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Low pressure systems off the New South Wales coast and associated hazardous weather: establishment of a database

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The New South Wales (NSW) coast is subject to heavy rain, strong wind and large waves resulting from low pressure systems over the adjacent Tasman Sea that develop from a variety of synoptic and mesoscale mechanisms. A database of these maritime lows and their impacts has been developed in the NSW Climate Services Centre of the Bureau of Meteorology. The database currently extends back to 1970 and includes data on rainfall amounts, with wind speed and significant wave height data still to be added. The database events were classified into six synoptic types based on the mean sea level pressure synoptic pattern in which the lows formed. The six types are: inland trough lows (30 per cent), easterly trough lows (14 per cent), and ex-tropical cyclones (4 per cent), all of which originate in the subtropical or tropical easterlies; and, lows forming on a wave on a front (37 per cent) decaying front lows (12 per cent) and lows in the westerlies (3 per cent), the latter two of which originate from mid-latitude low pressure systems or fronts in the westerlies. Since 1970, only inland trough lows have shown a significant increase in frequency which is consistent with a slight increase in spring rainfall in an area over northeast NSW over the same period. In contrast, there has been a decrease in ex-tropical cyclone numbers impacting the NSW coast since 1970, which is consistent with a decrease in summer rainfall generally along the NSW coast. The development of the database is ongoing but it is planned to extend it back in time to further investigate the relationship between maritime low pressure development and NSW coastal rainfall trends.

Introduction

Maritime cyclones off Australia's east coast have a significant impact on the climate affecting much of the population, and have been responsible for some of the extremes in weather recorded in eastern New South Wales. The severe weather phenomena that can accompany these maritime cyclones include extreme wind speeds, large ocean waves and heavy rain. However, the resulting impacts of these phenomena vary considerably between events. For example, the nature of the impact of a storm surge at a particular location on the coast is dependent on the location of the low's centre over the Tasman Sea (McInnes and Hubbert 2001). Also, river flooding depends on the antecedent conditions in the river catchment. Moreover, trees may be uprooted at low wind speed thresholds depending on the degree of soil wetness. A

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detailed historical account of the weather phenomena associated with maritime cyclones needs to be readily available for users and disseminators of weather information such as emergency managers, weather forecasters, hydrologists, the insurance and re-insurance industries and shipping organisations. Furthermore, a long, detailed record is critical in decision planning by structural engineers and, in a broader context, is a vital component in developing a scientific basis for scientists and policy makers to aid in distinguishing anthropogenically induced climate change from natural climate variability. In terms of new Australian detection and attribution studies, the highest priority would appear to be the decline in east coast rainfall (Nicholls 2006, p.199). A recent World Meteorological Organization (WMO) report on climate extremes (WMO 2007) emphasised the significance of establishing and sharing databases of hazardous weather phenomena such as extra-tropical cyclones, for disaster mitigation and capacity building the necessary components for an early warning sytem for extreme events, and for climate change adaptation through increased understanding of natural variability and the relationship to global warming. To this end a comprehensive database of maritime cyclones and associated weather affecting the NSW coast is being established. This paper describes the database including the categorization of database entries into synoptic-mesoscale types and analyzes recent trends in the types with a focus on their relationship to rainfall.

Background

There have been several studies of marine low pressure systems in the Australian region. Qi et al. (2006) presented a climatology of 21 marine low pressure systems covering the area from the NSW coast to 170° E and spanning the period 1992 to 2001. Holland et al. (1987) concentrated on the explosive east coast low, and documented three main types according to their main distinguishing kinematical, dynamical and thermal environmental characteristics using a manual classification on a total of 21 systems from 1970 to 1985. Hopkins and Holland (1997) concentrated on a rainfall threshold for east coast stations in identifying 80 east coast cyclones over the period 1958 to 1992. Feren (1995) investigated 37 cases between 1981 and 1990 of an upper tropospheric cloud pattern termed 'striated delta', that often is a precursor to major extratropical cyclogenesis within the eastern Australian-western Tasman Sea region. Leslie and Speer (1998) investigated a short range ensemble forecasting approach to east coast lows and Callaghan (2004 and www.bom.gov.au/severe) lists major east coast low impacts from the 1900s.

Several types of maritime cyclone affect NSW. One type is the classic "east coast low", as in the studies mentioned above, for which a practical working definition used in the NSW Regional Office of the Bureau of Meteorology is, "a system with a closed cyclonic circulation at the surface, forming and/or intensifying in a maritime environment within the vicinity of the east coast". Based on the studies mentioned above, maritime low pressure systems affecting the NSW coast can be further characterized as:

- having the centre located between 20° and 40° S,
- occurring at any time of year but most common in autumn and winter
- being associated with western boundary currents and coastal orography
- sometimes associated with a blocking high
- varying in size from meso- to synoptic scale
- often moving parallel to the coast
- often exhibiting rapid deepening (so called "bombs")
- development often occurring overnight

However, large waves and heavy rain along the NSW coast may also occur when large-scale systems such as tropical cyclones (TCs) or ex-TCs move southward. Such systems may be centred well away from the area affected. For example, Sydney (Observatory Hill) received its record 24 hour February rainfall on 3 February 1990 when ex-TC Nancy was centred just east of Brisbane, even though rainfall amounts further north of Sydney and closer to Nancy, were less (Speer 1992). The study area is indicated in Fig. 1.

Fig. 1 Eastern Australia and adjacent Tasman Sea showing the maritime lows database area. Also indicated are the fifteen NSW Bureau of Meteorology observing stations in the database.

Data and methodology

It is planned to amalgamate separate databases containing data for large waves, heavy rainfall and wind speed and direction meeting threshold criteria previously developed, which will then be routinely updated, thereby providing a comprehensive database of heavy rain, hazardous winds and large ocean waves together with details of the main weather system responsible for the affected parts of NSW. This database will form the basis for ongoing climatological studies of maritime cyclones off NSW and their impact on coastal areas. Only rainfall from 1970 to 2006 is available from the database thus far.

The rainfall impact is gauged using a grid of fifteen Bureau of Meteorology stations distributed along the NSW coast (Fig. 1). Rain is flagged at three levels: the event is flagged for rain if ≥5mm was recorded at any station due to the system; it is flagged for significant rainfall if ≥25mm occurred at at least two of three adjacent stations; and for heavy rain if ≥100 mm was recorded for at least one station.

The rain category is used to indicate that there was some rain impact. Hence, only one station is needed to reach the threshold. The significant rain category is used not only to indicate passing a threshold amount, but also a significant areal extent of the rainfall impact for river catchments and agricultural purposes. The heavy rain category is used to capture the risk of flash flooding and/or river flooding, so it is considered that reaching the threshold at one site is appropriate.

The data sources used include the Bureau of Meteorology archives of station data, mean sea level pressure (MSLP) and satellite imagery. Recorded details for each event are the date and storm track[1] (latitude/longitude) of the event; whether the system formed in the database area as defined in Fig.1 or entered the area; if it entered the area, whether it intensified; if it intensified, whether the intensification was "explosive" (greater than 10 hPa in 24h)[2]; and, finally, categorization of the system by its synoptic-mesoscale environment.

[1]Storm track data for each system can be entered.

[2]Sanders and Gyakum (1980) defined a normalized central pressure deepening rate (NDR_C) for explosive development (termed 'bombs') in a 24 h period as,

$$NDR_C = \frac{\Delta p_c}{24h} \frac{\sin 60°}{|\sin \varphi|} = 1$$

Where Δp_c is the change in central pressure and φ is latitude. For latitude $\varphi = 25°$, $\Delta p_c = 11.7$ hPa and for $\varphi = 40°$, $\Delta p_c = 17.8$ hPa, which represent the normalized deepening rates for a 'bomb' at approximately the northern and southern latitudes of the study area, respectively. To allow margin for error in estimating central pressures, the NSW maritime low database flags explosive intensification as a minimum of 10 hPa in 24 h.

Synoptic typing

The remainder of this paper focuses on the categorization of each impact event into its synoptic-mesoscale environment and trends in those categories. Principal analytical methods of synoptic climatology can be classified as, manual classification; correlation-based map-pattern classifications, eigenvector-based classification; composites; and, circulation indices. The reader is referred to Yarnal (1993) for an in-depth description of these methods and their advantages and limitations. An assumption of all synoptic climatologies is that the temporal scales of the observations and the atmospheric circulation processes match. This is not an issue for the marine low phenomena of interest in this study since the diagnostic processes associated with the low pressure systems operate on the order of from one to a few days which is the same temporal scale of the systems themselves. However, in automated synoptic climatologies (the latter three mentioned above), there is also an assumption that the spatial scales of the gridded data and the circulation coincide. This is not a problem when atmospheric features are larger than the horizontal dimensions of the grid but when the grid scale is larger than the size of the atmospheric feature, high-wavenumber characteristics are effectively filtered. This scale problem associated with gridded archive data has been mentioned previously in relation to NSW coastal ridging (Speer and Leslie 1997, p.836). Subtropical marine low pressure systems and associated low pressure troughs invariably span the meso-synoptic spatial scale range. Therefore, some of the marine low pressure systems, with small centres or merely cyclonic curvature in the MSLP contours, may not appear on digitally archived synoptic analysis charts so an objective analysis, such as principal component analysis, that searches for MSLP patterns in an attempt to explain significant pattern variations is problematical. Here, we categorize each system manually from the manual MSLP chart archives, based on meteorological expertise within the Bureau of Meteorology in NSW. Six synoptic-mesoscale types have been identified, namely, (1) ex-tropical cyclones, (2) inland trough lows, (3) easterly trough lows, (4) wave on front lows, (5) decaying front lows, and (6) lows in the westerlies, as indicated in Fig. 2 and Table 1, and these are now described.

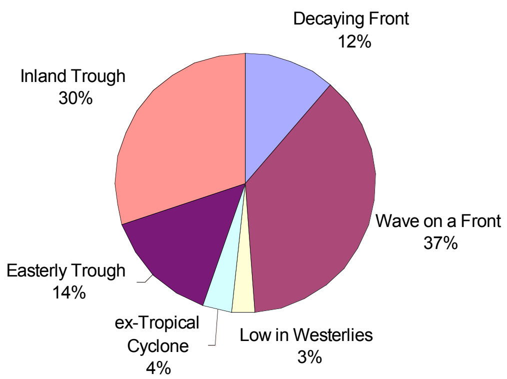
Ex-tropical cyclones

A generic example of an ex-tropical cyclone is shown in Fig. 3(a). While this category represents only 4 per cent of the database (Fig. 2), strong, moist easterly winds normally affect the northern NSW coast in these situations with rain, wind and large waves all likely to impact the area. The monthly distribution clearly shows that they are a late summer/autumn phenomenon (Fig. 4(a)). While they mainly affect the northern part of the NSW coast a small number also create

Table 1. Frequency of NSW maritime lows by synoptic type

	Inland trough low	Easterly trough low	Ex-tropical cyclone	Wave on front low	Decaying front low	Low in westerlies
With rain	215	102	24	180	54	14
Total	253	119	30	308	96	24

Fig. 2 Database distribution of maritime lows by synoptic type from 1970 to 2006.



an impact when reaching the southern part of the study area (Fig. 5(a)).

Inland trough lows

In this case an inland low pressure trough is usually oriented NW-SE through northeast NSW and a low centre near the coast in the trough may either have one or more closed MSLP contours (Fig. 3(b)) or possibly no closed contours. Such troughs are common in summer when they are a semi-permanent feature and as a consequence inland trough lows have a warm season (Sept/March) maximum (Fig. 4(b)). The impact from this type on rainfall in coastal areas can be significant. Lows associated with inland troughs represent 30 per cent of events in the database (2). Their formation density is spread over the study area (Fig. 5(b)) with a slight minimum on the NSW north coast, that is, well north of the apex of the typical axis position.

Easterly trough lows

Low pressure circulation systems that develop over the Tasman Sea either adjacent to the coast or further seaward may originally start from low pressure troughs off the coast in the easterlies (Fig. 3(c)), and these represent 14 per cent of the database (Fig. 2). They can occur throughout the year with a maximum frequency that straddles the autumn/winter period (Fig. 4(c)). Their formation density is concentrated in the northern half of the study area (Fig. 5(c)) where, generally, the position of the subtropical jet (STJ) maximum, in winter and the transition seasons, is likely to be a major influence. The core velocity of the STJ averages 70 ms^{-1} at 25° S over Australia in winter and 30 ms^{-1} at 31°S in summer (Linacre and Geerts 1997). The impacts are likely to be rain, confined to the coast, and especially strong winds and large waves if the systems intensify.

Wave on a front lows

The most common form of low pressure development impacting the area (representing 37 per cent of the database) occurs when a low pressure centre develops from a cold front within a large scale mid-latitude trough in the Tasman Sea longitudes (Fig. 3(d)). This development peaks over the winter/spring period (Fig. 4(d)) when the winter westerly regime south of the continent is strongest and hence their formation density is concentrated in the southern half of the study area (Fig. 5(d)).

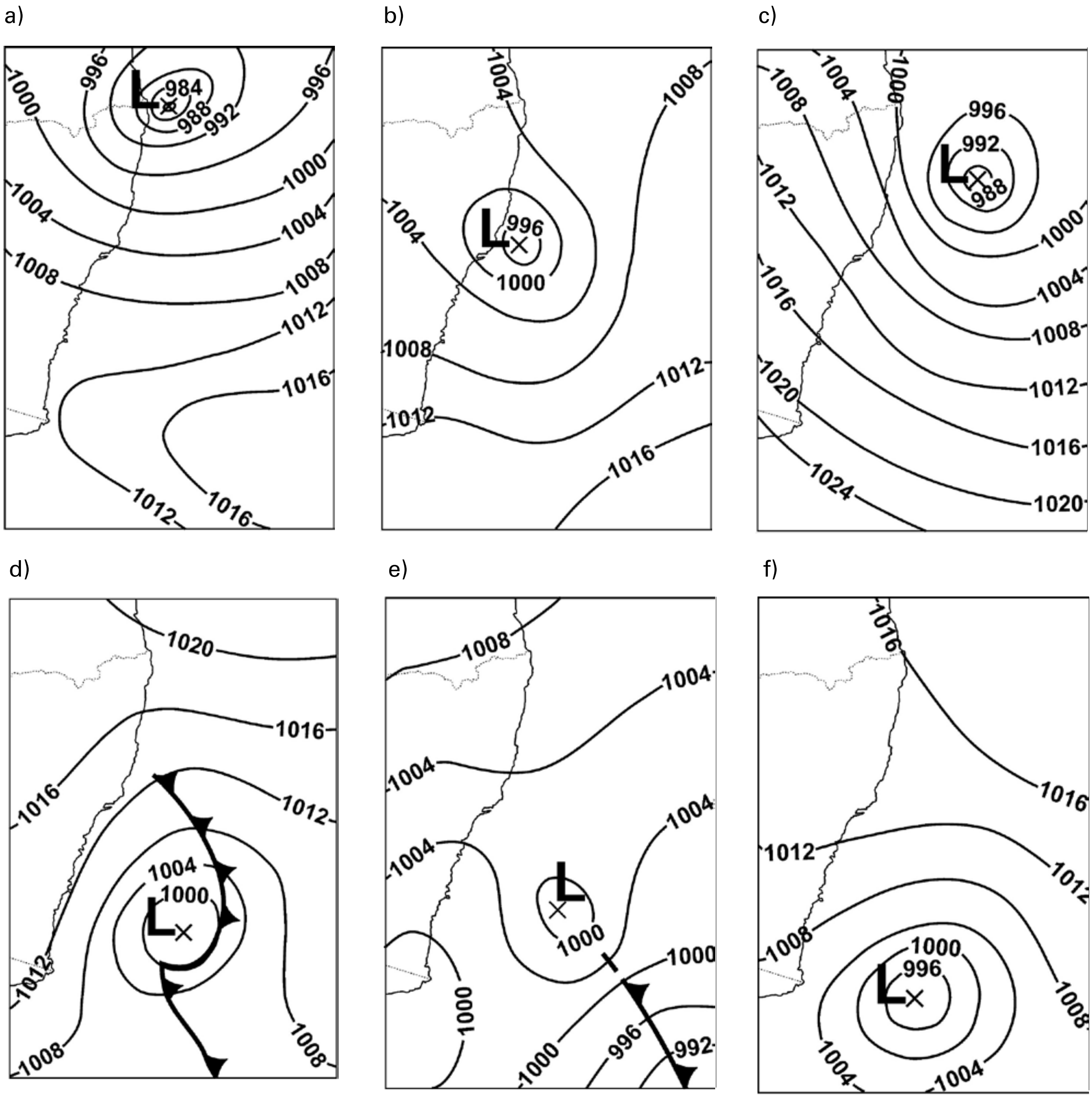
Decaying front lows

Lows over the Tasman Sea that form on the northern portion of a mid-latitude cold front represent 12 per cent of the database. The development of a low pressure circulation occurs in the sub-tropical easterly regime which dominates the weakening northern portion of the cold front (Fig. 3(e)). While this development can occur any time of year there is a tendency for a slight maximum to occur in the warmer months when the subtropical easterly wind regime dominates NSW latitudes (Fig. 4(e)). As their formation is dependent on the existence of a mid-latitude cold front to the south of the study area, their formation density tends to also concentrate in the south (Fig. 5(e))

Lows in the westerlies

Lows in the westerlies (3 per cent of the database) as their name implies are pre-existing lows in the westerlies that enter the database area. They are predominantly winter phenomena, and are likely to be located in the southern half of the study area (Figs 3(f), 4(f), 5(f)). When these larger scale low pressure systems are intense they can produce significant wind speeds and large waves, particularly in the south of the area.

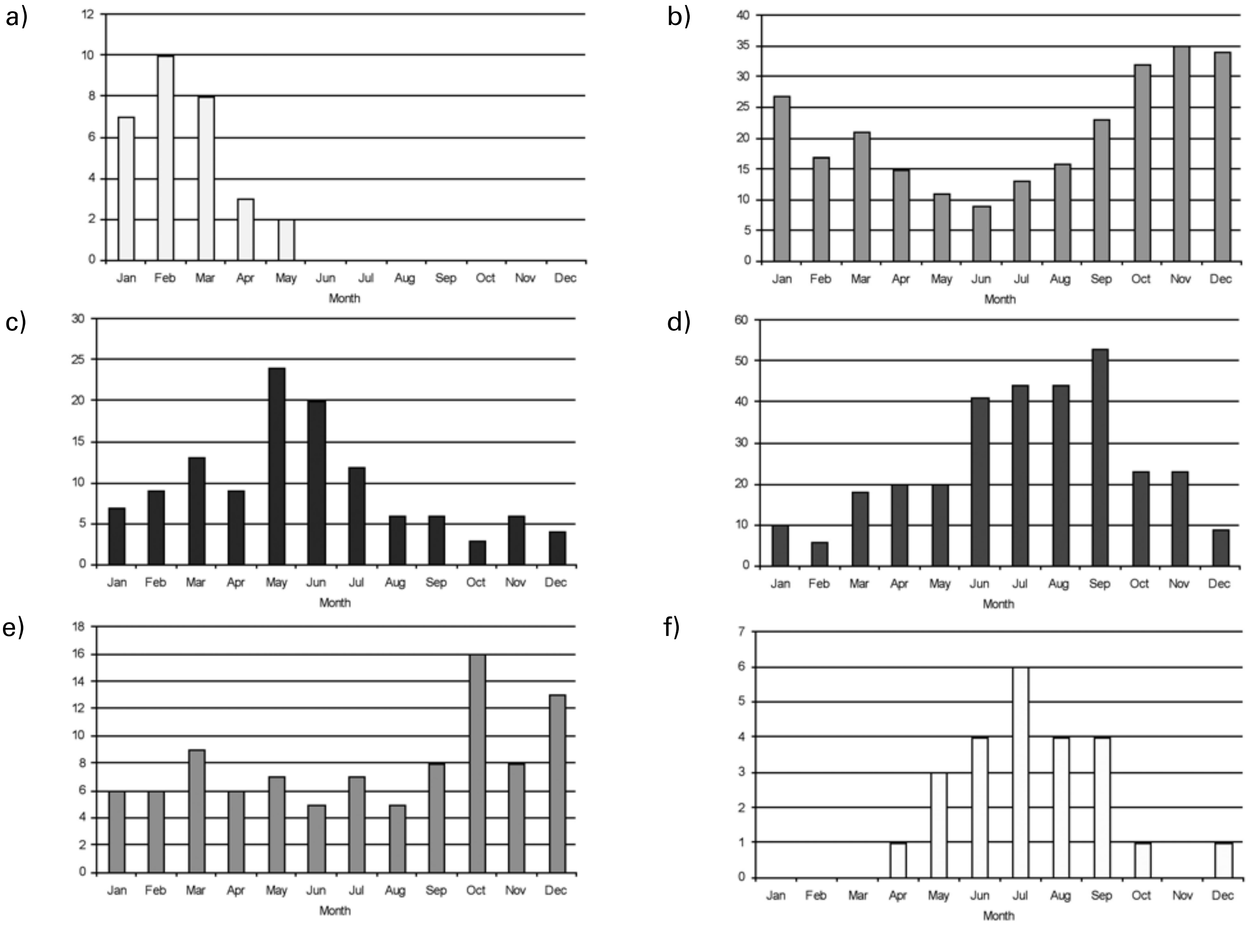
Fig. 3 Generic mean sea-level pressure (MSLP) features of NSW maritime lows classified as, (a) ex-tropical cyclones, (b) inland trough lows, (c) easterly trough lows, (d) wave on front lows, (e) decaying front lows, and (f) lows in the westerlies.



'Explosive' lows by synoptic type

The rapid and intense development of low pressure systems (i.e. 'bombs'), mentioned earlier and defined in the database as a 10 hPa or more lowering of central pressure in 24 hours, has occurred with all of the above synoptic types except ex-tropical cyclones. Ex-tropical cyclones, by definition, have made transition from a tropical cyclone into a, usually, weaker sub-tropical low pressure system with a higher central pressure at the surface. For the other five synoptic types, the percentage of database events involving explosive lows is shown in Fig. 6(a). Explosive surface development with these various synoptic types occurs with the influence of a strong STJ or polar front jet above, which usually occurs in the winter and transition seasons at NSW latitudes. As mentioned in the easterly troughs discussion, the core velocity of the STJ averages 70 ms^{-1} at 25° S over eastern Australia

Fig. 4 Monthly distribution from 1970 to 2006 of the six synoptic types of maritime lows, (a) to (f), as defined in Fig. 3.



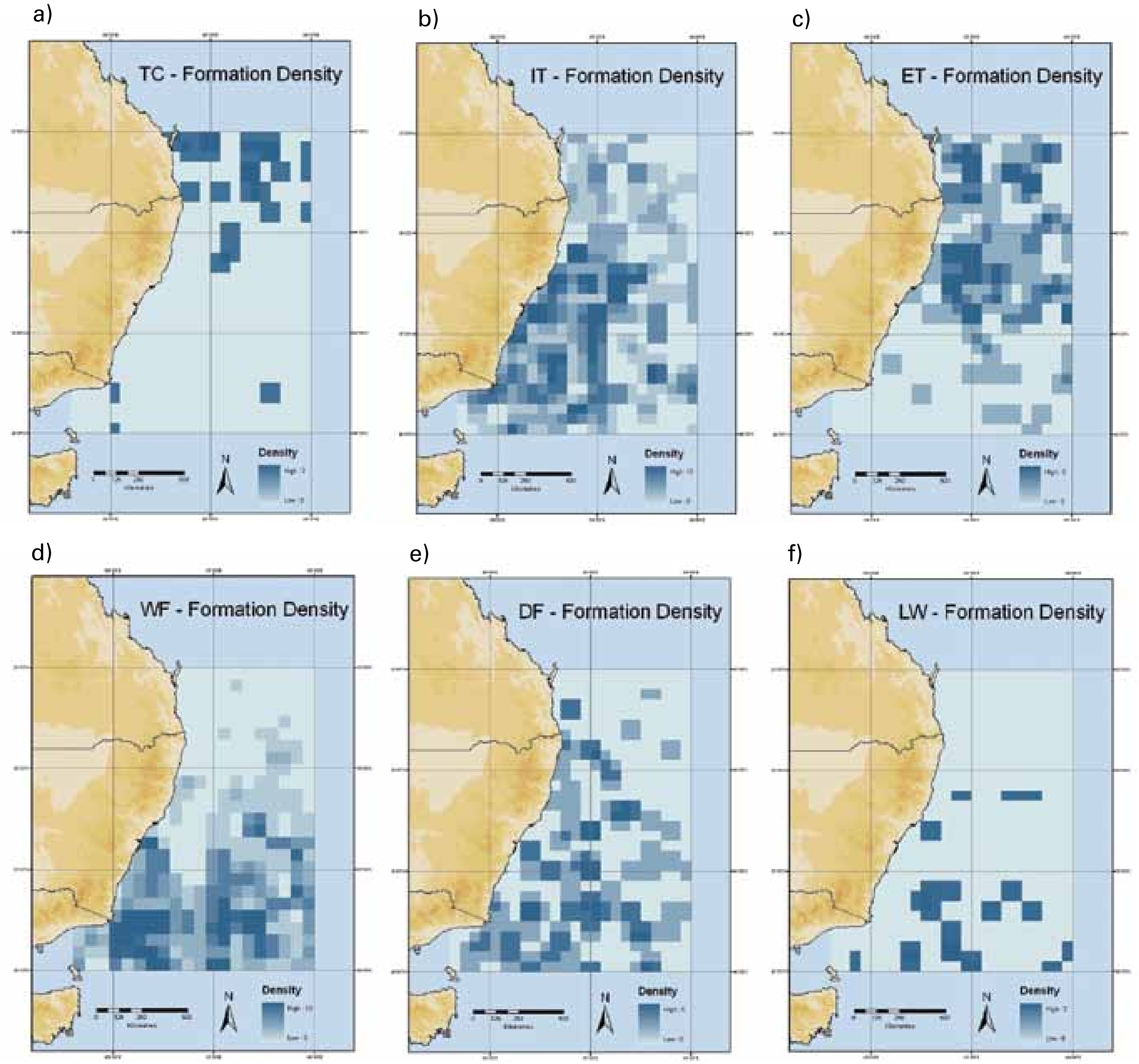
in winter and 30 ms^{-1} at 31°S in summer (Linacre and Geerts 1997). Hence, the monthly distribution peaks occur in the cooler months of the year (Fig. 6(b)). These systems tend to form in the southern half of the study area (Fig. 6(c)), which is consistent with the formation density locations generally of lows that form from a wave on a front, easterly trough lows and inland trough lows. However, inland trough lows tend to form in the warmer months (Fig. 4(b)) which implies that other physical processes, apart from dynamically associated jet stream processes and enhanced land-sea temperature gradients, are likely to be important for their explosive development.

Heavy rain events by synoptic type

Although wave on front lows make up 37 per cent of all events, they represent only 17 per cent and 9 per cent of significant rain and heavy rain events, respectively. Their formation density is concentrated in the south of the study area (Fig. 5(d)) during winter and spring when the winter westerly wind regime is strongest and moisture availability onto the NSW coast is usually least favourable. Two synoptic categories dominate when considering events that produce significant rain according to the threshold of 25 mm in this study. As shown in Fig. 7(a), these are the inland trough lows (39 per cent) and the easterly trough lows (25 per cent). Rain is even more important for these two categories when the amount reaches the heavy rain threshold of 100 mm, since the proportion for inland trough lows increases from 39 per cent to 43 per cent and for easterly trough lows from 25 per cent to 32 per cent (Fig. 7(b)). It is worth noting that while the ex-tropical cyclone category represents only 7 per cent of the significant rain category it also represents 9 per cent of the heavy rain synoptic category. However, for the remaining three synoptic categories, namely, wave on a front lows, decaying front lows and lows in the westerlies, the percentage amount of significant rain for each of the three synoptic categories is greater than (or equal to, in the case of lows in the westerlies) the percentage amount of heavy rain.

A more general observation about the distributions of significant rain lows and heavy rain lows from Figs 7(a) and (b) is that systems that develop within subtropical easterly wind regimes, namely, inland trough lows and easterly trough lows account for 71 per cent of the significant rain

Fig. 5 Formation density in the study area of the seven types of maritime lows, (a) to (f), as defined in Fig. 3.



events when combined with the ex-tropical cyclone category and 84 per cent of the heavy rain events. This is consistent with these three systems being characterized by warm, moist low-level air compared to the relatively cooler, drier and generally faster moving low-level air associated with the other three synoptic categories whose systems primarily develop from dynamical processes in the mid-latitude westerlies over the southern part of the study area.

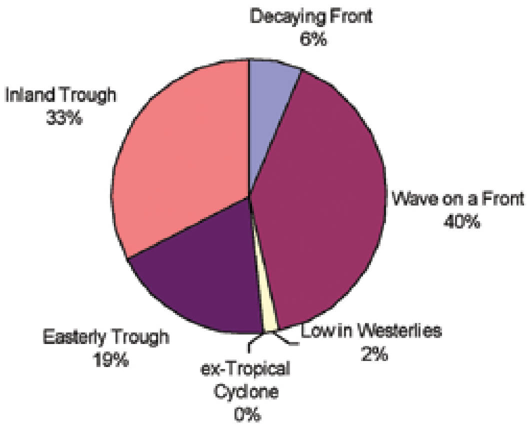
Recent trends in synoptic types

Figure 8(a) shows three time series containing the total number of events (includes rain and no rain), and the number of events with significant rain and heavy rain, for all the synoptic types of NSW maritime lows since 1970. There are no significant long term trends in any of the three time series. However, for both the total number of maritime low events and those with rain, there has been a decreasing trend since about 2002. This recent decreasing trend reflects the severe drought conditions over eastern Australia since that time.

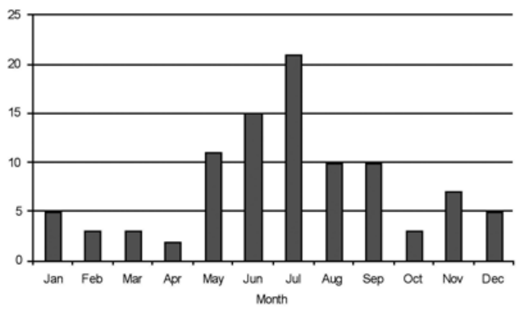
For five of the six synoptic categories of maritime lows there is no significant long term trend in numbers since 1970. The one exception is for the inland trough lows. For this category, Fig. 8(b) shows an increasing trend in the total number of events since the mid-1980s. Similarly, there is an

Fig. 6 (a) Database distribution of explosive lows by synoptic type, (b) monthly frequency of explosive maritime lows in the database, (c) formation density of explosive maritime lows in the database.

a)



b)



c)

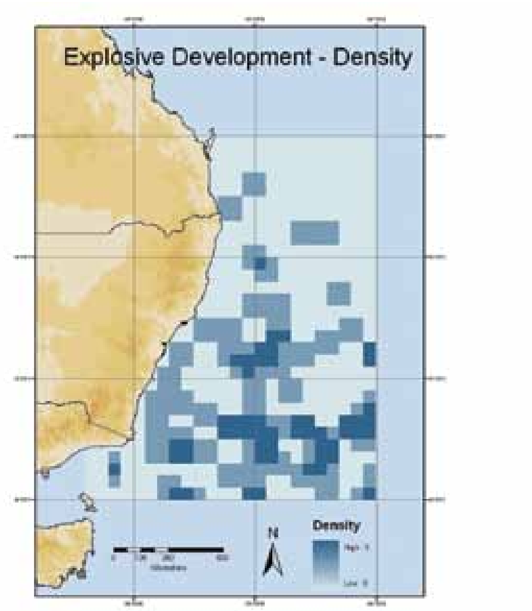
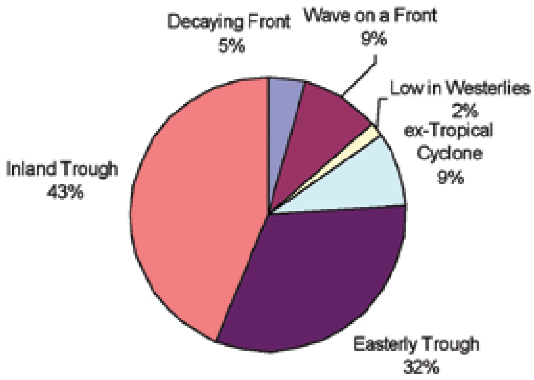
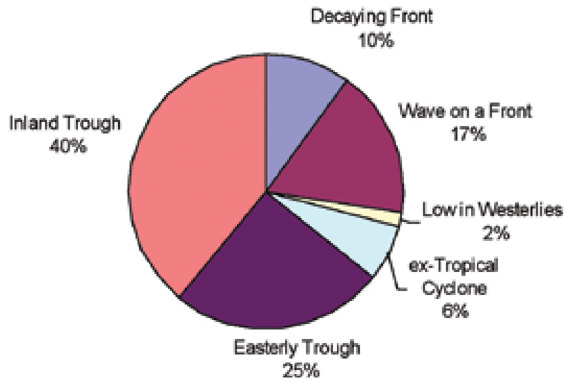


Fig. 7 (a) Database distribution of significant rain (25 to 100 mm) from maritime lows by synoptic type, (b) as in (a), except for heavy rain (≥100 mm).

a)



b)



increase in the 5 to 25 mm rain category (not shown). Using the non-parametric Mann-Whitney U test this increase in total inland trough lows since 1986 is statistically significant at the 5 per cent level and, for the number of events with rain since the mid-1980s, it is statistically significant at the 1 per cent level. This is consistent with a slight increase in spring rainfall for northeast NSW since 1970 (Fig. 9(a)) in a band similarly oriented to the typical axis position of the surface inland trough (Fig. 3(b)). An increase in rainfall since 1970 in northeast NSW has also occurred in autumn and winter but, in contrast, there has been a decline in summer rainfall (Figs. 9(b),(c),(d)). Autumn is not a peak time for inland trough lows to form off the northern NSW coast. The peak time is in the warmer months of September to March (Fig. 3(b)). This means that there must be other tropospheric mechanisms which are contributing to rainfall in that area in autumn. One possible explanation is that the inland surface low pressure trough may be produced in response to upper tropospheric jet stream dynamics without necessarily leading to the formation of a maritime low. A major contributing factor to the summer decline in coastal rainfall in the same area is most likely due to the decrease in ex-tropical cyclone numbers and associated rainfall (Fig. 8(c)). Finally, the winter increase in rainfall in central inland NSW since 1970 appears not to be related to any of the six categories since the classification in this study focuses on coastal rainfall. Further work investigating rainfall trends will be undertaken once the database includes upper-level features and extends back to 1950.

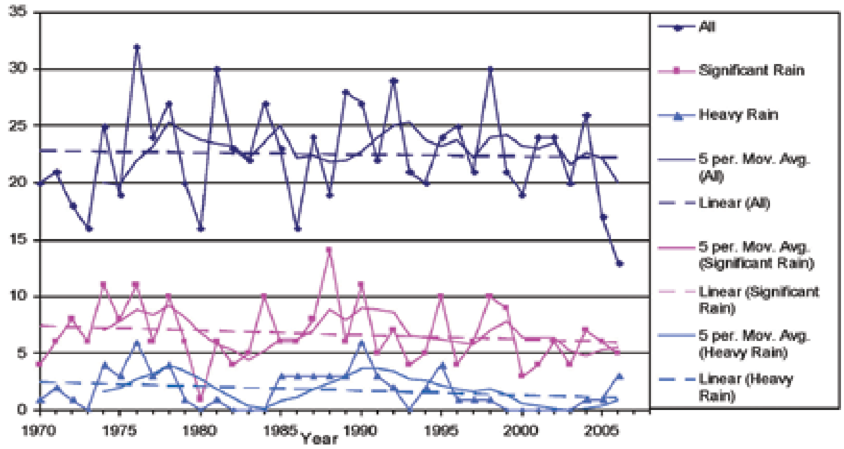
Summary and conclusions

An ongoing database of maritime low pressure systems affecting the NSW coast is being developed and maintained by the NSW Bureau of Meteorology Climate Services Centre. Thus far, rain threshold values based on the records of 15 meteorological observing stations along the NSW coast determine the inclusion, or otherwise, of an event in the database. The 24 hour threshold values for rain are 5 mm to less than 25 mm (rain) for one station, 25 mm to less than 100 mm (significant rain) for at least two of three adjacent stations and greater than or equal to 100 mm (heavy rain) for one station. A synoptic-mesoscale classification of the MSLP for the rainfall events showed that there are six broad categories leading to development of maritime low pressure systems that have affected NSW coastal rainfall since 1970. The categories are: (1) ex-tropical cyclones, (2) inland trough lows, (3) easterly trough lows, (4) wave on front lows, (5) decaying front lows, and (6) lows in the westerlies.

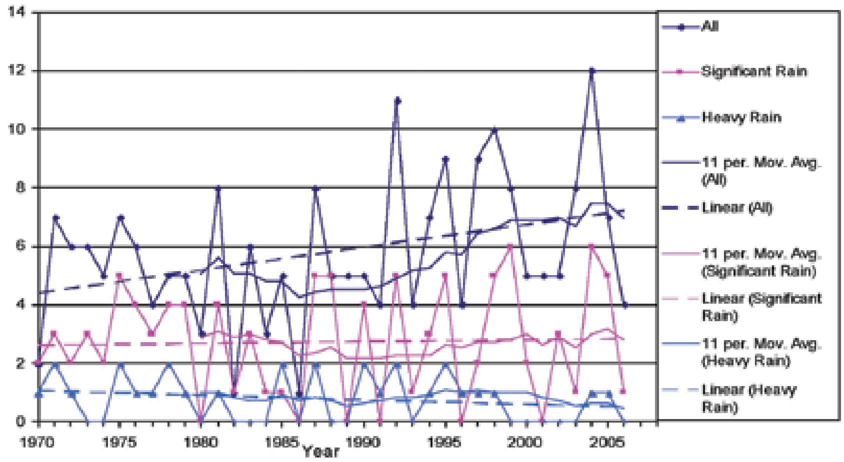
In regard to trends, the inland trough category dominates the other five categories in both significant coastal rain and heavy coastal rain, and shows a statistically increasing trend in both total number and those with rain since the mid-1980s. This matches the slightly increasing trend for spring rainfall on the coast (and further inland) based on the Bureau of Meteorology's high quality rainfall dataset (Lavery et al. 1997) trend analysis near where the position of the inland trough axis is typically located. None of the other categories of maritime low pressure development show any significant long term trend since 1970 apart from the decline in numbers

Fig. 8 Time series of database events from 1970 to 2006 with significant rain (25 to 100 mm), and heavy rain (≥ 100 mm) for, (a) all NSW maritime lows, (b) inland trough lows, (c) easterly trough lows.
Note that the 5 to 25 mm rain category has been omitted for clarity.

a)



b)



c)

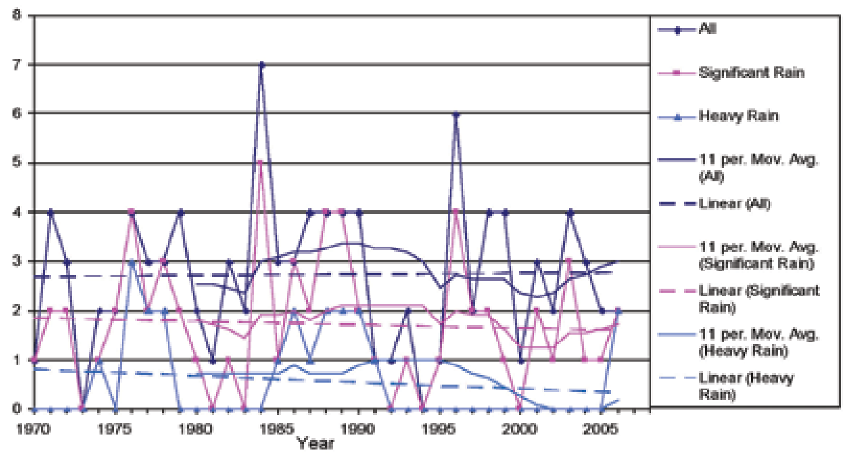
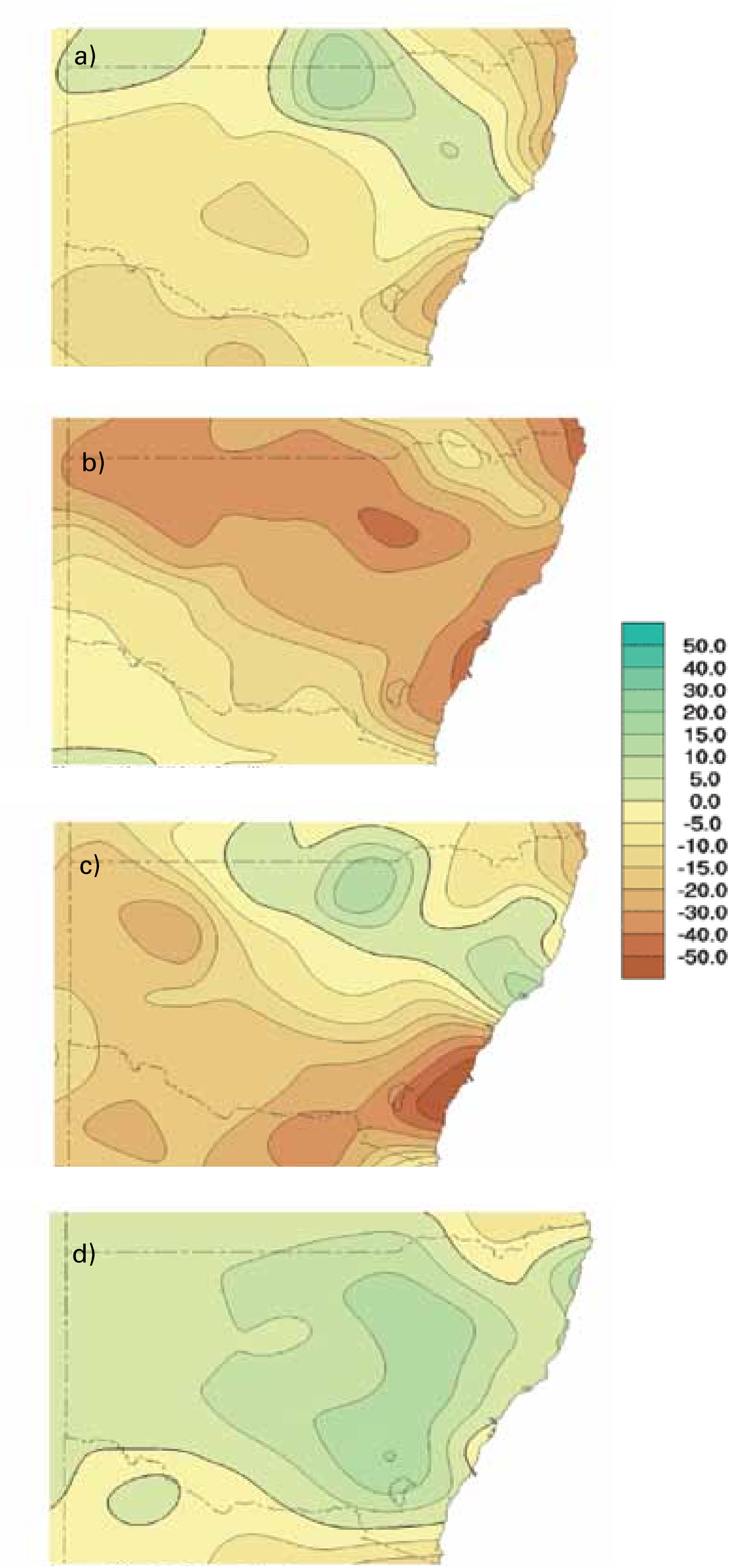


Fig. 9 Trends in NSW total seasonal rainfall (mm/10 years) from 1970 to 2006 based on the Australian Bureau of Meteorology high quality rainfall dataset for, (a) spring, (b) summer, (c) autumn, and (d) winter.



within the ex-tropical cyclone category, which helps explain the decrease in summer coastal rainfall.

The slight increases in spring, autumn and winter rainfall in northeast NSW since 1970, based on the Bureau of Meteorology's trend analyses and relationships to the synoptic classification presented in this study, need to be put in the context of longer time scales and rainfall influences other than maritime lows. Northeast NSW rainfall trends 1970 to 2006 differ from 1950 to 2006 trends to the extent that the decrease is not so marked starting from 1950. Even though only rain associated with maritime lows is recorded in the database, it would be interesting to see whether this change in rainfall trend is accompanied by frequency changes within the database synoptic categories back to 1950.

Finally, the database will be extended further to include the period from 1950 and upper tropospheric features will also be added to the database in future. In addition, further work is underway to use an algorithm which can automatically detect location of gridded field minima (or maxima) and hence low pressure tracks on NCEP/NCAR reanalysis data (Kalnay et al. 1996) and the Australian Bureau of Meteorology's mesoscale limited area prediction system (MESOLAPS) data (Puri et al. 1998). This would provide a test as to whether the software could reproduce the manually derived database, thereby leading to an automated system for ongoing additions to the database.

Acknowledgments

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