Studies of ‘cva maxima’ south of Australia.
Part 1: a long-lived enhanced cumulus cluster and induced cyclogenesis

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(Manuscript received October 1996; revised January 1997)

A long-lived mesoscale area of enhanced cumulus clouds was observed on satellite imagery moving from far south of Australia to Victoria over a two-day period, where it appeared to interact with a frontal cloudband and induce surface cyclogenesis over the western Tasman Sea. Such features on satellite imagery have been known since the 1960s as ‘cva maxima’, as they have been shown to be frequently associated with mid to upper-tropospheric centres of cyclonic vorticity advection, and so to mark potential areas of upward vertical motion or height falls.

This paper uses the objective analyses from an operational limited area data assimilation system, LAPS, to assess the ability of LAPS to resolve the structure of this subsynoptic-scale system over the Southern Ocean, and to compare this structure with previous studies of ‘cva maxima’. It is shown that the cloud feature was closely associated with a centre of height falls forced by cyclonic Isentropic Potential Vorticity (IPV) advection near the tropopause, and that this more dynamically based diagnosis shows a closer association with the enhanced cumulus cluster than does diagnosis based on cyclonic vorticity advection alone. Further, it is shown that satellite imagery-based ‘instant occlusion’ and the NWP model-based ‘IPV thinking’ conceptual models of cyclogenesis complement each other in interpreting the NWP model forecast guidance.

Introduction

On 4 April 1995 a surface low developed over eastern Victoria, Australia (near 38°S 150°E), as a region of enhanced cumulus cloud moved from the southwest and overtook a frontal cloudband, producing rainfalls over central Victoria of between 25 and 50 mm. While the cyclogenesis was not intense, this region of enhanced cumulus clouds had moved some 5000 km from near 56°S 110°E over a 48-hour period, and was clearly visible in the GMS-4 satellite imagery as it moved north-eastwards. The particular aspect of this cloud feature which attracted the author’s attention was its long lifetime (compared to an individual cumulus cloud), coherence and relatively small and constant horizontal scale.
Since satellite imagery became routinely available to meteorologists in the 1960s, the regions of enhanced cumulus activity in equatorward flow west of mid-latitude upper-tropospheric troughs have been known to be associated with regions of upper-tropospheric cyclonic vorticity advection (Anderson et al. 1966), and are thus known to forecasters as ‘cva maxima’. The significance of these phenomena lies in the three broad categories of cyclogenesis (the ‘frontal occlusion’, the ‘instant occlusion’ and ‘cold air cyclogenesis’) to which they may be precursors (Zillman and Price 1972). The underlying dynamic theory is the linking of upper-tropospheric differential cyclonic vorticity advection with the forcing of height falls or ascent using Sutcliffe (1947) development theory, or via quasi-geostrophic theory (e.g. Bluestein 1992).

Cases of ‘instant occlusion’ cyclogenesis in the northern hemisphere have been reported by Locatelli et al. (1982), McGinnigle et al. (1988) and McGinnigle (1990). Cases of comma-cloud or polar-low cyclogenesis have been reported by, for example, Reed (1979), Mullen (1979, 1983) and Reed and Blier (1986a,b), again for the northern hemisphere. Southern hemisphere studies of these oceanic phenomena have concentrated mostly on the later stages of development (i.e. after the cloud mass has developed a distinct comma shape and a surface vortex has developed), and have been generally climatological in character (e.g. Streten and Troup (1973), the satellite climatology of Carleton and Carpenter (1990), and references therein, and the composite study of Sinclair and Cong (1992)). Sinclair and Cong (1992) point out the lack of southern hemisphere cases in the literature, in spite of the importance of these features to forecasters, perhaps indicating the difficulty of undertaking individual synoptic case studies over the data-sparse southern oceans.

These studies all agree that such fields of enhanced convective activity mark centres of cyclonic vorticity advection in the middle or upper troposphere, either associated with a short wave trough or, more commonly, on the cyclonic shear side of an equatorward-moving jet streak, and in a region of lower tropospheric cold-air advection. There is usually some tropospheric baroclinicity associated with the systems, with Browning and Hill (1985) and McGinnigle et al. (1988) using gradients in 800 hPa wet-bulb potential temperature to mark these baroclinic zones. Cyclogenesis usually occurs as the ‘cva maximum’ moves into regions of reduced static stability in the lower troposphere.

Most of the studies cited above have concentrated on the later stages of cyclogenesis, when a clearly identifiable ‘comma-cloud’ has developed, and show a vast range of possible outcomes in either scale or intensity of cyclogenesis in the latter stages of development. Many of these studies also refer to pre-existing fields of enhanced cumulus clouds prior to the developments which they report. This study thus provides an opportunity to document the structure and evolution of such a cumulus field.

Recognition of features in satellite imagery such as ‘cva maxima’ provides information independent of that which is input to or present in numerical weather prediction (NWP) guidance. This can then provide a guide to a forecaster as to whether the NWP model is ‘on track’ or not; i.e. does the NWP model contain features which can be associated with the satellite-observed feature or not? If the model output does contain the feature, then the forecaster can have some confidence in the subsequent forecast, while if no evidence for the cloud feature is found in the model, then less confidence can be placed in the NWP guidance. Clearly, this process can only be effective if the forecaster has available a conceptual model of the structure of the satellite-observed feature to compare with the NWP guidance, and a means to display this structure. While conceptual models of the environment in which cva cloud features occur in the later stages of their evolution have been extensively documented in the references cited above, the ability of synoptic-scale NWP systems to resolve these subsynoptic features over the data-sparse southern oceans prior to the development of a surface circulation is less well established.

The main aim of this paper is to document the synoptic environment of the cumulus cluster through its life cycle from its initial detection in the satellite imagery far to the south of Australia up to its loss of individual identity as the closed low forms on the surface. The analyses from a limited area numerical weather prediction data assimilation system with a resolution of 0.75° (the operational system for the Bureau of Meteorology, BoM, from mid 1996) will be used to generate diagnostic fields for comparison with the imagery, and to identify features in the analyses or forecasts which are characteristic of the environment of the cumulus cluster, and to compare these with previous studies of cva maxima. These diagnostics will demonstrate that the analyses do subjectively resolve structures which can be related to the cloud features, although there are some differences from northern hemisphere studies. It will be shown that these structures are consistent with other conceptual models of cyclogenesis such as the isentropic potential vorticity (IPV) thinking concepts of Hoskins et al. (1985). One aspect to be particularly addressed is the lack of a surface signature in the analyses until the very late stages of induced cyclogenesis.

While direct confirmation that these structures in the analyses are ‘correct’ cannot be achieved, it will be shown that numerical forecasts based on these analyses, both at the same 0.75° resolution of the analysis grid, and at higher (0.25°) resolution, accurately forecast the
development of the surface cyclone up to 36 hours ahead, indicating that quantitative accuracy is also present in the analyses. In order to prevent possible confusion when relating the imagery and the NWP model fields, the cloud feature, which would be termed by forecasters a 'cva maximum', will be termed for the remainder of this paper as an 'enhanced cumulus cluster', or ECC, so that the expression 'cva maximum' can be reserved for the description of calculated cyclonic vorticity advection. The next section of the paper will describe the data sources used in this study, followed by a synoptic description of the event, a diagnosis of the environment of the ECC, and the diagnostic and modelling studies.

Data sources and methodology
The concept of using assimilated analyses from real-time NWP systems to provide balanced, internally consistent datasets for synoptic/diagnostic studies has been applied in the Australian region by this author in several papers (e.g. Mills and Wu 1995), and also over the Southern Ocean by Sinclair and Cong (1992) in their composite study. This is the approach taken again in this paper; however, as much of the area of interest is far from any conventional observations, the results will be heavily reliant on the way in which the analysis scheme utilises remotely sensed data and also the way in which the forecast model links the analyses in time and generates subsynoptic-scale detail. This is a difficult test of the assimilation system, and will obviously require care in its interpretation. The data available to the system are thus of great importance to the end result, and data availability and distribution during the period of this study will be described in some detail.

The assimilation system used in these experiments was, at the time, being trialled in the Bureau of Meteorology Research Centre (BMRC) prior to being offered to the BoM National Meteorological Operations Centre (NMOC) for operational use. As such, the system was run with operational data cut-offs, and its performance is that which would be achieved operationally. Both the analysis and the forecast models are new, and will be described in detail elsewhere (Puri et al. 1996), but a brief description of the two systems is provided here.

The analysis system
Both analysis and forecast models use the same latitude/longitude/sigma coordinate system (in the configuration used in this study 160x110 grid-points at 0.75° spacing in the horizontal, and 19 vertical levels with an upper sigma level at sigma = 0.05).

The analysis system is a limited area adaptation of the global multivariate statistical interpolation (MVSI) analysis described by Seaman et al. (1995). The MVSI analysis interpolates the observed increments from a first guess of geopotential height, geopotential thickness, and winds to produce three-dimensional grid-point fields of geopotential height, geopotential thickness and wind components. Surface data are transformed to increments of geopotential before use. The height-wind correlation functions are adjusted for geostrophic consistency outside the tropics, and are progressively decoupled equatorward of 30°. The system allows the analysis of divergent wind increments, following Daley (1985). Horizontal correlations are defined by a Gaussian correlation function with a length scale of 500 km. The vertical correlation functions follow Hollingsworth and Lönnberg (1986), and a Gaussian temporal correlation function with a time-scale of six hours is used to account for asymptotic observations. The scheme is formulated to use large data volumes, and a series of smaller overlapping analysis sub-volumes. In the application described in this paper, two data volumes are used, and analysis sub-volumes typically have lateral dimensions of the order of 100 km. Analysis sub-volumes may be further subdivided in the vertical if data density indicates that this is necessary. Quality control consists of a very wide gross error check followed by 'cross-validation'. Detailed descriptions of the analysis design, sub-volume strategy and data checking are given in Seaman et al. (1995).

The forecast model
The forecast model (see Puri et al. 1996) is a hydrostatic model formulated in latitude/longitude/sigma coordinates on the Arakawa 'A-grid'. It uses high-order finite differencing and has been designed to make maximum use of the vector and parallel processing functions of the BoM Cray YMP-4 computer. It includes a comprehensive physics package (Hart et al. 1990; Puri et al. 1992; Tiedtke 1993), and the digital filter initialisation of Lynch and Huang (1992). Lateral boundary values are provided by the BoM Global ASversion and Prognosis NWP system, GASP (Bourke et al. 1995).

Assimilation strategy
In the form run here, the assimilation consisted of a 'cold-start', where the analysis is first-guessed from the global analysis twelve hours prior to the desired forecast basetime, followed by two initialisation/six-hour forecast/analysis 'spin-up' cycles, and a 36-hour forecast nested inside the global forecast. The analysis/forecast domain extends from 65°S 65°E to approximately 15°N 185°E, this large domain being chosen to keep the lateral boundaries as far as practical from the Australian continent and surrounding waters. Thus the ECC is entirely within the analysis area throughout the period of
study; however, the area which it traverses is almost entirely devoid of 'conventional' observations. Apart from a few ship observations and isolated drifting buoys, surface data consist of bogus surface data generated in the NMOC every 12 hours using the techniques of Guymer (1978). Tropospheric data are confined to TOVS thickness and humidity profiles, with a mix of local retrievals (Le Marshall et al. 1994a), and lower resolution retrievals transmitted on the Global Telecommunications System (GTS), cloud-drift winds produced by the BoM (Le Marshall et al. 1994b) and by the Japan Meteorological Agency. Thus the analyses used in this study will be critically dependent on the way in which these data specify the environment in which the ECC was observed. (It should be noted that the TOVS data are assimilated into the analysis as five deep layers of thickness, rather than as individual layer thicknesses). Accordingly, the data distributions for surface (MSLP) and TOVS observations for each analysis through the period 2300 UTC 2 April 1995 to 2300 UTC 4 April 1995 were examined closely. Typical data distributions for 1100 and 1700 UTC time periods are shown in Figs 1 and 2. These particular times were chosen to demonstrate (a) the coverage of surface data at the two times, and (b) the difference between a 'good' and a 'poor' coverage of TOVS data. The area where the ECC was located is well covered by local TOVS retrievals at all times other than 0500 and 1700 UTC 3 April and 0500 UTC 4 April 1995. Thus the environment of the ECC was well observed by the locally retrieved TOVS data at least every 12 hours through this study period. Only at 1100 UTC 3 April was a surface bogus observation generated at the location of the ECC. Thus, apart from at this time, any surface feature associated with the ECC had been generated by the NWP forecast model.

Synoptic description

Figure 3 shows the infrared satellite imagery from the GMS-4 satellite at six-hourly intervals from 0500 UTC 3 April to 2300 UTC 4 April 1995; Figs 4 and 5 show the mean sea-level pressure (MSLP) and overlayed 900 hPa equivalent potential temperature ($\Theta_e$), and the 300 hPa geopotential/isotach analyses at 12-hour intervals from 2300 UTC 2 April 1995 to 2300 UTC 4 April 1995. The ECC is indicated by the arrows in each panel of Fig. 3, and its position marked by an asterisk on the objective analyses.

At 0500 UTC 3 April the cloud feature was an area of stratiform cloud near 55°S 110°E, well to the west of a frontal cloudband. The frontal cloudband was associated with the progressive deep tropospheric frontal system which was moving through the Great Australian Bight and into southeastern Australia during this period.

The stratiform cloud area was west of the area of cold air marked by the open cellular cumulus field at this time, and was west of both the surface and 300 hPa troughs. It was in a region of anticyclonic curvature of the geopotential contours at 300 hPa, but on the cyclonic exit side of a southwesterly jet streak, where a maximum of cyclonic vorticity advection would be expected from the four quadrant model of vorticity/divergence patterns associated with a straight jet streak (e.g. Carlson 1991, p.366).

Both the jet streak and the ECC moved northeastwards, with the ECC moving into the cold air cumulus
By 1100 UTC 4 April the ECC had reached the Victorian coast and was approaching the rear edge of the frontal cloudband which was nearing Melbourne (38°S 145°E). Figure 6 shows an enhanced image sequence at higher time resolution than shown in Fig. 3 of the clouds as the ECC overtakes the frontal cloudband. At 1100 UTC 4 April the ECC had an open centre; the frontal cloud had a band of high cloud near Melbourne, and a layer of lower cloud to its rear with a narrow cloud-free area between it and the ECC. Between 1100 and 1700 UTC the low cloud to the rear of the frontal band appeared to wave, or bulge, towards the ECC, which had expanded to form a continuous cloud mass, but still with a clear zone between it and the frontal cloud. This ‘bulging’ lower cloud has been referred to as a ‘cloud head’ (Young 1995), and its appearance on the poleward edge of the frontal cloudband has been used as an indicator of potential or incipient cyclogenesis. During this period the frontal cloudband tilted northeastwards, and apparent cyclonic rotation can be seen in animated imagery, with the clouds at the western edge of the frontal cloudband moving southwestwards, and the ECC moving to the east-northeast. It was also in this final 12 hours that the upper trough amplified to almost develop a cut-off low and became negatively tilted as the jet streak moved to its apex, the surface trough amplified, and a closed low developed just east of Victoria.

McGinnigle et al. (1988) and McGinnigle (1990) discuss several ‘instant occlusions’ in the north Atlantic, some of which did develop and some not, and suggest that the ECC/’cva maximum’ must approach the downstream cloudband by a minimum distance in order for complete merging of cloud features to take place, but it may induce a frontal wave while its cloud signature still remains visually separate. It is this latter model which most resembles the case under discussion here. Several of the cyclogenesis classifications of Evans et al. (1994), and Young (1995) have similar features to this case; it is difficult to unambiguously choose a single class, although Young’s ‘induced wave cyclogenesis’ is very close. It is perhaps reasonable to conclude that the range of possible outcomes of satellite imagery associated with cyclogenesis is large, and also that regional differences may also make the application of conceptual models developed in one part of the world problematic when applied to another.

There appears to be little or no consistent surface feature associated with the ECC. Cyclonic curvature of the isobars can be seen at 02/2300, 03/1100, and 04/2300, but not at other times. Only at 03/1100 was a bogus observation generated in the location of the ECC by the NMOC analysts, and only at this time was a surface trough present in the analyses prior to the overtaking of the downstream trough by the ECC. Sinclair and Cong (1992) resolved a surface trough and cyclonic vorticity
Fig. 3  Six-hourly enhanced GMS-4 infrared satellite images from 0500 UTC 3 April 1995 to 2300 UTC 4 April 1995. The position of the ECC is indicated by arrows.
Fig. 4 Twelve-hourly MSLP assimilated analyses over a sub-region of the full analysis domain. Contour interval 4 hPa. The dashed contours show the 900 hPa equivalent potential temperature ($\theta_e$) at 4 K intervals from 296 to 316K. The position of the ECC is indicated by the asterisk.

centre at the early stages of development in their composite study; the lack of a surface signature in these analyses will be further discussed later in this paper.

Diagnostic description

The structure of the enhanced cumulus cluster
In order to best identify the levels at which the signatures of the ECC are strongest in the analyses, a series of cross-sections normal to the 300 hPa flow (shown by the solid lines in Fig. 5) and centred on the ECC were constructed, and Figs 7-10 show these at 12-hour intervals from 1100 UTC 3 April to 2300 UTC 4 April 1995. These sections show temperature, IPV, relative vorticity and isotachs.
Fig. 5 Twelve-hourly 300 hPa assimilated geopotential height/isotach analyses over a sub-region of the full analysis domain. Contour interval for geopotential (full contours) 60 gpm, for isotachs (dashed contours) 10 m s\(^{-1}\). Isotachs are shaded between 30 and 40 m s\(^{-1}\), and between 50 and 60 m s\(^{-1}\). The position of the ECC is indicated by the asterisk, and the lines mark the locations of the cross-sections shown in Figs 7-10.

Common features throughout the sequence are:
(a) a cyclonic relative vorticity maximum at 300 hPa almost exactly above the location of the ECC, and on the cyclonic side of a jet streak. (Note that a higher, stronger jet streak is also present at the northwest end of the sections in Figs 7 to 9. This is the subtropical jet.)
(b) a frontal zone between 900 and 600 hPa northwest (left of centre on the cross-section) of the ECC at 1100 and 2300 UTC 3 April. This feature is not as marked in the last two sections, but a region of enhanced thermal gradient is still present.
(c) a depressed dynamic tropopause, as shown by the IPV=1 contour, near the location of the ECC throughout
this two-day period. Particularly early in the period there is also a secondary maximum of cyclonic IPV at around 700 hPa.

These cross-sections show the close association of the ECC with an upper-tropospheric cyclonic vorticity maximum, in this case at 300 hPa, and located on the cyclonic shear side of a southwesterly jet streak. These features are consistent with previous studies, although 300 hPa is a little higher in the atmosphere than many northern hemisphere studies have identified. It is not clear whether these studies have used 500 hPa as their level of choice because the signal is maximised there, or because it is the level used in Sutcliffe’s (1947) development theory. (It should be noted that with the tropopause sloping downwards with increasing latitudes, it might be expected that the appropriate ‘upper troposphere’ level would be lower in the north Atlantic, where many of these studies have been based, than immediately south of Australia.)

Thus we find the features which we would expect to find associated with a ‘cva maximum’: upper-tropospheric cyclonic vorticity advection, a mid-tropospheric baroclinic zone, and a depressed dynamic tropopause (also known as an IPV anomaly, or as a tropopause undulation). The analysis scheme has qualitatively captured these features.

An alternative view of the evolving structure of the environment of the ECC is shown in Fig. 11, where a series of skew-T/log-p diagrams are shown at the location of the ECC. The dramatic feature of these diagrams is the evolution of the marked inversion between 850 hPa and 600 hPa at 2300 UTC 2 April, which is gradually eroded over the two-day period to 2300 UTC 4 April. Note that there is only little change of temperature above the inversion level, with the 700 hPa temperature increasing by only 3 K, while that at 900 hPa increases by 16 K over the two-day period.

In order to relate the features identified in the cross-
Fig. 7  Cross-sections at 1100 UTC 3 April 1995 along the line shown in Fig. 5. Upper panel shows temperature (heavy lines, contour interval 5K) with overlaid IPV, contour interval 1 PVU, alternate contour bands shaded. The lower panel shows contours of relative vorticity, contour interval 30x10^{-6} sec^{-1}, negative (cyclonic) contours dashed, overlaid with isotachs at 10 m s^{-1} intervals from 30 m s^{-1}, with alternate contour bands shaded. The location of the ECC is shown by the ‘X’.

Fig. 9  Cross-sections at 1100 UTC 4 April 1995 along the line shown in Fig. 5. Upper panel shows temperature (heavy lines, contour interval 5K) with overlaid IPV, contour interval 1 PVU, alternate contour bands shaded. The lower panel shows contours of relative vorticity, contour interval 30x10^{-6} sec^{-1}, negative (cyclonic) contours dashed, overlaid with isotachs at 10 m s^{-1} intervals from 30 m s^{-1}, with alternate contour bands shaded. The location of the ECC is shown by the ‘X’.

Fig. 8  Cross-sections at 2300 UTC 3 April 1995 along the line shown in Fig. 5. Upper panel shows temperature (heavy lines, contour interval 5K) with overlaid IPV, contour interval 1 PVU, alternate contour bands shaded. The lower panel shows contours of relative vorticity, contour interval 30x10^{-6} sec^{-1}, negative (cyclonic) contours dashed, overlaid with isotachs at 10 m s^{-1} intervals from 30 m s^{-1}, with alternate contour bands shaded. The location of the ECC is shown by the ‘X’.

Fig. 10  Cross-sections at 2300 UTC 4 April 1995 along the line shown in Fig. 5. Upper panel shows temperature (heavy lines, contour interval 5K) with overlaid IPV, contour interval 1 PVU, alternate contour bands shaded. The lower panel shows contours of relative vorticity, contour interval 30x10^{-6} sec^{-1}, negative (cyclonic) contours dashed, overlaid with isotachs at 10 m s^{-1} intervals from 30 m s^{-1}, with alternate contour bands shaded. The location of the ECC is shown by the ‘X’.
Fig. 11  Skew-T/log-p thermodynamic diagrams, showing vertical temperature and dew-point profiles from the analyses at the locations of the ECC at 12-hour intervals from 2300 UTC 2 April to 2300 UTC 4 April 1995. The asterisk marks the surface temperature.

sections to plan view synoptic charts, the 300 hPa relative vorticity overlaid with relative vorticity advection, and the 700 hPa temperature overlaid with the 700-950 hPa wet-bulb potential temperature difference (as an indicator of lower tropospheric convective stability) are shown in Figs 12 and 13 for the same times as the panels in Figs 4 and 5. From 1100 UTC 3 April there is a clear centre of maximum cyclonic relative vorticity at 300 hPa immediately upstream of the ECC, and a maximum of cyclonic vorticity advection immediately downstream of the ECC, and the absolute magnitudes of both these centres increase with time. At the early times this centre of cyclonic vorticity is west of, and separate from, the axis of the trough. If the panel for 1100 UTC 3 April is taken as a basis for discussion, several centres of cyclonic vorticity can be identified and related to the
Fig. 12 Twelve-hourly 300 hPa relative vorticity analyses over a sub-region of the full analysis domain. Contour interval 30 s$^{-1}$, units scaled by $10^6$. Negative contours (cyclonic values) are dashed, the position of the ECC is shown by the asterisk, and the letters refer to features described in the text. Shaded regions indicate cyclonic vorticity advection, with the shading commencing at $-10 \times 10^{-10}$ s$^{-2}$, with a contour interval of $30 \times 10^{-10}$ s$^{-2}$. Positive (anticyclonic) values of relative vorticity advection and the zero contour have been suppressed for clarity.

Trough/jet patterns at the same level (Fig. 5). Centres A and D are associated with shear on the cyclonic side of the subtropical jetstream. Centre B is associated with the cyclonic shear side of the northwesterly jet on the downstream side of the upper trough, the axis of maximum curvature of the trough extends northwestwards from U to V, and centre C is associated with the cyclonic shear on the poleward side of the southwesterly jet. As C moves northeastwards it overtakes the axis of the trough and becomes the major vorticity feature on the chart as the trough develops a negative tilt (see Fig. 5) and forms a closed low.

The ECC is seen to lie just poleward of the 700 hPa
Fig. 13 Twelve-hourly 700 hPa temperature analyses (dark lines, contour interval 2 K), and 700-950 hPa wet-bulb potential temperature difference (dashed contours, negative areas shaded, contour interval 2K) over a sub-region of the full analysis domain. The position of the ECC is marked by the asterisk.

Temperature gradient (Fig. 13), which was seen as a mid-tropospheric front in the cross-sections, and marks the deep tropospheric baroclinicity associated with the polar jet streaks identified in Fig. 5. The ECC is also associated with a short wave thermal trough at this level. The 700-950 hPa wet-bulb potential temperature difference shows the ECC moving from a (weakly) statically stable environment at 2300 UTC 2 April to a progressively less stable environment. The transformation of the ECC from a stratiform to a cumuliform appearance coincides with its movement from a convectively stable lower troposphere to a convectively neutral or even unstable environment around 1100 UTC 3 April.
Twelve-hourly analyses of IPV on the 330 K isentropic surface over a sub-region of the full analysis domain. Contour interval 1 PVU (1 PVU = 10^{-6} m^2 s^{-1} K^{-1} kg^{-1}). Dashed lines show the pressure (hPa) of the surface (contour interval 50 hPa), and the vectors show the wind analysis on that surface. The vector in the southwest corner of each chart is scaled to 40 m s^{-1}, and the position of the ECC is shown by the asterisk. Note that the region displayed is smaller than that in the other contour analyses, and also varies geographically in each panel.

An IPV description of the ECC environment and the instant occlusion
It was shown in the cross-sections of Figs 7 to 10 that a distinct tropopause undulation developed with the ECC, and it is of interest to apply ‘IPV thinking’ (Hoskins et al. 1985) concepts to the current case. The level chosen should be near the tropopause (it has been proposed that the height of the dynamic tropopause is the most appropriate field), as once a level is above the tropopause, the increased static stability reduces the effective forcing of IPV advection at these levels. For this case the IPV patterns on the 330 K isentropic surface are shown (Fig. 14). This level was chosen because it is the lowest level
Fig. 15  The magnitude of the forcing term in the quasi-geostrophic height tendency equation at 300 hPa at 12-hour intervals from 2300 UTC 2 April to 2300 UTC 4 April 1995. Solid contours (positive values, alternate contour bands shaded) indicate the forcing of height falls. The position of the ECC is shown by the asterisk, and the zero contour has been suppressed to reduce clutter.

(in 5 K intervals) which shows a closed centre of IPV which is very closely aligned with the ECC (below this level an open IPV trough is found below the centre marked by the asterisk). Until the final panel, the IPV centre is immediately upstream of the ECC, and as the wind flow on the 330 K surface flows through the IPV centre, there will be advection of IPV immediately downstream of the IPV centre – a situation that qualitatively suggests forcing of height falls or cyclonic development in this area of IPV advection.

This can be made a little more quantitative using quasi-geostrophic height tendency equation arguments. Following Bluestein (1992), the pseudo-potential vorticity form of the quasi-geostrophic height tendency equation is
Fig. 16  Vertical profiles at the position of the ECC of the magnitude of the forcing term of the quasi-geostrophic height tendency equation (solid), and of the Eulerian temperature advection on pressure surfaces (dashed line, units 10⁻¹ K day⁻¹).

\[
\{ \nabla^2 + \frac{f_0^2}{\sigma} \frac{\partial^2}{\partial p^2} \} \chi = f_0 \left[ \nabla \cdot \nabla \chi \right] \quad \ldots 1
\]

where the pseudo potential vorticity \( q \) is expressed as

\[
q = \frac{1}{f_0} \nabla^2 \chi + f + \frac{\partial}{\partial p} \left[ \frac{f_0}{\sigma} \frac{\partial \chi}{\partial p} \right] \quad \ldots 2
\]

and \( \chi \) is the geopotential tendency, \( \sigma \) is the static stability, \( \Phi \) is the geopotential, \( f \) is the Coriolis parameter and the subscripts \( \circ \) indicate a mean value, \( g \) indicates a geostrophic wind, and \( p \) indicates differentiation on a constant pressure surface.

The attraction of the pseudo potential vorticity is that its variation on a pressure surface is approximately the same as the variation of IPV on an isentropic surface.
Figure 15 shows the magnitude of the forcing term in Eqn 1 (the rhs) at 300 hPa at the same 12-hourly intervals as in the previous diagram. Comparing Figs 14 and 15 shows that the regions of cyclonic IPV advection on the 330 K surface, indicated by the wind vectors directed towards numerically lower values of IPV, are very closely correlated with the quasi-geostrophic forcing of height falls, and that in the 24 hours to 1100 UTC 4 April the ECC is associated with an area where geopotential heights will be tending to fall due to differential IPV advection.

Comparing the surface charts in Fig. 4 and these IPV analyses, it can be seen that the upper cut-off low formed as the IPV centre marked by the ECC overtook the upper trough, and before the surface low formed. Further, the surface low developed as the upper IPV anomaly was advected over the low-level baroclinic zone (defined by the 900 hPa $\theta_e$ gradient) associated with the downstream trough (Fig. 4) and into a region of decreasing static stability (Fig. 13).

Figure 16 shows the vertical profile of the forcing term in Eqn 1 and of the Eulerian temperature advection at the location of the ECC, with the vertical coordinate the same as that for the skew-$T$/log-$p$ diagrams of Fig. 11. The main feature shown is a steadily increasing upper-level forcing of height falls with time, with the level of maximum forcing around 300 hPa. In the latter three panels there is cold advection (in the Eulerian framework) in the lower troposphere, and warm advection in the upper troposphere, with the layer of warm advection increasing with time. Hirschberg and Fritsch (1991a,b) have shown using hydrostatic arguments that height falls in the lower troposphere are associated with upper-tropospheric warm advection. The downward extent of the forcing of height falls roughly agrees with the height of the inversion shown in Fig. 11, and it may be argued that the higher static stability associated with the inversion limits the depth of penetration of the upper forcing. Not until 2300 UTC 4 April does the forcing of height falls extend to near the surface, consistent with the diagnosed reduction in static stability in the lower troposphere at that time, allowing a greater depth of penetration of the upper forcing. The lack of a surface feature observed in the analyses before 2300 UTC 4 April is supported by these arguments.

This is an excellent example of the 'IPV' thinking conceptual model of cyclogenesis proposed by Hoskins et al. (1985) in their Fig. 21, where upper and lower-tropospheric IPV anomalies interact in a region of decreasing static stability (increasing depth of penetration) to develop a deep tropospheric cyclone.

**Summary**

In this section it has been shown that two different conceptual models of cyclogenesis – the satellite imagery-based 'instant occlusion' model of Zillman and Price (1972), (later refined by the authors cited above), and the IPV thinking concepts reviewed by Hoskins et al. (1985), which, by their nature, need some form of gridded NWP data for their use, can each be successfully applied as a conceptual model in this case of cyclogenesis.

An important result is the ability of the objective analyses from the operational LAPs data assimilation system to qualitatively resolve features which can be associated with the cloud feature identified as a 'cva maximum'. Whether these features in the analysis are quantitatively correct is not demonstrated as yet, and this is difficult to do directly, as all available data have been used in the generation of the analyses. This issue will be discussed in the next section.

**Forecast model behaviour**

While a feature may be subjectively present in the analysed fields, it will not be retained through the numerical forecast if the fields are not in dynamic balance, or if the scale of the numerical model is inadequate to resolve the features or their evolution. Thus, even if the initial state of a forecast model is 'correct', the subsequent forecast may be in error for a number of reasons. However, if a forecast represents the observed evolution of the atmosphere well, then it is likely that the analyses on which the forecasts are based are substantially correct.

The major issue to be explored here is the ability of the forecast model to predict the cyclogenesis over eastern Australia at lead times of 36, 24 and 12 hours, and at resolutions of 0.75° and 0.25° grid spacing. The higher resolution forecasts are nested inside the corresponding coarser resolution forecasts. In this way, aspects of temporal continuity in the analyses, the need for spin-up time in the model, and whether improved horizontal resolution in the forecast model will lead to significantly improved forecasts can be addressed. A secondary issue is to see if the forecast model, at either 0.75° or 0.25° grid spacing, will generate a cyclonic surface signature in association with the ECC while it is traversing the data-sparse areas south of Australia, since no such feature was resolved in the analyses during this period.

Figure 17 shows 24-hour forecasts at 0.75° and 0.25° resolution from 1100 UTC 3 April 1995, together with the verifying analysis. Both forecasts accurately predict the position of the front over Tasmania, but do not generate any cyclonic surface feature associated with the ECC up to 1100 UTC 4 April. This suggests that, at the very least, any surface signature of the ECC over the ocean in this case was at very small horizontal scale, and makes it more likely that the cloud feature was associated with upper-level forcing alone, as was suggested by the dynamic arguments in the previous section.
Figure 17 Twenty-four hour MSLP forecasts valid 1100 UTC 4 April from the 0.75° (top) and 0.25° (middle) forecasts, with the verifying analysis on the bottom panel. Contour interval 2 hPa.

Figure 18 shows a 36-hour 0.75°, and 12 and 24-hour 0.75° and 0.25° resolution forecasts valid at 2300 UTC 4 April 1995, with the verifying analysis. All forecasts have simulated the cyclogenesis just east of Victoria very well. Both higher resolution forecasts have predicted slightly lower surface pressures than their lower resolution counterparts, but not by a great amount, and there is some suggestion that the 12-hour 0.75° forecast has not completely ‘spun-up’, but overall the forecasts are very good. While this verification is slightly incestuous, as the same forecast model is used in the assimilation system which produces the analyses used in the diagnosis of the previous section and as the initial state for the forecasts, these results indicate that the structure of the cva maximum resolved by the analyses is quantitatively correct.

Conclusions

This study has demonstrated that the assimilated analyses from the new LAPS data assimilation system can resolve the environment of a mesoscale cloud system over the ocean south of Australia. The features of the synoptic environment are: (a) a region of marked cyclonic vorticity, cyclonic vorticity advection and cyclonic IPV advection in the upper troposphere on the poleward side of a meridionally oriented jet streak; (b) a mid-tropospheric baroclinic zone just equatorward of the enhanced cumulus cloud signature; and (c) the cloud area becomes markedly cumuliform as it moves into a region of decreasing static stability in the lower troposphere. The ECC was found to be more closely aligned with the forcing of height falls by advection of IPV in the upper troposphere than maxima in the cyclonic vorticity, the cyclonic IPV advection, or the cyclonic relative vorticity advection individually. As these individual fields are proxies for more complete forcing of vertical motion or height falls, this is not surprising, and it is encouraging that the diagnosed dynamics from these assimilated analyses represent these dynamics at the location of the ECC so well.

While these features closely agree with other published studies of ‘cva maxima’, there are some small but significant differences (although most of the studies quoted have studied the environment of Zillman and Price’s ‘comma cloud development’, when the cloud cluster has evolved to a distinct comma shape, and have also generally studied systems at higher latitudes than this one). The first difference is that the largest signal was found rather higher in the atmosphere than reported in many of these studies, and second that no surface cycloonic signature was associated with the ECC until very late in its evolution. Variations in static stability in the atmospheric column below the upper-tropospheric
Fig. 18  MSLP forecasts valid 2300 UTC 4 April 1995: (a) verifying analysis, (b) 36-hour 0.75° forecast, (c) 24-hour 0.75° forecast, (d) 24-hour 0.25° forecast, (e) 12-hour 0.75° forecast, (f) 12-hour 0.25° forecast. Contour interval 2 hPa. Where possible the same geographic area has been shown for each panel to facilitate comparison, but different forecast areas were chosen for the 0.25° forecasts to keep the ECC well within the fine-mesh area in each case.
forcing affect the downward extent of this forcing. Use of conceptual models of a ‘cwa maximum’ in meteorological analysis should take these variations into account.

It has also been shown that the ‘instant occlusion’ or ‘induced cyclogenesis’ conceptual models of cyclogenesis, which are largely satellite imagery based, and the IPV thinking conceptual model of cyclogenesis, based on the gridded fields from the NWP models, can each be successfully applied to this case, and are complementary. IPV thinking can aid in the understanding of why the forecast model is predicting cyclogenesis, but these data are not independent from the model. However, the satellite imagery is. Thus, once a feature such as the ECC in this study is identified in the satellite imagery early in the validation period of a NWP model forecast, then if a forecaster can identify in the forecast model the IPV and other features shown in this paper to be associated with the ECC at its location, then by following the subsequent evolution of these features, greater confidence can be placed in the later predictions of the forecast model.

Acknowledgments

The comments of Noel Davidson and Ian Bell on an early version of this paper aided the presentation. David Pike and the BoM drafting section assisted with some of the diagrams. Finally the analyses and forecasts used in the study could not have been generated without the efforts of Kamal Puri and the other members of the Regional Meteorology Group in BMRC to the development of LAPS.

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