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Review of Australian east coast low pressure systems and associated extremes

Andrew J. Dowdy[1] · Acacia Pepler[1] · Alejandro Di Luca[2] · Leone Cavicchia[3] · Graham Mills[4] · Jason P. Evans[2] · Simon Louis[5] · Kathleen L. McInnes[6] · Kevin Walsh[3]

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Abstract

Intense cyclones often result in severe impacts on mid-latitude coastal regions of southeastern Australia, including those due to associated natural hazards such as extreme winds, ocean waves, storm surges, precipitation, flooding, erosion, lightning and tornadoes in some cases. These low-pressure systems, known as east coast lows (ECLs), have been examined in a wide range of different studies, with considerable variations between such studies in what they consider to be an ECL, and their findings on the characteristics of these storm systems. Here we present reviews of literature and other information such as operational forecasting approaches, which are then used to produce a comprehensive synthesis of knowledge on ECLs and associated weather and ocean extremes. This includes aspects such as their definition, formation, meteorology, climatology and drivers of variability from short-term weather time scales up to long-term historical climate trends and future projections. Australian ECLs are also considered here in relation to similar phenomena from other regions of the world. A definition based on this synthesis of knowledge is as follows: ECLs are cyclones near southeastern Australia that can be caused by both mid-latitude and tropical influences over a range of levels in the atmosphere; Intense ECLs have at least one major hazard associated with their occurrence, including extreme winds, waves, rain or flooding. Knowledge gaps are examined and used to provide recommendations for future research priorities. This study is intended to lead to improved guidance and preparedness in relation to the impacts of these storms.

Keywords Cyclones · Extreme · Weather · Climate · Hazards

1 Introduction

1.1 Overview

Cyclones cause severe weather and major damage in many mid-latitude regions of the world. They are intense low-pressure systems and include tropical as well as extratropical cyclones. In the Australian region, while extratropical cyclones occur most frequently in the Southern Ocean storm track region to the south of the Australian continent (Hoskins and Hodges 2005; Neu et al. 2013; Catto 2016), there is also a relatively high occurrence frequency of cyclones in the Tasman Sea between Australia and New Zealand, including systems that can be cut-off from the main extratropical storm track (Jones and Simmonds 1993; Fuenzalida et al. 2005; Allen et al. 2010; Dowdy et al. 2013a). Figure 1 illustrates this local maximum in cyclone activity based on mean sea level pressure (MSLP), as well as 500 hPa geopotential height, noting that some of the more intense systems can be

✉ Andrew J. Dowdy
andrew.dowdy@bom.gov.au

[1] Climate Research, Bureau of Meteorology, Melbourne, Australia

[2] Climate Change Research Centre, School of Biological, Earth and Environmental Sciences, University of New South Wales, Sydney, Australia

[3] School of Earth Sciences, University of Melbourne, Parkville, Australia

[4] Monash University School of Earth Atmosphere and Environment, Clayton, Australia

[5] National Operations - NSW, Bureau of Meteorology, Sydney, Australia

[6] CSIRO Oceans and Atmosphere, Aspendale, Australia

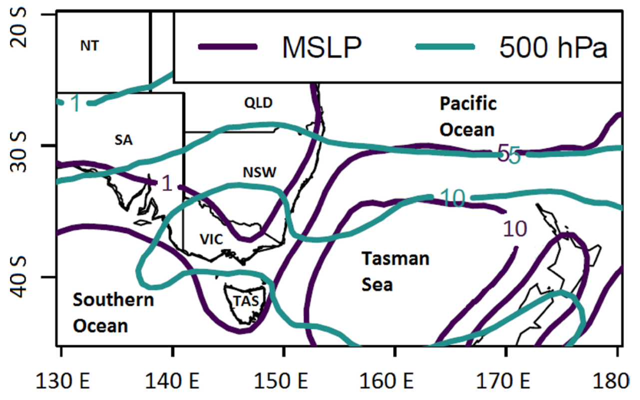


Fig. 1 Cyclone activity near eastern Australia, showing the annual mean number of low-pressure system events (per 5°×5° region) based on applying a tracking method for MSLP and 500 hPa geopotential fields from the ERA-Interim reanalysis from 1979 to 2009 [as described in Pepler et al. (2015)]. Also shown are coastlines of Australia and New Zealand (to the southeast), with latitude and longitude, names for maritime regions as well as Australian states of Queensland (QLD), New South Wales (NSW), Victoria (VIC), Tasmania (TAS), South Australia (SA) and Northern Territory (NT)

well-defined over a large depth of the troposphere. Many of these systems have severe impacts on the Australian east coast, where they are typically referred to as east coast lows (ECLs), while noting other descriptive terms that have also been used previously (e.g., east coast cyclones or maritime lows).

ECLs can occur through a variety of different physical processes, including mid-latitude baroclinic drivers of cyclogenesis such as commonly occur for frontal-cyclone evolution (Bjerknes 1922; Eady 1949; Lindzen and Farrell 1980; Shapiro and Keyser 1990), and sometimes also a contribution from other (i.e., more barotropic) influences including convective processes and the release of conditional instability in hybrid storm cases (Hart 2003; Garde et al. 2010; Browning and Goodwin 2013; Pezza et al. 2014; Cavicchia et al. 2019). During the warmer months of the year they can also develop from a tropical cyclone transitioning to become a post-tropical (also referred to in Australia as 'ex-tropical') cyclone (Speer et al. 2009; Callaghan and Power 2014). ECLs can undergo rapid intensification, which can lead to significant forecasting challenges, with some ECLs satisfying the Sanders and Gyakum (1980) "bomb" criterion for explosive development (Lim and Simmonds 2007; Allen et al. 2010; Cavicchia et al. 2019). Although they can occur at any time of the year, they are more common during the cooler months of the year, particularly for many of the more intense systems that have caused severe damage (Holland et al. 1987; Speer et al. 2009; Mills et al. 2010; Dowdy et al. 2011, 2013a). In contrast, tropical cyclones in the southwest Pacific region near Australia predominantly occur during the warmer months of the year.

The high frequency of occurrence of these cyclones and associated severe weather hazards near the east coast of Australia provides one indication of the unique nature of ECLs as compared to cyclone characteristics in other regions of Australia. ECLs have some similarities with cyclones in other regions of world, often at subtropical latitudes near the east coasts of continents as well as around Hawaii and the Mediterranean Sea, including a characteristic vorticity signature in the middle and upper troposphere (e.g., Catto (2016) and da Rocha et al. (2018), as discussed further in Sect. 5.4).

This paper reviews knowledge on ECLs obtained from a range of perspectives, including research studies and operational forecasting information. Various characteristics of ECLs are summarised in individual sections of this paper including their definition (Sect. 2), meteorology (Sect. 3), extreme weather and ocean conditions (Sect. 4), historical climatology (Sect. 5), as well as future projected changes (Sect. 6) which includes a concise summary table detailing the influence of climate change on ECLs and associated hazards (Table 1). A synthesis of this information is then provided (Sect. 7) as a concise source of information on ECLs based on the comprehensive range of studies and knowledge considered here, including a definition of an ECL intended for general use, together with recommendation for future research directions. This is followed by a brief conclusions section.

1.2 Motivation

East coast lows can cause severe hazards for maritime and land regions, including loss of human life, as well as other social, economic and environmental impacts. Their impacts can also be desirable as ECLs can contribute significantly to streamflow (Dowdy et al. 2013b) and water availability (Pepler and Rakich 2010). The propensity of these cyclones to cause severe coastal impacts has led to a substantial number of studies on ECLs and their associated severe weather and ocean conditions, particularly in recent years. This growing interest in ECLs (and growing number of ECL studies) is in part related to a number of recent cases that have had severe impacts on the most heavily populated part of Australia (i.e., the eastern seaboard), including a series of ECLs in June 2007 that remains the eighth-most expensive Australian disaster of the last 50 years. The growing interest in ECLs is also related to an increasing awareness of the importance of understanding extreme weather and ocean hazards in a changing climate, including the need for accurate climatological knowledge to enable effective planning and preparedness (e.g., for disaster risk reduction applications).

A key motivation for this article is to examine the definition of ECLs. The wide variety of approaches and different aspects of focus in previous studies has resulted in

Table 1 Summary of climate change influences on ECLs and their associated extremes

Climate change influences on ECLs and associated weather and ocean extremes	
ECL occurrence frequency	Fewer ECLs likely due to increasing greenhouse gas emissions, primarily due to fewer ECLs during the cooler months, with larger uncertainties around ECL numbers during the warmer months
ECL intensity and duration	Intensity changes are largely uncertain based on current knowledge, as are changes in associated extreme wind speeds
ECL-related rainfall	Fewer events, particularly during winter, but with increased rainfall intensity in some cases (estimated at ~7% per degree of warming for heavy daily rainfall and ~15% per degree of warming for short-duration extremes), corresponding to increased flood risk factors
ECL-related convective hazards	Convective rainfall extremes likely to have large increases but larger uncertainties for future convective wind extremes and lightning activity associated with ECLs
ECL-related waves	Fewer large wave events are likely in the future, particularly during winter, while noting uncertainties around the intensity of extreme wave events (given uncertainties around projections of ECL intensity)
ECL-related coastal hazards	Sea levels will continue to rise, thereby increasing risks from ECLs associated with storm surge, coastal flooding and erosion (while noting uncertainties around changes in wave direction)

considerable variations in how the characteristics of ECLs are described between studies. For example, their estimated annual frequency ranges by an order of magnitude from about 2 events per year (Hopkins and Holland 1997) to over 20 events per year (Speer et al. 2009). This has resulted in considerable uncertainty as to the variability, trends and impacts of ECLs, as well as their relationships with major modes of climate variability such as the El Niño-Southern Oscillation (ENSO) and analysis of long-term climatological trends in their occurrence and associated hazards.

In addition to a wide range of definitions of ECLs, there have also been a wide range of datasets and analysis methods used for studying ECL characteristics. Various early studies examined observations for historical cases, particularly those which caused severe impacts from extreme winds and rainfall (Leslie et al. 1987; Holland et al. 1987; Hopkins and Holland 1997). A number of early studies examined the localised drivers of ECLs at relatively short spatial and temporal scales as represented by models (McInnes and Hess 1992; McInnes et al. 2002), as well as based on operational numerical weather prediction (NWP) model output (Leslie and Speer 1998) and including case studies of extreme events [such as the storm that affected the Sydney to Hobart yacht race in 1998 (Mills 2001)]. A widely utilised database of ECL events was produced in the New South Wales (NSW) regional office of the Bureau of Meteorology (BoM) based on manual interpretation of MSLP charts, providing a subjective climatology of events and their characteristics, including formation environments as well as associated extremes (Speer et al. 2009). Subsequent studies utilised a range of different reanalyses and climate model output to systematically examine the characteristics of ECLs for the historical climate (Dowdy et al. 2010, 2013c; Browning and Goodwin 2013; Ji et al. 2015; Pepler et al. 2015; Di Luca et al. 2015) and future projected climate (Dowdy et al. 2013a, 2014; Di Luca et al. 2016; Pepler et al. 2016b).

The wide range of different approaches that have been used to examine the characteristics of ECLs, and the hazards they can cause, provides motivation for a collation and synthesis of this information. This paper provides a comprehensive knowledge-base of the characteristics of ECLs and associated extreme weather and ocean conditions. This synthesis of information is intended for use in planning and decision making, as well as for other research and operational forecasting guidance applications.

2 Defining, identifying and classifying ECLs

A number of different definitions of ECLs have been used in the literature, generally based on describing an ECL as a cyclone that occurs in the Tasman Sea off the Australian east coast (Fig. 1), but with a wide range of additional criteria applied depending on the individual study. The different definitions used previously are discussed in this section, including pressure-based detection approaches, classification methods based on energetics and vertical structure, approaches focussed on their hazards and impacts, as well as potential subcategories for different ECL types. The definition of an ECL is further considered in Sect. 7, which provides a synthesis of various previous definitions together with the meteorological and climatological knowledge presented in other sections of this paper.

2.1 Pressure-based detection approaches

A number of studies have focussed on low pressure systems in maritime regions near the east coast of Australia (Speer et al. 2009; Browning and Goodwin 2013) while others also include systems over adjacent land areas (Dowdy et al. 2011; Di Luca et al. 2015; Pepler et al. 2015). Such definitions can also vary in their latitude range and eastward extent into the

Pacific Ocean, generally ranging from about 25°S to 40°S in latitude (spanning latitudes from around the southeast of the Australian state of Queensland, throughout NSW and eastern Victoria as well as towards the northeast of the island of Tasmania) and east to about 160°E in longitude.

Additionally, a variety of different definitions for identifying the low-pressure systems have been used, which can lead to significant variations between different studies. Some approaches have focussed on local minima in pressure-related fields, with MSLP commonly being used to represent near-surface signatures of ECLs. However, this can result in a large number of systems due to small-scale and short-lived fluctuations (depending on the spatial and temporal resolutions of the data used), with many of these systems defined by a local minimum in MSLP having little or no impact on the coast (Speer et al. 2009) such that additional criteria are often required (e.g., if coastal impacts are a focus of a particular study). These additional criteria have included one or more of the following: movement parallel to the coast (Hopkins and Holland 1997); formation or intensification in the vicinity of the coastline (Speer et al. 2009); orientation of pressure gradients requiring that the maximum geostrophic wind is directed towards the coast (Browning and Goodwin 2013); and intensity of pressure gradient above a minimum threshold (Pepler et al. 2015). In addition to studies based on MSLP, ECLs have also been investigated using geopotential height at various isentropic and isobaric levels to identify low pressure systems with strong cyclonic vorticity in the middle and upper troposphere (Dowdy et al. 2011, 2013c; Pepler et al. 2015; Ji et al. 2015, 2017).

Different criteria specifying the minimum duration of ECL events have been used in the various studies. Some methods have a minimum duration of about 6 h (Pepler et al. 2015), 12 h (Di Luca et al. 2015) or 18 h (Browning and Goodwin 2013), while others have used daily data with no specific additional duration criteria (Speer et al. 2009). The use of temporal thresholds in defining an ECL also requires a method for tracking individual systems, with the range of different approaches for tracking weather systems representing another factor that can vary between different approaches [e.g., Jones and Simmonds (1993), Browning and Goodwin (2013) and Catto (2016)].

2.2 Energetics and vertical structure classification approaches

In addition to studies that consider a single pressure level, ECLs have also been defined based on their vertical and thermal characteristics. The vertical organisation of cyclones in this region can vary substantially, from relatively shallow surface pressure minima to vertically well-organised deep systems associated with a well-defined cut-off low or strong trough evident over a range of levels of the troposphere (Lim and Simmonds 2007; Dowdy et al. 2010; Mills et al. 2010).

As well as extratropical cyclones with deep cold cores, the east coast experiences a high frequency of cyclones with subtropical or hybrid characteristics, with a shallow warm core or warm seclusion near the surface as well as a cold core in the upper troposphere (Hart 2003; Pezza et al. 2014; Yanase et al. 2014; Yanase and Niino 2015; Cavicchia et al. 2019; Quinting et al. 2019a). These characteristics provide a means of defining ECLs as a phenomenon distinct from tropical cyclones, including based on identifying different types of cyclones according to the three-dimensional structure and energetics of the low-pressure system (i.e., providing insight on their physical processes including baroclinic and barotropic influences). This has proved useful in helping determine whether an ECL is more similar to an extratropical or tropical cyclone, such as in the case of the ‘Duck’ hybrid cyclone (Garde et al. 2010; Pezza et al. 2014; Cavicchia et al. 2018). Section 3.2 provides further details on the meteorology of hybrid systems, including discussion of tropical cyclones that transition in this region to become ECLs with more extratropical characteristics.

2.3 Hazard-based classification approaches

Some approaches have also referred to ECLs as those cyclones that have severe hazards and impacts on southeast coastal regions of Australia, through their associated strong winds, intense precipitation and flooding, high seas and coastal erosion. For instance, Hopkins and Holland (1997) only considered those cyclones that were associated with heavy coastal rain, with some similarities in that respect to the recent approach of Callaghan and Power (2014) based on considering the cyclones in this region that caused severe rainfall leading to flooding events. There are also some similarities to operational forecasting approaches to classifying ECL events which need to have a focus on coastal impacts given the requirement to provide public warnings and guidance around potentially impactful weather and ocean conditions (as detailed in Sect. 3.4).

2.4 Classification methods for different ECL types

Some studies have proposed to classify multiple different types of ECLs. These studies have typically been based on surface indicators of synoptic characteristics associated with ECL formation.

Holland et al. (1987) examined 21 severe cyclones between 1970 and 1985, all of which were warm cored systems that developed from a trough or wave in the subtropical easterlies with a ridge on its poleward side, referred to as an “easterly dip”. These were further categorised into three subtypes: Type 1 was a tiny, hurricane-like vortex centre

(~ 100 km in diameter) that moved southward parallel to the coastline; Type 2 cyclones occurred as a mesoscale development within the easterly dip as part of a synoptic-scale storm system; while Type 3 cyclones were also very small and developed rapidly to the west of an easterly dip. Types 1 and 3 were reported to have lifetimes as short as 16 h, while Type 2 could cause more sustained hazards over several days. In subsequent research, Hopkins and Holland (1997) disregarded all events lasting less than one day, stating that although this may appear to exclude the smaller types 1 and 3 noted previously [by Holland et al. (1987)], those smaller types are normally also associated with a nearby larger and longer-lived system. These studies highlight the synoptic-scale characteristics of these systems as well as the potential for associated extreme weather conditions at finer scales (e.g., mesoscale features) in some cases.

Speer et al. (2009) identified surface cyclones within the Tasman Sea, which they grouped into six categories based on synoptic characteristics. As well as ex-tropical cyclones, they selected two types of systems that developed from a trough in the easterlies: “inland troughs” where the trough was oriented NW–SE through southeast Australia and “easterly troughs” where the trough was located off the coast. They also selected three types of systems that developed from the mid-latitude westerlies, with a small number of pre-existing lows in the westerlies that move into the Tasman Sea as well as cyclones that developed in the Tasman Sea either from a wave on a front or from a decaying front.

Studies have also categorised cyclones based on their development processes, including cut-off lows that form in the wake of a cold front, inland trough lows that develop as a trough in northern Australia before moving southeast and intensifying near the coast, as well as easterly trough lows that form as a trough in the easterlies near the coast (PWD 1985). Following these definitions, Shand et al. (2011) expanded to eight sub-categories, while Browning and Goodwin (2013) classified cyclones based on the direction of motion of the precursor surface low or trough: including “easterly trough” lows that tracked in a southerly direction to the east of the Australian coast; “inland trough” and “continental” lows that evolved mostly over land before tracking eastward; and “southern secondary” lows that tracked mostly over the ocean and northward.

In addition to studies focussed only on surface conditions, studies have also highlighted the value in considering higher levels when classifying different cyclone types in this region (including as discussed in Sect. 2.2). For example, Sinclair and Revell (2000) presented a classification of cyclones based on their development environments in the Southwest Pacific region, including influences of different types of troughs and fronts, with their results highlighting the importance of considering synoptic-scale upper-tropospheric signatures in classification approaches (e.g., about three quarters of the cyclogenesis events they identified were characterised by direct coupling with the upper-tropospheric jet).

2.5 Summary of previous approaches to define and classify ECLs

A review of approaches to ECL definitions was presented in this section, highlighting the many different approaches that have been used previously. Although it is challenging to select an all-encompassing conceptual model around which an ECL can be objectively defined, the following review sections on ECL meteorology and climatology provide a comprehensive summary and assessment of the characteristics that can help define what an ECL is. This enables the definition of ECLs to be revisited in the final synthesis section of this paper (see Sect. 7.2), where we provide a generalised definition of ECLs.

3 Meteorological development of ECLs

3.1 Cyclogenesis and forcing mechanisms

Numerous factors have been linked to cyclone development and intensification, including baroclinic influences associated with frontal wave systems, mid- and upper-tropospheric vorticity and jet stream features, Rossby wave breaking, stratospheric intrusions and tropopause intrusions, atmospheric stability, nearby high pressure ridges or blocking systems, as well as more barotropic influences associated with convective processes and diabatic heating including latent heat release (Bjerknes 1922; Eady 1949; Lindzen and Farrell 1980; Hoskins et al. 1985; Shapiro and Keyser 1990; Hirschberg and Fritsch 1991; Bluestein 1993; Hoskins and Hodges 2002, 2005; Ulbrich et al. 2009; Ndarana and Waugh 2010; Dowdy et al. 2013c; Willison et al. 2013; Catto 2016). ECLs have a range of distinct characteristics as compared to cyclones that typically form in other regions around Australia. They can often be cutoff lows occurring equatorward of the subtropical ridge, distinct from the more typical frontal cyclones that occur further poleward in the strong westerly winds of the main extratropical storm tracks on the poleward side of the subtropical ridge (Risbey et al. 2009; Pook et al. 2013). Additionally, they can often include various combinations of both baroclinic and barotropic influences for some events (Pezza et al. 2014; Yanase et al. 2014; Cavicchia et al. 2019; Quinting et al. 2019a).

Mills et al. (2010) provide a detailed assessment of a severe ECL in June 2007, known as the Pasha Bulker storm, named after a ship that ran aground during that event. That study also examined the Pasha Bulker event in relation to 11 other impactful ECLs, including the Sygna storm from May 1974 named after another ship that ran aground during an ECL event (Fig. 2). A common pattern of evolution was identified based on these extreme examples of ECLs:

- 48–72 h prior to cyclone intensification, there is an upper tropospheric split jet or blocking pattern, and a positively tilted trough (southeast to northwest tilt) or cut off low over southeast Australia.
- The upstream trough over the Indian Ocean amplifies, followed by downstream amplification of the ridge south of Australia.
- A southerly jet streak develops on the western side of the positively tilted trough over eastern Australia.
- As this southerly jet streak propagates towards the apex of the trough (lower latitudes), the trough/cut-off low deepens and begins to negatively tilt (towards the northeast) and move towards the coast.
- The northwesterly jet on the northeast flank of the upper cut-off low strengthens, becomes highly focussed, and a region of very strong cyclonic shear near its exit becomes located very close to the centre of the upper cut-off low. This leads to a focussing of potential vorticity advection on the northeast side of the cut-off low which forces pressure falls at the surface.
- If low-level ingredients are suitable, such as strong baroclinicity and weak static stability, rapid development (i.e., intensification) of an ECL occurs.

This pattern of evolution, including distinct signatures in the higher levels of the troposphere (e.g., Fig. 2), contains some similar elements to other cyclogenesis concepts based around upper-tropospheric advection of vorticity as a forcing mechanism (Godson 1948; Hirschberg and Fritsch 1991; Dowdy et al. 2013c; da Rocha et al. 2018). In relation to the extreme weather that can be caused by ECLs, the results of Catto et al. (2015) indicate that this region near eastern Australia has a relatively high proportion of warm conveyor belts associated with upper-tropospheric features (rather than low-level fronts), noting that warm conveyor belts can be associated with uplift and hence precipitation within extratropical cyclones. Additionally, a recent study of cyclones near eastern Australia objectively classified events into four distinct clusters, each of which highlighted the importance of the upper-tropospheric conditions for cyclogenesis at lower levels (Catto 2018). The sensitivity

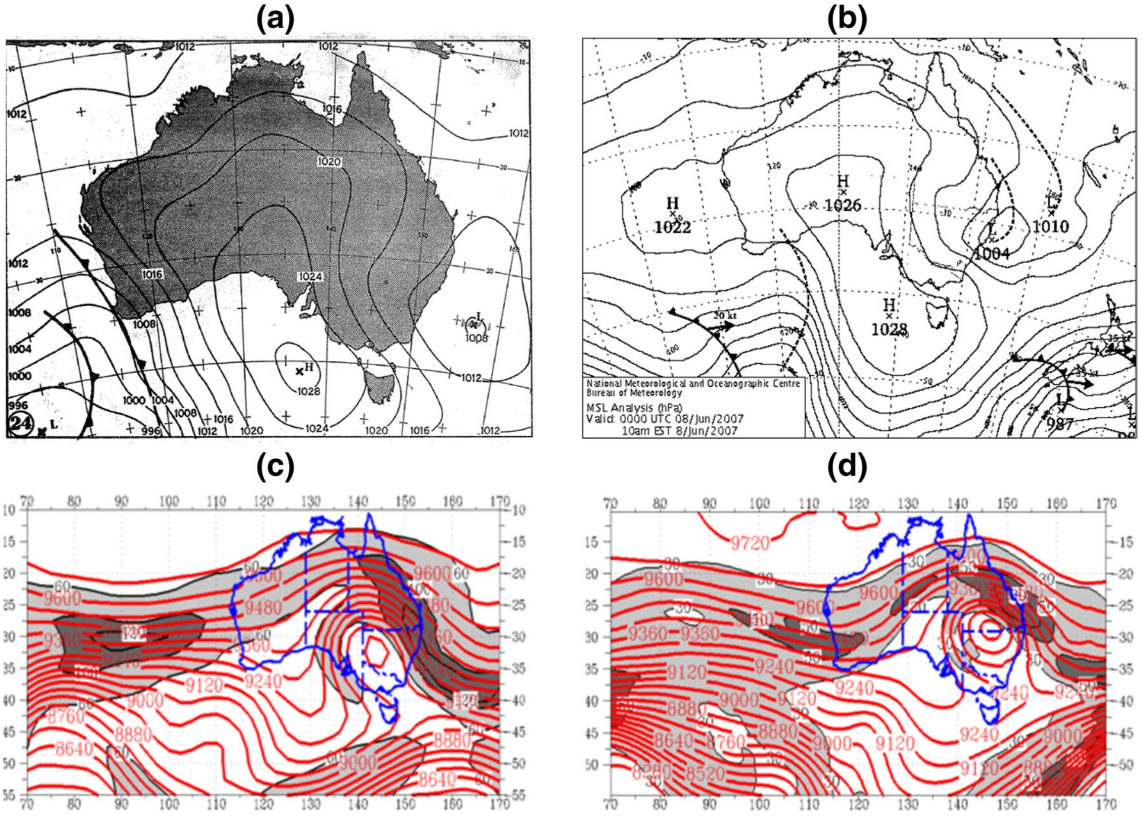


Fig. 2 Comparison of two extreme ECL events. MSLP fields are shown from BoM analysis charts for the peak of the Sygna (**a**) and Pasha Bulker (**b**) events, as well as 300 hPa geopotential height (red) and wind speed (shaded greyscale) from Mills et al. (2010) shown for the Sygna (**c**) and Pasha Bulker (**d**) events with latitude, longitude and state boundaries also presented

of lower-tropospheric cyclogenesis to upper-tropospheric vorticity is mediated by static stability. In particular, lower values of static stability, as noted in the pattern of evolution listed in the steps above, are more conducive to deeper penetration depth of an induced circulation (Hoskins et al. 1985; Bluestein 1993; Mills 2001).

ECLs can have explosive development in some cases [i.e., very rapid intensification meeting the 'bomb' criterion (Sanders and Gyakum 1980)] making it challenging to forecast their occurrence and associated hazards. Australia's east coast region typically experiences about one or two bomb cyclones each year on average (Speer et al. 2009; Allen et al. 2010; Lim and Simmonds 2007).

The following sections provide further details on ECL development mechanisms. This includes information for hybrid events, warm seclusions and transitioning tropical cyclones (Sect. 3.2) as well as convection and sea-surface temperatures (Sect. 3.3).

3.2 Hybrid events, warm seclusions and transitioning tropical cyclones

As discussed in Sect. 2.2, ECLs can differ in their physical structure and energetics, including variations in their prevailing amounts of barotropic or baroclinic characteristics, noting that these balances may evolve through the life cycle of an individual ECL. For example, the classification system of Hart (2003) has been used in some studies to help understand cyclone structure and the processes that lead to cyclone development, be they primarily baroclinic (as is common for extratropical cyclones) or barotropic (as is the case for tropical cyclones) or a more balanced combination of baroclinic and barotropic conditions in the case of some cyclones near eastern Australia described as hybrid cyclones (Garde et al. 2010; Browning and Goodwin 2013; Pezza et al. 2014; Cavicchia et al. 2019; Quinting et al. 2019b). The Hart (2003) classification system includes a consideration of lower tropospheric thermal symmetry, with tropical storm structures being more thermally symmetric or non-frontal than extratropical storm structures which are more asymmetric or frontal. In particular, hybrid cyclones are characterised by a warm core at low levels and a cold core at upper levels. Examples such as these highlight the value in considering vertical structure when classifying cyclone types in this region.

There are a few cases in the literature that have clear barotropic features in their structure [including some events in the Mediterranean Sea (Miglietta et al. 2013; Cavicchia et al. 2014; Walsh et al. 2014; Gaertner et al. 2017)] but clear examples are not available in the literature for the Australian east coast region: i.e., that don't have highly asymmetric low-level wind and rainfall patterns while still being unambiguously cold core, albeit with some complexity. Further research into such topics could help avoid difficulties around classification of storm type. The Duck event was a cyclone near eastern Australia which some people considered a tropical cyclone given its size and intensity, but which has since been confirmed in various studies to be more consistent with a hybrid type of system (Cavicchia et al. 2018). Improved knowledge on the development and structure of hybrid systems could be important including for some weather forecast applications or in relation to planning for extreme weather impacts.

Another category of events are ECLs with a prevailing warm core structure in the lower troposphere are warm seclusion cyclones. These systems represent the mature stage of the lifecycle described by Shapiro and Keyser (1990), with characteristics such as rapid pressure falls and eye-like features near their centre in some cases, noting that cyclone phase space diagnostics portray a thermally warm core and symmetric frontal structure (Maue and Hart 2006). It should be noted that Schultz et al. (1998) suggested that these cyclones were an alternative life-cycle of extratropical cyclogenesis to that offered by the warm occlusion paradigm of the Bergen School (Bjerknes 1922) due to their development under diffluent (occlusion) or confluent (warm seclusion) upper trough environments. They can also cause severe hazards including extreme winds and rainfall sometimes at relatively small spatial scales due to baroclinic processes (distinct from thunderstorm-related processes that can cause hazardous convective rainfall, wind gusts and tornadoes). In addition to the relatively small-scale (e.g., mesoscale) of some low-level warm seclusions, and as a consequence of the warm seclusion process, a characteristic of these cyclones is a strong low-level wind maximum asymmetric to the storm (Mills et al. 2010).

Another ECL development pathway involving variations in barotropic and baroclinic characteristics is given by transitioning tropical cyclones. Previous studies focusing on extra-tropical transitions of tropical cyclones in the South Pacific region (Sinclair 2002) estimated that about one-third of tropical cyclones in the region migrate south of 35°S. It was also found that the structure change (i.e., transitioning from tropical to extratropical) occurs closer to the Equator as compared to Northern Hemisphere tropical cyclones, with baroclinic effects already starting to be important at 20°S. Sinclair (2002) note the following for 25°S: "the average tropical cyclone having lost the characteristic symmetric anticyclonic outflow aloft and acquired the characteristics of a baroclinic mid-latitude storm, including regions of warm and cold frontogenesis, a vertical motion dipole and a westward tilt with height". Examples such as this also highlight the value in considering vertical structure when classifying cyclone types in this region.

3.3 Convective processes and sea surface temperatures

A range of localised processes may also be important for ECL development, including noting that deep convection can amplify cyclogenesis by increasing low-level convergence. For example, an early numerical modelling case study showed that a 10-level 150 km resolution model can capture ECL genesis, while also indicating that small-scale processes including moist convection and latent heat release can also contribute to some aspects of ECL development and intensification (Leslie et al. 1987). Deep convective processes were also evident for the Pasha Bulker ECL, including from examinations based on lightning observations (Dowdy and Kuleshov 2014) and modelling (Chambers et al. 2014). In addition to case studies, a systematic study found that the maritime east coast region of Australia is the favoured location in the South Pacific Ocean for cyclones to occur together with deep convective systems (thunderstorms) and frontal passages for causing storm-related weather extremes (Dowdy and Catto 2017).

The warm East Australian Current (EAC) could potentially influence some aspects of ECL activity, such as by increasing the land-sea temperature contrast, moisture availability and baroclinicity during the cooler months of the year, similar to the influence of western boundary currents on cyclone characteristics reported in some other regions of the world such as the Gulf Stream, Agulhas Current and Kuroshio Current (Majodina and Jury 1996; Nelson and He 2012; Hirata et al. 2016). Modelling studies have indicated that warm-core mesoscale eddies in the EAC can change the location of strongest convection during cyclones (Chambers et al. 2014, 2015), as well as increase the likelihood of surface cyclone development given less favourable upper-tropospheric conditions and increase the average rain rate of ECLs (Pepler et al. 2016a). However, evidence for the impact of warm SSTs on strong ECLs is mixed (McInnes et al. 1992; Chambers et al. 2014, 2015), noting that ECLs were found to still occur even after completely removing the EAC in model studies as long as the upper-tropospheric conditions were suitable (Pepler et al. 2016a).

Holland et al. (1987) suggested that the elevated topography of the east coast could play a role in convective processes associated with ECLs, due to advection of warm and moist air from offshore on the poleward side of the ECL over the coastal ranges which could aid convection and rainfall (i.e., due to the availability of low-level moisture and relatively warm air combined with uplift associated with the topography of the Great Dividing Range). While noting that orographic uplift could play a role in enhancing the rainfall produced by ECLs close to the coast, a modelling study (Pepler et al. 2017) found that topography may play a relatively minor role in ECL development, reporting little change in total number of ECLs recorded after removing topography in a regional climate model simulation for eastern Australia.

Surface cyclone development can sometimes occur in the absence of an upper level low, particularly during the warm season and in the northern part of the region, and are generally associated with smaller and less-impactful systems (Pepler et al. 2016a). Such systems during summer may potentially be related to other phenomena including types of convective systems. For example, mesoscale convective systems (MCSs), which can be associated with severe thunderstorms and the generation of convective hazards such as tornadoes and extreme wind gusts, could potentially be indicated by a localised region of low pressure in fine-resolution model output or reanalyses (e.g., mesoscale convective vortex with a core diameter of the order of 50–100 km) (Houze 2004).

3.4 Forecasting guidance on ECL meteorology

The operational approach to forecasting the likelihood of an ECL developing in the medium to long term is to use deterministic and ensemble NWP guidance to identify the likelihood of a favourable arrangement of the synoptic weather patterns (e.g., development of upper jets, location and structure of the poleward high-pressure system). Different scenarios developing between deterministic models or within an ensemble are communicated with emergency managers and the media.

Once confidence increases that a low is likely to develop, the focus then shifts to include more use of observational data such as satellite and radar for assessment of short-term intensification and likely degree of impact. An example of this in the short-term would be identification of a line of deep convective cells developing offshore along a line of horizontal wind shear, and that are likely to advect across a sensitive river catchment or heavily populated part of the coastline. Other sources of guidance that are useful in assessing the level of threat include high resolution convection-allowing models, which are often better at identifying the peak wind speeds and rainfall amount, but which are currently deterministic-only models in the Australian domain rather than ensembles and suffer from phase errors and relatively short lead times; and the BoM's operational storm surge model, for assessing the risk of flooding in low-lying coastal areas.

The current working method of defining an ECL in BoM is based on the observation that over time emergency services, the media and the broader community have come to associate the term 'east coast low' with significant weather impacts. As a result, labelling an upcoming system as an ECL can result in a stronger response from these groups. To ensure that the level of response matches the threat posed by the system to the greatest extent possible, a classification has been developed that is focussed on distinguishing the more intense cyclones likely to have significant impacts. The label 'ECL' is reserved for intense closed cyclonic circulations at the surface, with a trough or cut-off low evident in the middle and upper troposphere, that remain within 2°–3° of the east coast for at least 12 h. This approach identifies primarily those cyclones that have a higher risk of causing strong winds and heavy rain, and distinguishes them from other types of coastal lows. This operational approach highlights the value in considering vertical structure when classifying cyclone types in this region.

Lows that develop over land, and then intensify as they cross the coast before moving away rapidly to the east are labelled 'transient lows'. These can produce a short period of severe wind or rain but typically not thought to be associated with high impact events. Lows that are deep and persistent, but too far offshore to cause coastal severe weather are labelled 'Tasman lows' by forecasters. These 'Tasman lows' can still produce severe coastal erosion and large waves, which may be important to consider for some coastal engineering applications (Shand et al. 2011). Lows that develop within a coastal trough but remain weak and shallow are labelled as 'coastal troughs'. These are typically too weak to produce strong winds or large waves but can produce some heavy coastal rain. This communication and community response-based approach could be considered similar to a type of hazard-based approach, as described in Sect. 2.3.

A key part of effective communication in the lead-into significant weather events is ensuring that the message to the public is as consistent as possible between key information sources. The approach and aims of this classification method have been discussed by the NSW state office of BoM with stakeholders such as the state emergency services (NSW SES), a government media organisation (the ABC) and a private company providing weather information in Australia (Weatherzone) and efforts have been made for consistent use of this terminology in recent weather events. In particular, having labels to use in events that are not considered likely to be high impact has proven effective in promoting a more consistent message to the public.

In the NSW state office of BoM, a checklist has been developed to assist operational meteorologists with identification of the dynamical conditions that lead to the development of coastal lows (Fig. 3). This is based primarily on the model for development by Mills et al. (2010) described in Sect. 3.1, but also considers other potential forcing mechanisms such as ocean eddies (e.g. as discussed in Sect. 3.3). This checklist generally identifies the more intense ECLs that cause significant weather impacts, noting that this approach has practical benefits for public engagement applications.

4 Weather and ocean extremes generated by ECLs

This section presents a summary of different types of weather and ocean extremes, based on the various approaches used in previous studies of ECLs and their impacts. Further details, on temporal variation in hazards associated with ECLs, are also included in Sects. 5.2, 5.3, 6.3 and 6.4.

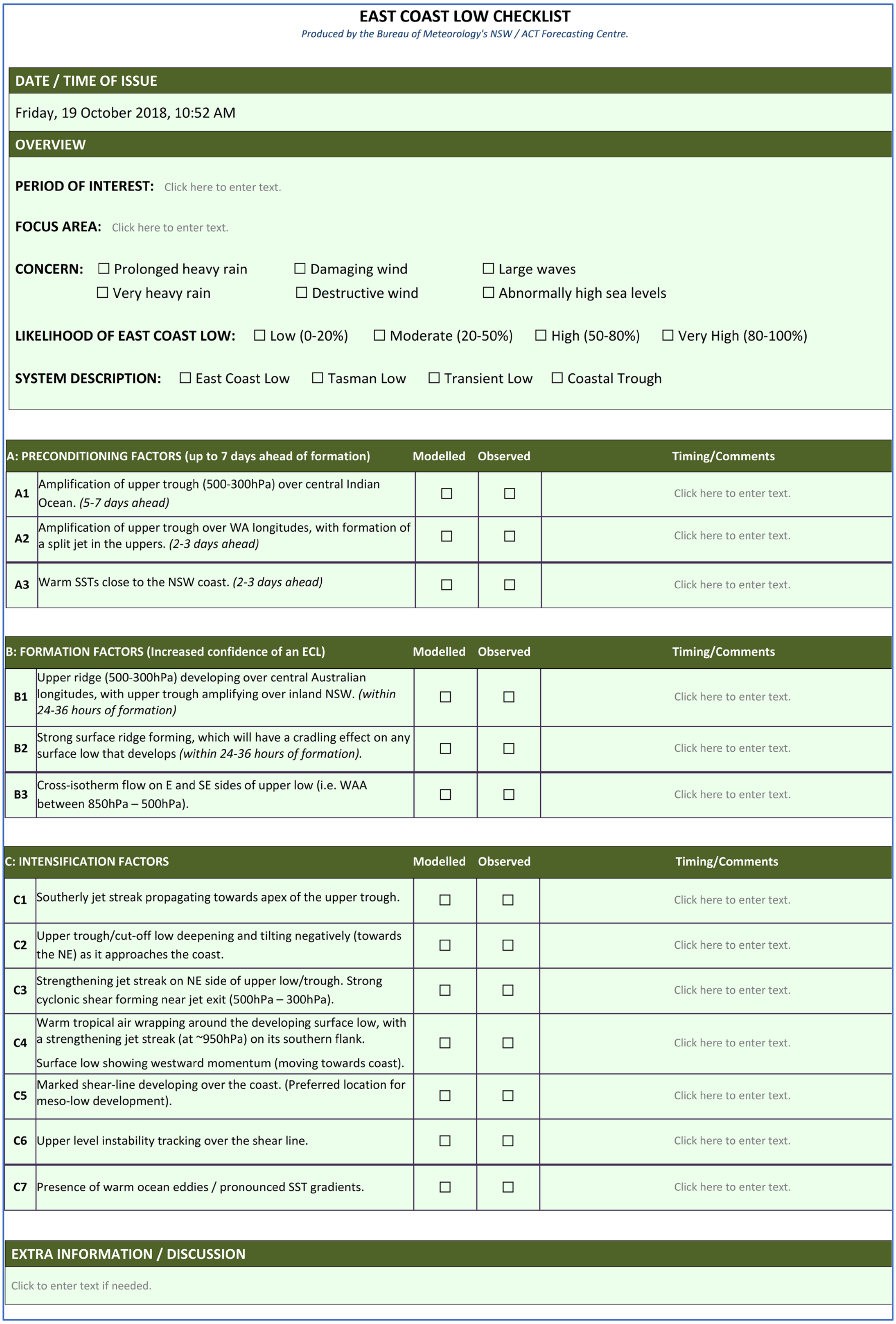
As well as being important for water availability in this region (Pepler and Rakich 2010; Dowdy et al. 2013b), many of the most severe impacts on eastern Australia from natural hazards have been associated with ECLs. This includes impacts associated with gale or storm force winds along the coast and adjacent waters, heavy widespread rainfall and flooding (including riverine flooding, flash flooding and storm surge) and rough seas and prolonged heavy swells over coastal and ocean waters, which can cause coastal and maritime hazards.

Health impacts can include loss of life including from flooding, falling trees and other extreme wind-related hazards, noting also the many shipwrecks and losses of small craft that have occurred during ECLs (Callaghan and Helman 2008; Mills 2001), with a comprehensive list of historical events also provided by Callaghan and Power (2014). The range of hazards that can be caused by ECLs [including from compound events (Dowdy and Catto 2017)] can lead to various economic, social and environmental impacts, dependant on additional factors such as the level of exposure and vulnerability to a hazard (Zscheischler et al. 2018).

4.1 Extreme precipitation and flooding

East coast lows are responsible for many of the largest rainfall totals on the east coast, including the record for Sydney of 328 mm during an ECL on 6 August 1986. A recent ECL event from 4 to 6 June 2016 resulted in 365 mm recorded at Robertson (Illawarra, NSW, Australia) together with severe flooding as well as coastal erosion (around Collaroy in Sydney, NSW, Australia). Many other notable examples are listed in Callaghan and Power (2014), including historical events dating back to the 1800s.

Hopkins and Holland (1997) attributed over 16% of all coastal heavy rainfall between 20°S and 40°S to cyclones in this east coast region, and 7% of all major Australian disasters, based on a case study type of approach. The systematic studies of Dowdy et al. (2013b) reported that about 60–80% of extreme daily rainfall events in the NSW eastern seaboard could be associated with ECLs and Pepler



EAST COAST LOW CHECKLIST

Produced by the Bureau of Meteorology's NSW / ACT Forecasting Centre.

DATE / TIME OF ISSUE

Friday, 19 October 2018, 10:52 AM

OVERVIEW

PERIOD OF INTEREST: Click here to enter text.

FOCUS AREA: Click here to enter text.

CONCERN: ☐ Prolonged heavy rain ☐ Damaging wind ☐ Large waves
☐ Very heavy rain ☐ Destructive wind ☐ Abnormally high sea levels

LIKELIHOOD OF EAST COAST LOW: ☐ Low (0-20%) ☐ Moderate (20-50%) ☐ High (50-80%) ☐ Very High (80-100%)

SYSTEM DESCRIPTION: ☐ East Coast Low ☐ Tasman Low ☐ Transient Low ☐ Coastal Trough

A: PRECONDITIONING FACTORS (up to 7 days ahead of formation)		Modelled	Observed	Timing/Comments
A1	Amplification of upper trough (500-300hPa) over central Indian Ocean. *(5-7 days ahead)*	☐	☐	Click here to enter text.
A2	Amplification of upper trough over WA longitudes, with formation of a split jet in the uppers. *(2-3 days ahead)*	☐	☐	Click here to enter text.
A3	Warm SSTs close to the NSW coast. *(2-3 days ahead)*	☐	☐	Click here to enter text.

B: FORMATION FACTORS (Increased confidence of an ECL)		Modelled	Observed	Timing/Comments
B1	Upper ridge (500-300hPa) developing over central Australian longitudes, with upper trough amplifying over inland NSW. *(within 24-36 hours of formation)*	☐	☐	Click here to enter text.
B2	Strong surface ridge forming, which will have a cradling effect on any surface low that develops *(within 24-36 hours of formation).*	☐	☐	Click here to enter text.
B3	Cross-isotherm flow on E and SE sides of upper low (i.e. WAA between 850hPa – 500hPa).	☐	☐	Click here to enter text.

C: INTENSIFICATION FACTORS		Modelled	Observed	Timing/Comments
C1	Southerly jet streak propagating towards apex of the upper trough.	☐	☐	Click here to enter text.
C2	Upper trough/cut-off low deepening and tilting negatively (towards the NE) as it approaches the coast.	☐	☐	Click here to enter text.
C3	Strengthening jet streak on NE side of upper low/trough. Strong cyclonic shear forming near jet exit (500hPa – 300hPa).	☐	☐	Click here to enter text.
C4	Warm tropical air wrapping around the developing surface low, with a strengthening jet streak (at ~950hPa) on its southern flank. Surface low showing westward momentum (moving towards coast).	☐	☐	Click here to enter text.
C5	Marked shear-line developing over the coast. (Preferred location for meso-low development).	☐	☐	Click here to enter text.
C6	Upper level instability tracking over the shear line.	☐	☐	Click here to enter text.
C7	Presence of warm ocean eddies / pronounced SST gradients.	☐	☐	Click here to enter text.

EXTRA INFORMATION / DISCUSSION

Click to enter text if needed.

Fig. 3 Operational checklist used in the NSW state office of BoM for forecasting the likelihood of an intense ECL et al. (2014) found that ECLs are responsible for more than half of all events with widespread heavy daily rain on the east coast between May and August. Differences in such values between studies reflect the different types of events considered, with Hopkins and Holland (1997) only selecting the more intense events (i.e., only about 2 events per year on average), as compared to more than 20 events per year on average for those recent studies based on systematically-defined ECL events (Dowdy et al. 2013b; Pepler et al. 2014).

There is often a sharp contrast in ECL-related rainfall between the coast and inland regions (with rainfall primarily on the coastal side of the Great Dividing Range), as well as around small-scale topographic features [e.g., as discussed by Kiem et al. (2016)]. The significant contribution of ECLs to heavy and widespread rainfall along the east coast leads to over half of the major floods in this region being caused by ECLs (Callaghan and Power 2014). ECLs can also have positive impacts, such as contributing significantly to large inflow events for rivers (Dowdy et al. 2013b) that are important for water storage and availability. For example, Sydney Catchment Authority data indicates that significant inflows to reservoirs are generally from extreme events, rather than the sum of many weak events, and more than 60% of all major inflow events can be attributed to ECLs (Pepler and Rakich 2010). In addition, due to their propensity for strong southeasterly winds and high moisture, ECLs can cause significant snowfall in elevated regions of southeast Australia (Fiddes et al. 2015).

In relation to forecasting the risk of extreme precipitation associated with ECLs, ensemble-based modelling approaches have shown potential for representing the location and intensity of ECL-related rainfall. For example, a recent case study of an ECL event between 20 and 23 April 2015 found that although small synoptic-scale differences between ensemble members produce large differences in the location and strength of rainfall, the simulated ensemble-mean forecast rainfall was found to be in good agreement with the observed rainfall for that event (Zovko-Rajak et al. 2018).

4.2 Strong winds and convection-related hazards

Wind speeds for ECLs are typically lower than for tropical cyclones. However, the second strongest wind gust on record at a NSW observing station occurred on 26 May 1974 at Newcastle Nobbys during the Sygna ECL (Fig. 2), named after the ship that ran aground during that storm, with a 3-s wind gust of 170.6 km/h being recorded (at 0200 Local Time on 26 May 1974). This wind gust is second only in strength (for NSW records) to the tornado that occurred in the Sydney suburb of Kurnell in December 2015 (with a wind gust of 213 km/h being recorded). The gust of 170.6 km/h recorded for the Sygna ECL is within the range associated with a Category 3 tropical cyclone according to the BoM classification system for which maximum wind gusts within the range 165–224 km/h are required. The maximum wind gust recorded during the Pasha Bulker ECL in June 2007 was 135.4 km/h (at Nora Head at 0100 Local Time on 9 June 2007), falling with the range used by BoM for a Category 2 tropical cyclone.

The strongest winds generally occur on the south side of the low (Mills et al. 2010; Pepler et al. 2018). The impacts of surface ECLs can also increase when they occur to the north or northwest of a high-pressure system due to increased pressure gradients, and thus wind speeds, to the south of the cyclone. Quasi-stationary high-pressure features can result in blocking that can influence ECL activity (Dowdy et al. 2010), acting to slow down cyclone translational speed, or result in meridional movement patterns, which can extend the period for which significant coastal impacts occur over a given region (e.g., quasi-stationary influences could lead to slow translational speeds for cyclones in some cases). The relatively slow translational speeds of some ECL systems can cause prolonged periods of strong winds. For example, Sydney Airport recorded 10-min mean wind speeds above 50 km/h for 44 h during an ECL in April 2015.

ECLs can sometimes be associated with deep convective processes, including thunderstorms, with events such as the Pasha Bulker ECL recording a large amount of lightning activity (Dowdy and Kuleshov 2014; Chambers et al. 2014). The Pasha Bulker ECL was also influenced by a frontal system, in addition to convective processes, during the storm's development (Mills et al. 2010). Complementary to case study examinations such as these, systematic climatological investigations indicate that in subtropical east coast regions of Australia and other continents of the world, extreme weather conditions such as heavy rainfall and severe winds are frequently caused by compound events consisting of cyclones that occur together with fronts and thunderstorms (Dowdy and Catto 2017), including the maritime east coast region of Australia as a favoured location for the combined influence of cyclones together with deep convective systems (thunderstorms) and frontal passages for causing storm-related hazards.

Tornadoes have also been observed to occur in association with some ECLs, including a tornado event causing major damage at Kiama near Sydney in February 2013, as described in BoM monthly weather summary reports and analysed by Louis (2018). Another example of tornado event, in July 1962, which caused extensive damage and claimed three lives around Port Macquarie in northern NSW, occurred in conjunction with a closed upper cyclonic circulation as part of the synoptic-scale conditions that helped influence the formation of the tornado event (Zillman 1962).

4.3 Storm surges, waves, coastal flooding and erosion

Extratropical cyclones are the main mechanism for generating the strong winds that can cause large ocean waves in temperate regions of the world, with ECLs being associated with a range of coastal hazards in southeastern Australia (McInnes and Hess 1992; Mills 2001; McInnes and Hubert 2001; McInnes et al. 2002, 2016). Although tropical cyclones can have some influence on the occurrence of large waves in Australia's subtropical coastal regions, the largest waves in this region are most commonly attributable to ECLs (Short and Trenaman 1992; Dowdy et al. 2014). For example, extreme wave heights (e.g., above 14 m for maximum wave height, H_{max}) were reported in Sydney during severe ECLs in June 2007 and April 2015 based on ocean buoy observations (Kulmar et al. 2005). In Shand et al. (2011), all of the ten largest wave events for each coastal buoy south of 32°S were attributed to ECLs, as well as 70–80% of high wave events at stations between 27°S and 32°S, with the remainder associated with tropical cyclones. The extreme wind and wave conditions that ECLs can cause have resulted in many shipwrecks and small craft lost during these storms (Callaghan and Helman 2008).

Elevated sea levels are related to a number of factors including tides and storms (such as ECLs), as well as rising sea levels due to anthropogenic global warming (Stocker 2014; McInnes et al. 2015). Periods of prolonged strong winds associated with ECLs can also contribute to extreme sea level and storm surge events, with large waves also being associated with hazards such as coastal erosion and flooding (McInnes et al. 2016; Harley et al. 2017). McInnes and Hubbert (2001) attributed the majority of storm surge events on the east coast between 1966 and 1990 to cut off lows in the Tasman, which would generally be considered ECLs. This included the record tidal anomaly of 0.69 m at Coffs Harbour on 11 June 1974.

Due to their influence on water levels and wave heights, ECLs can also cause substantial coastal erosion. For the ECL in June 2016, 11.5 million m^3 of sand was eroded from a 177 km stretch of shoreline, with an average shift in shoreline position of 22 m, noting that a net deposit of sand occurred for the coastal zone overall when considering deeper regions away from the shoreline (Harley et al. 2017).

5 Historical climatology

This section examines the characteristics of ECLs and associated hazards primarily based on a climatological perspective spanning the historical period of reliable station and satellite observations (e.g., as distinct to paleotempestology investigations and potential decadal or multi-decadal oscillations, which are not the intended focus of this review). Aspects covered in this section include the mean characteristics of ECLs and associated weather and ocean hazards, as well as their seasonal variability and relationship with modes of large-scale variability (such as the El Niño-Southern Oscillation: ENSO). Climatological aspects of ECLs are also discussed in relation to cyclones with similar characteristics from other regions of the world, including around the subtropical east coasts of other continents. Long-term climatological changes and future climate projections are presented in the subsequent Sect. 6.

5.1 Climatological mean characteristics

The large variety in ECL definitions used in previous studies, as detailed in Sect. 2, results in a large range in the reported mean frequency of occurrence of ECL events. Studies that focus on severe cyclones with major coastal impacts identify only about one or two ECLs on average per year (Holland et al. 1987; Hopkins and Holland 1997; Callaghan and Power 2014). In comparison, Speer et al. (2009) manually identified all surface cyclones on the east coast between 1970 and 2006, reporting on average 22 ECLs per year occurring on about 36 days per year on average (as some events have durations longer than a day). Of the 22 ECL events per year, on average 7–8 caused widespread daily rainfall totals above 25 mm, 2–3 caused rainfall totals above 100 mm, and one underwent rapid development (i.e., intensification).

Cyclone frequencies identified in studies that apply automated tracking procedures are sensitive to various factors including choices of method, data resolution and intensity thresholds (Pepler et al. 2015; Di Luca et al. 2015), and thus are often tuned to match an assumed frequency. This tuning can be done by adding extra criteria to define a cyclone for methods that indicate too many events, such as by excluding events where the maximum geostrophic wind is not directed towards the coastline (Browning and Goodwin 2013). The method of Dowdy et al. (2011, 2014) is based on strong cyclonic vorticity using the 90th percentile as a threshold value [i.e., matched to the historical mean number of 36 ECL days per year from Speer et al. (2009)] which provides a consistent occurrence frequency across different datasets (e.g., that may differ in characteristics such as resolution).

The spatial climatology of ECLs is characterised by a local maximum in occurrence frequency near the east coast of Australia (Fig. 1), both as indicated from surface measures, as well as based on conditions higher in the troposphere. This region is characterised by a relatively high frequency of strong vorticity anomalies associated with cyclogenesis at various levels of the troposphere, including features relating to the strong jet stream in the upper troposphere that can occur, particularly around winter

(Hoskins and Hodges 2005). Strong vorticity anomalies in the upper troposphere in this region can be associated with variations in the jet stream, including strong curvatures or a split in the jet stream, as well as blocking systems that can influence the upper-tropospheric winds (Hoskins and Hodges 2005; Dowdy et al. 2010, 2013c; Ndarana and Waugh 2010; Yanase et al. 2014; Catto 2016). These features may potentially be interrelated to some degree, including at a hemispheric scale, through Rossby wave activity and quasi-stationary climatological features (e.g., associated with local orography and atmospheric conditions at different longitudes, as can be associated with strong temperature differences between a continent and adjacent ocean regions). Examining the role of such features in relation to ECL characteristics provides considerable scope for future research (as summarised in Sect. 7.3).

A recent study has examined the role of local environmental drivers of ECL activity, aimed at classifying each event into different categories according to their vertical and thermal structure (Cavicchia et al. 2019), finding that approximately two-thirds of the detected low-pressure systems are fully cold core storms while the remaining third show hybrid characteristics. A smaller fraction of events was found to be fully warm core cyclones, in part being transitioning tropical cyclones, as well as in part warm seclusion cyclones. Cold core cyclones are more frequent in the southern parts of the ECL region, while hybrid cyclones are more frequent closer to the tropics. Another study (Quinting et al. 2019a) considered the cyclone characteristics only at the time of peak intensity (in contrast to Cavicchia et al. (2019) who based the classification over the cyclone lifetime), reporting that 46% of ECLs were hybrid cyclones. This difference between studies suggests the possibility that hybrid characteristics might occur more frequently around the time of peak intensity than on average over the ECL lifetime.

5.2 Seasonal variability of ECLs and associated hazards

East coast lows can occur at any time of year but tend to have a maximum occurrence frequency during the cooler months (Fig. 4), while noting considerable variation in the mean seasonal cycle of ECL occurrence frequency as reported by various other studies. In particular, the cool-season maximum is stronger in studies that focus on the most extreme subset of events and explosive cyclones (Hopkins and Holland 1997) or well-defined deep cyclones that have clear signatures at higher levels of the troposphere (Dowdy et al. 2011, 2013a), whereas cyclones during the warm season are more likely to be small, shallow, weak, short-lived and poorly defined (Di Luca et al. 2015). It was recently shown (Cavicchia et al. 2019) that different types of ECLs show some differences in their seasonality, including that cold core cyclones in this region occur more frequently during the cold season, whereas hybrid storms occur with comparable frequency in the cold and warm seasons.

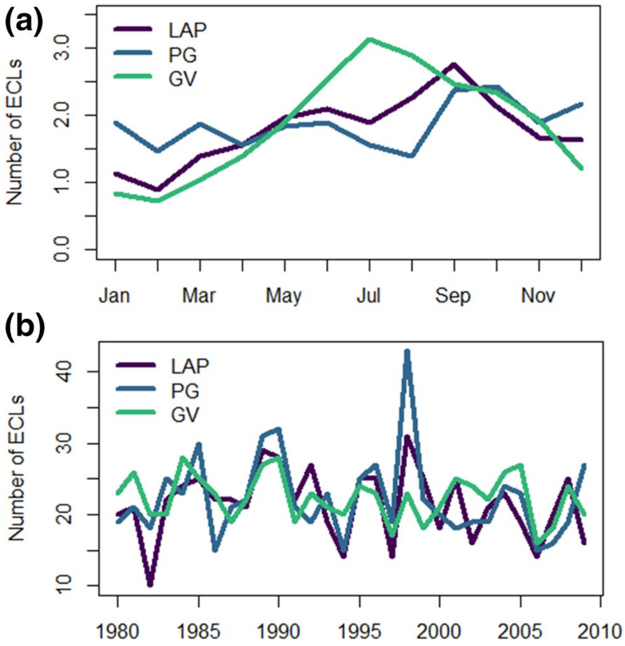


Fig. 4 Temporal variability of ECL activity based on three different detection approaches used in previous studies, including the monthly mean number of events (**a**) and the annual number of events (**b**). The data are based on ERA-Interim reanalysis from 1980–2009 following the methods described in Pepler et al. (2015), with the three detection approaches as described in Pepler et al. (2014) (purple: based on the Laplacian of MSLP, 'LAP'), Di Luca et al. (2015) (blue: based on surface pressure gradients, 'PG') and Dowdy et al. (2011) (green: based on strong cyclonic vorticity at 500 hPa, 'GV')

ECLs also make a large contribution to heavy and widespread rainfall during the winter months in the eastern seaboard region (Dowdy et al. 2013b; Pepler et al. 2014; Wu et al. 2018) while heavy summer localised rainfall in that region can also be influenced by phenomena other than ECLs (including convective systems such as severe thunderstorms). While most of the intense ECL events that have led to severe impacts from winds, waves, erosion and flooding have occurred between April and June, intense events can also sometimes occur during other months of the year. For example, a very significant ECL (including with extreme winds and waves) caused several fatalities during December 1998 (Mills 2001), noting that this warm-season event involved a mesoscale secondary low that formed near the larger synoptic-scale system in a reversed-shear environment. Examples such as this highlight the considerable variability between ECL events, including for their associated weather and ocean extremes, which can occur any time of the year.

5.3 Interannual variability and relationships to large-scale atmospheric and oceanic modes

ECLs exhibit large interannual variability, as shown in Fig. 4. The Speer et al. (2009) database had a standard deviation of 4.2 (~ 20% of the mean number of 22) events per year. Furthermore, the number of ECLs that caused significant rain varied from 3 in 2000 to 14 in 1988, with significant rain events defined in that study as multiple stations recording daily rainfall > 25 mm. Severe ECLs have sometimes occurred in temporal clusters, with notable clusters of five ECLs during the month of June 2007 and three ECLs during April 2015. Browning and Goodwin (2013) have suggested that temporal clusters of ECLs tend to be associated with persistent blocking, noting that although temporal clustering has been studied for northern hemisphere extratropical cyclones [e.g. Pinto et al. (2016)] it has yet to be studied in detail for the Australian region.

Seasonal or multi-week predictability of ECLs remains challenging, particularly given that there is limited evidence that ECLs are strongly influenced by large-scale modes of variability (such as ENSO). Hopkins and Holland (1997) suggested that some of the stronger events may be weakly related to ENSO phases, reporting a preference for the more intense cases to occur during the transition between El Niño and La Niña phases of ENSO. Recent systematic studies have found little relationship between ECLs and ENSO (Dowdy et al. 2013a; Pepler et al. 2014) and with results also being sensitive to the choice of ECL definition (Pepler et al. 2015). Relationships with other drivers are also generally weak, including the Indian Ocean Dipole (IOD), Southern Annular Mode (SAM) and East Australian Current (EAC) strength, while some relationship to the strength of the subtropical ridge has been reported (Dowdy et al. 2013a). Some results appear to depend on the various subtype-definitions of ECLs, with positive Southern Annular Mode (SAM) reported to be associated with an increase in winter easterly trough events but not with other subtypes of ECLs (Browning and Goodwin 2013). The mixed findings from studies such as these indicate considerable scope for further investigations into potential influences of large-scale modes on ECL formation processes.

Rainfall in eastern Australia is generally more common during La Niña than El Niño conditions, with the main exception being the eastern seaboard region where this relationship is relatively weak compared to regions on the other side of the Great Dividing Range ridgeline (Risbey et al. 2009). The weak relationship between ECLs and ENSO may be one reason for the weak relationship between rainfall and ENSO in this eastern seaboard region, while also noting a relatively weak relationship between thunderstorms and ENSO conditions in this region (Dowdy 2016). Power and Callaghan (2016) reported that ECL-related flooding is most common during La Niña years, indicating that the relationship between ENSO and ECL-related flooding may not simply be due to increased rainfall in general, but could potentially also relate to additional factors associated with flood risk [e.g., pre-existing soil moisture, as discussed in Johnson et al. (2016)].

5.4 Comparisons with other regions of the world

East coast lows have several similarities with cyclones in other regions of the world, often at subtropical latitudes near the east coasts of continents as well as around Hawaii and in the Mediterranean Sea. These similarities include a characteristic strong cyclonic vorticity signature in the middle and upper troposphere (e.g., Catto 2016; da Rocha et al. 2018) as well as a high percentage of hybrid systems defined by a significant combination from both barotropic as well as baroclinic influences (Garde et al. 2010; Black and Pezza 2013; Pezza et al. 2014; Yanase et al. 2014; Cavicchia et al. 2018, 2019; Quinting et al. 2019a) (for details see Sects. 2.2 and 3.2).

As noted in Sect. 3.1, ECLs can sometimes have very rapid intensification meeting the ‘bomb’ criterion of Sanders and Gyakum (1980) making it challenging to forecast their occurrence and associated hazards. On average, there are about 70 bomb cyclones worldwide each year (Lim and Simmonds 2007), with about two-thirds of these in the Northern Hemisphere, particularly off the east coasts of the US and Japan, and Australia’s east coast region typically experiencing about one or two bomb cyclones each year on average (Speer et al. 2009; Allen et al. 2010).

The term ‘subtropical lows’ is used to describe cyclones in some regions. These are cutoff lows that form on the equatorward side of the subtropical ridge (Simpson 1952). In that sense, the term ‘subtropical’ can be used primarily in relation to cyclones that are not tropical cyclones but occur equatorward from the main extratropical storm tracks, as distinct from ‘hybrid’ lows considered here based on structure and energetics considerations (as discussed in Sect. 3.2). In the region around Hawaii, subtropical lows are often referred to as Kona Lows, with a variety of different types of definitions used for these storms (Schultz et al. 1998; Otkin and Martin 2004; Caruso and Businger 2006; Timm et al. 2013).

In North America, mid-latitude lows near the east coast are referred to as “nor’easters” or “east coast cyclones”. These extratropical systems can intensify over the warm Gulf Stream waters with severe impacts including strong winds, storm surges, heavy snow (Hirsch et al. 2001; Booth et al. 2015; Colle et al. 2015) and cases of “thundersnow” where convection is embedded in the cyclone structure (Market et al. 2002). Additionally, subtropical cyclones have been extensively documented in the North Atlantic (Guishard et al. 2009; Mauk and Hobgood 2012).

In Europe, severe storms occur frequently with hybrid characteristics, sometimes referred to as "medicanes" when they occur in the Mediterranean region, including with characteristics similar to tropical cyclones in some cases (such as warm-core conditions over a large depth of the troposphere) (Miglietta et al. 2013; Cavicchia et al. 2014; Walsh et al. 2014; Gaertner et al. 2017), or hybrid features in other cases (Fita and Flaounas 2018). Similar hybrid systems have also been observed in the Northeastern Atlantic (González-Alemán et al. 2015), including the Bay of Biscay (Maier-Gerber et al. 2017). In the Indian Ocean, hybrid systems are known to occur on the southeast coast of the African continent, e.g., including around the warm Agulhas current (Majodina and Jury 1996). In the South Atlantic, the occurrence of cyclones with mixed tropical-extratropical features has been documented close to the coast of Brazil (Dias Pinto and Da Rocha 2011; Dias Pinto et al. 2013). Systematic studies of the occurrence of subtropical cyclones in the South Atlantic found similar frequencies to the other ocean basins (Evans and Braun 2012; Gozzo et al. 2014).

6 Climate trends and future projections

6.1 Historical trends

Several studies have examined historical trends in ECL characteristics using observations and reanalysis products. The large interannual variability in ECL occurrence together with the temporal inconsistencies of the underlying data (e.g., changes in the type/amount of assimilated data in reanalyses) has made it difficult to clearly identify significant trends in the historical record.

Speer et al. (2009) identified no strong trend in ECLs between 1970 and 2006 based on a subjective analysis of MSLP charts, although they reported a significant increase in the inland trough subtype of lows. ECL studies based on automated identification methods applied to different reanalysis datasets indicate a small but not significant downward trend in the frequency of ECLs over recent decades (Dowdy et al. 2013a; Pepler et al. 2015). A small decline in ECL frequency since the 1980s was also indicated using the Twentieth Century Reanalysis in Pepler et al. (2016c), with Browning and Goodwin (2013) suggesting that this might be associated with a decrease in a subtype of ECLs they refer to as "southern secondary lows". Ji et al. (2017) also examined ECLs in the Twentieth Century Reanalysis but used three different identification and tracking algorithms to show that this decline over recent decades occurred largely in winter, while an increase occurred in early spring. Using a network of station observations of air pressure (and implied winds), Alexander et al. (2011) found a decline in the frequency of "storminess" in southeast Australia between 1885 and 2008.

These studies indicate considerable scope for further research to investigate historical trends in ECL activity, noting that trends in the hazards associated with ECLs (such as extreme winds, waves, rainfall and flood risk) may potentially be different to the trends in the number of ECL events. For example, a recent study found increases in extreme rainfall intensity of about two to three times larger than the Clausius–Clapeyron scaling rate (i.e., about 6.5% per degree of temperature change) for different regions of Australia (Guerreiro et al. 2018) with this trend potentially having significant consequences for flood and flash flood risks. When considering such studies, in combination with the relatively small historical trend indicated in ECL occurrence frequency, it is perhaps not surprising that an increase in ECL-related rainfall extremes might occur. Relating to this point, Power and Callaghan (2016) identified an increase in the frequency of ECLs that cause coastal flooding between 1876 and 2014, based on a range of data sources including media reports and other historical records.

6.2 Projections of ECL characteristics

A range of different methods have been used to examine future changes in ECL characteristics. This includes methods based on global climate models (GCM) output, as well as a variety of different downscaling approaches. Projections have included future changes in the occurrence frequency of ECLs (as described in this section), as well as for aspects of their associated weather and ocean hazards (as described in Sect. 6.3).

Some early studies of potential future changes to ECLs used limited-area atmospheric models to test the sensitivity of low-pressure systems in this region to warmer SSTs, with results indicating potential increases in ECL-related wind speeds and rainfall due to warmer SSTs (McInnes and Hess 1992; McInnes et al. 1992). This was followed by an examination of the structure of low pressure systems in this east coast region in an early climate model under historical and doubled CO_2 conditions (Katzfey and McInnes 1996), with fewer though more intense low pressure systems indicated for the doubled CO_2 climate, while noting that the modelling approach underpredicted the number of lows (by about 45%) particularly during autumn and winter.

Projections of ECL characteristics for different emissions scenarios over the twenty-first century were first developed using methods based on knowledge from case studies examining their formation processes (Mills 2001; Mills et al. 2010), including a clearly-defined large-scale cyclonic vorticity signature for ECLs in the middle and upper troposphere (Dowdy et al. 2010, 2013c). A method for examining future projections of ECL activity, developed based on strong cyclonic geostrophic vorticity at 500 hPa, was subsequently applied to GCMs from the CMIP3 and CMIP5 set of

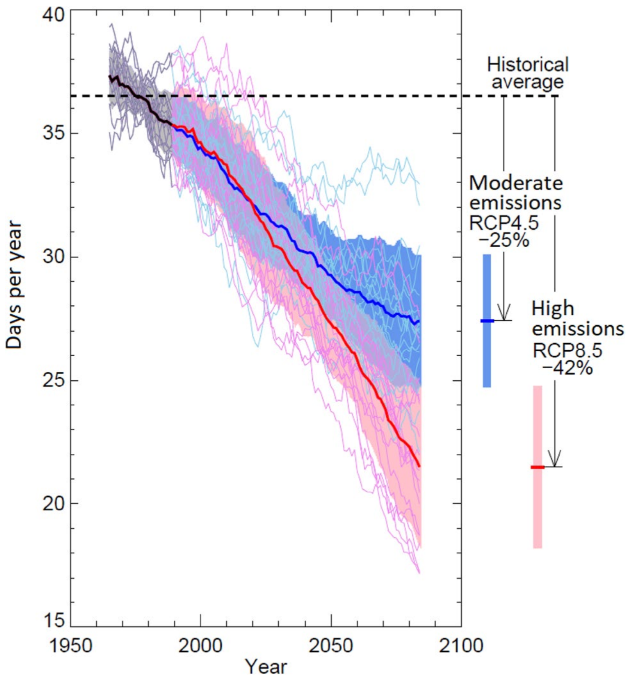


Fig. 5 Projected change in ECL occurrence frequency as indicated by large-scale diagnostics applied to 18 CMIP5 global climate models [for details see Dowdy et al. (2014)]. Projections from all 18 models are shown for moderate (blue, RCP4.5) and high (red, RCP8.5) greenhouse gas emission pathways, as well as for the historical period (black). A 30-year moving average is applied to show the climate signal. The mean values of the 18 models are shown (thick lines), as well as the standard error of the mean (shaded regions: representing one standard error above and below the mean). The mean and standard error for the period 2070–2100 are shown for moderate increase (RCP4.5) and larger increase (RCP8.5) in greenhouse gas emissions (as indicated by the coloured bars on the right of the figure) for comparison with the historical average number of events (dashed black line)

experiments, showing a decline in ECL frequency of about 25–40% by 2070–2100 depending on emissions scenario, particularly during the cooler months of the year (Dowdy et al. 2013a, 2014), shown in Fig. 5.

Although current GCMs can reproduce some characteristics of ECLs, including their large-scale environments associated with cyclogenesis and resultant synoptic-scale signatures (e.g., Dowdy et al. (2014) and references therein), they lack sufficient resolution to reproduce finer-scale aspects of ECLs. This includes their relatively small spatial scales for severe hazards (e.g., associated with mesoscale secondary lows or convective processes) and their rapid intensification in some cases [e.g., for systems that meeting the ‘bomb’ criterion (Sanders and Gyakum 1980)]. Furthermore, some orographic features are not well represented at the scale of current GCMs (e.g., topographical details of the eastern seaboard and Great Dividing Range). For reasons such as these, dynamical downscaling of GCM output data has also been used to examine projected changes for the future, including in the intensity of ECLs and associated extreme weather and ocean conditions, while also noting that these downscaling techniques are not necessarily giving more reliable projections in some cases (given that they depend on the larger-scale simulations with which they are forced).

Dynamical downscaling projections have focussed on surface pressure measures of ECL activity with results indicating a decline in the frequency of ECLs, particularly during the cool season (with the decline being more robust for lows located east of the coastline) and no change in the frequency or magnitude of the most intense cyclones (Ji et al. 2015; Di Luca et al. 2016; Pepler et al. 2016b). In contrast to the extreme ECL events during the cooler months of the year, projected changes in the future frequency of warm season events show larger uncertainties, with results being strongly sensitive on the choice of the climate model and the specific method used to identify ECLs (Ji et al. 2015; Pepler et al. 2015). This is shown in Fig. 6 for three different methods, including an upper tropospheric method based on geostrophic vorticity (“ULGV”) as well as two different methods that track low pressure systems using MSLP data (“LAP” and “PG”) each of which was run over data with two different horizontal resolutions (50 km and 150 km), as described in Pepler et al. (2015).

In addition to studies focussed specifically on ECLs, the broader analyses of southern hemisphere mid-latitude cyclones as provided in a range of other studies may also be useful to consider in relation to plausible future changes in ECL characteristics. For example, GCM simulations generally project a poleward shift of the main storm track latitude (i.e., the regions of maximum frequency of cyclones) accompanied by a general reduction in the frequency of storms over the coming century (Bengtsson et al. 2009; Chang et al. 2012; Grieger et al. 2014; Li et al. 2014). Complementary to this result in relation to the more southern ECLs, the more northern ECLs share some characteristics with tropical systems (including more barotropic and warm core conditions), with fewer tropical cyclones projected for the future climate in the region around Australia (Bell et al. 2018) while noting that some studies indicate a higher proportion of these tropical cyclones could be classed as severe (CSIRO and BoM 2015; Walsh et al. 2016).

6.3 Climatological changes in ECL-related weather and ocean extremes

Climatological change in ECL-related weather and ocean extremes could occur for a number of reasons. This includes due to changes in the characteristics of ECLs, as well as due to changes in other contributing influences. The specific characteristics of an ECL, including its intensity, speed of movement and distance from the coast can all influence the severity of hazards, noting that there are currently

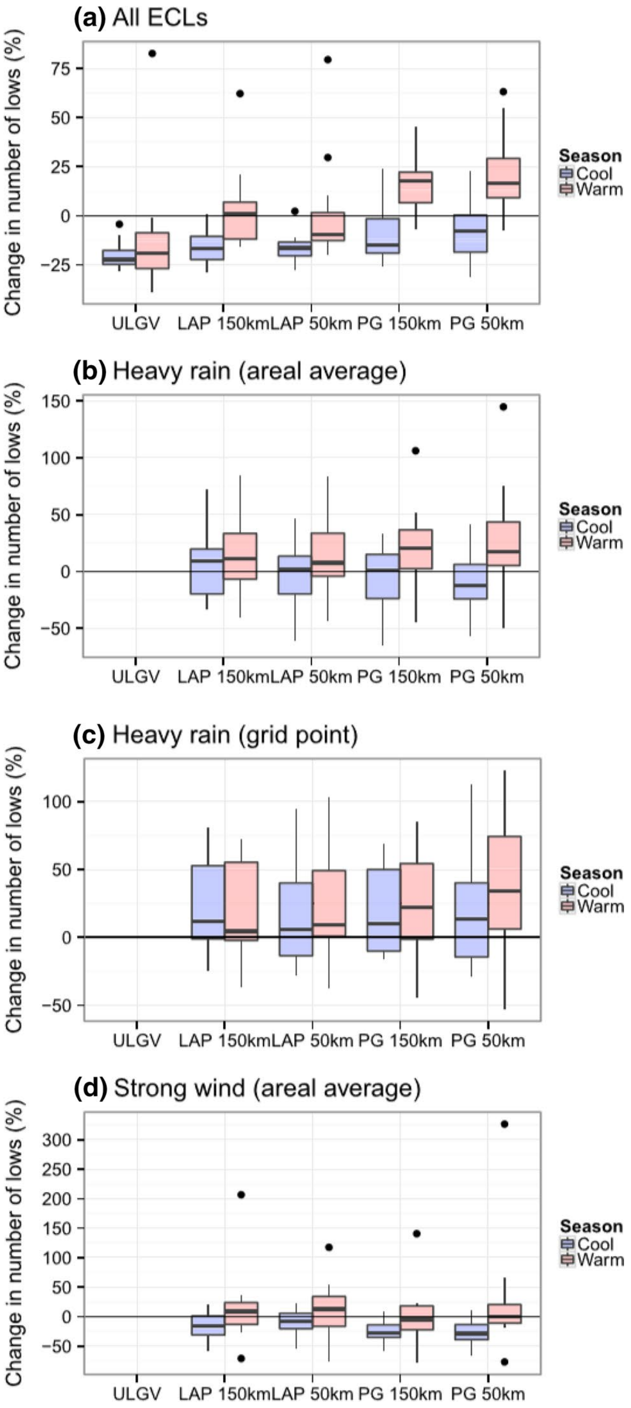


Fig. 6 Projected changes in ECLs and associated severe weather ▶ conditions, shown for warm and cool periods of the year based on a range of different modelling methods [“ULGV”, “LAP 150 km”, “LAP_50 km”, “PG_150 km” and “PG_50 km” from Pepler et al. (2015)]. **a** Percentage change in the total number of ECLs per year between 1990–2009 and 2060–2079; **b** percentage change in the number of ECLs where the mean rainfall intensity within 500 km of the low centre exceeds 6 mm in 6 h in at least one instance; **c** percentage change in the number of ECLs where the maximum rainfall intensity within 500 km of the low centre exceeds 50 mm in 6 h in at least one instance; **d** percentage change in the number of ECLs where the mean hourly wind speed within 500 km of the low centre exceeds 50 km/h in at least one instance. In all cases ECLs are selected using a model-dependent threshold that gives 22 ECLs per year in the current climate, with trends shown for the cool season (May–October) and warm season (November–April) separately. Black dots indicate outlier members of the model ensemble (using a 12-member ensemble of regional climate models). The projections are based on dynamical downscaling (using the WRF model) from CMIP3 GCMs for a high emissions scenario. Further details are provided in Pepler et al. (2015). Image used with permission; ©American Meteorological Society

considerable uncertainties around climatological changes to such characteristics. Additional contributing influences include potential changes to the wind and wave directions, which are also important in relation to aspects such as coastal erosion and sediment transport (Mortlock and Goodwin 2015; Goodwin et al. 2016; Harley et al. 2017), as well as rising sea levels due to anthropogenic global warming (Stocker 2014; McInnes et al. 2015) and changes in environmental moisture content (noting the Clausius–Clapeyron relation) which can influence rainfall characteristics as well as associated convection-related hazards (e.g., convective available potential energy is influenced by atmospheric moisture content). These aspects are discussed in this section, in relation to long-term climatological changes in ECL-related hazards.

6.3.1 Rainfall

Modelling case studies of ECLs between 2007 and 2008 found a 15–30% increase in the average rainfall within 250 km of the ECL for a 1°–2° change in SSTs, suggesting a potential for super-Clausius Clapeyron scaling (Pepler et al. 2016a), noting that observed changes similar to this rate of increase have been reported for short-duration rainfall extremes in Australia (Guerreiro et al. 2018). Studies such as these indicate potentially large increases in the upper limit of rainfall intensity that could occur for future ECL events in a warmer world, leading to increased risk factors for ECL-related flooding. Some indication of an increase in ECL-related flooding has already been reported based on observations (Power and Callaghan 2016), while noting that there are considerable uncertainties associated with climatological trends in observed flood events given the large number of contributing factors (Johnson et al. 2016). Early studies of projected changes in ECL occurrence noted that although fewer ECLs are projected to occur in the future, the events that do occur could potentially produce more intense rainfall in some cases (e.g., given the Clausius–Clapeyron relation) (Dowdy et al. 2013b). Regional model simulations show an increase in the average maximum rain rate of ECLs as well as the number of ECLs with heavy rainfall by 2060–2080, particularly during summer in general, despite decreases in total ECL frequency (noting larger reductions expected in ECL numbers during winter than summer) (Pepler et al. 2016b). Additionally, a comprehensive review of rainfall projections for the eastern seaboard region based on observations, process understanding, GCMs and downscaling found that a general enhancement of the seasonal cycle of rainfall was likely, with less rainfall in winter as compared to summer (Dowdy et al. 2015).

Based on considering the results presented in the various studies described above, it is estimated here that widespread or long duration extreme rainfall events associated with ECLs could increase in intensity at about 7% per degree of warming, with larger increases being estimated for short-duration localised extreme rainfall events of the order of about 15% per degree of warming, while noting a plausible magnitude range both above and below this best estimate rate.

The projected warming of the EAC (CSIRO and BoM 2015) could also potentially contribute to an increased risk of heavy rainfall in this region in the future, while noting that previous studies identified a relatively minor role of SSTs on the characteristics of intense ECL events (as detailed in Sect. 3.3). Additionally, regional model simulations suggest that the projected warming of the EAC may also contribute to an increase in the frequency of weaker east coast cyclones near the coast, however, this is unlikely to have a large effect on the frequency of the more severe ECL events (for which upper-tropospheric vorticity is more important) (Pepler et al. 2016a).

6.3.2 Winds and waves

In comparison to rainfall, climatological changes in extreme winds are less certain in general for this region. For example, based on regional model simulations (Evans et al. 2014), Pepler et al. (2016b) found no significant changes to the frequency of ECLs with strong winds, while Walsh et al. (2016) report that maximum wind speeds are projected to increase for summer ECLs but remain relatively unchanged for winter ECLs. However, the mechanisms behind projected future changes in wind extremes associated with ECLs remain to be investigated. Additionally, no studies to date have assessed projected future changes in the direction of strong winds from ECLs.

Dowdy et al. (2014) found that extreme wave heights along the NSW coast (from buoy observations) were primarily associated with offshore ECL events, and demonstrated that these events could be identified using their large-scale signatures resolvable by GCMs, with future simulations indicating fewer extreme wave events in the future associated with ECLs. In particular, larger decreases were projected for higher emissions scenarios, with differences between scenarios clearly distinguished (i.e., greater than the standard error in the model ensemble means) emerging from around the middle of this century onwards. Although not specifically focussed on ECL-related waves, simulations of future waves along eastern Australia using wave models forced by regional climate models also show a decrease in wave heights in general (Hemer et al. 2013a), with that study also noting uncertainties in projected changes in extreme wave heights (such as can be produced by ECLs) based on that particular modelling method. The projected change reported was 0.05–0.10 m for the change from 1981–2000 to 2081–2100 in mean significant wave heights.

Hemer et al. (2013a, b) also projected an anticlockwise shift in the mean wave direction around the more northern regions of NSW and a clockwise shift in the more southern regions of the eastern seaboard, particularly during the winter months. However, no studies have assessed changes in the average wave direction specifically associated with ECLs, while noting that waves can propagate into the east coast region from remote locations, including from tropical regions (e.g., associated with tropical cyclones around northern Australia) as well as extratropical regions (e.g., associated with the main extratropical storm track to the south of the Australian continent). Changes in wave energy flux in NSW regions have also been linked with storm characteristics in eastern Australia, including a directional shift in wave power, reported to likely lead to future changes to sediment transport (Mortlock and Goodwin 2015; Goodwin et al. 2016; Harley et al. 2017).

6.3.3 Coastal impacts

Anthropogenic sea level rise (Stocker 2014) will lead to increases in some coastal impacts of ECLs. The likely global sea level rise by 2081–2100 relative to 1986–2005 is 32–63 cm for midrange emission scenarios, and 45–82 cm for high emissions scenarios. Overall projected sea level rise for the Australian coastline is similar to the global average (McInnes et al. 2015). However, the strengthening of the subtropical gyre circulation of the South Pacific Ocean is projected to lead to larger increases off the south-eastern Australian coastline (McInnes et al. 2015; Zhang et al. 2017a, b). These projections do not fully capture the potential contribution to sea level rise from the large ice sheets (Greenland and Antarctica), whose response to global warming is uncertain and possibly underestimated (Vermeer and Rahmstorf 2009; DeConto and Pollard 2016), with rises exceeding 2.4 m being physically possible later this century as listed in a recent US government synthesis report (USGCRP 2017).

Due to sea level rise, the frequency and magnitude of coastal flooding is expected to increase significantly this century, regardless of changes in storm events such as ECLs (CSIRO and BoM 2015). Notably, a projected sea level rise of 45–82 cm for coastal Australia under mid-range emissions scenarios later this century is comparable to the highest storm surge ever recorded for an ECL, of 69 cm (for details see Sect. 4.3), such that a similar ECL storm surge event occurring in a warmer future world could effectively double the magnitude of the largest event in the historical records.

6.4 Summary of climate change influences

Table 1 provides a summary of the information presented in Sect. 6 on long-term trends and projected future changes. This includes details on the influence of climate change on the occurrence of ECLs as well as on their associated weather and ocean extremes.

7 Synthesis and discussion

The reviews presented in previous sections are synthesised here to provide a concise resource of information on ECL characteristics. It is intended that this information will be beneficial for guidance in planning, preparedness and policy applications relating to ECLs and their impacts, as well as for future research efforts. The includes detail on characterising (Sect. 7.1) and defining (Sect. 7.2) ECLs, as well as summarising key gaps in knowledge to help highlight future research needs (Sect. 7.3).

7.1 ECL characteristics

Cyclones that occur near the central and southeast coastal region of Australia have a range of distinct characteristics as compared to cyclones in other regions around Australia. This includes aspects such as:

- A local maximum near eastern Australia in the occurrence frequency of strong cyclonic vorticity at different levels throughout the troposphere.
- Occurrence at any time of the year, but most common during the cooler months of the year (in contrast to tropical cyclones).
- Large interannual variability in the number of ECL events, but without a strong relationship with ENSO (in contrast to tropical cyclones in this region).
- A relatively weak influence from sea surface temperatures (in contrast to tropical cyclones).
- A large number of hybrid systems in this region (in contrast to the extratropical storm track region further poleward and to the tropical cyclone region further equatorward).
- A high occurrence frequency of intense cyclones that can cause a range of extreme weather and ocean conditions, including due to the relatively slow translational speeds of some systems.
- Strong cyclonic vorticity at synoptic scale in the mid- and upper-troposphere, particularly for the more extreme events during winter.
- Potential for rapid development, and fine spatial scale for associated extreme conditions.
- Convection and frontal influences often interacting with the cyclone, exacerbating the weather extremes in some cases.
- Strong winds often on the southern side of the low, sometimes including small-scale (mesoscale) low-level wind maxima asymmetric to the storm.

Aspects such as these highlight the point that ECLs are an important phenomenon to consider for a range of reasons. Although there are significant differences between methods employed in previous studies, as well as noting other operational forecasting practices, all of the most impactful ECL events are typically identified regardless of the method employed, which suggests a reasonably common set of elements across all methods. These common aspects are used in the subsequent Sect. 7.2 to provide a suitable generalised definition of an ECL.

7.2 ECL definition

Common aspects for previous definitions (as detailed in Sect. 2) is that ECLs are intense low-pressure systems that occur near the east and southeast coastal regions of Australia. This region is typically defined as between southeast Queensland and eastern Tasmania, including the adjacent maritime region in the Tasman Sea. This region spans a range of latitudes from around the edge of the tropical cyclone region of occurrence in the north, to around the edge of the main extratropical storm track region in the south, with ECLs representing a combination of these different types of cyclones in some cases. As shown by Cavicchia et al. (2019), the ECL climatology includes a spectrum of cyclone types, including hybrid tropical/extratropical systems in some cases, based on their vertical structure and environmental forcing conditions. ECLs often have distinct characteristics in the mid- to upper-troposphere, in addition to surface-based characteristics. This point is also noted in the operational forecasting definition of ECLs from the more intense systems of relevance to extreme weather and ocean impacts on this region (Sect. 3.4).

Considering the meteorological and climatological characteristics discussed throughout this review on ECLs and intense systems associated with extreme weather and ocean conditions, a generalised definition is provided below. The purpose of this definition is to provide a description that can be used for a broad range of purposes, including in meteorological/oceanographic and climatological research as well as applications in various other sectors (such as for emergency services authorities, insurance groups, government agencies and coastal management organisations). The ECL definition highlights aspects of their formation, including mid-latitude and tropical influences with vertical structure acknowledged, as well as a hazards-based approach for Intense ECLs:

> *East coast lows (ECLs) are cyclones near southeastern Australia that can be caused by both mid-latitude and tropical influences over a range of levels in the atmosphere;*
> *Intense ECLs have at least one major hazard associated with their occurrence, including extreme winds, waves, rain or flooding.*

This definition includes key aspects of the range of definitions applied previously for research studies, as well as for operational purposes (e.g., hazards and vertical structure are considered for operational applications in BoM as detailed in Sect. 3.4). It is intended that this definition can be adapted in some cases depending on the specific application at hand. For example, although this definition is relatively generalised, less-detailed definitions have also been useful for applications in some previous studies, including for projections of future climate (Dowdy et al. 2014; Pepler et al. 2016b). More detail could also be considered in some cases. For example, specific sub-types and more constrained variations based on the above definition as a foundation may be practical for some applications, including using additional criteria for identifying ECL events in a specific data set, or for the examination of specific hazards associated with ECLs. Additional constraints could include measures of severity, vertical depth or duration (e.g., longer duration events may have relevance in relation to generating large swell-wave events). However, it is also noted that including additional criteria can potentially add significant uncertainty and differences between different studies (e.g., event duration will depend on the particular tracking method applied) as discussed in Sect. 2. The relative characteristics of cold and warm cored conditions also provide a means of systematically classifying ECLs (i.e., relating to their relative degree of extratropical and tropical characteristics). Definitions which consider the larger-scale environmental conditions and signatures of ECLs over a range of levels of the atmosphere could be beneficial for some climate applications (e.g., changes in regional cyclone characteristics, such as could potentially occur in relation to a possible expansion of the tropics (Yin 2005; Nguyen et al. 2015; Sharmila and Walsh 2018).

7.3 Future research needs

This review has highlighted several knowledge gaps on ECLs and their associated weather and ocean extremes. These topics are noted as follows, providing a summary of ECL research needs. The topics are simply listed here without assessing the relative importance of each, noting that this could be done in the future based on surveying the needs/priorities of various user groups for this information.

- Update the dataset of ECLs as described in Speer et al. (2009) based on examination of MSLP charts.
- Investigate how the vertical structure of ECLs relates to the severity of the hazards they cause, including for deep systems that are well-defined over a range of levels in the troposphere.
- Understand interrelationships between various upper-tropospheric phenomena associated with cyclonic vorticity and their role in driving ECL-related extreme weather and ocean conditions (such as jet stream variations, blocking events, Rossby wave breaking and quasi-stationary hemispheric features associated with orography and mean temperature distributions).
- Examine the possibility of temporal clustering of ECLs (i.e., clusters occurring more frequently than would be expected due to random chance alone), including for intense ECLs during winter.
- Improve knowledge on the spectrum of hybrid cyclone characteristics, as well as their size and relationship with warm seclusion systems, including how these aspects may relate to the intensity of their associated extreme weather and ocean conditions.
- Improve understanding for the meteorology of mesoscale features and small-scale convective processes associated with ECLs.
- Investigate factors that might drive the large interannual variability in ECL activity, including potential influences from large-scale atmospheric and oceanic modes of variability, as well as potential for seasonal prediction of ECLs.
- Improve methods for identifying historical trends in ECL activity as well as in associated weather and ocean extremes.
- Improve methods for projecting changes in future ECL intensity, as well as ECL numbers during the warm season.

8 Conclusions

This review has covered a wide range of ECL characteristics, including their meteorology, the extreme weather and ocean conditions they can cause, their climatology and the influence of climate change on their characteristics. This was based on a wide range of literature and other knowledge sources, including operational forecasting guidance and practises. These aspects were all considered in relation to providing a practical definition of ECLs, as well as for providing concise summaries of their distinctive characteristics.

Recommendations for future research were also provided. This synthesis of knowledge is intended for use in applications relating to improved planning and preparedness for ECL impacts on this highly populated region of Australia, as well as to help inform future research directions.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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