Fog and low cloud detection over northern parts of the Northern Territory using geostationary satellite data, June to September 2004

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(Manuscript received April 2006; revised November 2006)

An investigation of large-scale fog and low-cloud events over the northern part of the Northern Territory, Australia, during the dry season of 2004 was performed using a variety of Geostationary Operational Environmental Satellite (GOES) 9 imagery. In the course of this an evaluation of an Enhanced Dual Channel Infrared Difference method is conducted. The method has been developed within the Australian Bureau of Meteorology to assist in the detection of night-time fog and low cloud. This analysis was conducted on a large scale over the whole domain, and on a smaller scale in the vicinity of selected meteorological stations. Results indicate that on a large scale the method detects developing fog and low cloud well, however on the smaller scale it is limited by its finite resolution, giving good results only for some of the selected stations. Favourable geographical locations for fog and low cloud are identified for each month, and for the full four months of data. Analysis of the total area occupied by the fog and low cloud for each day over the duration of the study shows that the events cluster into episodes. Both the episodes and the geographical distribution of the fog and low cloud appear to be related to the synoptic-scale wind flow over the domain. Characteristics of the night-time formation and daytime dissipation of the fog and low cloud are presented for each month and for the full four months, and critical times and periods are identified. It was found that during the night the evolution of the fog and low cloud was influenced by linear disturbances moving through favoured locations, whilst during the day the dissipation of the signal is much slower over maritime areas than over land. The local sea-breeze is postulated to stimulate the dissipation over the southern Gulf of Carpentaria.

Introduction

The detection and short-term forecasting of large-scale fog and low cloud (FLC) as it forms during night-time hours relies heavily on temperature-sensitive (infrared) imagery from either polar-orbiting or geostationary satellites. However, these very low altitude clouds are nearly invisible in single-channel infrared images due to the small temperature differences between the cloud top and the earth’s surface. The Enhanced Dual Channel Infrared Difference...
(EDCIRD) method is based on the observation that the emissivity of clouds containing small water droplets varies for different wavelengths in the infrared spectrum. In particular, the emissivity at around 3.9 µm is less than at around 11 µm (Hunt 1973), and subtracting the former from the latter channel gives an infrared temperature difference of between 2 and 5 K for FLC. This is sufficient to reveal these classes of cloud in night-time EDCIRD images. This technique was first used for night-time detection of fog by Eyre et al. (1984) using Advanced Very High Resolution Radiometer (AVHRR) imagery from polar-orbiting NOAA satellites. It was later adapted to hourly image data from the geostationary GOES 7 satellite for better temporal resolution of the data (Ellrod et al. 1989). Further studies of nighttime FLC detection using the EDCIRD method have since been conducted (Ellrod 1991, 1994, 1995; Park et al. 1997; Weymouth and Rea 2003). The research described in this paper evaluates an EDCIRD technique developed within the Australian Bureau of Meteorology (BOM) by Weymouth, and previously tested in detecting FLC events over southern Australian locations (Weymouth and Rea 2003). The present paper extends this evaluation, using EDCIRD images from GOES 9 to investigate FLC events over northern Australian locations. Here the enhanced satellite images are used in conjunction with single-channel infrared and visible satellite images and with observations conducted at selected meteorological stations.

The geographical area investigated here is shown in Fig. 1 and includes the Top End, the Gulf Country and the northern Victoria River District of the Northern Territory (NT) of Australia. The ‘Top End’ is defined as that part of the NT north of about 15°S. The Gulf Country includes the catchments south of 15°S draining into the Gulf of Carpentaria, and the northern Victoria River District is located to the southwest of the Top End. Elevations are typically 500 metres in the far southwest, 400 metres on the Arnhem Land Plateau and 300 metres in the hinterland of the southern Gulf of Carpentaria. At elevations below 200 metres the three largest catchments are the Roper, Victoria and Daly River basins. There have only been a few studies of fog and low cloud over the chosen domain. The most detailed is a study of fog at Darwin Airport by Lloyd (1988). Two unpublished BOM discussion papers have also been written by McGuffie (1990, 1997). The first is a guide for fog and low cloud forecasting for Top End locations, and the second describes the conditions favourable for FLC formation over the Roper Valley, Katherine and Tindal areas. For the period of this investigation, some reference to FLC development over this domain is given in *Monthly Weather Review, Northern Territory* (MWRNT) (2004a–d). This lack of research material can be attributed to the sparse population and few meteorological stations located within the area. For example the most FLC-prone areas in the domain, the Roper and Daly River valleys (McGuffie 1990), have only two monitoring stations.

The domain of this research, showing locations mentioned in the text. Place names are: NG = Ngukurr, MF = Mango Farm, BRL = Borroloola, CI = Centre Island, AP = Alyangula Police, GA = Galiwinku, ALP = Arnhem Land Plateau. Catchments are: 1 = Daly River, 2 = Roper River, 3 = Towns River, 4 = Walker River, 5 = Victoria River.
within their catchments, with one of these (Ngukurr) conducting very infrequent observations. Hence it is an advantage to study the FLC over this area using remotely sensed data because these give coverage over the whole area. Such a study is useful because there are a number of airports and aerodromes located here, some of which service regular morning flights. The detection and forecasting of FLC would be of value to the operations of the relevant aviation companies, particularly for locations experiencing frequent episodes of FLC.

This paper summarises data from the period 1 June to 30 September 2004, when the northern NT was experiencing the dry season. This time of the year is characterised by a dry continental east to southeast airflow, from high pressure systems located over southern parts of the continent, and little mid and high-level cloud. Areas of extensive morning FLC have often been observed whenever the synoptic flow tends more easterly or if it weakens (McGuffie 1990, 1997; MWRNT 2004a–d). This combination of near cloud-free skies, subdued topography and favoured areas of FLC make the northern NT dry season ideal for the study of FLC and for evaluating the EDCIRD method. However, the sparse and uneven coverage of meteorological field stations over the area is a distinct disadvantage, especially when comparing the results of the method with surface observations.

Data and methods

Data used in this research include GOES 9 satellite images and surface and low-level observation (SYNOP) data from selected stations. Details of the satellite data used are presented in Table 1. Hourly or near-hourly EDCIRD images were used to study the development of FLC during the night. Because sunlight strongly affects one of the infrared channels used in the differencing method, the last useful EDCIRD image of each night was at 2040 UTC. The first visible image of the day (at 2228 UTC) and the 2040 UTC single-channel infrared image were used in close comparison with the corresponding 2040 UTC EDCIRD image, and the full set of visible images were used to study the dissipation of the FLC signal during daylight hours. All of the satellite images used here were produced by the Man-computer Interactive Data Analysis System (McIDAS). Satellite scan time over the northern NT occurs 15 minutes after nominal image start time, and henceforth all references to satellite image time will be in terms of this scan time.

A detailed account of the preparation of the EDCIRD images is the subject of a future paper by Weymouth, so only a brief summary is given here. After the raw image data are received from the satellite, a computer program digitally subtracts brightness values in the 3.8–4.0 μm channel from the 10.2–11.2 μm channel. Differences between cloud-top and ground temperatures are determined by comparing the infrared temperature of picture elements (pixels) belonging to the cloud, with nearby cloud-free pixels after a fixed sub-adiabatic lapse-rate adjustment for topography. These data are then enhanced into their final format at full thermal resolution by calibrating these temperature differences according to a colour code. Various blue and pink colour enhancements define cloud-top-to-ground temperature differences (T_{ct} - T_{sfc}) less than 5 K, corresponding to fog and very low cloud. Yellow and green colour defines (T_{ct} - T_{sfc}) between 5 and 9.5 K, corresponding to cloud with higher tops. For each image produced in the above manner, Weymouth provides a matching ‘cloud mask’ (MASK) image. This incorporates a degree of quality control by identifying all of the FLC contained in the processed image, including additional weak detec-

| Table 1. Summary of the satellite data used in this paper. |
|---------------|-----------------|-----------------|--------|
| GOES 9 images | Nominal image start time (UTC)* | Scan time (UTC)* | Sub-point resolution (km) |
| EDCIRD        | 0925,1013,1056,1125, 1225,1325,1425,1525, 1613,1648,1725,1825, 1925,2025 | 0940,1013,1104,1140, 1240,1340,1440,1540, 1628,1705,1740,1840, 1940,2040 | 4 by 4 |
| Visible (0.55–0.75 μm) | 2213,2325,0025,0125, 0225,0325,0413,0525, 0625,0725 | 2228,2340,0040,0140, 0240,0340,0428,0540, 0640,0740 | 1 by 1 |
| Infrared (11.5–12.5 μm) | 2025 | 2040 | 4 by 4 |

* Dataset for EDCIRD images after 17 August from 1525 UTC to 2025 UTC only (1540 UTC to 2040 UTC scan time).
tions, and tagging rejected FLC signals. All signals that are not rejected are given a dark blue colour if they have (T_{ct}-T_{sfc}) less than 5 K and a green colour if (T_{ct}-T_{sfc}) is between 5 and 9.5 K. Images produced by the EDCIRD method and the MASK enhancements are shown in Fig. 2.

Recorded 0600 Central Standard Time (CST) (2030 UTC) SYNOP data for all meteorological stations within the domain were extracted from the Australian Bureau of Meteorology’s (BOM) database. Observations of FLC in these SYNOps were compared to the corresponding signal in the relevant EDCIRD images. To assist in the interpretation of the results, surface wind observations from Centre Island and the Darwin and Gove gradient-level (1000 metre) winds were also used.

**Limitations and sources of error in the data**

There are a number of sources of ambiguity and inaccuracy in the satellite and SYNOP data that must be addressed in order to obtain quality results from the research. These include ambiguities in the detected cloud types and cloud-base heights, false signals in the images, poor mapping of the satellite data by the relevant image-mapping software and limitations in the collected dataset.

Because infrared and visible frequency satellite data image the cloud tops, it is difficult to distinguish between low cloud and fog using these data. This is further complicated over terrain with significant topography, where low cloud over a valley grades into fog along the upper slopes. Mid and high-level cloud may also cover FLC and this can occur if the higher clouds are precipitating and in this way generating low cloud, or if the higher cloud moves over the FLC. Because the satellite data are also compared to ground-station observations of cloud-base height, inaccuracies in this height determination by the observer can be a source of error. Fortunately, the domain of this study has subdued topography over FLC-prone areas. As the investigation occurs during the dry season, most of the days are free of higher level cloud and associated precipitation. In addition, ground-based observers at some stations have additional instruments to assist in cloud-base height determination.

False signals in the images can be attributed to the finite spatial resolution of the satellite data, to the amount of atmospheric moisture and to the nature of the ground surface. The finite pixel size of the image and the optical depth of the FLC impose limitations in the capacity of the EDCIRD method to detect FLC. Since pixel dimensions are 4 by 4 km sub-point, areas of patchy fog or low-cloud entities with dimensions much less than this may give an incorrect temperature or may not be detected. Optical thickness becomes an issue for layers of FLC less than 100 metres thick, as these are unlikely to be detected by the EDCIRD method (Ellrod 1995). Comparing the FLC signal in the EDCIRD images to the corresponding signal in the higher resolution visible images of the same morning reduces this source of error. Atmospheric mois-
ture variations can also be a problem, with weaker FLC detection over moist tropical regions and the generation of false signals over dry, arid regions (Ellrod 1995). However, this is unlikely to be an issue here because of dry season conditions prevailing over the domain, with total precipitable water limited to 15–25 mm during the four months of this study (NCEP/NCAR Reanalysis). The land or maritime surface of the earth can have a variety of effects on the EDCIRD image. Over land infrared emissivity varies for different soil types, with coarse sandy soils likely to produce a false FLC signal (Sutherland 1986). For maritime surfaces FLC \((T_{ct}-T_{stc})\) in the EDCIRD image are greater than for adjacent land surfaces, because land temperatures are usually colder than maritime surface temperatures during the night. This may result in cloud-top height assignment errors at the land-sea interface. A land-sea mask is used in the MASK enhancement images, but this depends on accurate mapping of the satellite image. Unfortunately, poor mapping of the satellite image in the McIDAS computer program is evident as a distinct offset between the coastline in the satellite images and the coastline in the map overlay. To compound this error, the offset varies across the dataset. Therefore, for an accurate analysis of FLC events over an extended period of time the accurate remapping of the images is mandatory.

Limitations in the dataset include missing satellite images, variations in the time of sunrise over the duration of the study, and time differences between the last EDCIRD image of the night and the first visible image of the day. Missing satellite data occur between 17 August and 30 September, with no EDCIRD images between 1040 and 1540 UTC. As these images occur during the early part of the night, their absence only affects the analysis of FLC formation. The time of local sunrise varies from around 2130 UTC (0700 CST) during June, July and August, to around 2100 UTC (0630 CST) at the end of September. As the first visible image of the day is at 2228 UTC, this means that for the latter part of September the FLC signal in this image may be much reduced because of significant dissipation by sunlight. Unfortunately, the hourly time intervals of the satellite data do not permit compensation for this source of error. Finally, there is a time difference of almost two hours between the last EDCIRD image of the night (at 2040 UTC) and the first visible image of the day (at 2228 UTC). That is an important consideration, as fog is normally thickest around sunrise (Findlater 1985) or may even form with sunrise. Hence it is likely that the EDCIRD image will generally underestimate the FLC signal, when compared to the corresponding visible image.

**Classification and selection of data**

To assist in distinguishing between true and false FLC detections and to follow the evolution of the various enhanced cloud entities during a night, the hourly images are looped in animation (Ellrod 1995; Weymouth and Rea 2003). This shows FLC formation and development and, by allowing the tracking of undesirable higher level cloud, shows how this interferes with FLC development during the night. Comparison of the last enhanced infrared images (raw EDCIRD or MASK) of the night with the first visible image of the morning is useful for distinguishing between true FLC signals and false detections, and helps determine enhancement colours which best capture the FLC. In the visible images the FLC signal is generally easy to identify, with a characteristic bright and flat uniformly textured upper surface, sharply defined boundaries casting little or no shadow and often coinciding with topography. In addition, each EDCIRD image is compared with the single-channel infrared image of the same time. This reveals higher altitude small droplet stratuscumulus and altocumulus cloud that can masquerade as low cloud (Ellrod 1995) and also identifies any cirrus cloud that may be present.

Using the aforementioned methods, each morning’s EDCIRD and visible image pair have been classified as good, intermediate, marginal or bad quality data. Good data contain insignificant or no mid-level or high-level cloud. If the FLC signal is present it must occupy a distinct and well-defined area in both EDCIRD and matching visible images. The EDCIRD images may contain some false ground signal, typically of a yellow-green colour, but this should be geographically well separated from the FLC. Data of intermediate quality must have either the EDCIRD or the matching visible image as good quality data. The poor quality image of the pair commonly has significant higher level cloud, or contains a FLC signal of inferior quality (i.e., pixelated or indistinct). In the marginal quality data neither EDCIRD nor the matching visible image are good data. One example is an EDCIRD image with a ‘noisy’ (pixelated) FLC signal and a small and indistinct FLC signal in the corresponding visible image. Another example is where the low-cloud signal grades into higher level cloud, and where the two cannot be separated. In this case the area occupied by the higher cloud must be much less than the area of the FLC. Marginal quality data must be used with caution, and for that reason are flagged to distinguish them from the better data. Bad quality data contain extensive thick mid and high-level cloud over most of the domain. Although a FLC signal may sometimes be detected within gaps in this
higher cloud, it is not possible to determine the geographical extent of the signal. These data are rejected. Over the 122 days, good quality data occur on 77 days (or 63 per cent of the total dataset), intermediate quality data on 21 days (17 per cent), marginal quality data on 5 days (4 per cent), and bad data on 19 days (16 per cent).

For the ground-based observations, there are sixteen meteorological stations that record morning FLC over the domain. Although nine of these stations have between 90 and 100 days of 6 am weather observations over the period of interest, only Gove (44 days), Mango Farm (49), Galiwinku (23), Alyangula Police (25) and Darwin (23) have more than twenty days when satellite FLC signal can be compared with ground observations. These numbers are further reduced if subsets to the data are analysed. Therefore, with the exception of Mango Farm, Gove and Alyangula, all of the remaining stations have fewer than the recommended 25–30 independent events required for adequate statistical analysis. The accuracy of cloud-base height determination must also be considered. Darwin and Gove stations have highly trained BOM observers with access to ceilometers and morning sonde flight data. Cooperative (non-BOM) observers staff the other stations and do not have access to these additional data. Nevertheless, these observers have a long history of BOM affiliation, with high standards of recording data (Garry O’Sullivan, personal communication). Examination of the observations shows that only Alyangula has the bulk of data as ‘borderline low-cloud’ (cloud-base height between 1500 and 2000 ft), without the benefit of additional ceilometer or sonde flight data. Because of the potential inaccuracy of cloud-base height determination in the absence of supporting data, the Alyangula dataset has been removed from the analysis. Galiwinku observations must be used with caution as this station has a quarter of the FLC data in the form of ‘borderline low-cloud’, without supporting data.

Preparation and analysis of the data
After classifying the satellite data, suitable 2040 UTC EDCIRD and 2228 UTC visible image pairs were remapped manually by matching the coastlines of the image and map overlay. It was found that the McIDAS map overlay offset varied between 5 and 15 km in relation to the image, with displacement to the north and northeast. After remapping, the domain of interest was subdivided into a grid of 0.25º by 0.25º squares. For each grid square where the FLC signal fills more than half the area a value of 1 is assigned, for verified FLC. For each grid square where the FLC signal fills less than half its area a value of 0 is assigned, for no FLC. This results in two 25×35 matrices for each day, one for the EDCIRD and one for the visible data. For each dataset the matrices are then summed over each month and over the four months of the study to give integrated monthly and seasonal FLC distributions for each image type. Because each grid is composed of squares having nearly identical dimensions, it is possible to calculate the approximate area occupied by the FLC signal for each day for each type of satellite image.

As EDCIRD images can show the formation and development of FLC during the night, an approximate time of FLC formation can be determined. Because the image data are recorded at near-hourly time intervals, formation time is taken to occur midway between the first image showing the FLC signal and the preceding image. Only those signals that can be continuously tracked across successive hourly images, and are present on the 2040 UTC EDCIRD image, are used. In a similar manner, the hourly visible images are used to determine the time of FLC dissipation during the day. Dissipation time is taken as occurring midway between the last image in which the signal was still visible, and the first image where it was not. To integrate the four months of data it was necessary to correct for differences in local sunrise and sunset time for each day. Therefore, time of formation and dissipation of the FLC signal is compared to the time of local sunset and sunrise respectively, for a location at the centre of the domain (14ºS, 133ºE). At the request of forecasters at the Darwin Regional Forecasting Centre, the monthly FLC formation and dissipation distributions are also presented. Whereas the four months of data are large enough to permit statistical analysis of FLC formation and dissipation, the monthly datasets contain fewer than the minimum 25–30 independent events required for adequate statistical analysis (Roeder and Harms 2002), and conclusions derived from these data must be treated with caution.

Contingency table analysis is used to compare the EDCIRD FLC signal in the vicinity of selected stations at 2040 UTC (0610 CST) (as categorical short-term forecasts), with 0600 CST ground observations of FLC at these stations. A schematic diagram of a contingency table is given in Table A1 in the Appendix, and this method of analysis permits skill scores of Probability of Detection (POD), False Alarm Ratio (FAR), Critical Success Index (CSI) and False Alarm Rate (FAR*) to be determined. There are four datasets upon which contingency table analysis is performed and each combines different EDCIRD FLC signals and station observations. The EDCIRD signal is evaluated within two areas around a station, the first centred on the station and having a radius of 8 km, and
the second with a radius of 16 km. The inner area corresponds to the area within which weather phenomena can make a significant contribution to surface observations. Phenomena confined to the outer area are usually considered as being distant from the station. Any thick FLC confined to the outer area may have thinner or more scattered FLC extensions that are below the coarse resolution of the EDCIRD method, but extend into the inner area and affect the observations at the station. The FLC signal analysed within the above-mentioned areas includes moderate to strong signals with $T_{\text{sfc}} - T_{\text{ct}}$ less than 5 K, and all signals with $T_{\text{sfc}} - T_{\text{ct}}$ less than 5 K in the MASK images (dataset M). Each of the E and M datasets is further subdivided into two subsets. The first subset includes all classes of signal within 16 km of the station, labelled EA and MA respectively. The second subset is similar to the above, but does not include data having only poor quality signals (less than 10 per cent signal coverage) within an area greater than 8 km but less than 16 km from the station. These datasets are defined as ES and MS respectively, and represent the situation where FLC occurs at the station and/ or exists in extensive amounts in the vicinity. FLC observation data at ground stations are also selected and subdivided into two groups. In this study all fog measurements are included, however only low-cloud observations with cloud base 2000 feet (610 metres) or less above the station are used. These observational data are divided into two subsets. The first includes all FLC observations (dataset GA). The second excludes low-cloud coverage less than 2 oktas (an okta is 1/8th of the celestial dome) and patchy and shallow fog (dataset GS), and this is more consistent with what may be detected in the coarse resolution EDCIRD images.

All of the abovementioned subsets are combined into the four datasets upon which contingency table analysis is performed. The first two combine the complete set of station FLC observations and satellite FLC signal and are labelled (EA, GA) and (MA, GA) for raw EDCIRD and MASK data respectively. The remaining two datasets address the limitations in the resolution of the satellite detection method by combining station observations of extensive low-cloud coverage and thick fog with a substantial satellite signal occurring within 16 km of the station. These are labelled (ES, GS) and (MS, GS) for raw EDCIRD data and MASK data respectively. To assist in the interpretation of contingency table results, the POD and FAR* values for all the datasets of the all stations are plotted on a graph. For this type of graph the closer a point is located to the top left-hand corner (POD = 1, FAR* = 0), the better the agreement between the forecast satellite signal and what is observed at the station (Mason 1982; Grace and Ferriere 2001). Conversely the diagonal line joining points (0, 0) and (1,1) represents a chance or random relationship between satellite signal and ground observation.

Results

From inspection, a comparison of EDCIRD and visible images revealed that the light-blue, blue-grey and pink enhancement areas in the raw EDCIRD images best match the FLC signal in the corresponding visible images. These colours correspond to a moderate to strong signal with $T_{\text{ct}} - T_{\text{sfc}}$ less than 5 K. The blue enhancement colour in the MASK images, corresponding to the total signal with $T_{\text{ct}} - T_{\text{sfc}}$ less than 5 K, is much noisier (pixelated) and generally over-forecasts the FLC when compared to the first visible image of the day.

The integrated monthly totals of FLC days for each square within the total matrices for the raw EDCIRD and visible images are given in Figs 3(a)–(d) and (e)–(h) respectively. Integrated totals over the season June to September 2004 for raw EDCIRD and visible images are given in Figs 4(a) and (b). The area occupied by the FLC signal in both types of images for each day over the duration of the study is presented in Fig. 5. Comparing Figs 3 and 4 with Fig. 1 shows that favoured locations include the Roper and Daly River valleys as well as the coast and adjacent valleys of the eastern Top End and the Gulf Country. Over maritime areas favoured locations are mainly confined to the southern Gulf of Carpentaria. Overall, the eastern Top End is more FLC prone than the western Top End. Figures 3, 4 and 5 show that for July, August and September both the geographical distribution and the area of the FLC captured by the integrated EDCIRD signal compares well with that detected in the visible images, whereas for June it does not. Inspection of Fig. 5 shows that FLC events can be grouped together into episodes of varying geographical extent and duration. Episodes occurred during early June, the first half of July, late July to early August, the last week in August and with three minor episodes during September.

Formation of FLC statistics for the months of June to September is shown in Fig. 6(a) for the total data and in Fig. 6(b) for each month. The curves show the number of images having a FLC signal at any one time during the night as a percentage of the total monthly or four-monthly datasets. For each data point the error bars extend from the time of the last image with no FLC signal, to the time of the first image with signal. The time of formation for the season data is
Fig. 3 Integrated monthly totals of FLC days, for each square within the total grid for the 2040 UTC EDCIRD and 2228 UTC visible images. EDCIRD data: (a) = June, (b) = July, (c) = August, (d) = September. Visible data: (e) = June, (f) = July, (g) = August, (h) = September. Locations are: D = Darwin, G = Gove, N = Ngukurr, B = Borroloola, M = Mango Farm.
Fig. 4  Integrated seasonal totals of FLC days, for each square within the total grid for (a) 2040 UTC EDCIRD data and (b) 2228 UTC visible images. Topography above 200 metres is shown in orange; locations are as given in Figs 3(a)–(h).

Fig. 5  Area of FLC signal detected in the 2040 UTC EDCIRD and 2228 UTC visible satellite images over the total domain for each day.
related to the time of sunset, whereas in the monthly
data it is given as UTC time. The season data are sub-
divided into pre-17 August and post-17 August sets
because of the missing images in the later data. The
line of best fit in Fig. 6(a) has an ‘S’ shape with the
steepest slope, corresponding to favoured formation
time, between six and ten hours after sunset.
Comparing the pre-17 August with the post-17
August curves indicates that FLC formation tends
to occur earlier in the night after 17 August. The monthly
data curves support this, with FLC during July to
September forming earlier than during June.

The season summary FLC dissipation statistics
for land and maritime regions are shown in Fig. 7(a),
whereas the monthly summaries are shown in Figs
7(b) and (c). The FLC dissipation curve for maritime
areas for June has not been plotted, as there are insufficient data available for that month. The curves and the error bars in these graphs are constructed in a similar fashion to Figs 6(a) and (b), though here the error bars from each data point extend from the time of the last image with a FLC signal, to the time of the first image having no signal. Clearly, FLC dissipation over land occurs more rapidly than over maritime regions. For the season summary FLC dissipation data in Fig. 7(a), the lines of best fit show a reverse ‘S’ shape with favoured dissipation time over land between 2.5 and 3.5 hours after sunrise, and over maritime regions between 4 and 7 hours after sunrise. For the monthly data, the rate of FLC dissipation over land across each dataset decreases from June to September. For maritime regions, the curves of best fit for July and August data depart from the reverse ‘S’ shape, and in that way they look different from the September curve.

To compare the EDCIRD signal with station observations, contingency table statistics for the four datasets (EA, GA), (MA, GA), (ES, GS) and (MS, GS) for Mango Farm, Galiwinku, Darwin Airport and Gove Airport are presented in Tables 2(a)–(d). Inspection of these tables shows that the MASK data have better verified forecast statistics and a reduction in unforecast events compared to the raw EDCIRD data, but at the price of higher false alarms.

Table 2. Contingency table statistics for dataset (EA, GA) in Table (a), (MA, GA) in (b), (ES, GS) in (c), (MS, GS) in (d). See Table A1 in the Appendix for an explanation of symbols used.

(a)

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<th>H</th>
<th>F</th>
<th>M</th>
<th>POD</th>
<th>FAR</th>
<th>CSI</th>
<th>FAR*</th>
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(b)

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(c)

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<th>CSI</th>
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(d)

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<td>0</td>
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Comparing these results with the POD and FAR* graph of Fig. 8 shows that Mango Farm and Galiwinku statistics are above the ‘random diagonal’, with most of the datasets having POD greater than 0.5. Gove and Darwin Airport statistics are disappointing, most of the datasets having POD less than 0.5. For Mango Farm and Galiwinku the subset datasets (ES, GS);(MS, GS) are located closer to the ‘perfect forecast’ than the (EA, GA);(MA, GA) datasets.

Discussion

In this evaluation of the BOM EDCIRD method it was useful to conduct the analysis on the broad expanse of the northern NT and surrounding maritime regions, as well as on the smaller domains within 16 km of the selected meteorological stations. The results from these two scales of investigation will be discussed in turn. On the large scale and by inspection, comparing the geographic distribution and area of the integrated monthly raw EDCIRD data with that of the visible data shows good correspondence for all months except June. For June both the geographic distribution and area of the signal in the visible images is much more extensive than in the EDCIRD images. This could be because most of the June FLC formed after the time of the last EDCIRD image (after 2040 UTC), or because the greater depth of atmospheric moisture during the month resulted in a weaker EDCIRD signal. Indeed this was an unusual dry-season month, with showers and storms affecting western parts of the NT (MWRNT 2004a). A greater depth of atmospheric moisture could also favour low-cloud formation during the early morning hours. This is supported by 0600 and 0900 CST ground observations from Mango Farm, Galiwinku, Darwin Airport, Alyangula Police and Gove Airport, recording a much higher ratio of low-cloud to fog mornings for June than July to September. The geographic distribution of the seasonally integrated FLC signals shows that much of it is constrained by topography and is hemmed into river valleys (compare Figs 4(a) and (b) with Fig. 1). Exceptions occur over the eastern parts of the Arnhem Land Plateau and the maritime areas of the southern Gulf of Carpentaria. The most favoured location for FLC during the dry season is over the Walker and the easternmost Roper River catchments where the average rate of occurrence of FLC events is one every four days. The geographic distribution and the strength of the integrated FLC signal vary for different months. During June and July most of the FLC occurred over the eastern Top End, with the most north and westward penetration being into the Roper River Valley and onto the eastern Arnhem Land Plateau for the season. One explanation is that an enhanced easterly synoptic flow could have assisted FLC development in these parts. This is supported by the monthly averaged 2300 UTC (0830 CST) gradient-level wind observations for Gove, with strongest southeasterly winds occurring during June and July (Table 3). Further examination of the limited number (17) of mornings with large-scale FLC in the northwestern Roper Valley (west of 134ºE) shows that the mean 0830 CST Gove gradient wind for these days was stronger and more southeasterly (113º at 40.5 km/h), compared to mornings with FLC over the eastern Top End, but with little or none in the northwestern Roper Valley (101º at 32.7 km/h). Furthermore, looped EDCIRD image data indicate that in the majority of cases FLC is advected into the northwest Roper Valley from the east and southeast. Synoptic wind flow therefore appears to play a part in the deep penetration of FLC into this part of the Roper Valley, and is similar to the low-cloud advection mechanism for the Katherine and Tindal area (McGuffie 1997). During August the FLC was most widespread and it is possible that local sea-breezes may have been the dominant agent for introducing low-level moisture into the valleys. This is supported by the weak gradient-level winds measured at Darwin and Gove during the month, as shown in Table 3. For September, stronger gradient winds and unseasonably low humidity levels over the northwestern Top End (MWRNT 2004d) could explain the very weak FLC signal over the western Top End.
A graph of the area occupied by the FLC signal for each day for both EDCIRD and visible image datasets in Fig. 5 shows that the signal in the EDCIRD image is of smaller area than for the corresponding visible image. The area percentage of EDCIRD signal versus visible image FLC is 71 percent for July, 70 percent for August, 98 percent for September, but only 31 percent for June. This could be due to the under-forecasting of the thresholded raw EDCIRD method. However, it is also consistent with the observation that fog is normally thickest and most developed around sunrise (Findlater 1985), or that FLC may have formed with sunrise. The low percentage for June may indicate that most of the FLC formed after the last EDCIRD image. The high percentage for September is the result of the earlier sunrise time, with substantial dissipation of FLC occurring between sunrise and the first visible image. Closer inspection of the data indicates that the FLC days can be grouped into episodes, interspersed by periods where there was little or no signal. Comparing these results with monthly climate summaries (MWRNT 2004a–d) suggests that FLC-free periods often correspond with dry, cold southeast trade winds originating from high pressure systems over southern Australia. Good examples of this occurred during 14 to 28 June, 17 to 24 July, 1 to 6 September and 12 to 14 September. Conversely, the FLC episodes frequently correspond to a more easterly wind regime, or a weakening of the pressure gradient over the target area with local sea-breezes dominating.

Inspection of the curves of best fit for the monthly FLC formation statistics shows that for June to September the bulk of the FLC formed between 1500 and 1900 UTC (0030 and 0430 CST). For these months this period is of primary importance when monitoring overnight FLC in the EDCIRD images. June 2004 data has a near-linear curve-of-best-fit, with FLC having an equal probability of forming at any time between 1200 and 2000 UTC. These observations suggest that at 0600 CST the FLC was still actively forming during June, whereas the rate of formation had slowed down and was almost complete during the other months. Although the monthly data contain a relatively small ensemble of points, the larger four-monthly dataset statistics support the observation that FLC tended to form earlier in the night during the later months. Because of its capability to detect the FLC signal during the night hours, the EDCIRD method can also give an insight into the evolution of FLC during its formative stage. Of particular interest in the June to September 2004 data was the observation that linear disturbances passing through favourable locations influenced FLC development there. Such linear disturbances were often observed as temperature discontinuities in the single-channel infrared images prior to interacting with the FLC signal. As shown in Fig. 9, the passage of such lines can either enhance the FLC signal causing it to become more widespread, or displace the signal ahead of the disturbance. From inspection, it appears that the geographical distribution and preferred direction of movement of these lines varies for different months.

Examination of the FLC dissipation statistics for each month and for the season shows that this occurs more rapidly over land than over maritime areas. That is because the rising sun heats the land surface more effectively than the ocean. This rise in surface temperature causes convectively induced mixing in the lower atmosphere, which is the dominant mechanism for FLC dispersal here (Roach 1995). The monthly data curves show that FLC has dispersed over land by 0100 UTC during June, July and September and by 0200 UTC during August, and over maritime areas by 0100 UTC during September and 0500 UTC during July and August. FLC dissipation over land commences earlier for September, due to the earlier time of sunrise. Over maritime regions FLC dissipates more slowly during July and August than during September. This is due to the more widespread marine FLC that occurred during July and August, as can be seen when comparing Figs 3(f)–(g) with 3(h). A notable feature of the July and August curves is the change in slope between 0300 and 0400 UTC, anno-

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Table 3. 0830 CST mean monthly gradient-level wind speed and direction for Gove and Darwin.

<table>
<thead>
<tr>
<th>Month</th>
<th>Gove Mean gradient-level wind speed (km/h)</th>
<th>Gove Mean gradient-level wind direction (degrees)</th>
<th>Darwin Mean gradient-level wind speed (km/h)</th>
<th>Darwin Mean gradient-level wind direction (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>June</td>
<td>119.7</td>
<td>41.6</td>
<td>103.3</td>
<td>43.7</td>
</tr>
<tr>
<td>July</td>
<td>111.2</td>
<td>40.8</td>
<td>103.5</td>
<td>35.0</td>
</tr>
<tr>
<td>August</td>
<td>100.3</td>
<td>25.5</td>
<td>89.8</td>
<td>18.3</td>
</tr>
<tr>
<td>September</td>
<td>96.4</td>
<td>36.7</td>
<td>96.5</td>
<td>30.9</td>
</tr>
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</table>
tated as ‘Js’ and ‘As’ in Fig. 7(c), corresponding to an increase in FLC dissipation. This may be due to sea-breeze circulation assisting in the breakup of the FLC, as most of the maritime FLC occurred within 50 km of land over the southern Gulf of Carpentaria. This cannot be directly verified, as the only suitable coastal station in the area (Centre Island) is limited to three-hourly SYNOP data. However, the July and August mean wind data for this station indicate that the general south to southeast wind flow changes to an easterly sea-breeze by local noon (0230 UTC). However, caution is advised as the monthly data contain a relatively small ensemble of points and the size of the error bars may mean that the change in slope in the curves is an artefact.

Comparing the EDCIRD FLC signal with ground observations at selected stations using contingency table analysis yielded good results for Mango Farm and Galiwinku, with disappointing results for Gove and Darwin Airport. The results for Mango Farm and Galiwinku are similar to the results obtained by Weymouth and Rea (2003), who used EDCIRD NOAA imagery over southern Australian locations to obtain a 68 per cent fog detection rate. Datasets that combined station observations of good low-cloud coverage and thick fog with a substantial satellite signal in the vicinity of the station gave better POD and FAR* results for Mango Farm and Galiwinku. Gove Airport had a large number of FLC events that were not forecast by the EDCIRD method. A possible explanation for this is the shallow nature of the fog and the sparse sky cover of the low cloud at this location. This is supported by McGuffie (1990) and local BOM observers at Gove. Indeed less than 2 oktas of low-cloud cover was observed on 29 mornings at Gove from a total of 48 low-cloud events at 0600 CST. For most of the above stations the MASK enhancement data yielded better verified forecast statistics than the raw EDCIRD data, though at the price of greater over-forecasting of FLC events. Indeed MASK enhanced images generally over-forecast the area of FLC, when compared to the corresponding signal in the visible images.

**Conclusion**

This research has evaluated the performance of the EDCIRD method of Weymouth for short-term forecasting of FLC over the northern NT during the dry season of 2004. The analysis was performed on the broadscale of the total domain, and on a smaller scale in the vicinity of selected meteorological stations. Results of the broadscale analysis showed good correspondence between the geographical distribution and area of the FLC detected in the last EDCIRD images of the night and the first visible images of the day for July, August and September. For the whole season,
favourable areas of FLC include the Roper and Daly river basins, the eastern coastal Top End, the Gulf Country and the southern Gulf of Carpentaria. Overall, the eastern Top End and Gulf Country is more FLC prone than the western Top End, with the Walker and eastern Roper River catchments experiencing morning FLC one day in four over the season. Both the monthly geographical distribution of the FLC and the temporal modulation of FLC activity into episodes during June to September 2004 appear to be affected by the strength and direction of the synoptic wind flow.

For July, August and September the bulk of the FLC started to form between 1500 and 1900 UTC (0030 and 0430 CST), whereas for June the bulk formed after 2030 UTC (0600 CST) and probably included a high proportion of low cloud. During many mornings FLC formation and development appeared to be influenced by propagating linear disturbances passing through favourable locations. These disturbances either enhanced the developing FLC or advected this to adjacent locations. The dissipation of FLC was more rapid over land than over maritime regions, with most of the signal gone over land by 0100 or 0200 UTC though persisting over maritime regions beyond 0300 UTC during July and August. Over maritime regions the onset of the sea-breeze appeared to assist in the dissipation of the FLC.

Evaluation of the EDCIRD method on the small scale around selected stations involved contingency table analysis and the plotting of POD and FAR results for the four datasets containing various classes of EDCIRD FLC signal and various classes of FLC ground observations. Results obtained for Mango Farm and Galiwinku were comparable with those obtained in the southern Australian study of Weymouth and Rea (2003), whilst results for Darwin Airport and Gove were disappointing. There is some evidence that FLC at Gove was generally of small scale, and below the resolution of the method. In comparison with the raw EDCIRD data the MASK enhancement gives improved probability of detection of FLC at the selected stations, though with more false alarms.

Scope for future work would include improving and extending the existing analysis. Improvements would involve digitally remapping the image and then capturing the large-scale FLC signal in a grid of higher resolution than used here. It would be useful to extend this work into a climate summary by also analysing satellite data from the dry season months of 2003 and 2005. This larger dataset would improve confidence in the monthly FLC formation and dissipation statistics, as well as in some of the contingency table statistics presented here. More research into the relationship between the geographical distribution and episodes of FLC and large-scale synoptic patterns may assist in the longer term forecasting of FLC events, as synoptic patterns typically change slowly from day to day. Further research could also involve a more detailed analysis of the linear disturbances that affect FLC development. It may be possible to investigate their origin, whether they are related to synoptic systems, and if they have characteristic timing that could assist in FLC forecasting.

Acknowledgments

The author would like to thank Gary Weymouth for making available the EDCIRD images. Bert Berzins assisted by providing satellite data from archive. Guidance offered by Geoff Garden and Gary Weymouth during the research for this paper is appreciated. Andrew Tupper, Gary Weymouth and two anonymous reviewers proofread this paper, and their suggestions greatly improved the final presentation. I acknowledge the support of the Staff at the Darwin Regional Forecasting Office of the Australian Bureau of Meteorology for helpful comments during seminar presentation of this material and assistance in providing the resources required to produce this paper.

References


NCEP/NCAR Reanalysis. NOAA-CIRES Climate Diagnostic Center Map Room Weather Products, viewed 3 April 2006 (www.cdc.noaa.gov/cgi-bin/Composites/printpage.pl).


Appendix

Table A1. The contingency table of forecast and observed events and non-events.

<table>
<thead>
<tr>
<th>EDCIRD method Forecast</th>
<th>Observed at the station</th>
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</thead>
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<tr>
<td></td>
<td>Fog/low cloud</td>
<td>H</td>
<td>F</td>
</tr>
<tr>
<td></td>
<td>No fog/low cloud</td>
<td>M</td>
<td>C</td>
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</table>

H= hit
M=miss
F= false alarm
C= correct negative

POD = probability of detection = H/(H+M)
FAR = False Alarm Ratio = F/(H+F)
CSI = Critical Success Index = H/(H+M+F)
FAR* = False Alarm Rate = F/(F+C) (from Mason 1982)