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A new, objective, database of East Coast Lows

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East Coast Lows (ECL), strong low pressure systems off the east coast of Australia, can cause severe rain and flooding in this highly-populated region, in addition to strong winds, heavy seas and coastal erosion. While some databases of such events have been previously compiled, this paper discusses a new database developed using an objective low tracking scheme and MSLP reanalysis data between 1950 and 2008, which can be maintained and updated with relative ease on an ongoing basis. The database is verified in comparison to previous subjective ECL analyses, with a particular focus on detection of ECLs associated with significant wind and rain events, and used to develop a climatology of ECLs between 1950 and 2008.

Introduction

The Eastern Seaboard of Australia (ESB) is frequently impacted by strong low pressure systems, which are commonly referred to as East Coast Lows (ECLs). These systems have been described by Speer et al. (2009) as low pressure systems with closed cyclonic circulation at the surface which form or intensify in a maritime environment in the vicinity of the Australian east coast. In addition to the surface low, ECLs are often associated with a disturbance in the upper levels, and in some cases may be better defined above the surface (Dowdy et al. 2012a). ECLs can also intensify very rapidly, causing additional forecasting challenges; such events are colloquially classed as 'bombs' (e.g. Speer et al. 2009).

The precise thresholds of intensity, location and impacts that distinguish an East Coast Low from other low-pressure systems vary substantially between studies. For example Qi et al. (2006) and Hopkins and Holland (1997) both considered only events associated with threats to life or property due to associated rain, wind or sea state impacts, with similarly impact-based criteria used in the database of Callaghan (2004). These studies thus identified fewer events than in the more comprehensive database of Speer et al. (2009), which distinguished ECLs by their meteorological parameters prior to investigation of impacts.

Regardless of the definition used in individual studies, ECLs have been widely identified as a major cause of heavy rain, wind and wave impacts in eastern Australia. Hopkins and Holland (1997), using an impacts-based definition, found ECLs were responsible for seven per cent of all major Australian disasters between 1967 and 1992. The pressure fields associated with severe rain events on the New South Wales central coast resembled ECLs in 78 per cent of winter cases (Abbs et al. 2006), while 60 per cent of the largest inflow events into Sydney dams were associated with coastal lows (Pepler and Rakich 2010). More recently, a comprehensive database of ECLs identified from manual inspection of pressure analyses (Speer et al. 2009) was used to attribute 23 per cent of annual ESB rainfall and 40 per cent of widespread heavy rain events to ECLs (Pepler et al. 2014).

Due to their potential to cause severe coastal flooding, coastal erosion and wind damage, as well as their implications for water supply, it is valuable to develop a more systematic, objective and consistent database of ECL events. Such a database can be used to investigate the spatial and temporal variability of ECLs, to track their formation and movement, as well as to match ECLs with their associated impacts. An additional advantage of an objective approach is that it more readily allows sensitivity analyses, updates to data and supports reproducibility. The multi-faceted use of the database precludes defining events solely on the basis of impacts, as the impacts are spatially varying and may not correlate with ECL intensity.

For this purpose ECLs are defined by meteorological parameters as per Speer et al. (2009) rather than by associated impacts, to allow relevant users of the database to define the impacts of interest as well as offering the potential to identify the distinguishing features of significant or non-consequential ECLs. This allows groups including emergency management authorities and natural resource managers to better understand the distribution of ECLs and their impacts, while a consistent database and definitions can improve consistency among the research community.

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The Maritime Low Database

The New South Wales Maritime Low Database (MLD) is the most comprehensive database of East Coast Lows that currently exists, and is described in Speer et al. (2009). This database is comprehensive between 1970 and 2006, but due to large resource requirements for maintenance has not been kept up to date or extended back in time. It provides the location and central pressure of all identifiable closed low pressure systems in the region between the Australian east coast and 160°E and between 25°S and 40°S. These low pressure systems are then classified by the associated impacts and the associated synoptic environment.

This database suffers from relying on manual detection of lows and the use of hand drawn (manual) pressure charts through time. The practical realities of manual analysis in a forecasting office means that different individuals are responsible for identifying closed low pressure systems in a mean sea level pressure (MSLP) analysis over time, while several individuals were also involved in compiling the ECL database from the MSLP charts. The primary MSLP charts used in constructing this database were the daily 00Z (1000 EST) manual synoptic charts produced by the Australian National Meteorological and Oceanographic Centre, with satellite imagery also used in some cases to support interpretation. The database also includes some impacts information, with Speer et al. (2009) designating ECLs as significant based on rainfall exceeding 25 mm at several east coast stations; wind and ocean data were intended for a later extension of the database.

The advantage of this approach is that it uses human pattern recognition to identify and classify ECL events based on the synoptic situation. The disadvantage is that variations between both the operators of the database and the drawing of the MSLP charts may result in inconsistent identification of lows, particularly borderline or weak events and those near the boundary of the ECL region. Increasing availability of satellite data over time and improving understanding of ECLs may also influence their detection in the manual MSLP charts. Of course, the approach also lacks reproducibility, consistency, is very expensive in terms of human resources, and human analysis is not able to capture the full breadth of observations which are now available for numerical assimilation systems (e.g. Kalnay et al. 1996).

The alternative: an 'objective' database

One alternative to the MLD is to use gridded MSLP reanalysis data in combination with software that identifies and tracks low pressure systems. Such 'objective' techniques have been extensively used for tropical cyclones (e.g. Walsh 1997, Sinclair 1997, Dowdy et al. 2012b) as well as for extratropical cyclones across the globe (e.g. Hirsch et al. 2000, Neu et al. 2013), and have previously been applied to southern hemisphere cyclones and anticyclones (Jones and Simmonds 1993, 1994).

The foremost advantage of such schemes is the ease of maintenance and update of the database, and they can be easily applied to data of a variety of spatial and temporal resolution for increased detection of short-lived events. They also minimise the influence of human error and inconsistency, with the rules for inclusion or exclusion of ECL events consistently applied to each pressure field. However, there remains some element of subjectivity in choosing the criteria that distinguishes an East Coast Low from other systems, and numerical analyses will show some drift over time owing to changes in the underlying data that can be used for analysis.

In this paper we describe the use of one such low identification and tracking scheme to identify East Coast Lows between 1950 and 2008, and discuss the development of a set of criteria used to define an East Coast Low. This is developed through comparison with the subjective Maritime Low Database of Speer et al. (2009), through optimising the detection of major or significant East Coast Lows and minimising 'false alarms'. The Maritime Low Database cannot be considered 'truth'; however, as the most robust ECL database currently in existence it provides a useful point of comparison, particularly as all ECLs with major impacts are expected to be included. Results from the objective ECL database are then used to extend previous analyses of ECL trends and variability for the full 1950 to 2008 period. Particular attention will be paid to the influence of ECLs on heavy rain along the ESB, due to the high detail of rainfall data available, with the association between ECLs and strong winds also investigated for those stations with a sufficiently long record of wind gusts.

Data and methodology

The tracking scheme used in this paper is based on that described in Jones and Simmonds (1993), which is an update of that described in Murray and Simmonds (1991) and more recently applied in Dowdy et al. (2012b). This scheme can be applied to any gridded scalar data to identify both low pressure systems with closed circulation ('closed' lows) and instances of strong inflexions in the pressure field ('open' depressions). The scheme identifies low pressure systems through a search for minima in the absolute value of the local pressure gradient, as well as a maximum in the 'curvature'. This is defined by the Laplacian of the pressure field, $\nabla^2 p$, and can be related to the cyclonic geostrophic vorticity (ξ) by:

$$\xi = \frac{1}{\rho f}\nabla^2 p$$

where ρ is the air density and f is the coriolis parameter. For the purposes of this paper, individual instances of an ECL identified in a pressure grid are referred to as 'fixes', in order to distinguish references to an instantaneous low at a given time from the discussion of persistent low pressure systems. The curvature is a useful proxy for the strength of the pressure gradients and consequently the intensity of a low, and is frequently used to restrict analyses to 'intense' lows (e.g. Murray and Simmonds 1991).

The tracking scheme involves a number of adjustable parameters for both low identification and tracking, with this paper employing the current default parameters, including requiring a minimum curvature of at least 0.15 hPa (deg.lat)$^{-2}$. Lows are then linked into ECL 'tracks' based on a probability function of predicted and observed cyclone characteristics and positions. Each ECL track constitutes a single ECL event, with an ECL day identified where any ECL is identified between 00Z and 18Z on a day. As would be expected for an automated scheme, there is significant capacity to fine tune parameters for detecting and tracking low pressure systems. These are expected to have relatively little impact on the study of major ECLs, owing to the relative intensity of these systems, but may influence the detection of borderline events or the identification of ECL tracks.

This tracking scheme was applied to the NCEP reanalysis grids of MSLP between 1950 and 2008 (Kalnay et al. 1996) to create an 'objective' ECL database. The reanalysis data has a grid resolution of 2.5 degrees at six-hourly time intervals, and was selected due to its relatively long length of record and widespread prior use. This enables decadal scale variability to be assessed along with long-term changes in the intensity, frequency and distribution of ECLs along the ESB. However, the generalised nature of the tracking scheme used makes it possible for improved ECL databases, based on future reanalysis data, to be incorporated in the future.

The Australian Water Availability Project (AWAP; Jones et al. 2009) is the main gridded meteorological dataset for Australia, with rainfall data available since 1900 at a 0.05º resolution. The grids are based on the daily rainfall data from more than 6000 Australian rainfall stations, with particularly high station densities along the ESB. For this study, an ECL is associated with the rain recorded on the following day, reflecting the 24 hours to 9.00 am local time. This is equivalent to 2200 UTC during daylight savings time, and 2300 UTC otherwise. Daily ESB rainfall is the average of the AWAP grids across the domain in Fig. 1, while ESB rainfall events were defined from the AWAP analyses using the 'cluster rain event' method described in Dowdy et al. (2013).

The impacts of ECLs are not limited to rainfall and so daily maximum wind gust observations are also included for 17 coastal wind stations. These cover the ESB from East Sale in Victoria to Maryborough in southeast Queensland, with seven stations maintaining records since the 1960s. A strong wind day is identified where the maximum wind gust at any one station exceeds 90 km/h (48.6 kts), consistent with the Bureau of Meteorology severe thunderstorm criterion.

For the purposes of this comparison the subjective MLD is used as the base for comparison, with 'hits' occurring where both the subjective and objective databases concur on a low while 'misses' refer to ECL days in the MLD which are not identified using the objective scheme. Note, of course, that neither the subjective or objective database can be considered as 'truth', with the subjective scheme expected to underestimate the true frequency of ECLs; however, these conventions are used to simplify the comparison process, and it is expected that the majority of ECLs with substantial impacts would be identified by the manual processes involved.

The objective and subjective ECL databases are thus compared in terms of the 'hit rate' (HR), the proportion of subjective ECLs detected by both the objective and subjective databases, and the 'false alarm rate' (FAR), the proportion of ECLs in the objective database that were not identified in the subjective database, with ECLs not present in the subjective database labelled 'false alarms'. The critical success index (CSI) was also used as a combination of these metrics, which rewards instances where the databases agree (hits) while penalising cases where the databases disagree:

$$CSI = \frac{Hits}{Hits + Misses + FalseAlarms}$$

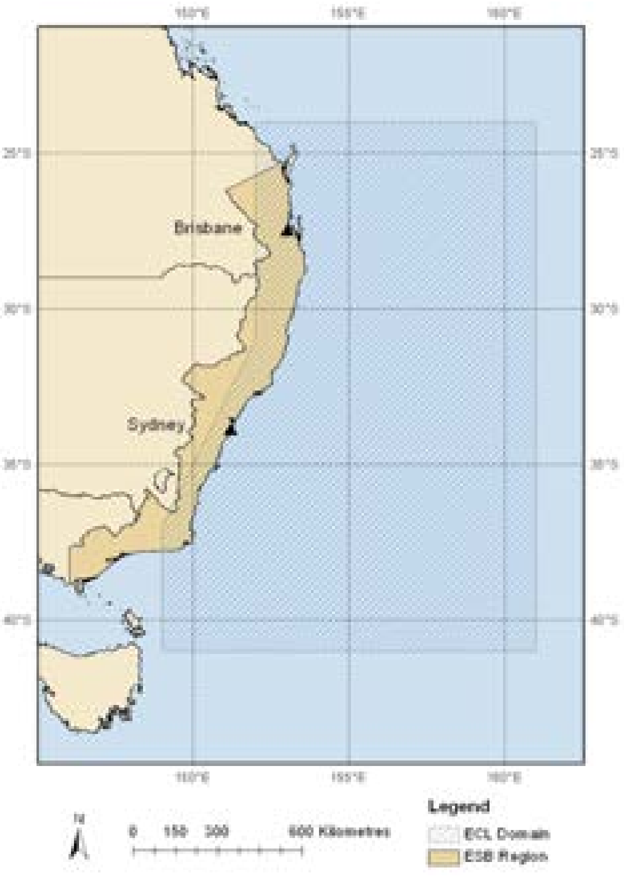
Misses and false alarms were also manually investigated through random sampling of the database, to identify any consistent patterns in 'incorrect' identification. Note that, while the MLD is assumed to have detected all East Coast Low events, this may not be the case; however, due to the subjective nature of the database it is unlikely that large events with major impacts will be absent.

Verification

The tracking scheme used in this study was initially designed for large-scale analyses, with the output including track details for all low pressure systems at any location across the globe. A low is identified from a maximum in the curvature field, and hence a maximum of cyclonic geostrophic vorticity, with a low defined as closed when a corresponding pressure minimum (a region of closed isobars) can be identified; more than 96 per cent of lows in the ECL region are closed. In order to distinguish East Coast Lows from other low-pressure systems such as tropical cyclones and inland lows, as well as from any errors in the pressure grids and weak lows embedded in troughs and frontal systems, it was necessary to apply some level of filtering to the output.

The database was first-order filtered on the basis of a common definition so as to include only those tracks that occur off the east coast of Australia for at least one instance (referred to as a fix). The database was first-order filtered to include only those tracks that occur off the east coast of Australia. Specifically, at least one instance of the ECL track (referred to as a fix) must fall in the domain indicated in Fig. 1. This corresponds to the region used in Speer et al. (2009), but is 1° larger in all directions to accommodate the 2.5° spatial resolution of the NCEP/NCAR grids. Each low identified by the scheme also required at least one fix to have closed surface circulation (a 'closed' low), to minimise the inclusion of strong troughs or other inflexions. It is important to note that the resolution of the MSLP reanalysis data (2.5 degrees) may affect whether a low is considered closed or open, while some 'open' lows could potentially be

Fig. 1. The Eastern Seaboard of Australia and the domain used to identify East Coast Lows.



associated with closed circulation at higher levels. As open fixes are relatively few this is deemed a minor issue, but may be investigated through application of the tracking scheme to other reanalysis data at a later stage.

The resulting database was then used to identify a set of 'ECL days' to best correspond with the daily 00Z ECL data in the MLD. An ECL day was defined when any ECL was identified between 00Z and 18Z (1000–0400 EST), which best approximates daily rainfall measurements at 0900 EST while avoiding double-counting of events.

Duration thresholds

The initial version of the database resulted in an average of 83 ECL events per year, compared to an average of 22.5 ECL events in the MLD. Of these events, 31 per cent consisted of only one fix, while only 43 per cent persisted for at least four consecutive analyses (Fig. 2). As per Murray and Simmonds (1991), the curvature of the low can be used as a method of distinguishing strong low pressure systems from those with relatively weak pressure gradients. While 98 per cent of events that persisted for at least four fixes had maximum curvatures above 0.2 hPa (deg.lat)$^{-2}$ only 31 per cent of single fixes reached this threshold, suggesting such events are typically weak.

It is expected that a large proportion of these single-fix events are related to anomalous inflexions in the reanalysis pressure fields, rather than a 'true' low pressure system. It has been common practice to require a minimum event duration in previous objective analyses of low synoptic systems; for instance, Jones and Simmonds (1993) required two consecutive fixes at a 24-hour resolution, while most tropical cyclone tracking studies referenced in Walsh et al. (2007) required the event to persist for at least one day.

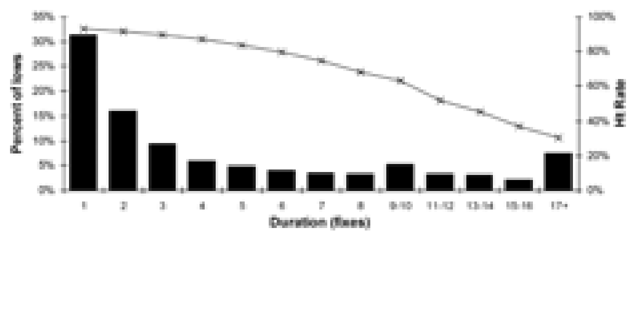
Figure 2 also displays the hit rate for increased duration thresholds, showing a small decline in hit rate for minimum durations between 1–4 fixes but a larger decline for durations greater than one day. For this study we used a minimum duration of six hours (two consecutive fixes). This decreased the false alarm rate without substantially impacting the detection of ECLs (Table 1). Only six of the 263 ECLs associated with 'significant' rain impacts by Speer et al. (2009) were entirely missed using this duration threshold; in four cases the low was borderline, with curvature at the minimum threshold of 0.15, while a fifth had a maximum curvature of 0.18.

The exception to the successful detection of events was 27 July 1990, a day with three consecutive single-fix events which the tracker did not identify as a single event. This event intensified rapidly over the day into a fully-fledged ECL with curvature of 0.58 by 12 Z, before moving outside the designated ECL domain; inclusion of this low in the MLD based on 00Z fixes alone was arbitrary. This suggests that the tracking scheme used may have some issues with tracking events that move or intensify rapidly. However, as this is the only such case within the 37 years of comparison this is unlikely to be a major issue.

In this case, the 00Z synoptic chart (Fig. 3) shows no clear area of closed isobars, with the low only indicated through a localised 'x', so this low does not satisfy the subjective criteria of the MLD. This further demonstrates the subjective nature of the MLD, with this event a key example of one included based on the observed impacts rather than the synoptic criteria.

Using the two fix duration threshold, the objective database has considerable success in identifying ECLs, with

Fig. 2. Distribution of ECLs by number of consecutive fixes (columns), in addition to the hit rate for each minimum duration threshold (line). An ECL with at least two fixes has a minimum lifetime of six hours and a maximum duration of 18 hours noting the use of six-hourly MSLP. An ECL with at least 17 fixes has a minimum lifetime of over 96 hours (four days).



92 per cent of days with 'significant' ECLs in the MLD also identified in the objective database. Additionally, 97 per cent of significant ECL days (92 per cent of all ECL days) are correctly identified within ±1 day. Manual inspection of the synoptic charts for 'missed' events found that the low in all cases was either very weak or outside the designated ESB region, with at least one 'missed' event a result of miskeying of dates in the MLD. Such 'misses' are therefore attributed to the subjective nature of the MLD database in identifying borderline events rather than errors in the tracking scheme per se.

While the objective database successfully identifies the ECL day, it is important to know how well the tracker identifies individual low tracks, particularly in cases where there are multiple lows in the ECL region. Almost one in five days has two distinct ECL events in the ESB region, with 56 per cent of ECL events consequently overlapping on at least one occasion. To investigate the impact of this, 50 ECL events were selected at random from the objective database to check for incorrect tracking, of which 24 overlapped with at least one other event

- Twelve events had two independent events at some distance from each other.
- Eight events had two consecutive ECL tracks which appeared to be the same system upon visual analysis of the corresponding charts, i.e. an ECL track that terminated at 00Z followed by a second track in the same region initiated at 06Z. Such events may be considered 'broken' during the tracking process.
- Two events had a double centre at some point, resulting in two slightly overlapping tracks.
- Two events had several fixes in close proximity, with the tracker showing difficulty in correctly identifying the low progress. For example, Fig. 4 shows only one low on 27 December but two distinct low centres on the previous day, with the choice of the 'correct' low movement somewhat arbitrary.

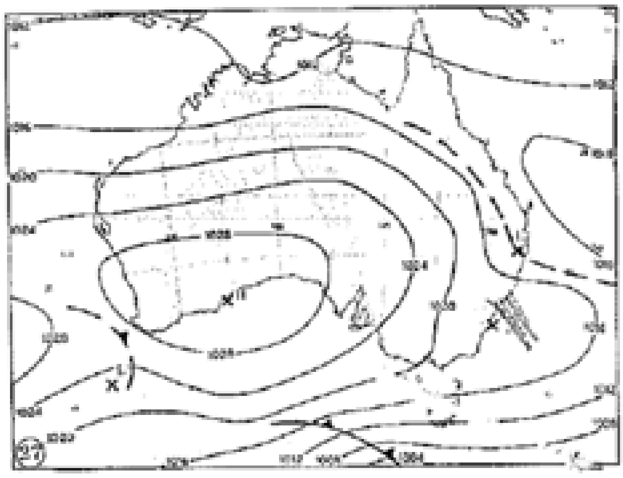
This suggests that 20 per cent of events in the objective ECL database are part of a larger event, which creates difficultly in defining the exact evolution of low centres and tracks. This may be due to development of a second centre (~4 per cent) or of less obvious cause (~16 per cent). These 'broken

Table 1. Frequency of ECL events based on various minimum duration thresholds, and comparison statistics for ECL days relative to the MLD. The MLD includes an average of 22.5 events per annum, across 35 ECL days.

Duration (hours)	*Events p.a.*	*Days p.a.*	*Hit rate*	*False alarm rate*	*Hit rate (sig*)*
All	82.7	95.3	86%	68%	93%
6+	56.7	82.7	84%	64%	92%
12+	43.5	72.4	81%	61%	90%
18+	35.6	64.8	77%	59%	87%

* Days associated with 'significant' ECLs in the MLD.

Fig. 3. Bureau synoptic chart for 00Z on 27 July 1990, with two weak lows indicated on the east coast by an x.

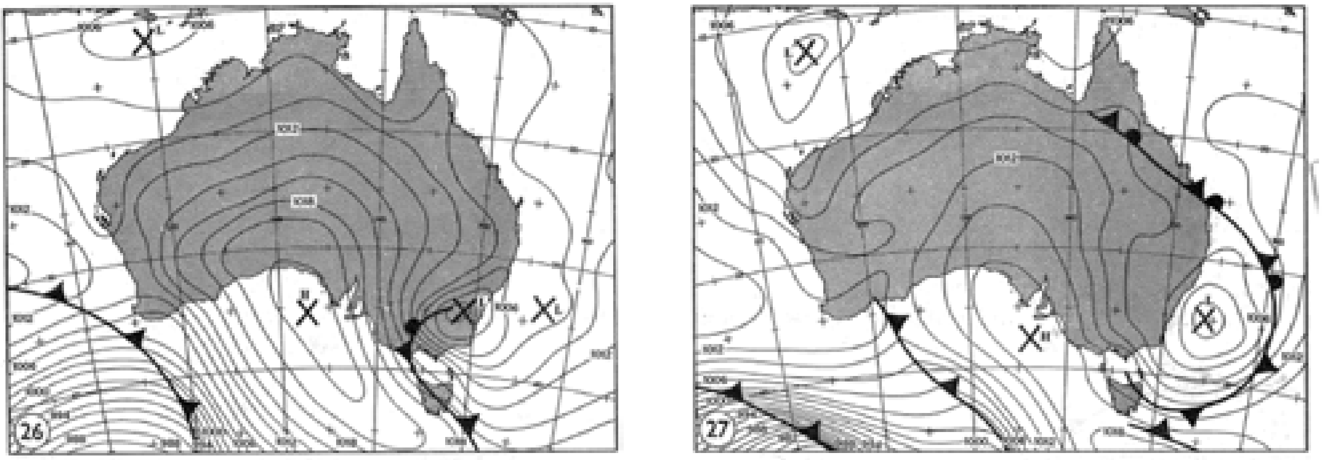


tracks' are potentially related to rapid change in movement, particularly retrograde motion (e.g. Murray and Simmonds 1991), rapid intensification, or a temporary weakening, which means that the rules for tracking suggest a low probability of continued track. A low duration threshold of six hours is therefore used to avoid losing parts of 'broken events', and means the database will overestimate the number of ECL events and underestimate the average duration. It is likely that there are other ECL days comprised of several single-fix events that have been missed. These are expected to be a minor proportion of the database, but could potentially be included by employing a high curvature threshold for single-fix events.

These issues raise the question of whether it is sensible to define ECL events on the basis of the numbers of distinct ECL systems. Many ECLs show more than one centre, and in other cases the transition from a low over land to a low over the ocean or a shift from warm cored to cold cored mean that being clear about the exact evolution of centres is not possible. While we have found that the detection of individual low centres can be made relatively objective, the issue of how low centres are joined to form tracks (or systems are determined to decay and form) is rather more complicated, and it is not clear that either the manual or NCEP reanalyses provide sufficient information to make a correct decision. Consequently, for this study rather than comparing identified ECL events, analysis will focus on ECL days, defined for the objective database as any day with at least one low pressure system in the ESB (i.e. a track at any of 00Z, 06Z, 12Z or 18Z).

Further improvements may potentially be achieved through changes to the parameters used in the low tracking scheme; this is beyond the scope of this paper. Options include the inclusion of different variables such as upper level analyses, or changing the parameters of the tracking procedure. However, at least four per cent of ECLs are instances with double centres where any tracker is expected to have difficulty correctly forming tracks; this may be of issue for users who rely on correctly

Fig. 4. Bureau synoptic chart for 00Z on 26 and 27 December 1968; these charts show a complicated low situation with multiple centres and an occluded front, with the tracking scheme identifying multiple overlapping ECL tracks.



distinguishing the source of lows.

Accounting for differences in low detection

Using the minimum duration of six hours (two fixes), there are 57 ECL events per year, which persist for an average of 46 hours and spend an average of 21 hours in the ESB region. There are on average 83 days per annum with at least one ECL identified in the ESB region, significantly higher than the 33 days per annum. in the Maritime Low Database. Thus, while the hit rate for ECLs deemed significant by Speer et al. (2009) is greater than 90 per cent, the false alarm rate is also high—64 per cent of days with ECLs in the objective database have no corresponding ECL day in the MLD (Table 1).

This, to some degree, can be attributed to three key differences in the underlying MSLP analyses that the two databases use:

- The six-hourly time step of the objective ECL database allows short-lived, rapidly intensifying, or fast-moving lows to be identified. This is investigated by considering only those lows identified at 00Z.
- The six-hourly time-step of the objective ECL database can more easily identify the start and end of an event, and thus maintain an event for additional days. This is investigated by counting an objective ECL as a hit within ±1 day.
- The objective database can identify weaker or smaller-scale lows that were not apparent on the manual synoptic analyses, particularly in earlier years. This is investigated through use of intensity thresholds.
- The manual database is likely to preclude some low pressure systems because they are not considered significant or having the characteristics of ECLs.

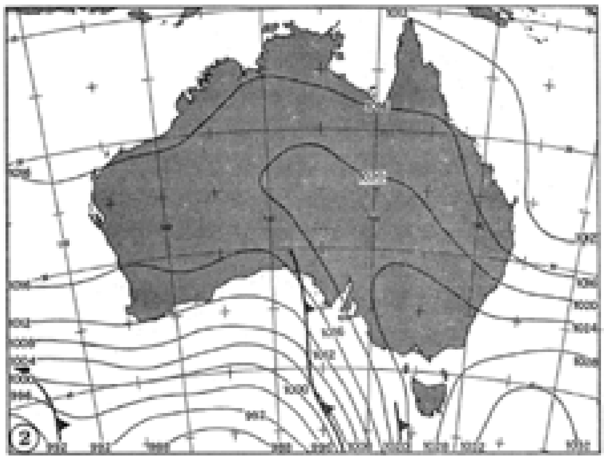
The differing frequency of MSLP analyses used in compiling the ECL databases has a clear impact on comparisons between the two databases; restricting analysis to only those lows identified at 00z decreases the false alarm rate from 64 to 46 per cent, with a similar decrease when considering MLD ECLs within ±1 day (Table 2). This suggests that a key factor of disagreement is the difference in the frequency and timing of MSLP analyses, with the six-hourly resolution used in the objective database offering a substantial advantage. The FAR is almost halved to 34 per cent when both these factors are considered. Both these outcomes demonstrate the improved detection capability of the objective ECL database rather than methodological flaws, with the CSI unfairly penalising cases where the objective ECL database correctly identifies an ECL day which is missing from the MLD.

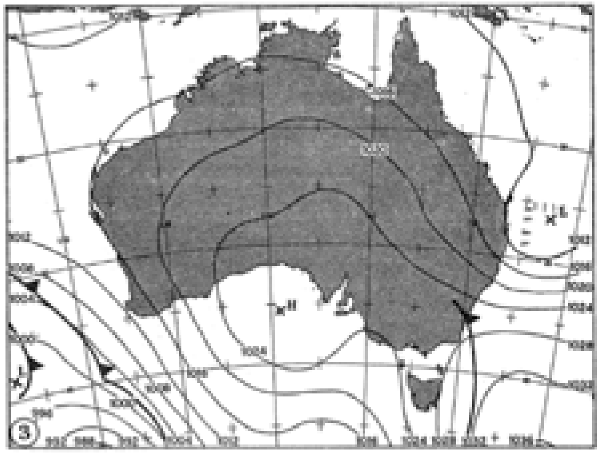
Intensity thresholds

The significantly higher frequency of ECLs identified in the objective database may increase the number of ESB severe weather events that are attributed to small, weak, short-lived or distant ECLs. One example is 1–3 June 1974, for which the objective system identifies a small ECL with low curvature and a minimum central pressure of 1009.4 hPa. This is never considered an ECL in the MLD, with the only presence of a low in the manual MSLP charts indicated by an 'x' on the 3rd (Fig. 5). This borderline low and the associated onshore flow patterns were associated with widespread coastal rain. Such events become challenging, as the presence of a weak low embedded in an easterly airstream likely enhances coastal rainfall, but might not be considered the major driver for severe weather.

The desirability of such 'weak' ECLs for research will vary depending on the goals of the study, but a restriction to 'intense' ECLs will require some intensity threshold. Minimum central pressures were found to have little value as a predictor of ECL impacts, with thresholds based on central pressure offering no improvement in any skill score. This partially reflects the low spatial resolution

Fig. 5. Manual synoptic chart for 00Z on 2 June 1974 (left) and 00Z 3 June 1974 (right). Note that the 'x' at approximately 26°S, 155°E on 3 June is the only instance that an East Coast Low is visible on the manual charts, while the objective database identifies an ECL in the same region 2 June.





of the NCEP reanalysis data, and also the potential for a manual analyst to extrapolate surface pressures below that which might be implied by the available pressure and wind observations. It also reflects variance in the mean pressure field between seasons and locations; a low ('strong') MSLP threshold would artificially bias the database towards southern and winter ECLs, which tend to be more 'intense' by these criteria but not necessarily in terms of impacts. For example, at 00Z on 26 May 1974 a strong ECL (Fig. 6) was causing severe impacts on the Eastern Seaboard, but the central pressure identified by the low tracker was only 1003 hPa. Instead, maximum curvature was found visually to show a stronger relationship with the strength of the pressure gradient and consequently to circulation and associated impacts, consistent with its use in Murray and Simmonds (1991); in this instance the curvature was 0.39 hPa (deg.lat)$^{-2}$. Future development of this database will include the use of higher resolution reanalysis data, which may offer some advantages in defining the central pressure of lows.

Two methods can be used to restrict the database based on curvature. The first approach considers a low significant if the maximum curvature reaches a certain threshold, and considers all days when that ECL is in the ESB region an ECL day. The advantage of this approach is that it includes the end of very intense events; however, it may also include weak troughs as 'ECL days' prior to the development of a 'true' ECL. The alternative option only considers an ECL day if there is an ECL fix within the ESB region that exceeds a given curvature, thereby excluding the weak tail ends of events.

In this case we used curvature increments of 0.05 hPa (deg.lat)$^{-2}$ and compared the subjective and objective databases for all ECL cases (Table 3). A fix-based threshold of 0.25 hPa (deg.lat)$^{-2}$ was found to decrease the FAR to 55 per cent (32 per cent within ±1 day) while still detecting 72 per cent of ECL days and 80 per cent of days associated with significant ECLs; such events will

Table 2. Hit rate, false alarm rate and critical success index for various subsets of the Objective Low Database in comparison to the Maritime Low Database, where a low persists for at least two consecutive fixes.

Restriction	*Hit rate*	*False alarm rate*	*Critical success index*
All ECLs	84%	64%	0.34
±1 day*	92%	51%	0.47
00Z only	73%	46%	0.45
Combined	86%	34%	0.59

*Where a 'hit' occurs where an objective ECL day has a MLD event on either the previous or subsequent day, while a 'miss' occurs where an ECL in the MLD does not have an objective ECL on surrounding days.

be considered 'strong' ECLs. This approach decreases the annual frequency of ECL days to 55.5, which remains higher than the MLD database, but this is expected from the improved detection of events as discussed above as a result of six-hourly MSLP analyses.

In using this approach, it is important to note that the curvature thresholds used in this database are dependent on the resolution of the NCEP reanalysis. It is likely that curvature thresholds will vary based on both the spatial and temporal resolution of the pressure fields used, as well as on the definition of an East Coast Low; Murray and Simmonds (1991) used a curvature threshold of 0.4 hPa (deg.lat)$^{-2}$ when using analyses at a 5° resolution. Note also that similar results can be achieved using an events-based curvature threshold of 0.30 (Table 3), with event-based thresholds increasing both the hit rate and false alarm rates when compared to thresholds based on individual tracks.

Table 3. Comparison statistics for the MLD and objective database, based on a variety of curvature thresholds.

Curvature *hPa (deg.lat)$^{-2}$*	*By event*			*By fix*		
	HR	*FAR*	*CSI*	*HR*	*FAR*	*CSI*
0.15 (all)	84%	64%	0.34	84%	64%	0.34
0.2	83%	62%	0.35	80%	60%	0.36
0.25	78%	59%	0.36	72%	55%	0.38
0.3	73%	57%	0.37	64%	50%	0.39
0.35	66%	55%	0.36	53%	45%	0.37
0.4	59%	53%	0.36	43%	41%	0.33

Detection of ECL events with significant rain or wind impacts

From a user perspective, the main question is whether the objective ECL database effectively identifies those ECLs with significant weather impacts on the ESB. These impacts are typically related to a combination of heavy rain, strong winds, and high seas; while ocean data is less available, particularly prior to 1980, both wind and rain impacts of ECLs can be examined. For the remainder of this paper, only these 'intense' ECLs with an instantaneous curvature of at least 0.25 hPa (deg.lat)$^{-2}$ will be discussed, as distinguishable from other weak coastal lows.

An ECL is considered significant in terms of rainfall if an ESB rain event is identified by the method used by Dowdy et al. (2013). This is based on the AWAP gridded rainfall data, 24-hour rainfall measured at 9.00 am; while the MLD is based on observations at 00Z (10.00 am) only, with ECLs assigned to the same-day rain event, an objective ECL can be identified at any time between 00Z and 18Z, so associated rain is recorded to 9.00 am the following day. Between 1970 and 2006, there are on average 45 ESB rain events per year; 16.5 of these are associated with an objective ECL and 14.8 with a subjective ECL.

As shown in Table 4, the objective database successfully detected 81 per cent of subjective ECLs associated with ESB rain, with only 18 per cent of objective ECL rain days not associated with a subjective ECL within ±1 day. The CSI is significantly higher than observed for non-rain events, suggesting that the majority of false alarms are due to borderline events which had little impact in terms of rainfall.

A selection of seventeen long-record wind gust stations were identified along the east coast, from which a time series of 'maximum coastal wind gust' was obtained; all days with a maximum wind gust exceeding 50 knots (90 km/hr) were considered to be strong wind days. There were an average of 28.9 such days per year along the entire study region, with the MLD considering 20 per cent of strong wind days to be ECLs, compared to 35 per cent in the Objective Database, a substantially higher proportion.

Of the MLD ECLs associated with strong winds, 84 per cent were also considered ECL days by the objective database. Manual inspection of the charts for 'missing' events found that the ECL in such cases was either outside the ESB domain (38 per cent) or weak (62 per cent). In almost all such cases the strong winds were most likely associated with an event independent of the low, typically a cold front with strong southerly winds, although some instances were associated with localised thunderstorm activity. In comparison, 51 per cent of days with strong winds on the ESB and an ECL identified by the objective database were not considered ECLs by the MLD. Notably, 72 per cent of these 'false alarm' days either had a subjective ECL on the surrounding days or had no ECL fix at 00z, implying this may be related to the poor detection of fast-moving ECLs by the MLD.

Table 4. Hit rate, false alarm rate and critical success index for the 'intense' ECL days with fix curvature ≥0.25 hPa (deg.lat)$^{-2}$ in comparison to the MLD where an ESB rain event is present.

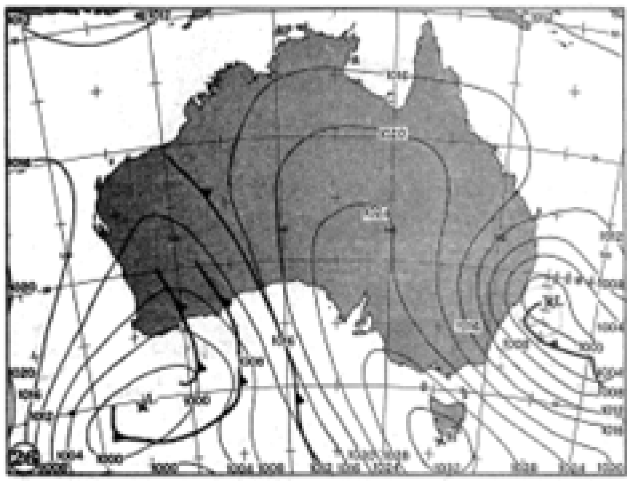
	HR	*FAR*	*CSI*
Intense ECLs	81%	35%	0.57
±1 day	90%	18%	0.75

Twenty such events with an objective ECL associated with strong winds, but no corresponding low in the MLD, were selected at random for manual inspection. Of these, 60 per cent had low pressure systems that failed to satisfy ECL criteria at 00Z, generally either very weak or outside the ECL region, before developing over the day, while an additional 30 per cent had no low at all visible in the 00Z manual MSLP chart but a clear ECL on the subsequent day. The remaining two events were only apparent as strong cold fronts in the daily MSLP analyses, which the objective database identified as having a closed low. The large majority of 'false alarms' (90 per cent) were thus related to poor detection of fast-moving and quick-developing ECLs by the MLD, suggesting that the improved temporal resolution of the objective database allows better identification of ECLs with significant wind impacts on the ESB.

Comparison of Subjective and Objective Databases, 1970–2006

The MLD has been demonstrated to have substantial difficulty in detecting strong wind events, while data for wind along the ESB is relatively sparse. The two databases

Fig. 6. Manual synoptic chart for 00Z on 26 May 1974.



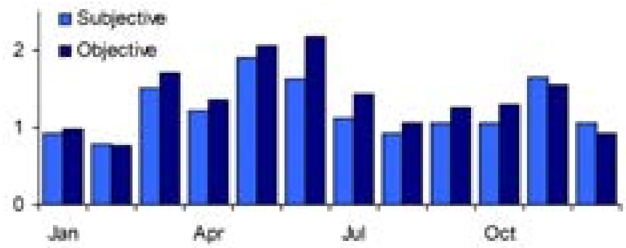
will thus be compared in more detail in terms of rainfall impacts, with such lows more consistently identified by both databases. This allows the two databases to be compared using approaches similar to the analyses of the MLD by Speer et al. (2009) and Pepler et al. (2014), to confirm whether the objective ECL database shows similar characteristics in terms of rainfall impacts. An ESB rain event remains defined by the criterion of Dowdy et al. (2013), which is influenced by widespread heavy rainfall that is centred on the ESB, a typical feature of major ECL events.

While the number of ECL days is higher in the objective database, the seasonal distribution is very similar between the two databases for ECLs associated with significant ESB rainfall events (Fig. 7). In both cases there is a peak in ECL days in May and June, responsible for 24 per cent of ECL-related significant rain days in the MLD and 26 per cent in the objective database, with secondary peaks in March and November and lowest frequency in February.

The skill of the objective database varies throughout the season, with CSI highest between May and August and lowest during January and February. In January and February less than 70 per cent of MLD ECL rain days are detected, while more than 40 per cent of objective ECL rain days are not present in the MLD (Fig. 8). This appears to be related to the distribution of weak or borderline ECLs; while only 38 per cent of ECL rain days occur between November and March, 53 per cent of rain days with a low too weak to be considered an ECL (curvature less than 0.25 hPa $(\text{deg.lat})^{-2}$) occur at this time of year. Such lows are more subjective in both representation in the manual MSLP charts and inclusion in the MLD database, resulting in enhanced disagreement between the objective and subjective databases.

On an interannual basis there is strong agreement between the subjective and objective databases (Fig. 9), with an annual correlation of 0.61 for the number of ECL days and 0.71 for ECL days associated with an ESB rain event. There is again a better match during the cool season, when the correlation

Fig. 7. Monthly distribution of ECL days associated with an ESB rain event in the MLD, compared to 'intense' objective ECLs with curvature exceeding 0.25 hPa $(\text{deg.lat})^{-2}$.



between the databases for ECLs associated with an ESB rain event is 0.75, compared to 0.59 for November–April. However, there are several periods where an increase is observed in the objective database, notably during the 1970s and in 1984–1985, which is consistent across both seasons.

The differences in the early period may be related to poor detection of low pressure systems in the early manual synoptic charts, as well as a lower quality of the NCEP reanalysis data prior to the advent of geostationary satellite data in 1979. This early period of more frequent ECLs in the NCEP data results in a weak and statistically insignificant declining trend in the objective database that is not seen in the MLD.

Several La Niña events occurred during the 1970s (e.g. Braganza et al. 2009), with relatively few El Niño events. Consequently, the increased frequency of cool season (May–October) ECLs in the objective database is more pronounced in La Niña years than El Niño years (Table 5), resulting in weakly positive correlations between the May–October SOI and the simultaneous numbers of ECL days. However, these results are not statistically significant, with a p-value of 0.07 using a two-tailed t-test.

Extension of database to 1950

Using the objective database and the included ECL track information, we are able to extend the analysis of ECLs and associated rainfall impacts from Speer et al. (2009) and other studies (e.g. Pepler et al. 2014) to the rather longer 1950–2008 period. Notably, when repeating the analysis from Table 5 for the period 1950–2008, the frequency of ECL rain events during May–October of both El Niño years (9.1) and La Niña years (9.4) is lower than in neutral years (11.2). This is consistent with the lack of statistical significance for the previous analysis and suggests the difference for the 1970–2006 may be purely a result of random variations. However, further research is necessary into the cause of the large differences in 1976 and 1978, particularly the extent to which they are related to the improvements of reanalyses with increased satellite data in the 1980s.

The objective database also includes more detailed information on the position of the low, enabling further analysis of low formation, movement and location. Figure 10 displays heatmaps of the low centres for all ECLs with curvature

Fig. 8. Monthly variation in the proportion of misses (1-hit rate) and the false alarm rate for the intense East Coast Lows. Also shows the relative frequency of days with East Coast Low days that fail to reach the curvature threshold of 0.25 hPa (deg.lat)$^{-2}$, and the relative frequency of associated rain days.

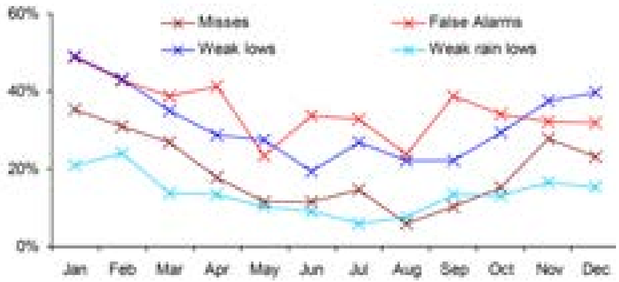


Fig. 9. Annual distribution of ECL days associated with an ESB rain event in the subjective database and objective ECLs with an instantaneous curvature of at least 0.25 hPa (deg.lat)$^{-2}$.

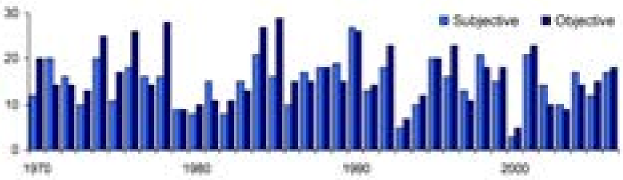


Table 5. Annual average number of ECL days (1970–2006) associated with an ESB rain event by ENSO state, as defined by the Bureau of Meteorology.

Season	*May–October*		*November–April*	
State	*Subjective*	*Objective*	*Subjective*	*Objective*
El Niño	6.8	7	5.9	6.8
Neutral	8.4	10.4	7.1	6.9
La Niña	7.1	9.4	8.7	8.4

greater than 0.25 hPa (deg.lat)$^{-2}$ associated with an ESB rain event, in comparison with the average annual frequency of days with rainfall exceeding 25 mm associated with ECL events, consistent with the significant rain threshold of Speer et al. (2009). ECLs can be clearly seen to occur throughout the region of definition in both the warm and cool seasons. The rainfall impact is most concentrated in the southern ESB between May and October, while ECL-related rain is more common in the northern ESB in November–April, consistent with the results for the MLD in Pepler et al. (2014).

The total number of ECL days observed per annum shows no noticeable change throughout the period of analysis, with the decadal average frequency varying between 51 and 58 days. There is a more marked decline in the frequency of lows related to ESB rain (Table 6), with a decline in frequency between the 1950s and 2000s equal to the standard deviation (6.5 days). This coincides with a period of declining rainfall in

Fig. 10. ECL locations and corresponding rainfall impacts in November–April (left) and May–October (right). Each figure shows (over ocean) a heatmap of all low centres with a curvature greater than 0.25 hPa (deg.lat)$^{-2}$ where an ESB rain event was recorded on the subsequent day, with darker shades indicating a higher relative frequency of lows. Figures also show (over land) the average number of days p.a. with daily gridded rainfall greater than 25 mm where an ECL is present.

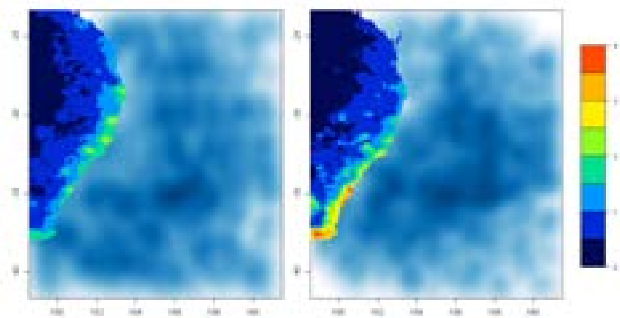
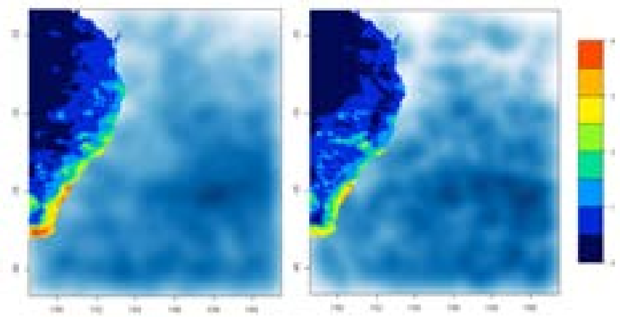


Fig. 11. As for Fig. 10, but for the May–October period in 1950–1989 (left) and 1990–2008 (right).



southeast Australia (e.g. Murphy and Timbal 2008); however, no decline in ECL days is apparent during the autumn months, when rainfall trends are strongest. The most consistent decline in ECLs is during the winter months, while both spring and summer exhibit significant decadal variability.

This decline in the number of ECL days associated with rain is not apparent in the number of total ECL days, which averages 18 winter days per annum between 1950 and 1969 and 16 days per annum between 1990 and 2008. It also does not reflect any changes in the intensity of ECLs in the NCEP/NCAR reanalyses, with an average curvature of 0.43 hPa (deg.lat)$^{-2}$ for both the 1950–1969 and 1990–2008 periods. There is an apparent change in the latitude of all ECLs in 1990–2008 relative to earlier periods, with an increase in the proportion of lows south of 37°S from 32 per cent to 42 per cent. However, while such lows are less likely to have rain impacts, the proportion of lows north of 37°S associated with ESB rain also decreases between 1990 and 2008, from 53 per cent to 44 per cent of days, with rain-bearing lows less likely to cause rainfall above 25 mm across the ESB coast (Fig. 11).

Table 6. Annual frequency of ECLs for decades spanning 1950–2008

Decade	*Total ECL days*	*ECL days with an ESB rain event*	*Autumn*	*Winter*	*Spring*	*Summer*
1950s	55.2	19.5	3.2	8.3	3.8	4.2
1960s	54.7	19.3	5.4	6.9	3.7	3.3
1970s	57.4	18.0	5.5	5.8	4.3	2.4
1980s	55.9	16.4	4.3	4.1	5.3	2.7
1990s	58.4	17.2	5.1	4.8	3.4	3.9
2000s*	51	14.0	5.1	4.6	3.1	1.2

* Nine years counted in this decade

Conclusions

In this paper we used an objective low tracking scheme and the six–hourly NCEP MSLP reanalysis data to develop a database of East Coast Lows for the 1950–2008 period. The database was filtered using the following criteria:

- Location: an ECL must be in the ESB region in Fig. 1
- Duration: the low must persist for at least two MSLP analyses, implying a minimum life time of six hours.
- Intensity: the low must have an instantaneous curvature of 0.25 hPa $(\text{deg.lat})^{-2}$.

Using these three criteria, the database identifies an average of 55 ECL days per year (i.e. days on which an ECL was detected), of which an average of 16.5 are associated with significant/heavy rainfall on ESB using the Dowdy et al. (2013) ESB rain event database. When compared to the Speer et al. (2009) Maritime Low Database, the objective ECL database detects more than 80 per cent of ECL days associated with either an ESB rainfall event or wind gusts greater than 90 km/hr on the Eastern Seaboard of Australia. While the false alarm rate is relatively high, with 35 per cent of ECL rain days not associated with a low in the MLD, this appears to be mainly due to improved detection through the use of six-hourly (rather than daily) MSLP data and so we suggest the objective values are likely to be more accurate.

This objective database offers several advantages over previous subjective ECL databases. The improved temporal resolution of MSLP fields allows improved detection of fast-moving, rapidly-intensifying and short-lived events, as well as the start and end of ECL events to be more clearly defined. Notably, the objective database provides a better match with recorded high wind events on the ESB, suggesting that the manual database misses a number of events. The use of a standardised set of criteria also reduces subjectivity in the identification of weak or borderline ECL events, particularly during the warm season when systems are often weaker, allowing criteria to be applied more consistently. Note that the criteria employed in this case are specific to the reanalysis data used; a different reanalysis may well require different intensity thresholds to be used.

The automated nature of the tracker enables easy extension of the database to a longer 1950–2008 period, improving the ability to analyse ECL trends and variability. It is also able to be applied to other data such as model predictions and projections, to identify potential future changes in ECL occurrence or characteristics. However, the database appears to have some difficulties in tracking the full extent of events, with an estimated 16 per cent of events associated with a track that has been anomalously split. It is expected this is a particular issue for fast moving events or those with rapidly changing tracks; further work will investigate the tracking parameters used to improve on this. It is arguably the case that there is no 'correct' track for the more complex ECLs as these can be multi-centred with the centres forming and decaying in complex ways which cannot be uniquely defined by MSLP at resolution.

Using the extended ECL database, we identified a declining trend in cool season ECL days with rainfall impacts relative to the 1950s. This appears to reflect a decrease in the proportion of ECL days that occur in the northern part of the domain, as well as a decrease in the proportion of ECLs that are associated with rainfall greater than 25 mm along the ESB. While further research is required, it is proposed this decline may relate to recent intensification of the subtropical ridge (e.g. Timbal and Drosdowsky 2013), particularly given that recent studies indicate a significant relationship between the subtropical ridge and ECL formation (Dowdy et al. 2012c). East Coast Lows continue to demonstrate only weak relationships with ENSO during the cool season when the 1950–2008 period is considered, consistent with previous studies, although an increase in objective ECL events was noted during the 1970s. This means the ability to predict and explain interannual variations of ECLs in terms of this dominant mode of climate variability remains low.

Future work will include applying the tracking scheme used in this paper to other reanalysis datasets such as ERA-Interim, in addition to climate model output to investigate potential future changes, as well as a comparison with other tracking schemes. Future work will also include a more detailed analysis of the relationship between ECL frequency and large-scale drivers such as the Indian Ocean Dipole (IOD) and Subtropical Ridge, as well as analysis the causes of observed trends, with a particular focus on the differences between pre– and post–satellite periods (1979).

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