features revealed in selected time-averaged fields.

Figure 2 shows 5-day means, centred on 26 0000 GMT, of the infrared (IR) temperature distribution and of the 500 mb geopotential height field. The banded structure of the IR isotherm field through central Australia, New South Wales and Victoria highlights the influence of the major cloud that dominated the period of interest. The band is aligned ahead of the major long wave cold trough and extends into the downstream ridge. Fig. 3 shows 3-day means of the IR temperature distribution and the MSL pressure field. The main cloud band features are again evident and in particular the cut-off low is highlighted in the vicinity of the Eyre Peninsula. Interestingly the centre of the tropospheric 'cold pool' that attends the cut-off low is identified by a relatively 'warm core' in the infrared imagery. In time averaging the IR data it is recognised that a relatively warm area can result from a true preponderance of lower clouds or might simply reflect a relatively more transient occurrence of higher clouds. However, given that this same feature is recognisable in individual images, it would appear for the most part not to be an artefact of the averaging process.

Figure 4 shows Hovmöller diagrams for 35°S of:

(a) 5-day mean values of the 500 mb geopotential height field (less 500 decametres) (this field is interpreted as representing the 'long-wave' structure);

(b) departures (decametres) of the daily 500 mb heights from the 5-day mean values (interpreted as the 'short-wave' field).
Fig. 1(b)  Mean sea level pressure (mb) at 0000 GMT 23-28 September 1978.
Fig. 2. Five-day means (centred on 26 000 GMT) of infrared temperature distribution and 500 mb geopotential (decameters).
Fig. 3 Three-day means (centred on 26 0000 GMT) of infrared temperature distribution and MSL pressure (mb).
Fig. 4 Hovmöller diagrams at 35°S:
(a) 5-day mean geopotential height (decametres less 500) of the 500 mb surface;
(b) daily geopotential height values less the 5-day mean values (decametres).
Two main features are revealed. First, the eastward trace speeds of the long-wave features are very small prior to 27 September (typically less than 10 kn). Short-wave features show similarly low speeds (10 to 20 kn). Second, on the 22nd the long-wave pattern is relatively featureless apart from a weak trough near 70 to 80°E. However, several short-wave features are prominent (ridges 60 to 80°E and 130 to 140°E; troughs 90 to 100°E and 10 to 120°E). The long-wave pattern then shows steady amplification and slow movement up until the 26th-27th, when faster movement can be noted. During this same period the short-wave field undergoes considerable changes. The short-wave ridge 60 to 80°E on the 22nd is rapidly replaced by a trough in that area with apparent retrogression. At the same time the trough-ridge systems in the vicinity of 120 to 150°E progressed eastward. As the long-wave trough begins to amplify near 130°E on the 25th, the short-wave feature temporarily declines. However, on the 26th both short and long-wave features are dominant near 135°E (trough) and 105°E (ridge). Following the 27th a short-wave trough develops near 80°E and a generally progressive pattern is established at all longitudes. Many of these features will be further identified in the following 12-hourly synoptic sequence.

The twelve-hourly synoptic sequence

Figures 5(a) to 5(e) show the MSL pressure field at the 1000-500 mb thickness field, superimposed on the satellite imagery at 12-hourly intervals from 25 0000 GMT to 27 0000 GMT. Some significant weather areas (i.e. as reported by the synoptic scale network) are also indicated using conventional symbolism. Comments on the temporal evolution of cloud features and the overlaid fields appear on each of the figures.

Guymer (1978) has recently provided a valuable and comprehensive report on the techniques used to infer quantitative details of the fields of MSL pressure and 1000-500 mb thickness, from satellite imagery. In the following discussion some knowledge of the material contained in that report will be assumed.

Cloud features and the MSL pressure field

(a) Location of the MSL low pressure centre. As noted by Guymer (1978), when details of the low cloud features are unobscured (e.g. on 25 September) there is little difficulty in determining the location of the surface centre. On occasions of partial obscurity (e.g. on the 26th), rules relating to spiralling of the 'occluded' sections of the frontal band give good results.

(b) Central pressure values of the low. From 25 to 27 September the low would be designated type C-D according to the classification of Troup and Streten (1972). The observed central pressure anomaly of 10 to 11 mb on the 25th would relegate it to a slightly weaker than average system according to the range of variability indicated by Streten and Kellas (1973), (Table 1 of Guymer 1978). On the 26th and 27th the anomalies reach values of 20 mb, placing it in the 'strong' category of a D stage system. On the other hand the marked broadening of the main cloud band over eastern Australia between 25 1200 and 26 0000 GMT (accompanied by only a moderate change in the central pressure) highlights the potential difficulties of applying rules that use the location of the leading edge as a determinant factor (Zillman and Price 1972). Other features of note are the extreme eastward displacement of the
The main surface low is located at the head of the Bight (32°S, 130°E) with a central pressure of 1004 to 1006 mb. In the 1000 to 500 mb thickness field, the main cold trough is located just west of the surface centre (central value ~543 dm). Note also the short wave trough–ridge features over South Australia and Victoria. These have moved from around 120°E on the 23rd (see Höv moller diagrams – Fig. 4). Looking at the cloud features themselves one notes a major cloud band over central Australia with the remnants of an earlier band just to the north of it. The main band appears somewhat fragmented around lat 30°S where the aforementioned short wave trough extends into that area. The northeast–southwest band structure over Victoria is the result of stratiform upslope in the short wave ridge. Thunderstorm clusters are evident within the main cloud band over central Australia and in the cold trough over the Eyre Peninsula.
The surface low has moved slowly eastward, the central pressure remaining around 1006 mb. The short wave 1000 to 500 mb trough over western Victoria—South Australia continues to be evident—the main thermal trough tends to remain in the vicinity of the Bight (central values around 545 dm).

The main cloud band over central Australia appears more continuous and better organised than at 25 0000 GMT. Intense convection is again indicated within this band and on the periphery of the cold pool in the Bight. The stratiform upslide band now lies northeast–southwest over Melbourne. The cold front approaching from south of the Bight appears to be moving at 20 to 25 km.
Fig. 5(c) 26 0000 GMT  The main surface low is now located just southwest of Adelaide, with a central value of 1002 mb. A second surface centre is indicated to the northwest near Ceduna, lying directly under the sharply defined cold pool in the 1000 to 500 mb thickness field. There is still a tendency for the main thermal trough to remain in the vicinity of 125 to 130⁰E as evidenced by persistent northwesterly shears at Forrest. The main cloud band over the eastern states has broadened with extensive cirrus blow off from the many thunderstorms within the band. The southern front is moving at 25 kn and interaction with this southern system is imminent.
The surface low is located south of Mt Gambier with a central pressure of 994 mb. In the 1000 to 500 mb thickness field, the short wave trough is located at 140°E with a northeasterly shear at Mt Gambier and a south-southeasterly shear at Adelaide. The main thermal trough remains at 130°E. The main cloud band has become somewhat diffuse north of 25°S while south of latitude 30°S appears to have moved onto or off the east coast and a secondary cloud complex has developed over central New South Wales, and Victoria. (This secondary complex is treated in the section on 'mesoscale' aspects.)
Fig. 5(e)  27 0000 GMT  The surface low is now northeast of Tasmania, central pressure 994 mb. The short wave trough in the 1000 to 500 thickness is located just to the west of the surface low, while the main thermal trough remains in the eastern Bight and tilts back to the northwest. The southern front has merged with the cloud complex near Tasmania. The main cloud band over central Australia shows complex line structures, while at 35°S 155°E it shows an apparent break in continuity where the exit region of the upper level jet moves into the axis of the ridge.
main cloud band relative to the surface low and the absence of any distinctive accompanying feature in broadscale analyses of the MSL pressure field.

Cloud features and the 1000-500 mb thickness field

Guymer (1969, 1978) has developed models to infer the thickness field directly from satellite imagery. Application of the model framework in this study confirmed the rules outlined by Guymer (1978) relating to the location of the thermal ridge. On the other hand difficulties were encountered in attempting to establish the line of zero departure from the monthly mean and the location and magnitude of the region of largest negative (1000-500 mb) thickness departures in the cold trough. As indicated in Fig. 6 (from Guymer 1978) the rear edge of the cloud band is used as a primary indicator of the 'zero-departure line' on the eastern side of the vortex. Fig. 7(a) shows that at 25 0000 GMT there is a reasonable correspondence of the zero line and the rear edge, but that at 26 0000 and 27 0000 GMT (Figs 7(b) and 7(c)), the zero line is widely separated from the rear edge of the cloud and at 26 0000 GMT crosses it almost orthogonally. Guymer (1978) has alluded to the need for adjustment of the model when a broad and marked clear zone occurs behind the frontal band and hopefully further studies with GMS imagery will lead to suitable quantitative modifications.

At 25 0000 GMT the location of the short-wave trough (cold pool) in the vicinity of the Eyre Peninsula is readily identified by the enhanced convection there (Fig. 5(a)). Similarly the appearance of enhanced convection near 125°E to 130°E 30°S, and the swirling configuration of lower and intermediate clouds in this area, gives a good indication of the location and configuration of the main thermal trough. What one notes in the anomaly patterns of Fig. 7, is that the important short-wave feature barely appears as a small perturbation in anomaly patterns drawn at 4 decametre intervals and that the largest anomalies in the main thermal trough are some distance to the northwest of the enhanced cumuliform formations and just south of the boundary of the lower-intermediate cloud formations. At 26 0000 and 27 0000 GMT (Figs 5(c) and 5(e)) this same feature in the intermediate and lower cloud formations continues to outline the persistence of the main thermal trough over western and central Australia.

850 mb, 300 mb and cross-sectional analysis for 26 0000 GMT

In order to further examine broadscale features of the situation at 26 0000 GMT, in particular aspects relating to the main cloud band, analyses of 850 mb isotherms and contours, 300 mb contours and isotachs, and a cross-section from Forrest to Williamtown are shown in Fig. 8.

The 850 mb isotherm analysis shows two major baroclinic regions - the first over central Australia, the second extending from the Nullabor Plain over the Eyre Peninsula and through Bass Strait. Superposition of the contour field and individual wind plots reveals cold advection over the western half of the continent, particularly in the Nullabor-Eyre Peninsula region, and warm advection over central Queensland, New South Wales and Bass Strait. The configuration of the main cloud band suggests that upslide attending the warm advection is the main operative factor in producing cloud at this level rather than bodily lifting along the baroclinic zone itself. At 300 mb (Fig. 8(b)) the main jet streak is lying northwest-southeast, extending from north of Alice Springs to the Cobar region. The main cloud band appears to be
Fig. 6  Method of locating four key reference features from the basic cloud pattern (from Guymet 1978).
Fig. 7(a) Observed departures of the 1000 to 500 mb thickness field at 25 0000 GMT from the September mean (isopleths are decametres).
Fig. 7(b) As for 7(a) except at 26 0000 GMT.
Fig. 3.8(a) 300 mb contours (full line) (decameters) and isotherms (dashed) (°C) at 26,000 ft MSL September 1978.
rotated clockwise with respect to the orientation of the jet axis at this level. The cross-section from Forrest to Williamtown depicted in Fig. 8(c) shows that the baroclinicity over eastern Australia is largely concentrated above 500 mb with the upper level jet maximum substantially in advance of the low tropospheric maximum near Mildura (note the attending southerly shear over Cobar between 850 and 450 mb). The enhanced convection near Ceduna-Woomera lies on the cyclonic side of the southerly jet in this region.

MESOSCALE ANALYSIS

It is clear from the 12-hourly sequence shown earlier in Fig. 5 that substantial changes in the cloud mass structure over New South Wales and Victoria occur between 25 1200 and 26 1200 GMT. In this section we examine these developments using the regular 3-hourly IR imagery and also the special once-hourly visible imagery requested from the JMA. The analysis is concentrated in the Broken Hill-Mildura area where hail-bearing thunderstorms formed behind the main cloud band and wrought considerable damage.

The 3-hourly IR sequence 25 2100 to 26 0600 GMT

Figure 9 shows the relevant satellite imagery with 'near coincident' surface observations and isobars superimposed. (Because surface observations are based on local time, those in South Australia are necessarily 1.5 hours behind picture times while Victoria and New South Wales observations are 1 hour behind. Errors in the gridding of the imagery appear to be <20 km (6 to 7 picture elements or pixels) at 35°S.)

25 2100 and 26 0000 GMT (Figs 9(a), 9(b))

The main cloud band lies well in advance of the surface discontinuity in pressure and wind (the location of this discontinuity is based on temporal and spatial continuity) and within this main band there are both nimbostratus and cumulonimbus formations. It is also notable that in the absence of 'enhancement', the low cloud features as reported in the station plots are not readily discernible in the IR imagery.

26 0300 GMT (Fig 9(c))

Substantial wind changes at Renmark (R) and Lameroo (L) indicate a marked convergence line still to the west of the main cloud band which has now entered central New South Wales.

A line of 'supercells' has developed north of Mildura (M), and Broken Hill (B) has been hit by a hail-bearing thunderstorm.

26 0600 GMT (Fig 9(d))

Mildura (M) has registered a significant wind shift and a temperature drop of 4°C. A major secondary disturbance line is now apparent to the rear of the main frontal band which has moved into eastern Victoria and New South Wales.
Fig. 9(a) Infrared imagery 25 2100 GMT with selected surface weather plots and isobars of MSL pressure (mb). Shading indicates a zone of discontinuity in surface wind and pressure.
Fig. 9(b) Infrared imagery 26 0000 GMT with selected surface weather plots and isobars of MSL pressure (mb). Shading indicates a zone of discontinuity in surface wind and pressure.
Fig. 9(c) Infrared imagery 26 0330 GMT with selected surface weather plots and isobars of MSL pressure (mb). Shading indicates a zone of discontinuity in surface wind and pressure.
Fig. 9(a) Infrared imagery 26 0600 GMT with selected surface weather plots and isobars of MSL pressure (mb). Shading indicates a zone of discontinuity in surface wind and pressure.
The special 'hourlies' - 26 0100 to 26 0200 GMT

Figures 9(e) and 9(f) clearly show the evolution of the 'supercells'. Their apparent movement is from the north at a speed of about 40 km. At 26 0300 GMT (Fig. 9(c)), a large supercell lies just north of Mildura. Damage reports suggest it passed that station around 26 0400 GMT. The nature of events at Mildura is illustrated in Fig. 10. The autographic traces clearly show the down draught gust front of the thunderstorm (substantial 'backing' with gusts to 40 kn around 0400 GMT) and the resulting temperature drop of some 6°C in 20 minutes. Around 0500 GMT the wind reverts back to north of west, prior to the passage of the main trough line at 0630 GMT. The wind direction then varies from 300° to 240° for an hour or so before again reverting to the north-northwest after 1000 GMT.

It would appear that the Mildura Meteorological Office registered only the peripheral effects of the thunderstorm cell. A few kilometres to the west, hundreds of hectares of crops and vines were badly damaged* by hail, wind and heavy rain (25 mm in 20 minutes). As noted in a later section, the track of the centre of a cell 'c' (as indicated by the core of coldest cloud tops) was some 80 km northeast of Mildura (Fig. 22). It is well known, however, that the major surface wind damage from thunderstorms is associated with their down draught regions. Accordingly, if the core of the coldest cloud tops is representative of the main up draught region, the damage regions will necessarily be displaced from it. Unfortunately the radar at Mildura does not have a weather-watch capability wherein more detail of the separation of these features might have been obtained.

The most important features to note in this section of the study are first, the considerable difficulty in establishing 'details' of synoptic scale discontinuities from the existing surface data network and, second, the rapid development of the thunderstorm cells (discussed more fully below) and the capabilities of the hourly storm imagery to locate them and trace their evolution.

CLOUD PARAMETERS AND RAINFALL ANALYSIS

In the remaining section we discuss the utilisation of the GMS imagery for describing rainfall location and estimating rainfall rates. Three major cloud systems that traversed New South Wales and Victoria are considered:

A. The main cloud band that entered the area around 25 0000 GMT (Fig. 5(a));

B. The mesoscale thunderstorm complex in the Broken Hill-Mildura area (Fig. 9);

C. The convective cloud in the southwesterly stream over Victoria following 26 2100 GMT (Fig. 5(e)).

---

* Damage at Broken Hill was similarly estimated at a value approaching $A1 million. Golf ball sized hail damaged hundreds of homes and cars, dozens of caravans and several parked aircraft.
Fig. 9(e) Visible Channel imagery 26 0100 GMT.
Fig. 10 Autographic traces of (a) pressure and temperature, (b) wind speed and direction at Mildura.
Cloud system A and the later stages of system B are similar, and comprise a mixture of middle-level cloud and deep convective cloud capped with cirrus. System C is typical of a southwesterly stream where the clouds are progressively contained in their vertical growth by the subsidence inversion of the following anticyclone.

Rainfall mechanisms

Observational reports indicated that system A comprised mostly middle and high-level cloud with some reports of cumulus and cumulonimbus. The satellite data indicated cloud top temperatures to -55°C which corresponds with the temperature at tropopause level at Mt Gambier and Laverton. Layer cloud bases were typically at 3 to 4 km, with cumulus/cumulonimbus bases at 600 to 900 m. The air mass type (Mason 1971, Spillane and Yamaguchi 1962) was deduced by calculating 48-hour trajectories prior to 26 0600 GMT. The trajectories reveal a purely continental influence during this period. Accordingly, we can postulate (Mason 1971) that any droplets the cloud contained were too small to initiate rain by coalescence. Most of the clouds lay well above the freezing level (about 3 km), so that a considerable proportion of the clouds was composed of ice crystals. In the altostratus layer between -5°C and -20°C (500 to 650 mb), the ice crystals would grow at the expense of supercooled drops and by direct diffusion. Cloud bases were close to the freezing level so that coalescence processes are unlikely to have operated for the liquid phase to any significant extent. The considerable height of the altostratus bases would have allowed evaporation to further reduce the rainfall, and expected surface rainfall rates would be typically less than 1 mm/h. It follows that in these systems convective clouds are necessary for higher rainfall rates, and in particular convective clouds that extend above the freezing level of 3 km.

In system C the cloud structure is simpler, and over the sea forms a characteristic cellular pattern. This convection results basically from the air-sea temperature difference, and it is driven onshore by the southwesterly stream. Depending on the strength of the stream these clouds penetrate inland with precipitation often extending to the ranges. In the present case, cloud top temperatures and heights vary from about 5.5 km and -20°C in the east, to about 1.5 km and 0°C in the west. The maritime origins of this air mass provide considerably fewer cloud condensation nuclei than the preceding continental air mass, so that these clouds are composed of larger droplets. Both coalescence and the ice crystal process can initiate showers in these clouds, and typically rates of 1 to 2 mm/h can occur with tops warmer than -5°C. The hourly totals observed in this case are significantly less than 2 mm, as they are affected by the dimensions, lifetime and translational speed of the cloud elements.

Rain structure

Satellite and radar data provide exclusive mesoscale information of systems such as those in this case study, but considerable interpretation of this data, both singly and jointly, is required to maximise the information content. As mentioned earlier, the rain producing mechanisms operate principally in the lower 5 km, the exception being deep convection such as cumulonimbus clouds. This implies that, for cloud top temperatures colder than about -20°C, unless the forecaster can distinguish between the high cloud that attends active convection and disassociated layers of cirrus or thin
altostratus, the satellite imagery is likely to be misleading as an indicator of the rain pattern in a system.

Radar echoes in PPI (plan position indicator) format were recorded on film by an automatic PPI camera at the WF 44 radar operated by the Victorian Regional Office. Unfortunately, defects in the system did not allow the full capability of the radar to be recorded on film. Features such as multi-level displays and some coded information such as the level of attenuation were not recorded. As a result the precise rain rate equivalent of the radar echoes could not be calculated. However, the spatial detail of substantive rainfall areas (> 1 mm/h) was captured.

System A passed over Melbourne from the northwest between 26 0000 and 26 0600 GMT. Cloud top temperatures ranged down to -50°C (near tropopause level). The cloud top isotherm pattern (Fig. 11) shows elemental line organisation in a northeast-southwest direction, parallel to the overall alignment of the cloud band.

At 26 0000 GMT radar echoes at a height of 3 km were similarly aligned (Fig. 11) with a band some 80 km wide moving to the east-southeast. However, the frequently observed transverse motion of echoes relative to the band was not discernible in this situation. Comparison of the satellite and radar imagery (Figs 11(a) and 11(b)) reveal little correspondence between the echoes at 3 km and the cloud top temperatures, confirming that the satellite view was of 'passive' high-level cloud and unrelated to the rainfall pattern.

At 26 0300 GMT the centre of the satellite-viewed cloud band was located over Melbourne. The rain echoes were generally scattered and again showing no detailed correspondence with cloud top temperatures (Figs 12(a) and 12(b)). At 26 0600 GMT the rear of the satellite band was almost through Melbourne (Fig. 13(b)) and the area of scattered echoes had moved east (Fig. 13(a)). A narrow band of echoes appears at the rear of the satellite cloud band, corresponding again not with the coldest cloud tops, but with cloud tops as warm as -10°C at a height of 4 km.

The translational speed of the satellite cloud band was about 9 m/s during the six-hour period it was advancing to the east-southeast. The individual radar echoes, however, moved in the same direction at about 20 m/s, which agrees well with the wind at all levels from 800 mb to 400 mb. Thus, the bands of radar echoes originated near the rear of the satellite cloud band and moved towards its leading edge at a relative speed of about 10 m/s.

In Figs 11 to 13 the wind shear at 26 0000 and 26 0400 GMT is shown along with the radar echoes for the layer between 700 and 500 mb, and at 26 0600 GMT for the 1000-700 mb layer. Only at 26 0600 GMT, at the rear of system A, is there correspondence in the alignment of the shear and the echo line. Throughout the period the highest rain echoes reached to about 4 km, except for the occasional thunderstorm where they reached 5 km.

The fringe of system B passed over Melbourne between 26 0900 and 26 2000 GMT. It produced only scattered echoes, similar to those of system A, and displayed none of the severe weather that had marked its genesis over western New South Wales six hours earlier.
Fig. 11(a) PPI echo display at 26 0000 GMT from Melbourne WF-44 radar (range setting 120 n mile; elevation 0.5°). Echoes correspond to inferred rainfall rates ≥1 mm/h.

(b) Cloud top temperature distribution at 26 0000 GMT. The leading edge of cloud band A (see text) lies just east of Port Phillip Bay. The rear edge of the band lies in the top left hand corner.
Fig. 12  As for Fig. 11 but at 260300 GMT.
Fig. 13  As for Fig. 11 but at 0600 GMT.
System C comprised progressively moderating stream weather showers in the southwesterlies. As discussed earlier, this type of system is almost exclusively made up of convective clouds and one would expect considerable coherence between radar echoes and cloud top isotherms. An example from the radar film for 27 0300 GMT is shown in Fig. 14(a). The line of cumulus cloud east of Melbourne formed from cumuli cells advancing inland from the southwest. Around 27 0200 GMT the line slowed down as it encountered the hills east and north of Melbourne. Comparison with the satellite imagery (Fig. 14(b)) shows that practically all of the areas enclosed by the -20°C isotherm, particularly in the western and southern sectors, are attended by radar echoes. The agreement is particularly good at radar ranges < 80 km. At greater ranges, the radar suffers inherently from attenuation by rainfall intercepted at the lower ranges, obstruction of the beam by the terrain to the north and east, and excessive beam height. Such situations highlight the potential advantage of the satellite imagery, since it covers a much greater area and its operation is free from terrain interference. At the same time deep convective clouds with narrow towers may be below the resolvable limit of the satellite IR sensors and may be indistinguishable from other clouds until more fully developed.

Rain yield

A fundamental question facing the forecaster on receipt of GMS imagery in real time is how much rain a cloud system will produce. In this section we analyse the amounts produced by the three systems.

System A and the later stages of system B. Surface observations for cloud system A contain about twice as many reports of middle-level cloud as of convective cloud. As discussed earlier, significant falls are more likely from the convective cloud in this system, so that area averaged totals could be expected to be relatively small. System B, which began as a cluster of thunderstorms just north of Broken Hill at about 26 0100 GMT, contained reports of middle-level cloud and convective cloud in almost equal proportions a few hours later. Three-hour rain totals for each system for the period 26 0000 GMT to 27 0000 GMT are shown in Fig. 15 and indicate that system B produced about twice the areal rainfall rate of system A.

Rainfall intensities were approximated by one hour totals from pluviograph stations. Unfortunately, the sparseness of such stations in western and central New South Wales did not allow rainfall rates to be obtained for system B during its rapid growth between 26 0000 and 26 0900 GMT. Correlation between rain rates and cloud top temperatures was practicable only over Victoria and southeastern New South Wales where system B was past the developing stage. However, even at that stage system B retained a higher proportion of convective cloud than system A, and this resulted in a good correlation between mean hourly falls and cloud top temperature (Fig. 16), both for the all-station means (solid lines) and the 'wet-station'* means (dashed lines). System A (with limited underlying convection) produced no such relationship, even though it appeared very similar to B on the imagery after 26 0900 GMT.

* A 'wet station' is one reporting some rainfall.
Fig. 14(a) PPI display at 27 0300 GMT from Melbourne WF–44 Radar. Echoes correspond to inferred rainfall rates \( \geq 1 \text{ mm/h}. \)

(b) Cloud top temperature distribution at 27 0300 GMT. Stippling denotes regions colder than \(-20^\circ\text{C}\).
Fig. 15 Normalised frequency of reports of 3-hourly rainfall totals for systems A, B, C for their duration over Victoria and southern New South Wales. The first interval up to 0 mm, refers to stations which reported no rain, the second interval to totals up to 1 mm, etc.
Fig. 16  Mean hourly rainfall totals as a function of cloud top temperature for systems A and B for their duration over Victoria and southern New South Wales. Solid lines refer to means including stations with no rain reported. Dashed lines refer to means based only on stations reporting rain. Numbers in brackets refer to the number of observations in each temperature class. (Cloud top temperatures $>-15^\circ$C were not considered.)
In the period 0000 to 0900 GMT system B passed over only eleven pluviograph stations where the mean hourly falls were much higher than for the system in its decaying stages. This is discussed separately in a later section. The relationships between rain rates and cloud top temperatures changed greatly as system B evolved from a number of small intense cells to a larger more diffuse cloud mass.

**System C.** This was examined as it affected Victoria from 26 1900 to 27 0900 GMT. This system comprised cumulus and stratocumulus cloud with tops much lower than in the other systems (i.e. rarely colder than -20°C). The frequency of three-hourly falls (Fig. 15), indicates that this system produced an areal rainfall rate two-thirds that of system A. The relationship between mean hourly falls and cloud top temperature, based on 368 observations, is shown in Fig. 17. A much stronger dependence is evident, both for the all-station (solid) and 'wet-station' (dashed) means. This is because the cloud tops sensed by the satellite are a direct measure of the depth of convection, a primary factor of rain production in a cumuliform system. A linear least squares fit was applied to the hourly total R (mm), and cloud top temperatures T (°C) with the following results:

\[
R = 0.18 - 0.02T; \quad (-15 < T < 10)
\]

The correlation coefficient was 0.96, significant at the 90 per cent confidence level. This regression relationship was then tested on independent data for the southwesterly stream situation of 10 May 1979*. The resulting subjective agreement (Fig. 18) suggests that regression relationships may be usefully applied in these convective situations and that evaluations over denser surface networks might lead to even more useful refinements.

**The early stages of system B**

As noted earlier system B comprised large clusters of thunderstorms and developed from about 26 0100 GMT, behind system A (Fig. 9). The storm's overall growth is quantified in Fig. 19, where the square root of the area enclosed by cloud top isotherms is plotted against time. From damage and hail reports and the lengthy duration of the individual clusters (9 hours), it is most probable that system B contained supercell storms. Taking cloud top temperature as an indicator of the up draught strength, the figure indicates that the most severe stage of the system occurred between 0300 and 0500 GMT. In particular, the -60°C isotherm peaks in area at about 0600 GMT (Fig. 19) while the warmer isotherms peak at progressively later times: after beginning with very strong and narrow up draughts, these later

---

* Digital GMS imagery for 0600 and 0900 GMT 10 May 1979 were interpolated to obtain estimates for 0700 and 0800 GMT. The regression relationship (Eqn 1) was applied to the fields for 0600, 0700 and 0800 GMT to estimate falls during the period 0530 to 0830 GMT (Fig. 18(a)). The observed three-hourly values (Fig. 18(b)) are based on a manual analysis of rainfall reports from the synoptic network at 0800 GMT. In ongoing studies aimed at refining these methods the need for evaluation over a much denser network has been recognised.
Fig. 17 Mean hourly rainfall totals in relation to cloud top temperature for system C. The solid line refers to 'all station means', the dashed line to 'wet stations only'. In calculating the linear regression relationship of Eqn 1 (see text) the class interval $<-15^\circ \text{C}$ was not included due to the relatively small number of observations.
Fig. 18(a) Estimated areal rainfall for the period 0530–0830 GMT 10 May 1979, obtained by applying the linear least squares regression equation of the September case study to cloud top temperature data for 10 May.

(b) Observed rainfall 0500–0800 GMT 10 May 1979 based on the synoptic reporting network.
Fig. 19 Temporal variation of the area enclosed by different cloud top isotherms of system B. The vertical scale is the square root of the number of pixels (i.e. picture elements). Each pixel is approximately 10 sq km.
subsided leaving the cloud material to be horizontally diffused with the wind. Thunderstorms persisted afterwards in the system, but at much lower severity. The tropopause at 26 0000 GMT at Cobar, about 300 km to the east of the storms, was at 217 mb with a temperature of -60°C. Cross-sectional analysis (Fig. 8(c)) suggests the tropopause at Mildura was located around 300 mb. The storms are estimated to have penetrated the tropopause at about 0300 GMT by at least a half of one kilometre to reach a height of about 11 km. The cloud top temperature at 26 0300 GMT was -65°C.

As previously noted, the special GMS observations at 26 0100 and 26 0200 GMT were made in the visible channel. Although of greater spatial resolution, these data are not immediately useful in determining cloud height (Gruber 1975). The variation of visible or reflected radiation with height is dependent on more factors than is the emitted IR radiation, so that any simple quantitative equivalence between the two data types is improbable. This problem is elaborated in the Appendix.

The digital IR imagery at 26 0300, 26 0600 and 26 0900 GMT are shown in Fig. 20 and reveal the substantial expansion of the band and its southeastward movement. The three original cells (marked 'a', 'b', 'c' in the figures) appear to have been maintained at least to 26 0600 GMT and there is a suggestion that 'a' and 'b' were still identifiable at 26 0900 GMT.

Figure 21 shows the movement of the centres of the three cells during the period. Movement was generally to the southeast at about 20 m/s, approximately the same speed as the leading edge of the band. The winds at Cobar (31.5°S 145.8°E) were 305°/20 m/s at 600 mb and 305°/30 m/s at 550 mb. Fig. 21 also shows the positions of pluviograph stations relative to the cell centres and the leading edge of the band. At 0200 GMT only two stations, Fowlers Gap and Mildura, were located near the band but neither recorded particularly heavy rainfall as they were not directly traversed by any of the three cells. The damage records from Broken Hill and the autographic traces at Mildura (Fig. 10), however, leave no doubt about the severity of the convective activity associated with these cells between 26 0300 and 26 0500 GMT.

There were no pluviograph stations in the vicinity of the three cells at 0600 GMT but during the period up to 26 1200 GMT, nine stations were influenced by the system. Most of these stations recorded significant peaks in rainfall as the cells 'a', 'b' and 'c' passed over them. Fig. 22 shows the maximum three-hour falls stratified by latitude. The sequence of hourly visible and three-hourly IR images (Fig. 9) establishes the sequence of cell development as 'c', 'b', 'a' and 'd', i.e. new cells formed progressively northward of the older ones. The youngest and northernmost of the three main cells, 'a', was still producing significant falls at 26 1200 GMT with progressively lesser amounts from 'b' and 'c'. This is in keeping with empirical schemes for estimating convective rainfall (e.g. Scofield and Oliver 1977) where the heaviest rates are attributed to the early and mature stages of cell development. Further, the horizontal gradient of cloud top temperature is a useful indicator in determining the location of the more active cells, and in avoiding the confusing effects of a large expanding cirrus shield (see Scofield and Oliver 1977). Fig. 23 shows this gradient is largest for cell 'a' which was associated with the heaviest maximum falls during the period after 26 0600 GMT, and smallest for cell 'c' which was the oldest cell with the lowest totals.
Fig. 21 Tracks of cells ‘a’, ‘b’, ‘c’ based on locations at 0200, 0300, 0600, 0900 GMT. The eastern edge of the system at 0300, 0500, 0900 GMT is also shown. The pluviograph stations are:

1 Deniliquin, 2 Fowlers Gap, 3 Cobar, 4 Griffith, 5 Wagga, 6 Naradhan, 7 Trangie, 8 Mildura, 9 Humula, 10 Hume Reservoir, 11 Condobolin.
Fig. 22 Maximum 3-hourly rainfall during the first 12 hours of system B. The circled numbers refer to stations identified in the previous figure. Stations are grouped according to the cell which affected them ('a', 'b', or 'c') and located on a relative latitude scale.
Fig. 23  Maximum 3–hourly rainfalls as a function of the gradient of cloud top temperature in the direction of movement of system B. (The period considered is 26 0000 to 1200 GMT.)
Finally, a comparison of the representation of the digital data (Fig. 20) with the photographic counterpart (Fig. 9), highlights the value of digital 'enhancement' in locating the cell structure within a complex cluster such as system B.

**Time averaged GMS data and rainfall**

In addition to the examination of one-hour and three-hour rainfall totals, an attempt was made to see if longer period rainfall patterns could be related to the time averaged cloud top temperature data. The temperature data for the area bounded by 30°S, 40°S, 140°E and 150°E were averaged for the transmissions at 0000, 0300, 0600, 0900, 1200, 1600, 1800, and 2100 GMT on 26 September (see Fig. 24(a)). These results were compared with manually drawn 24-hour isohyets for the region.

The temperature data were averaged by superimposing the digital arrays for each transmission. Unfortunately, the algorithm that locates the requested area in the transmissions received by MDUS is slightly inaccurate in locating the desired area (∓0.5° lat., ∓1.0° long.) so that successively extracted areas do not coincide geographically. This algorithm was not used for any other purpose such as locating surface observing stations. Such geographical locations were made by reference to the lat.-long. grid which remains fixed in relation to the imagery. Such errors are not important for broadscale applications, but are significant on regional scales.

Results confirm that the simple averaging of cloud top temperature data is not suitable for comparison with rainfall because it weights the residence time of a cloud element equally with its temperature, and assumes that rainfall rates are proportional to cloud top temperature for all cloud types. As discussed earlier, this assumption is false, particularly with middle level or layered cloud systems. The example shown in Fig. 24(a) exemplifies this. The rain maxima near 30°S 142°E and at 36°S 142°E (Fig. 24(c)) are not adequately reflected in the mean temperature pattern because they were caused by clusters of thunderstorms that moved out of the area within two or three hours and which were not necessarily at their most severe stage at GMS picture times. No temperature minimum exists to correspond to the large area enclosed by the 20 mm isohyet over central New South Wales. Over Victoria there is a broad correspondence with the rain maxima near 37°S 147°E and 38°S 142°E. Better correspondence in these cases might result if the location errors mentioned above were reduced.

Figure 24(b) shows average cloud temperatures based on 0000, 0300, 0600, 0900 and 1200 GMT only. In this case there is an area of minimum temperature defined by the -40°C isotherm in central New South Wales, but it remains displaced to the east of the 20 mm isohyets. Again, the thunderstorm rainfalls at 30°S 142°E and 36°S 142°E are not reflected in the 12-hour isotherm pattern.

In summary it appears that rainfalls from differing systems, such as intense, fast moving systems and weak, slow moving systems, cannot both be simultaneously represented by simple time averaging of cloud temperature data. There may be some improvement possible by time averaging of enhanced (or weighted) data, but that is unlikely to overcome the problem caused by different cloud types of similar cloud top temperature producing rain at very different rates.
Fig. 24(a) Average 24-hour cloud top temperature distribution obtained by averaging the 26 0000, 0300, 0600, 0900, 1200, 1600, 1800 and 2100 GMT data.
Fig. 24(b) Average 12-hour cloud top temperature distribution using data at 26 0000, 0300, 0600, 0900 and 1200 GMT.
Fig. 24(c) Isohyet analysis based on 24-hour rainfall totals for the period 26 0000 to 27 0000 GMT.
Orographic influences

A variety of possible mechanisms can markedly enhance rainfall in mountainous areas, e.g. increased insolation, direct orographic lifting of the air, and reduced subcloud evaporation resulting from cloud bases closer to the ground. When rainfall is inferred from cloud top temperatures, it is not always clear if orographic effects need to be considered separately and additionally, or if they are implicit in the cloud top data. In a first attempt to resolve this, cloud top temperature data and coincident hourly rainfalls were examined for the region south of 35°S.

Station elevations* in the region varied from MSL to 600 m, and data from two sequences 0000, 0300, 0600, 0900 GMT and 1800, 1900, 2000, 2100 GMT on the 26th were used to provide a broad range of cloud top temperatures ranging from 0°C to below -50°C, and broadscale flow from northerly to south-westerly.

An analysis of variance was performed separately on each data sequence to estimate the contribution to the variance of the mean rainfalls from elevation, cloud top temperature and their joint effect. Data from about 55 to 65 stations for each GMS imagery were grouped into nine categories, being combinations of three elevation groupings and three cloud top temperature groupings. Averages of hourly rainfall were computed for each category and these formed the basic data for the analysis of variance. Thus difficulties arising from the pronounced skewness of the rainfall totals' distribution were minimised. It was assumed that these averages were independent on the basis of the assumed independence of the constituent hourly rain totals. A sample examination confirmed that dependence between simultaneous hourly totals at adjacent stations was negligible, principally due to a mean station separation of over 60 km. A similar examination showed that autocorrelations of single station hourly totals produced similar conclusions in the first sequence, probably due to the three-hourly separation in the readings, and in the second sequence where the hourly readings were sequential but the rain events were much more intermittent. It was expected that each factor would contribute singly, but if elevation affects rainfall independently of cloud top temperature, then their joint contribution should be insignificant (e.g. see Moroney 1963). Results, shown in Tables 2 and 3, indicate that in this case elevation effects on rainfalls are reflected adequately in enhanced cloud heights. As might be expected the relationship between cloud top temperature and rainfall is stronger in the second case (Table 3), which comprised predominantly cumuliform cloud, than in the first case where middle-level cloud was more frequent.

* Station elevation (as opposed to gradients of elevation etc.) is taken as a suitable primary measure of orographic effects.
Table 2  Analysis of variance table for hourly rainfalls, cloud top temperatures and station elevation for the period 26 0000 to 26 0900 GMT.

**Analysis of Variance - Northwesterly flow, layer cloud**

<table>
<thead>
<tr>
<th>Effect</th>
<th>Sum of Squares</th>
<th>d.f.</th>
<th>Variance Estimate</th>
<th>F Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elevation</td>
<td>4.89</td>
<td>2</td>
<td>2.45</td>
<td>5.57*</td>
</tr>
<tr>
<td>Temperature</td>
<td>3.18</td>
<td>2</td>
<td>1.59</td>
<td>3.61+</td>
</tr>
<tr>
<td>Joint</td>
<td>2.45</td>
<td>4</td>
<td>0.61</td>
<td>1.39</td>
</tr>
<tr>
<td>Replication</td>
<td>11.96</td>
<td>27</td>
<td>0.44</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>22.48</strong></td>
<td><strong>35</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Significant at 99 per cent confidence level.  
+ Significant at 95 per cent.

Table 3  As for Table 2 but for 26 1800 to 26 2100 GMT

**Analysis of Variance - Southwesterly flow, layer cloud**

<table>
<thead>
<tr>
<th>Effect</th>
<th>Sum of Squares</th>
<th>d.f.</th>
<th>Variance Estimate</th>
<th>F Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elevation</td>
<td>2.00</td>
<td>2</td>
<td>1.00</td>
<td>5.88*</td>
</tr>
<tr>
<td>Temperature</td>
<td>3.08</td>
<td>2</td>
<td>1.54</td>
<td>9.06*</td>
</tr>
<tr>
<td>Joint</td>
<td>0.99</td>
<td>2</td>
<td>0.50</td>
<td>2.94</td>
</tr>
<tr>
<td>Replication</td>
<td>1.84</td>
<td>11</td>
<td>0.17</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>7.91</strong></td>
<td><strong>11</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Significant at 99 per cent confidence level.  
+ Significant at 95 per cent.
CONCLUSIONS

In this paper we have analysed a major weather producing system over eastern Australia with an emphasis on the use of GMS imagery. The analysis has embraced broadscale, mesoscale and rainfall related aspects. On the broadscale the results suggest that GMS data could be used to establish useful variations of the interpretation models pioneered by Guymet (1969, 1978). On the mesoscale, hourly imagery showing the growth of distinct thunderstorm supercells highlights the potential of such imagery in relatively accurate short term warnings (1 to 3 hour), which could facilitate considerable savings of both life and property. (While little can be done on such time scales to avoid loss to crops, the wind and hail damage to cars, vans and aircraft can be alleviated by protective action.)

While cloud top temperature was found to be poorly correlated with radar rain echoes and rainfall amounts in systems containing middle and high-level cloud, good correlations were found for convective situations. In particular, a potentially useful regression was obtained for the southwesterly stream situation over Victoria. It was also established that the effects of orography on rainfall appear to be adequately reflected in variations of cloud top temperature.

Finally we wish to stress that 'enhancement' of the digital imagery is essential to maximising its information content. This enhancement, however, should go beyond the production of a grey shade photographic print. To fully realise the potential of the imagery in a future operational context it will be necessary to invest in a computer-based system that can rapidly assimilate both conventional and satellite imagery.

ACKNOWLEDGMENTS

The authors thank N. Streten, A.B. Neal, P. Price, M. Van Dijk, A. Day, B. O'Connor, K. Stibbs, D. Pike, P. Yew, A. Jonas, C. Giblin and S. Martin for their support during different phases of this project. We also extend our gratitude to the many field staff of the Bureau who responded to calls for special observations.

REFERENCES


APPENDIX

Relationships between visible channel data and infrared data

Visible channel data are not as easily converted to quantitatively useful meteorological information as are infrared data. The intensity of the visible reflected radiation received by the satellite sensor depends on the relative inclinations of the sun, the sensor and the cloud surface, as well as the composition of the cloud, its thickness and the amount of attenuation by the atmosphere between the cloud top and sensor. Furthermore, the shadows cast by one cloud upon another, particularly when the sun is at a large angle of incidence (regular GMS visible transmissions are at 0000 and 0600 GMT), can create apparent anomalies.

Infrared emitted radiation (11.5 micron band) is isotropic, but is affected to small extents by atmospheric attenuation (limb-darkening) and water vapour absorption. The latter can account for an apparent temperature anomaly of over 5°C in tropical areas. The most important affect is due to the cloud thickness, which largely determines the cloud's emissivity. While a substantial examination of those problems as they affect GMS data interpretation are beyond the scope of this paper, a cautionary example is shown.

Simultaneous visible and infrared data for 25 0000 GMT over the South Australian coast are shown in Figs A1 and A2. Three areas of cloud I, II and III were examined, being part of system A, which illustrate ambiguities that can arise in interpreting visible channel data. For each area, shown in Figs A1 and A2, correlations were calculated between the visible brightness counts and the coincident cloud top temperatures. Quite different results were obtained in each case as shown in Table A1. In area I a brightness value of 80 units (on the DUS digitiser scale of 0 to 119) was associated with a cloud temperature of about -40°C, while in area II with -87°C and in area III with -27°C. The reasons may stem from the differing cloud types in each area, with area I comprising mostly cumulus cloud, area II altostratus and cirrocumulus, and area III low stratocumulus.

Table A1 Statistics for digital visible channel and IR data pairs in areas I, II, III of Figs A.1 and A.2. Data pairs were randomly selected in each area.

Relation between visible channel brightness counts and cloud top temperature

<table>
<thead>
<tr>
<th>No. Pairs</th>
<th>Correlation Coefficient</th>
<th>Mean Cloud Top Temp.</th>
<th>Mean Cloud Brightness</th>
<th>Least Squares Fitted Relation</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>-0.48</td>
<td>-32°C</td>
<td>56</td>
<td>T=-9.18-0.40V</td>
</tr>
<tr>
<td>II</td>
<td>-0.86</td>
<td>-35°C</td>
<td>32</td>
<td>T=-1.10-1.07V</td>
</tr>
<tr>
<td>III</td>
<td>-0.42</td>
<td>-20°C</td>
<td>56</td>
<td>T=-2.49-0.31V</td>
</tr>
</tbody>
</table>
Fig. A1 Infrared data for 25 0000 GMT over South Australian coast.

Fig. A2 Visible data for 25 0000 GMT over South Australian coast.