AdaptNSW

Eastern Seaboard Climate Change Initiative
East Coast Lows Research Program Synthesis for NRM Stakeholders

NSW Government
Office of Environment & Heritage

This is a synthesis of the current findings and outputs of the ongoing Eastern Seaboard Climate Change Initiative – East Coast Lows (ESCCI-ECL) research program. The report was prepared by Peter Smith in consultation with a number of key research staff involved in the program: Ian Goodwin, Acacia Pepler, Anthony Kiem and Jason Evans and Yvonne Scorgie.

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1 Introduction

This report is a synthesis of the findings of the Eastern Seaboard Climate Change Initiative – East Coast Lows (ESCCI-ECL) research program. It provides an overview for natural resource managers and emergency services on the effects of east coast lows (ECLs) and how they may alter under a changing climate.

The eastern seaboard, which is the area of land between the Great Dividing Range and the coast of NSW and southern Queensland, is home to almost nine million Australians and billions of dollars of public and private infrastructure. A variety of high-impact weather events occur in this region and generate damaging winds, flooding, heavy seas and swells that have significant impacts on the region's natural resources, infrastructure and communities. These high-impact weather events also play a critical role in water resource management, with many of the region's water catchments dependent on being replenished by the high flows generated by extreme rainfall events.

The eastern seaboard is susceptible to east coast lows (ECLs). ECLs are storms which can occur at any time during the year but are most frequent during late autumn and early winter and contribute significantly to annual rainfall totals along the coast and adjacent ranges. ECLs also cause a significant amount of damage along the east coast each year through very high winds, large waves and at times intense flooding, yet they are also a major source of water for the reservoirs serving coastal communities. Thus ECLs have a paradoxical role of being both vital to, and dangerous for, human activities in the area.

Although these storms are not generally as intense as tropical cyclones, ECLs tend to impact the more densely populated and developed latitudes of Australia's eastern seaboard, and in any one year insured losses from ECLs can exceed those of severe tropical cyclone events. Disaster statistics from the Insurance Council of Australia show that Tropical Cyclone Marcia, which was a category five cyclone, resulted in $522 million of insured losses, while the ECL that impacted on the Sydney and Hunter regions in April 2015 led to $922 million of insured losses[1].

The major message of this synthesis is that east coast lows are a very common, prominent and pervasive feature of the east coast climate, possibly even more so than are cyclones for our tropical coastal regions. Research into modern, historical and pre European climates show us that ECLs are highly variable from year to year and decade to decade, and that there is the potential for more intense and frequent storms than we have experienced in the recent past. It is therefore vital that management and planning for NRM and emergency services takes this into account.

1.1 What is an east coast low?

East coast lows (ECLs) or *east coast cyclones* are low pressure systems that develop off the east coast of Australia, from about Fraser Island in the north down to East Gippsland in the south. East coast lows often intensify rapidly overnight, making them one of the more dangerous weather systems to affect the eastern coast of Australia. At the same time, ECLs are a very important and significant source of rainfall for most of the coastal water supply catchments along the eastern seaboard.

Air pressure is arguably the single most important element driving local and regional weather. The main reason for this is that differences in air pressure (the gradient) drive the strength and direction of winds. The greater the gradient in pressure the higher the intensity of the wind. Where the wind originates and its intensity and direction can have a major influence on local temperature and weather conditions. For example, during the summer period hot dry north-westerly winds from the interior of Australia can significantly raise local temperatures and lower humidity.

1. Insurance Council of Australia Ltd 2015, *Disaster statistics*, viewed November 2015, www.insurancecouncil.com.au/industry-statistics-data/GI-statistics

The air pressure on Earth is not the same everywhere and at any one time there are areas of high and low pressure. In simple terms, wind moves ('blows') from areas of higher pressure to lower pressure, in an attempt to make the pressure in the two areas equal. In a high pressure system the air tends to move outwards slightly from the centre and begins to rotate. In the southern hemisphere, due to the rotation of the Earth, this air rotates in an anticlockwise direction. For low pressure systems air moves towards the centre of the low and rotates in a clockwise direction.

The distribution of high and low pressure does not only influence the winds. In high pressure systems air tends to descend, and as it descends it dries out, leading to clear skies and warmer daytime temperatures (Figure 1). In low pressure systems air rises. As it rises, it cools and water vapour condenses to form clouds, which can lead to rain. Consequently, the weather affected by a low is often cloudy, wet and windy.

The more intense the 'low', that is, the greater the pressure gradient from the centre to the outside of the low, the stronger the winds and the higher the chance of large rainfall events. The best known and most extreme low pressure systems in Australia are tropical cyclones, which are well known for producing high winds, extreme rainfall and significant impacts. However, tropical cyclones are not the only significant low pressure systems to affect Australia, and east coast lows are weather systems of potentially equal importance for people living along the eastern seaboard.

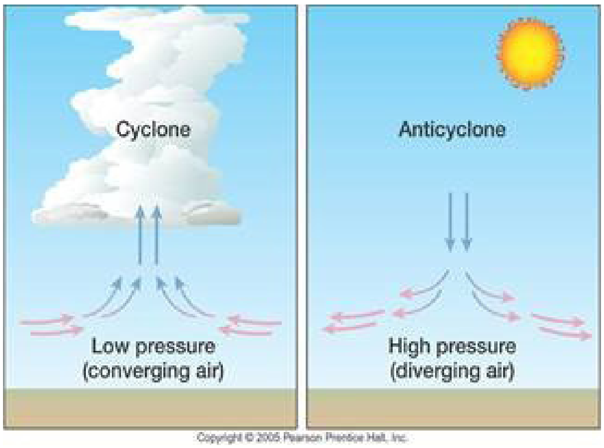


Figure 1: Air movement in a low presssure system versus a high pressure system (Pearson Prentice Hall Inc 2005)

1.2 An overview of the ESCCI-ECL research program

The Eastern Seaboard Climate Change Initiative – East Coast Low (ESCCI-ECL) project is an innovative research program aimed at improving the knowledge of past, current and future projected ECL events along the eastern seaboard of Australia. Importantly it was designed to use these different time scales to provide better information on how ECLs influence coastal zone dynamics and water security.

As ECLs are major drivers of ecosystem processes in this region it is imperative that we gain an understanding of them, including their impacts and their variability, and how they will change in the future. This is a necessary step in determining the impacts of climate change on natural and human systems and the implementation of effective adaptation strategies.

The ESCCI-ECL project was jointly developed by the NSW Government, the Bureau of Meteorology, and three universities: University of New South Wales, Macquarie University and the University of Newcastle. The vision for the project included four principal themes:

- an understanding of the historical and pre-historical (palaeo) climate variability of ECLs
- an understanding of how their long-term multi-decadal variability influences coastal processes and streamflows
- high resolution modelling of projected ECL frequency and intensity in response to climate change
- integration of findings from the above themes into an understanding of the impacts of ECLs on coastal and water resources, and guidance on potential changes to these impacts in response to climate change.

The NSW Office of Environment and Heritage in conjunction with the research partners, and with seed funding from the NSW Environmental Trust, developed a research program that consists of a suite of inter-related projects. A description of each of the projects can be found at www.climatechange.environment.nsw.gov.au/Impacts-of-climate-change/East-Coast-Lows/Eastern-Seaboard-Climate-Change-Initiative.

- **Project 1: Eastern Seaboard Climate Hazard Tool development**
  Project lead: Bureau of Meteorology
- **Project 2: Projections of future ECL frequency and intensity along the NSW coast**
  Project lead: Associate Prof. Jason Evans, Climate Change Research Centre of the University of NSW
- **Project 3: Understanding the long-term natural variability of ECLs by using palaeo climate information**
  Project lead: Associate Prof. Ian Goodwin, Climate Futures at Macquarie University
- **Project 4: Regional coastal and estuarine impacts of extreme ECLs**
  Project lead: Associate Prof. Ian Goodwin, Climate Futures at Macquarie University
- **Project 5: Regional water security impacts of extreme ECLs on south-eastern seaboard reservoirs**
  Project lead: Prof. Garry Willgoose and Assoc. Prof. Anthony Kiem, University of Newcastle
- **Project 6: Generic framework to determine the economic impacts of natural and human-made disaster events**
  Project lead: Dr Kevin Roche, Risk Frontiers, Macquarie University


Collaroy-Narrabeen Beach storm erosion, June 2016 (WRL 2016)

In addition to seed funding from the NSW Environmental Trust, the project received funding from the NSW Department of Finance and Services and Hunter Water Corporation and was supported under the Australian Research Council's Linkage Project LP120200494 and Discovery Project DP0772665. Research partners also contributed significant resources including staff, intellectual property and research infrastructure.

1.3 How the ESCCI-ECL project area aligns with the East Coast cluster group

The ESCCI-ECL concerns itself with the eastern seaboard of Australia (see Figure 3), with the eastern seaboard defined as the area that is currently impacted by ECLs, ranging from the Fraser Coast in Queensland, south to East Gippsland in Victoria. Figure 2 shows the study region that was the basis of the ESCCI-ECL program. Figure 3 shows the East Coast NRM cluster.

Roughly half the East Coast NRM region is affected by ECLs. This report will focus on a discussion of the ESCCI-ECL for the whole of the eastern seaboard area. The reason for discussing the whole ESCCI-ECL region is that much of the southern part of the East Coast cluster group, that is, from the Hunter through to Sydney, is similar to the southern regions of the eastern seaboard, but distinct from the northern part of the East Coast NRM cluster in terms of the frequency and impacts of ECLs.

The Commonwealth funded national NRM climate change adaptation program has divided the Australian continent into groups or clusters consisting of locally led NRM groups (or Local Land Services in NSW). The aim of this process is to provide these groups with information that assists them in developing climate change adaptation programs for their sector. The East Coast cluster group (see Figure 3) ranges from the Fitzroy Basin in Central Queensland, south to the Hawkesbury River Basin near Sydney.

Figure 2 (above): South-Eastern seaboard (Coutts-Smith *et al* 2011).

Figure 3 (right): East Coast cluster group. Climate change in Australia
http://www.climatechangeinaustralia.gov.au/en/impacts-and-adaptation/east-coast/

2 The distinctive climate of the eastern seaboard

The eastern seaboard is a special case in terms of impacts and climate change because it is climatologically different from the rest of south-eastern Australia. An obvious reason for this variation is the influence of the Tasman Sea and the proximity of the Great Dividing Range. The Tasman Sea and the warm East Australian Current (Figure 4) provide sources of moisture,. The mountains of the Great Dividing Range provide orographic enhancement. As warm moist air rises up the mountains it cools and increases the chance of precipitation (see Figure 5). The mountains reduce the influence of easterly winds from the Tasman Sea on the inland, as well as reducing the influence of westerly winds on the coastal zone.

Another significant reason for the different climatology of the eastern seaboard is the existence of east coast lows. ECLs can occur throughout the year but tend to be more common from autumn through to spring. Climate drivers such as the El Niño/La Nina cycle, which are known to have a major influence for most of eastern Australia, appear to have a very poor correlation with the frequency and intensity of ECLs. During particularly dry El Niño periods, when most of eastern Australia is in drought, it is still possible for an ECL event to occur that reduces the impact of the drought on parts of the eastern seaboard. For example, the 'Big Dry' that affected south-eastern Australia from 1990 to 2005, which was related to a strong clustering of El Niño events, was much less severe along the eastern seaboard. In fact, rainfall at the time was above average for many parts of this region. The southern part of the eastern seaboard had high rainfall in 1990 and 1998 while the rest of eastern Australia was in drought.

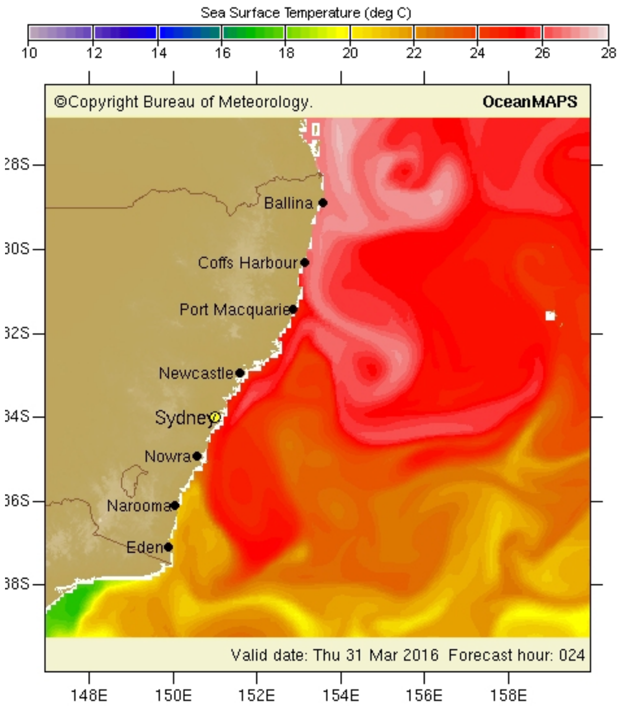


Figure 4: The warmer waters of the East Australia Current flow southwards along the coast. (BOM http://www.bom.gov.au/oceanography/forecasts/idyoc14.shtml?region=14&forecast=1)

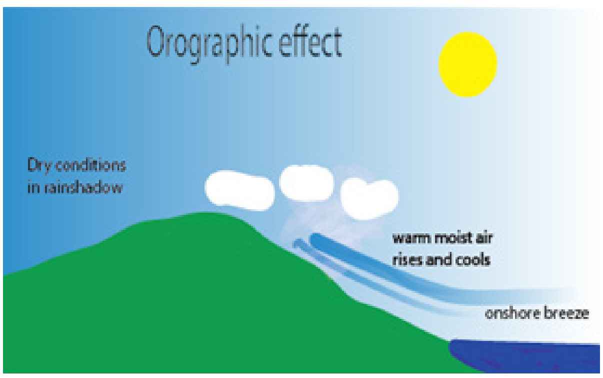


Figure 5: Schematic of the orographic effect of the Great Dividing Range (Dr Peter Smith 2016).

Fallen tree damages car (Carlos Amarillo).

2.1 Geographical and seasonal differences in ECLs

There is also a geographical and seasonal variation in the influence and intensity of ECLs. At its simplest, there are two zones within the eastern seaboard: a northern zone starting roughly in the Newcastle area and ranging north to the Fraser Coast; and the other from Newcastle south to Gippsland. In the northern part of the eastern seaboard, ECLs can occur in any month, while in the southern half ECLs occur more commonly in the cooler months (Figure 6).

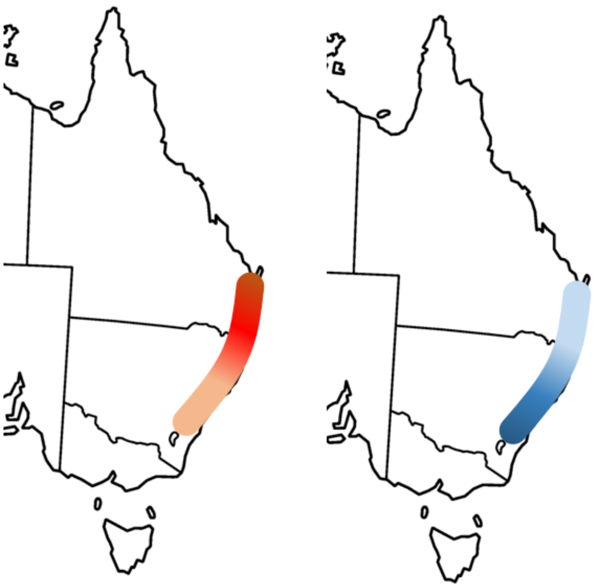


Figure 6: East coast lows are more frequent in the north during the warmer months and more frequent in the south during the cooler months.

There are also various types of ECL (see Section 2.2) and these develop in different parts of the region and have different atmospheric conditions as their precursor. Depending on their origin they have differing seasonal and geographical impacts on the eastern seaboard. In simple terms those storms with a tropical or subtropical origin are more common and have a greater influence on the northern part of the eastern seaboard, while those with an extratropical origin have a greater influence in the south. Importantly, the impact on our water supply and our coasts of the different types of ECL is also not consistent across the entire eastern seaboard.

2.2 Classification of ECL types

As part of the ESCCI-ECL project ECLs have been classified into five different subtypes.

ECL storm types vary from year to year, and decade to decade. This makes ECLs and their impacts difficult to understand and predict.

- **Easterly trough lows** are storms that form close to the coast in the Pacific Ocean and track mostly east of the Great Dividing Range and in a southerly direction. These make up about 23% of the storm types in the historical record (1871–2012).
- **Southern secondary lows** are storms that form in the southern Tasman Sea or Southern Ocean and track mostly over the southern Tasman Sea and in a northerly direction. These are the most common storm type in the historical record and account for about 34% of historical storms.
- **Inland troughs** are storms that evolve mostly inland west of the Great Dividing Range and north of 30° south. These comprise about 10% of the storms in the historical record.
- **Continental lows** are storms that evolve mostly over the inland west of the Great Dividing Range and south of 30° south. These make up 19% of the historical records of ECL storm types.
- **Extra tropical cyclones** are tropical storms that form to the north-east of Australia that sometimes track into the northern part of the eastern seaboard study region. These make up about 14% of the historical record.

Table 1 shows the seasonal dominance and geographical area of influence for each of these ECL types, while Figure 7 shows the general origin and average storm track of the various types of ECL.

Table 1: Seasonal dominance and geographical area of influence of ECL types

ECL type	Seasonal dominance	Regional location of storm activity
Easterly trough low (ETL)	All year, autumn to winter peak	Fraser coast to mid north coast of NSW
Southern secondary low (SSL)	All year but mid winter peak	Central coast of NSW to Gippsland
Inland trough low (ITL)	All year but more common in summer, spring and early autumn	Mid north coast of NSW to Gippsland
Continental low (CL)	All year but May to September dominance	Central coast of NSW to Gippsland
Extratropical cyclone (XTC)	Late summer to autumn	Fraser coast to far NSW north coast

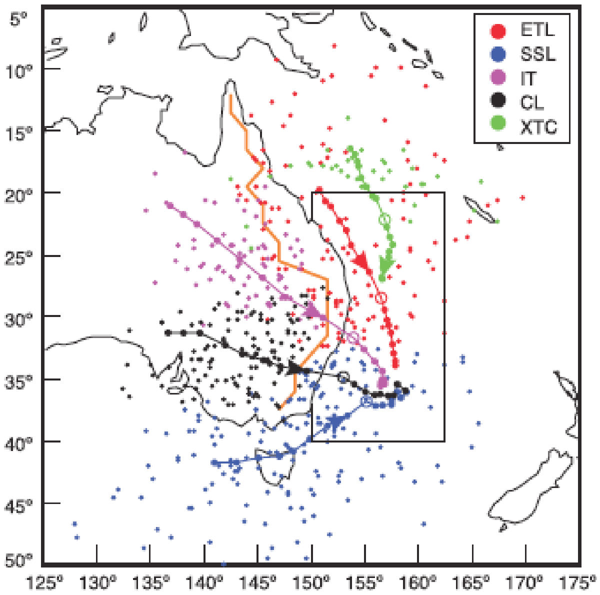


Figure 7: Mean storm tracks for each classified storm type: easterly trough lows (ETL), southern secondary lows (SSL), inland trough (IT), continental lows (CL), and extratropical cyclones (XTC) (Browning & Goodwin, 2013).

3 Significance of ECLs for the eastern seaboard

East coast lows play a paradoxical role on the eastern seaboard. On the one hand ECLs are responsible for significant damage from high winds, large and powerful surf, and flooding. On the other hand, they are responsible for a significant component of the flow into our water storage catchments. Until a decade ago we could only give a one day warning of a likely ECL; with improvements in forecast models, the Bureau of Meteorology can now predict possible ECLs at least four days ahead. However, prior to the ESCCI-ECL project, we did not have the knowledge necessary to start developing our capacity to give long-term or seasonal forecasts of ECL's.

In June 2007, an ECL caused significant damage to the coast near Newcastle, led to nine deaths and insurance claims of $1.6 billion, and the grounding of the Pasha Bulka bulk carrier. In 2008, a series of storms in south-east Queensland caused significant flooding and storm damage in Brisbane and the Gold Coast. In 2015 an ECL centred on the NSW central coast caused significant flooding and damage from high winds, with insurance losses of over $900 million. These weather events also generate conditions favourable to increased bushfire risk, lightning strike and strong winds. A study showed that more than six out of 10 high inflow events into water catchments for the Sydney region were attributed to ECLs.

3.1 Assessing the risk of significant impacts from ECLs

To understand the current and future risk we face from weather events such as ECLs, we need to consider how large, how often and where storms are likely to occur. To do this we need information on the probability of large storms and the clustering (e.g. the likelihood of storms impacting areas in quick succession) of large storms. We need to understand how the climate, and ECLs in particular, have behaved over long periods of time. One way of doing this is to use historical data on the occurrence of past storms.

Prior to the ESCCI-ECL project the collation of information on the historical extent and impacts of ECLs was either patchy or in formats not easily interrogated by users. ESCCI-ECL Project 1, led by the Bureau of Meteorology, was designed to bridge this gap. It combined a new database of ECLs with weather impacts across the eastern seaboard. This database was then made available via the development of a new online product: Maps and Tables of Climate Hazards on the Eastern Seaboard (MATCHES) (reg.bom.gov.au/climate - login required). MATCHES linked historical ECL events (1950–2008) with information on their impacts, and specifically the location and intensity of heavy rainfall, severe winds, extreme waves and storm surges. This new tool provides an easy way to link historical ECLs with their weather impacts through use of user-defined impact

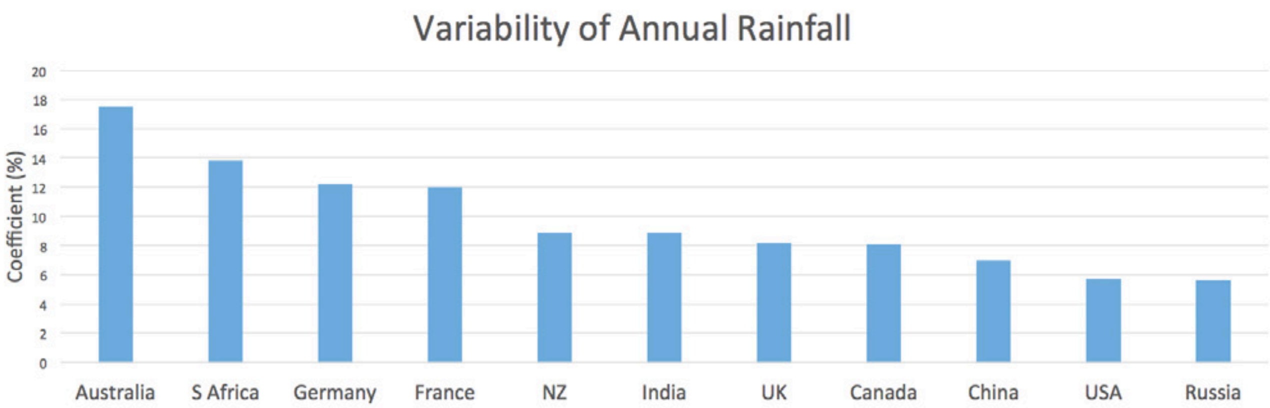


Figure 8: A comparison of Australian climate variability on a global scale, using annual rainfall as an example (Dr Phil Reid, Bureau of Meteorology, based on the Hulme dataset https://crudata.uea.ac.uk/cru/data/hrg/).

thresholds and an intuitive front-end interface.

Historical weather records in Australia are very limited and we have a poor understanding of pre-settlement climate. Added to this, our climate, particularly in relation to rainfall, is highly variable. In fact, it is more variable than most other places on the planet (Figure 8). Longer periods of data are required to cover this variability. This is even more critical for understanding the risk posed from large and rare events, as their rarity means we have fewer examples to analyse impacts.

One technique used by climatologists and water resource planners to overcome this lack of historical data is the use of statistical tools and simulations. By using a process called frequency analysis they can estimate the probability of occurrence of a given event, often referred to as the return period. These are commonly known as the 1 in 10 or 1 in 100 year events. Events such as the storm that lashed Sydney, the central coast and Newcastle in April 2015 was considered a 1 in 10 year event. For these large events we have very few records to use to make judgements about their likely impacts.

3.2 Using climate proxies to reconstruct past climates

Another way to look at the risk posed by large events and the clustering of large events is to use palaeoclimatology techniques to reconstruct long-term data sets on past climates and how these may have impacted the environment. Project 3 of the ESCCI-ECL research program, led by Assoc. Prof. Ian Goodwin at Macquarie University, used palaeoclimate techniques to examine whether ECLs have been a long-term climatic phenomenon on the eastern seaboard. This project also wanted to investigate what we can understand in terms of the variability in clustering and intensity of ECLs over a 1200-year timespan.

Past climates leave an imprint in both the biological and physical environment and these can help us glean information about past climates. These imprints are referred to as climate proxies; one example is the extraction of climate information from tree rings using a technique called dendroclimatology. This can be used to infer rainfall and temperature from the growth rings of very old living and fossilised trees. In a similar way, by examining core samples taken from corals, scientists can find evidence of past sea surface temperature and variability. Corals also provide information on a range of other environmental conditions including sea surface salinity, light penetration, water depth, and sedimentation. Ice cores from Antarctica can provide a direct measure of past rainfall variability and temperature. This is important because the atmospheric circulation patterns around coastal Antarctica are linked to the major circulation patterns around southern Australia. Therefore data from appropriate locations in Antarctica provides insights into the climate at the southern end of continents such as South Africa, South America, and most importantly for us, Australia.

This project used multi-climate proxies from a range of sources and locations, such as oxygen isotopes and tree rings from both sides of the Tasman Sea, coral cores from the eastern pacific, ice cores from Antarctica and speleothems from caves in NSW. This was used to infer the domination of synoptic patterns for major modes of climate variability, such as the Southern Annular Mode or the El Niño Southern Oscillation.

In the context of the past thousand years the project found that there have been three multi-decadal periods of high storm activity in the Tasman Sea:

- the mid 12th to the 13th century
- the middle of the 15th century, and
- a group of high storm activity periods between the 17th century and the beginning of the 20th century.

3.3 The current level of 'storminess' compared with the past

Project 3 found that the recent frequency of ECL storm activity has been relatively low in comparison with the most severe storm periods in the past 1200 years (see Figure 9 below). The 17th, 18th and 19th centuries all had a higher occurrence of severe storm decades than did the 20th century. The study found that the early 1970s are a reasonable example of some of the more extreme storm periods. Nevertheless the record does indicate that periods of storm activity more intense than the storm period of the early 1970s do exist and that it would be unwise to consider the 1970 storms as examples of the most extreme storm risk event.

Scientists estimated and compared the number of storm days per season during each decade. Figure 9 shows the frequency of storm events on a multi-decadal basis over the last 1200 years. Colour shading indicates periods of below average storm activity (green) and above average storm activity (orange) exceeding the 95% confidence level. The level of storm activity is not the only indicator of impact, different types and frequencies of ECLs occurred with differences in where these storms impacted the eastern seaboard during the past periods. As such, the impact of each of these periods is not consistent for the northern and southern coasts. Figure 10 shows an example decade (1640-1650) where the storm risk is different for the northern and southern parts of the eastern seaboard.

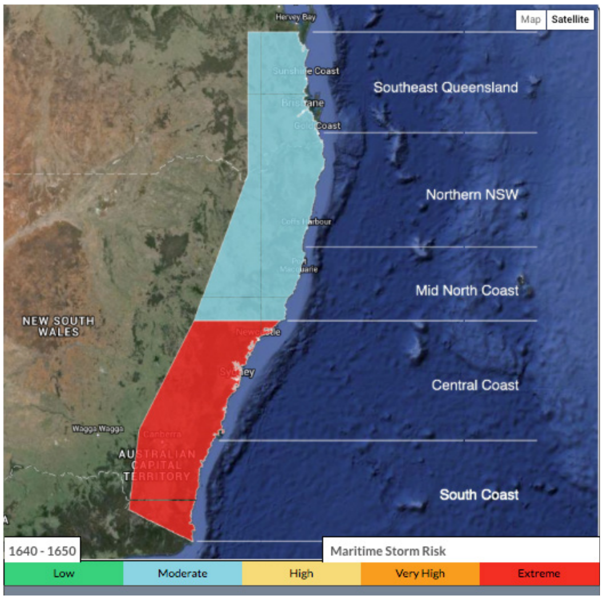


Figure 10: Storm risk during 1640-1650 based on the ECL storm frequency probability analysis.

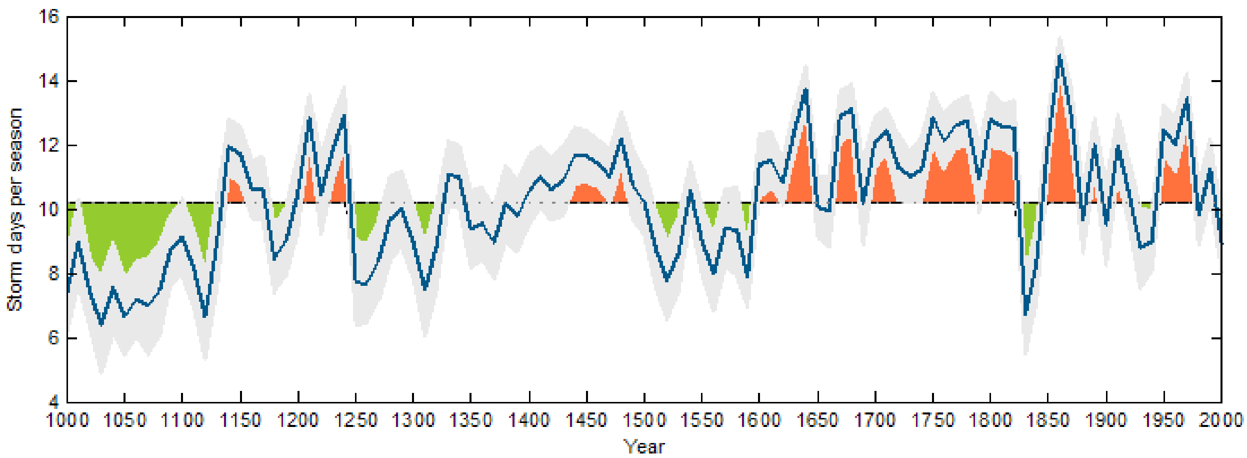


Figure 9: Time series of Normalised extreme storm days per season calculated from The PaleoR-Mq Paleoclimate Reconstruction (Browning and Goodwin, 2015, Goodwin and Browning, in preparation 2016)

Table 2 shows selected decadal periods from the Project 3 dataset against their risk of high frequency storm occurrence for the northern and the southern eastern seaboard regions. The coastal storm activity risk categories use the 1955–2012 median as a baseline for comparison. From Figure 9 we can see there was a period of high storm frequency in the 1680 to 1690 period, and this was consistent for both the northern and southern areas of the eastern seaboard. Conversely, 1860 to 1870 was another period of high storm frequency but it appears that in this period the high storm frequency was for the northern areas only and the southern regions had a low probability of frequent storms. Using the preliminary analysis from the Project 5 team at The University of Newcastle, led by Assoc. Prof. Anthony Kiem, we can also assign a tentative 'risk factor' to these same periods in terms of the reliability of streamflow and how that would have affected water security, i.e. the reliability of adequate water supply for consumption purposes (Table 2, right-hand columns).

Table 2: Data on selected decades demonstrating dominant storm type and likely risk of storm frequency in comparison to the late 20th century. Coastal storm activity risk is an assessment of the likelihood of the combination of frequency and magnitude of ECLs causing coastal erosion in comparison to the risk, with the late 20th century as a baseline. Water security risk is an assessment of the risk that water supply would be inadequate, at that nominated period, if current level of water demand and storage capacity remained the same.

Time period	Coastal storm activity risk		Water security risk	
	Northern eastern seaboard	Southern eastern seaboard	Northern eastern seaboard	Southern eastern seaboard
1955–2012 median value as baseline	Moderate	Low	2005–present – low 1980–2005 – high	
1970–1980	Extreme	High	Low	Low
1860–1870	Extreme	Low	Low	Moderate
1680–1690	Extreme	Extreme	Low	Low
1260–1280	Low	Moderate	Extreme	Extreme

A flooded road following heavy rains (Johan Larson).

4 The impacts of ECL types on natural resources

Over the next few decades sea level rise and severe maritime weather present the largest combined threats to the natural coastal systems and the intensely populated areas of the east coast of Australia. Likewise, the influence of climate variability on annual and seasonal rainfall and how that might alter with climate change is of major concern in planning for water security over the medium term.

In the tropics, NRM and emergency services managers are well aware of the impact of tropical cyclones as a major risk factor and as an important driver of disturbance regimes in natural systems. As such, cyclones are deeply embedded in our thinking in those regions. In the same way ECLs are a prominent feature of the east coast climate, potentially even more significant for natural resource management than cyclones are in our tropical coastal regions, and our management and planning needs to reflect this.

Old Bar Beach storm erosion, 7 July 2008 (Coastal Risk Management Guide, DECCW, Dec 2010).

East coast lows, though often not as large or dramatic as cyclones, occur more frequently and are a more consistent and pervasive feature of eastern seaboard climate. As a minimum, the ESCCI studies discussed show that ECLs, their origins and their distribution have significant impacts on water resource security and coastal dynamics. It is also important to acknowledge that the impacts of the various types of ECLs are not consistent across the region, and we need to tailor our management approaches to reflect this.

Using the reconstructed climate from Project 3, both Projects 4 and 5 have used this data to help understand how the variability in intensity and clustering of storms have affected coastal processes and potentially streamflow and water security. Project 4 at Macquarie University, led by Assoc. Prof. Ian Goodwin, provides information on the influence of ECLs on wave climate and coastal geomorphological processes. An understanding of the characteristic of storm waves associated with the different types of ECLs has been developed. This includes the propagation patterns and coastal impacts of such storm waves. Project 5 is led by Prof. Gary Willgoose and Assoc. Prof. Anthony Kiem at The University of Newcastle. This project investigated the influence of ECLs on precipitation and streamflow in catchments and how changes to the frequency, timing, intensity, location, and duration of ECLs can influence water security.

4.1 ECLs and coastal systems

Coastal systems are dynamic areas and the shape and location of features such as estuary inlets and beaches are dependent on a range of factors including the prevailing wave climate, mean sea level, ocean currents and sediment supply. Any change to any one of these conditions will result in a change in the coastal landform. The result is that changes in sand based coastal landforms occur on a continual basis.

Wave climate, i.e. the size, direction and frequency of waves as they hit the coast, is a significant component of what shapes the coastal landform. Project 4 has reconstructed the storm wave climate over a period of 500 years and has also analysed how this has affected the coastal landform along the eastern seaboard.

ECLs are a significant generator of coastal storms and waves along the east coast, but the impact of those storms on the coastline is very much a product of their type and origin. ECL types with a more northerly origin, i.e. easterly trough lows (ETLs) and ex-tropical cyclones, tend to produce wave conditions with a 'shore normal' or easterly direction, while those from the extratropics or of southerly origin produce waves that are oblique or more from a southerly or SSE direction. This directional pattern is very significant in terms of coastal processes and coastal erosion in the eastern seaboard. In general, periods of low storm activity such as the 1300–1600 period result in prograding coastlines (shorelines moving eastwards into the sea) and a similar sequence was observed for the 1980–2010 period. Periods of high storm intensity can lead to either shoreline regression or progradation, depending on the origin of the storm and which region of the eastern seaboard is being considered.

In general, waves from a more easterly direction have a greater erosive impact on the beaches. Persistent easterly waves can cause the beach profile to rotate in an anticlockwise direction as a result of more erosion of the northern ends of the beach. The Macquarie University team found that this was the case during the period from 1600 to the early 1800s, when there was a pattern of higher frequency and higher intensity ETLs and inland trough lows (ITLs) than we have experienced in recent times. The Macquarie University team have described this as the *Coastal erosion embaymentisation and stationary foredune aggradation/transgression phase*.

Waves that are more oblique, i.e. those that hit the coast at an angle from the south have less of an erosive impact on our beaches and can be important sources of onshore sand transport. Periods of high southern secondary low (SSL) type ECLs with southerly direction waves produce conditions suitable for alongshore sand transport. This can result in sand deposition in the northern sectors of beaches, resulting in a clockwise rotation of the beach planform (Figure 11). The period 1820 to 1900 was subject to persistent SSL storm types which led to sand deposition and a clockwise rotation of the beaches. The Macquarie University team have described this period as the *Coastal recovery, rotation, strandplain and foredune progradation phase*.

The coastal geology and geomorphology studies carried out in Project 4 indicate that the NSW north and central coasts were most impacted by storm events between 1600 and 1820, and from 1820–1900 the south coast was most impacted, as the storm centres shifted towards the south.

Project 4 also allows us to look at what we might potentially term the 'ultimate probable storm' and the coastal erosion along the eastern seaboard that would happen if this were to occur. Up until now, in NSW the 1974 storms have been typically used to estimate the maximum measured storm erosion. Using past climate reconstructions Assoc. Prof. Goodwin's team has shown that for large areas of the coastline the 1974 storm did not represent the maximum storm and in many cases the erosion scarp was further inland than after the 1974 storm (Figures 11 & 12). At some sites the 'ultimate' storm cut was more than double the observed erosion volumes seen in association with the 1974 storms.

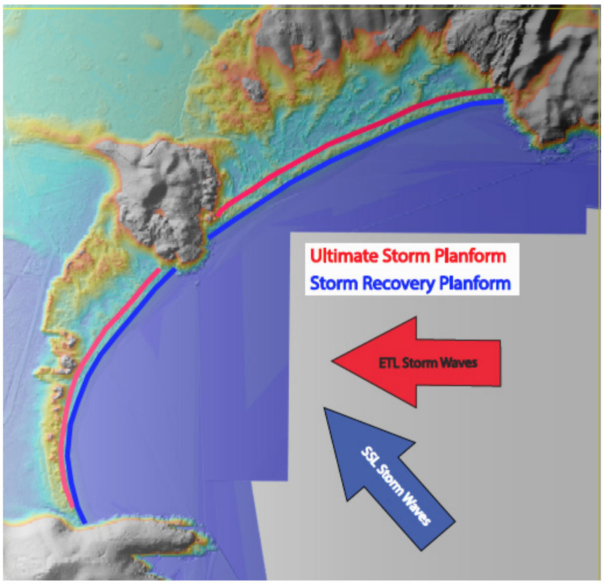
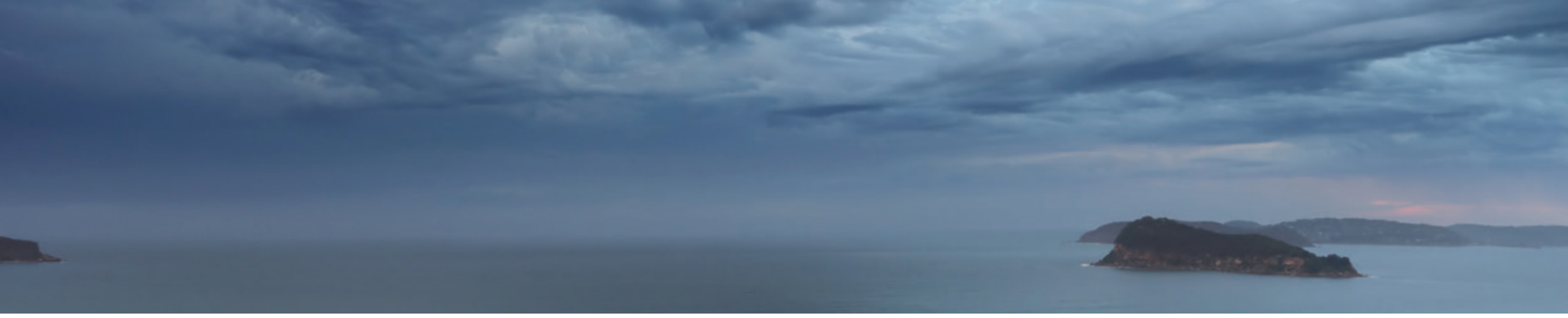


Figure 11: Persistent ETL storm wave events cause the shoreline to rotate anticlockwise (red line), whilst persistent SSL storm wave events cause the shoreline to rotate clockwise, and are often associated with subsequent storm recovery periods (Goodwin *et al* 2015).



From this they have recommended that future storm erosion hazard and risk analysis for the south-east Australian coast should consider the 1600–1900 period, using clustered statistics for extreme years of 1956, 1967, 1974, 2007 and potentially 2011 and 2014.

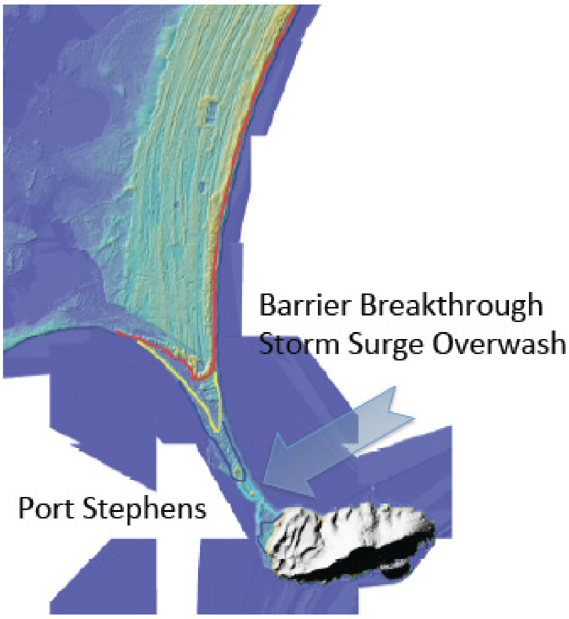
Again, there is a difference between the northern eastern seaboard and the southern. Based on this work the storm erosion hazard is underestimated for the northern half of beach compartments on the NSW central and north coasts and south-east Queensland coasts, and the centre third of beach compartments on the NSW south coast.

4.2 ECLs and estuary dynamics

As major drivers of coastal dynamics ECLs will have a major impact on the ecological functioning of estuarine environment. Storms and droughts substantially influence the relationship between the concentration of fresh versus saline water in estuaries and can even influence tidal flow via substantial changes in the geomorphology of coastal estuaries and wetlands.

These type of changes have been demonstrated for the eastern seaboard. As part of Project 4, Prof. Goodwin's team identified a number of periods during the last thousand years when modelled data sugggested ECLs were more frequent and possibly more intense, resulting in periods where most of the rivers and coastal lagoons were open to the sea. At other times, with a lower frequency of storms, many of these inlets had silted up and were closed off.

Changes in geomorphology have significant impacts on the biota of these inlets as they alter from saline and tidal conditions to brackish or even freshwater environments. During the 1600–1820 period the estuarine inlets were wide mouthed and persistently open from frequent fluvial flood discharge. Post the early 1800s the inlets were frequently closed and choked by high rates of sand transport.



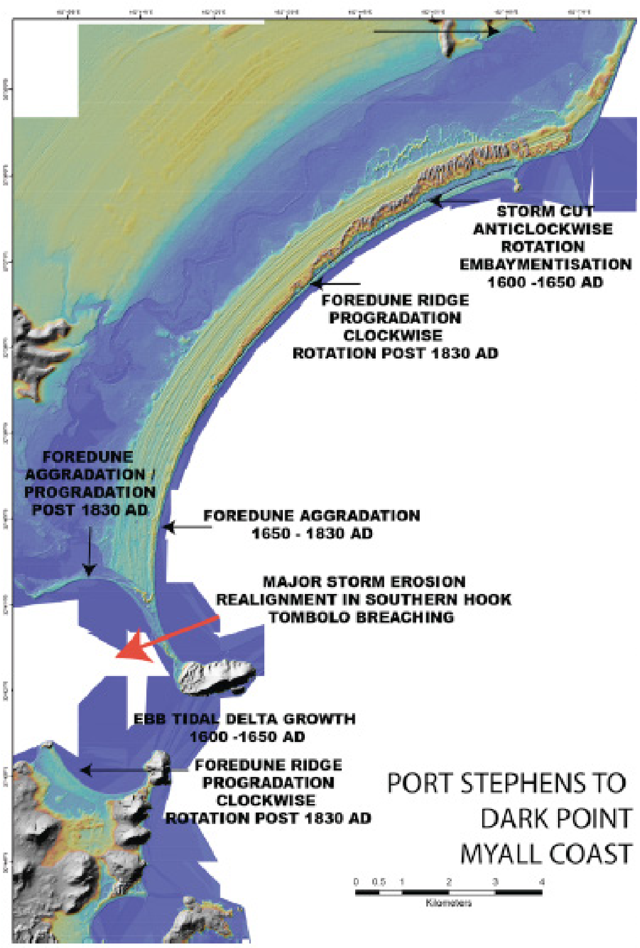


Figure 12: Map for the lower Myall Coast, Dark Point to Yacaaba Head showing the pre 1820's storm scarp (red) and 1974 storm scarp in blue. This shows the pre 1820's storm scarp is rotated anticlockwise. Source: Goodwin and Browning 2016.

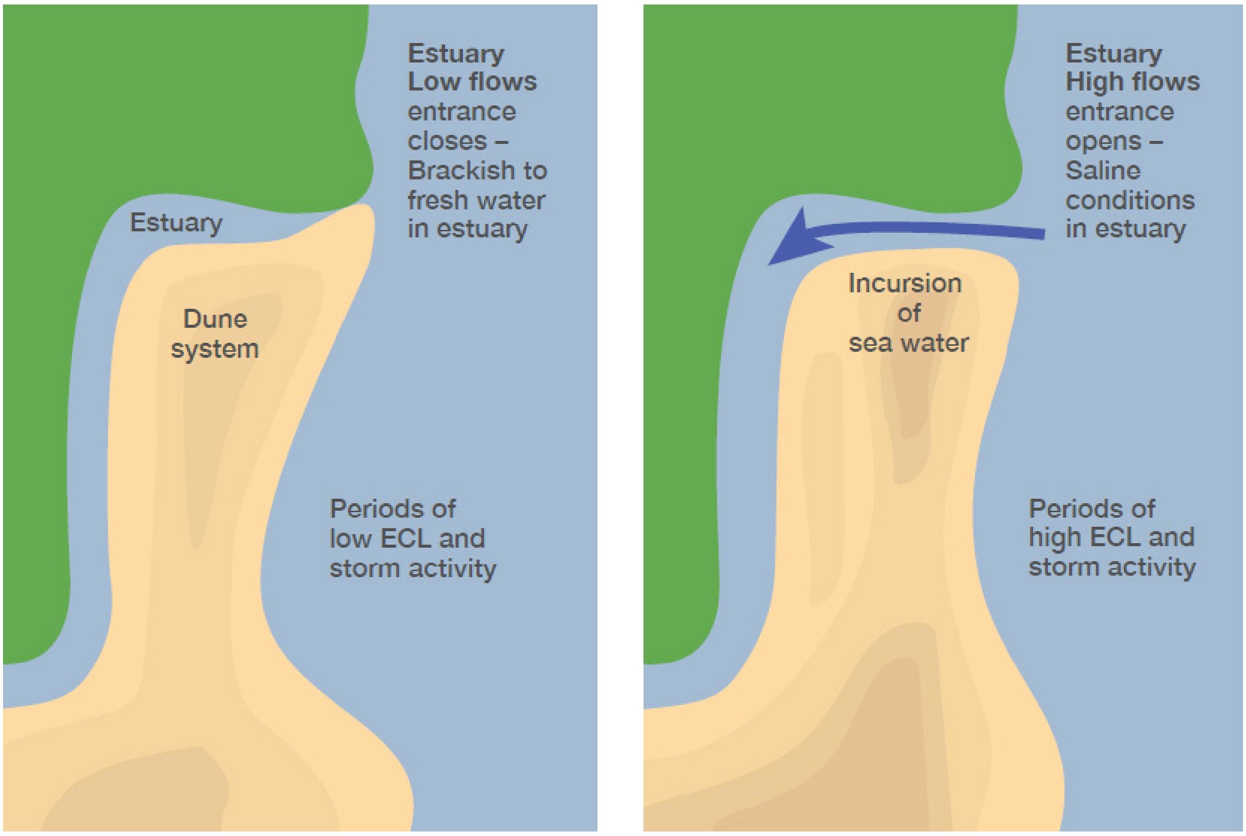


Figure 13: Influence of ECL frequency on estuarine structure and conditions.

Understanding and predicting how individual estuaries along the eastern seaboard will respond to the frequency and intensity of ECLs is complex. It requires a detailed understanding of the direction, power and frequency of waves and the nearshore and offshore coastal geomorphology, as well as how the ECL affects rainfall and therefore streamflow in the catchment.

Summarised below are the potential impacts of diferent types of ECLs on the north and south coast.

Persistent southern secondary lows and the south coast:

- High rain in catchments results in regular flooding opening river mouths and inlets.
- Shore oblique waves lead to high levels of sand deposition in estuary mouths.
- Estuaries potentially oscillate between fresh and estuarine conditions. The more frequent and intense the storms are in the catchment the more likely that the estuaries will be open mouthed.

Persistent southern secondary lows and the north coast:

- Shore oblique waves lead to sand deposition in estuary mouths.
- As SSLs tend to produce very little rain, on the northern eastern seaboard river mouths and inlets rarely open and estuaries become freshwater dominated and non tidal.

Persistent easterly trough lows and the north coast:

- High storm activity leads to high flows in estuaries and erosion of sand along beaches.
- The resulting conditions lead to more marine or saline conditions in estuaries and they become tidal dominated.

Persistent easterly trough lows and the south coast:

- The probability of high rain events from ETLs is lower in the southern eastern seaboard, but the easterly wave conditions tend to erode beaches. If these conditions persist they can lead to intermittent opening of estuary mouths.
- High wave power and high catchment flows are more likely to result in open mouthed estuaries. The more easterly the direction of the wave power the greater the likelihood of beach erosion and salt water intrusion into the estuary.

Hail (swa182).

4.3 ECLs and water resources

Project 5 is ongoing with results expected in late 2016. However, the preliminary work using the MATCHES database from Project 1 has indicated that ECLs play a major role in catchment dynamics along the eastern seaboard.

In terms of rainfall the eastern seaboard is not homogenous in space or time – and can be divided into two regions for summer, autumn and spring: (i) Moreton (QLD) to Sydney, and (ii) Illawarra to east-central Victoria; and three regions for winter: (i) Moreton (QLD) to the Manning region of NSW, (ii) Hunter to Sydney, and (iii) Illawarra to east-central Victoria. By separating ECL-related rainfall from the overall record and comparing the rainfall associated with different ECL types, it appears that the timing and location of ECL impacts are the reason for the non-homogeneous nature of eastern seaboard rainfall.

Further work is now underway using the palaeoclimate reconstructions from Project 3 to look at long-term historical variability and how that can guide water resource planning. As is the case with coastal processes, it appears that the type of ECL has a major bearing on which part of the eastern seaboard is likely to be impacted. Table 3 summarises the types of ECL, the time of year they are most common, and how they influence coastal processes and water security for the northern and southern sectors of the eastern seaboard.

ECLs are common events and studies of ECL frequency and their influence on rainfall from 1970 to 2006 by Acacia Pepler and others at the Bureau of Meteorology (2010) have shown an average of 22 ECL events each year, of which seven had rainfall of more than 25 mm. In addition, at least one storm per year with heavy rainfall over 100 mm occurs somewhere in the eastern seaboard. ECLs are responsible for 23% of the rainfall in the eastern seaboard and more importantly 40% of the widespread heavy rain events. ECLs also feature prominently in terms of high rainfall events. More than 78% of extreme rain events on the central coast of NSW were attributed to ECLs and more than six out of 10 of the high inflows into water catchments for the Sydney region were attributed to ECLs.

Table 3: A summary of the regional variation in ECL types and their impact on coasts and water resources, based on ECLs between 1950 – 2012 (Kiem et al 2016; Browning and Goodwin 2016).

ECL TYPE	Seasonal dominance	Regional bias for storm activity	Proportion of all ECLs (1979-2011 only)	Summary coastal impacts	Summary water resource impacts (heavy rain day = 100 mm or more)
Easterly trough lows	All year, peak May/June	Fraser coast to mid NSW coast	24% (124 events)	Large and powerful easterly waves, anticlockwise rotation of beaches. Minor influence in southern eastern seaboard; significant influence in middle and northern eastern seaboard	44% of ECL heavy rain days (15% of all heavy rain days)
Southern secondary lows	All year but peak in Autumn/ Winter (April to September)	From Sydney to Gippsland	32% (169 events)	Large powerful waves from the south, clockwise rotation of beaches. Larger impact on central and southern eastern seaboard	9% of ECL heavy rain days (3% of all heavy rain days)
Inland trough lows	All year but more common Spring/ Summer	Nth NSW coast to Gippsland	14% (75 events)	SSE direction of waves, clockwise rotation of beaches. Influence more significant from central to southern eastern seaboard	21% of ECL heavy rain days (7% of all heavy rain days)
Continental lows	All year but more prevalent July to December	NSW central coast to Gippsland	23% (122 events)	SSE direction of waves, clockwise rotation of beaches	17% of ECL heavy rain days (6% of all heavy rain days) 12% of days associated with an CL have heavy rain
Extratropical cyclones	Summer and early Autumn (December to April)	Fraser coast to mid NSW coast	7% (37 events)	Eastern direction of waves. Can have large effects on the far northern eastern seaoard (Fraser coast down to Nambucca), anticlockwise rotation of beaches	9% of ECL heavy rain days (3% of all heavy rain days) 17% of days associated with an XTC have heavy rain

5 East coast lows and future projections of climate

East coast lows are known to be high impact events leading to significant damages from high wind, flooding and coastal erosion. The pervasive nature of ECLs in the eastern seaboard climate mean they have a significant role to play in ecosystem functioning across the region. Therefore it is imperative to understand if the existing pattern and frequency of ECLs is likely to continue in the future in response to anthropogenic (human-caused) climate change.

If ECL frequency and intensity decrease there will be impacts on water security along the eastern seaboard. A reduction in the frequency of ECLs, however, leads to less impact on coastal systems from large wave events.

An increase in the frequency and/or intensity of ECLs could exacerbate the effects of sea level rise on coastal erosion, but increase the probability of maintaining water security into the future.

A significant component of the ESCCI-ECL project was to look at how the frequency and intensity of ECLs may change in the future. Project 2, led by Dr Jason Evans at the University of NSW was done in collaboration with the Bureau of Meteorology and the NSW Office of Environment and Heritage. There are challenges in modelling the impacts of future changes in the frequency and intensity of ECLs that relate to their small geographical size (compared to global models), relatively short-lived nature, and their multiple origins.

The first stage of the project determined how well global climate models simulate observed ECLs. To do that the project had to find methods for identifying an ECL in the model datasets and then methods for tracking its progress over space and time. Secondly, the project also looked at which physical mechanisms are the most important for the development of ECLs. Finally, the project used the high-resolution NARCliM model to perform high-resolution simulations of future climate, see www.climatechange.environment.nsw.gov.au/Climate-projections-for-NSW/About-NARCliM

5.1 Representing ECLs in models

- The fine scale regional climate model (RCM) data from NARCliM has provided us with the information necessary for the identification and tracking of ECL activity.
- There is a wide range in the frequency of ECLs in the reanalyses, with strong agreement for the large, intense ECLs and divergence for the smaller systems.
- Satellite sea surface wind observations indicate that there are many small systems agreeing with the high end of the modelled frequency range. The RCMs agree with this high frequency.
- A number of ECL tracking methods have been developed. Each is based on different attributes or indicators of ECLs such as mean sea surface pressure. These various identification and tracking methods agree and have a high reliability for tracking large, intense storms but are less consistent and more variable in their ability to track small, weak storms.
- As such, Project 2 indicates that for future modelling work it will be better to use an ensemble or several tracking methods to account for variability.

5.2 Future changes in ECLs

Project 2 modelled changes in the frequency and intensity of ECLs without distinguishing between different types of ECLs. As we have shown from Projects 4 and 5, the type and location of ECLs has a major bearing on natural resources, and therefore further modelling of ECLs by type is being progressed by the University of NSW.

Across all ECL types the Project 2 modelling indicates that there will be a decrease in the frequency of winter storms, and a small increase (or no change) in the frequency of summer storms.

However, if we classify the storms according to intensity we get a slightly different picture (see Figure 14 below). For low and middle level intensity ECLs, i.e. those with a wind speed above 8 m/s, there is a significant decline in the number of winter storms (–19%) and a very small increase in summer storms (+9%). If we look at the high intensity storms (>20 m/s wind speed) we find that there is a significant increase in the frequency of high wind summer storms (+28%) and a slight decrease in the frequency of high wind storms in the winter (-6%).

Without details on which types of ECL these changes relate to it is difficult to draw specific regional conclusions on the likely impact on coastal systems and water security. However, there is an indication that the winter ECLs, which are a significant component of the dam filling events in the southern and central eastern seaboard, are likely to be less frequent overall, but this may be offset by the increase in intense summer ECLs. The ongoing research in this field will be pivotal in addressing these uncertainties.

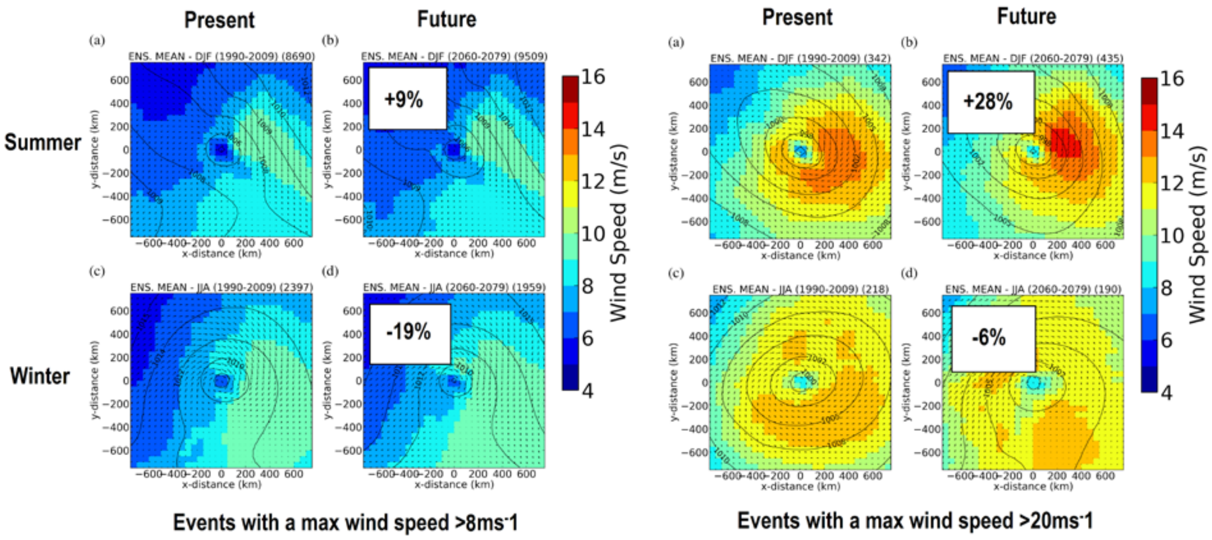


Figure 14: Changes in intensity of ECLs for summer and winter from the present to 2030 (low and high wind speeds) (Walsh et al 2016).

6 East coast lows and natural resource management

Section 4 above outlined the significant potential impacts of ECL events on coastal systems, estuary dynamics and water resources; however, the impacts of ECLs on natural resources are likely to be more pervasive than this. Although not studied as part of the ESCCI-ECL project, ECLs, via their influence on major physical processes such as rainfall, storms and coastal wave action, will have impacts on a number of ecosystem processes.

In terms of terrestrial environments ECLs have a significant influence on average and inter-annual variability of rainfall. In turn, rainfall has a significant impacts on vegetation dynamics. For example, a reduction in the frequency and intensity of winter ECL storm events is likely to result in drier winters. This is particularly relevant for the southern half of the eastern seaboard, where Bureau of Meteorology studies have indicated that ECLs are responsible for a third to almost half of the winter rainfall. Depending on the following warm season rainfall and temperature, the drier winters can result in lower soil moisture and drier fuels leading into the warmer seasons, thus increasing fire risk. Likewise, studies by the Department of Primary Industries have demonstrated that much of the forests and woodlands of NSW are dependent on groundwater to balance out the highly variable climate. Groundwater recharge depends on the distribution, amount and timing of precipitation, evapotranspiration losses, and land use or land cover. It also depends on soil permeability and the hydraulic properties of the regolith. Storms are a significant component of the recharge mechanism for groundwater and a long-term decline in storm activity could adversely affect groundwater, even without a significant reduction in average rainfall. In many areas of central and western NSW, streambed recharge can be significant. We can get significant recharge events from flood events that happened in Queensland as they slowly flow down the river system through NSW.

Due to the highly variable nature of rainfall in Australia many of our streams and rivers are ephemeral in nature. Storms or the lack of them play a major role in river ecology. In terms of freshwater aquatic systems ECLs are a significant component of the high flow events that are particularly important in the hydrology and ecology of our coastal streams.

The flooding from storms such as ECLs increases hydrological connectivity (connection of isolated wetlands to the river channel) and triggers booms in productivity. Storms may also physically alter the channel and morphology of rivers and streams resulting in bank erosion or even creation of new

Fallen tree due to storm damage in backyard of suburban home (Margoe Edwards).

channels. Large events can also mitigate salinity, such as in the Hunter catchment where saline water is released from mines during high flows to maintain stream water quality. A reduction in ECLs could result in drought like conditions, which in turn alters water quality and reduces habitat availability. An increase in these storms could lead to significant stream and river bank erosion but higher freshwater flows

6.1 ECLs and natural processes

ECLs are a pervasive part of the climate system; we need to stop thinking of them just in terms of being a natural disaster and more in terms of their role in driving many of the ecosystem processes that natural resources depend upon in the eastern seaboard. For example, all NRM managers are aware that although a single bushfire is a dramatic event, it is the sequence of fires or the bushfire regime that drives vegetation dynamics and the subsequent impacts on property and ecological functioning. The same applies to coastal tropical vegetation, with cyclones being a major driver of rainforest dynamics. This thinking needs to be applied to coastal ecosystems and ECLs. Just like fire, where the regime is important, the clustering of events drives a range of coastal processes like shoreline position, estuary entry conditions and water quality dynamics. ECL rain events influence sediment and nutrient flows into the coastal zone.

The impact of ECLs is not consistent along the eastern seaboard and depends in large part on the frequency and clustering of the various types of ECL. For example, a clustering of easterly trough lows and inland trough lows could have a greater effect on the north coast than in the south.

6.2 Using the past climate analysis for NRM

The analysis of past climates demonstrates that the frequency of clustering and intensity of ECLs is more variable than even our historical records show. Therefore in terms of designing for extreme storm events we need to consider the high probability of extreme storms occurring with a frequency and intensity outside of our historical knowledge.

The extreme erosion lines or ultimate storm scarp developed as part of Project 4 can be used as a guide for coastal planning. For example, when historical climate data is combined with the information from the palaeogeomorphological studies of beach dunes, it gives us a very good basis from which to understand or define how the ultimate storm will manifest itself on the coast, giving us a better baseline for determining risk.

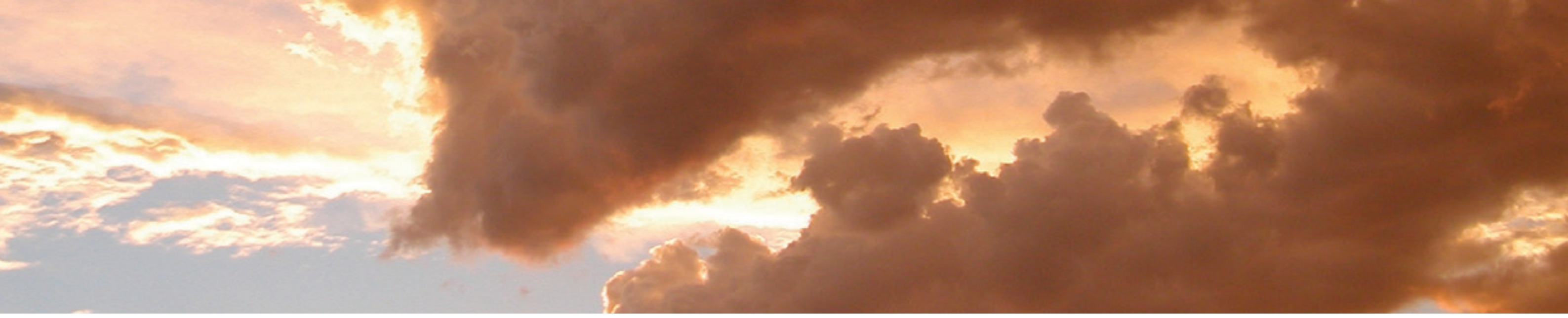
The preliminary projections are that medium level storms are likely to decline but high level storms will potentially remain the same. This is coupled with a slight increase in extreme rainfall events. We can look at past climate modes to this and see what the impact on coastlines and streamflow would look like.

For the south coast this could mean that flooding risk from extreme storms could increase even though the region could expect longer and harsher dry periods.

An improved version of MATCHES could allow NRM and emergency services managers to look at particular storms or clusters of storms and how they impacted on precipitation, wind and waves for their particular region.

Before and after the June 2016 East Coast Low, Narrabeen Collaroy Beach (WRL 2016)

1 June 2016 7 June 2016



6.3 Using the future climate projections for NRM

The existing projections were based on the modelling of ECLs as a single storm type. This has indicated that rainfall within the northern part of the region is likely to increase in summer and potentially decrease in the south, with a possibility of extended dry periods in the southern region. This could have a major impact on water security, forest management and land degradation. However, as the type of ECL and where it occurs has a significant bearing on how it will impact on coastal and water resources, there is a need for modelling of the future frequency and intensity of each of the five types of ECL.

Project 5 is currently testing the projections of future rainfall that are being delivered by Project 2 and the NARCliM ensemble. This work will provide us with a projection of possible impacts, but also outline the limitations of using this specific dataset for water resource planning.

In the meantime we can use the historical variability outlined in Project 3 as a guide to the range of ECL variability that we need to plan for.

6.4 Future work needed to help guide NRM and emergency services

A key component in understanding the likely future risks to coastal processes and water resources is the ability to look at the frequency, intensity and timing of each of the types of ECL. As we have demonstrated through the work on Projects 4 and 5, it is important to understand the type of ECL and its seasonal frequency and intensity if we are to make definitive projections of likely impacts due to climate change. The University of UNSW is progressing fine scale regional climate modelling of the five types of ECLs identified by the ESCCI-ECL Project.

- There is a high level need to improve seasonal forecasting of ECL clustering and intensity.
- In terms of future requirements, to make this work particularly relevant to natural resource management and emergency services managers, there is a need for region wide improvement in seasonal forecasting related to the probability of ECL storms both in terms of frequency and intensity.
- As the impacts are not consistent across the region this must be based on the types of east coast lows. This will allow resource managers and emergency services personnel to have a better understanding of the likely risks they face each season in terms of preparedness for disaster and planning for water resource security.
- The seasonal forecasting could be produced in a format similar to the regional impact profile proposed earlier in the report. In this way natural resource and emergency services managers could be provided with probabilities or visual clues as to the likelihood of erosion events or clustering of storms and how these may affect streamflow and flood risk.
- This will be particularly important for emergency services personnel looking at financial and human resources when preparing for the likely risk in the upcoming season. To do this will require significant investment in using information from Project 2 to produce more reliable seasonal outlooks. These could be similar to the cyclone warning outlooks for the upcoming season that the Bureau of Meteorology currently issues.
- An improved version of MATCHES, which captures information on ECL events and their rainfall, wind and wave impacts on an ongoing basis, would provide emergency services managers with readily accessible and up to date information of the risk posed by ECLs.
- A new research theme looking at the effect of ECLs on other natural processes such as groundwater recharge, and the influence of ECLs on fire risk would provide valuable information in the management of the native vegetation of the region in a changing climate.

OEH will continue to engage in collaborative research to address remaining knowledge needs as part of its ongoing climate impact and adaptation research.

7 Further reading

Read an editorial on the ESCCI-ECL project and associated papers in a special edition of the Journal of Southern Hemisphere Earth Systems Science 2016 66(2) 95-96

Project 1 Hazard tool development

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Project 2 Future ECLs

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Project 4 Coast and estuary impacts

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Mortlock TR & Goodwin ID 2015, Directional wave climate and power variability in the Tasman Sea. Continental Shelf Research 98, 36–53

Project 5 Water security

Kiem AS, Twomey C, Lockart N, Willgoose GR, Kuczera G, Chowdhury AF, Parana Manage N & Zhang L 2016, Links between East Coast Lows and the spatial and temporal variability of rainfall along the eastern seaboard of Australia. Journal of Southern Hemisphere Earth System Science 66(2), 162-176

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Project 6 Economic impacts

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