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Non-classic extratropical cyclones on Met Office sea-level pressure charts: double cold and warm fronts

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Introduction

The evolution of extratropical cyclones has traditionally been described in the context of the Norwegian cyclone model, where a developing cyclone grows on a stationary front, developing single cold and warm fronts, then occluding (Figure 1(a)). First described by Bjerknes (1919) and Bjerknes and Solberg (1922), the Norwegian cyclone model provided a context for scientists and forecasters to describe the evolution of cyclones and led to the modernisation of meteorology in the first half of the twentieth century (e.g. Namias, 1980; 1983; Newton and Rodebush Newton, 1994). The model has withstood the test of time, with relatively few modifications. One modification is that of the occlusion process as the wrap-up of the air masses involved rather than the catch-up of the warm front by the cold front (Schultz and Vaughan, 2011).

Not all cyclones undergo an evolution similar to the Norwegian cyclone model, however. In the 1980s, field programmes targeting rapidly developing marine extratropical cyclones and mesoscale numerical model simulations showed a slightly different evolution (Shapiro and Keyser, 1990). Instead of a narrowing warm sector during occlusion, as in the Norwegian cyclone model, the Shapiro–Keyser cyclone model exhibited a warm front nearly perpendicular to the cold front in a frontal T-bone, a bent-back front and an eventual warm seclusion (Figure 1(b)). Schultz *et al.* (1998) and Schultz and Zhang (2007) showed that cyclones in large-scale diffluence tended to form Norwegian cyclones and cyclones in large-scale confluence tended to form Shapiro–Keyser cyclones: the lower friction over water also facilitates the development of Shapiro–Keyser characteristics (Hines and Mechoso, 1993).

Over the central and eastern USA, other types of cyclone structures and evolutions are possible, including lee troughs and arctic fronts associated with lee cyclones (Keshishian *et al.*, 1994; Steenburgh and Mass, 1994) warm-sector rainbands caused by cold fronts aloft (Hobbs *et al.*, 1990; 1996; Locatelli *et al.*, 2002) and cyclones with multiple warm fronts (Metz *et al.*, 2004). Multiple fronts have also been documented in idealised modelling studies (Hoskins *et al.*, 1984). In the UK, Miles (1962) and Browning and Monk (1982) recognised the importance of prefrontal troughs and upper-level fronts in the split-front model (also known as a katafront), and multiple fronts have also been documented (Young, 2014).

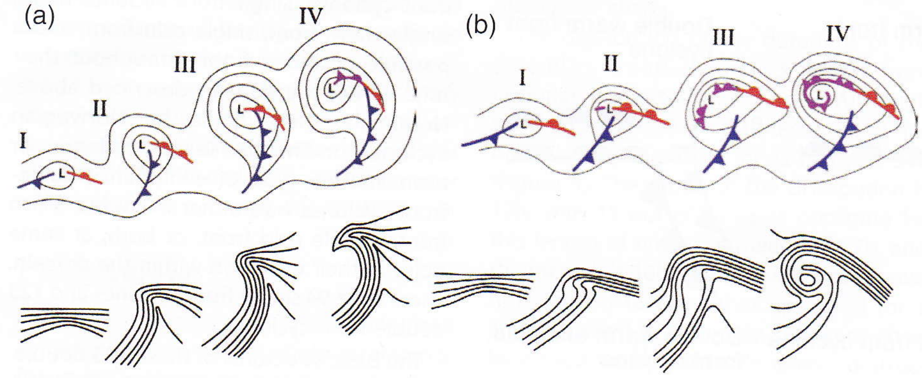

Figure 1. Two types of cyclone conceptual models: (a) Norwegian cyclone model, (b) Shapiro–Keyser cyclone model. (top) Lower-tropospheric (e.g. 850hPa) geopotential height and fronts, and (bottom) lower-tropospheric potential temperature. The stages in the respective cyclone evolutions are separated by approximately 6–24h, and the frontal symbols are conventional. The characteristic scale of the cyclones based on the distance from the geopotential height minimum, denoted by L, to the outermost geopotential height contour in stage IV is 1000km. (Figures and caption from Schultz and Vaughan, 2011.)

Consideration of the Met Office sea-level pressure charts for the North Atlantic Ocean and western Europe on a regular basis leads to the realisation that many cyclones possess frontal structures and evolutions inconsistent with the classic Norwegian cyclone model, specifically cyclones with an array of fronts (Figure 2). For example, the cyclone in Figure 2(a) consists of two warm sectors with two cold and two warm fronts, with a pre-warm-front trough and post-cold-front trough. The Met Office defines a trough as the following: *An elongated area of relatively low surface pressure. The troughs marked on weather charts may also represent an area of low thickness (thickness trough), or a perturbation in the upper troposphere (upper trough). All are associated with increasing cloud and risk of precipitation* (http://www.metoffice.gov.uk/guide/weather/symbols). In Figure 2(b) the cyclone is occluded with a bent-back front, an upper cold front, and warm and cold fronts to the north of the cyclone centre. In Figure 2(c), a cyclone with an occluded front, two warm fronts and three cold fronts is connected to an occluded cyclone to its northeast. In Figure 2(d), a cyclone with a bent-back occluded front is associated with three other warm sectors, each with its own cold and warm fronts, and one even having another bent-back front.

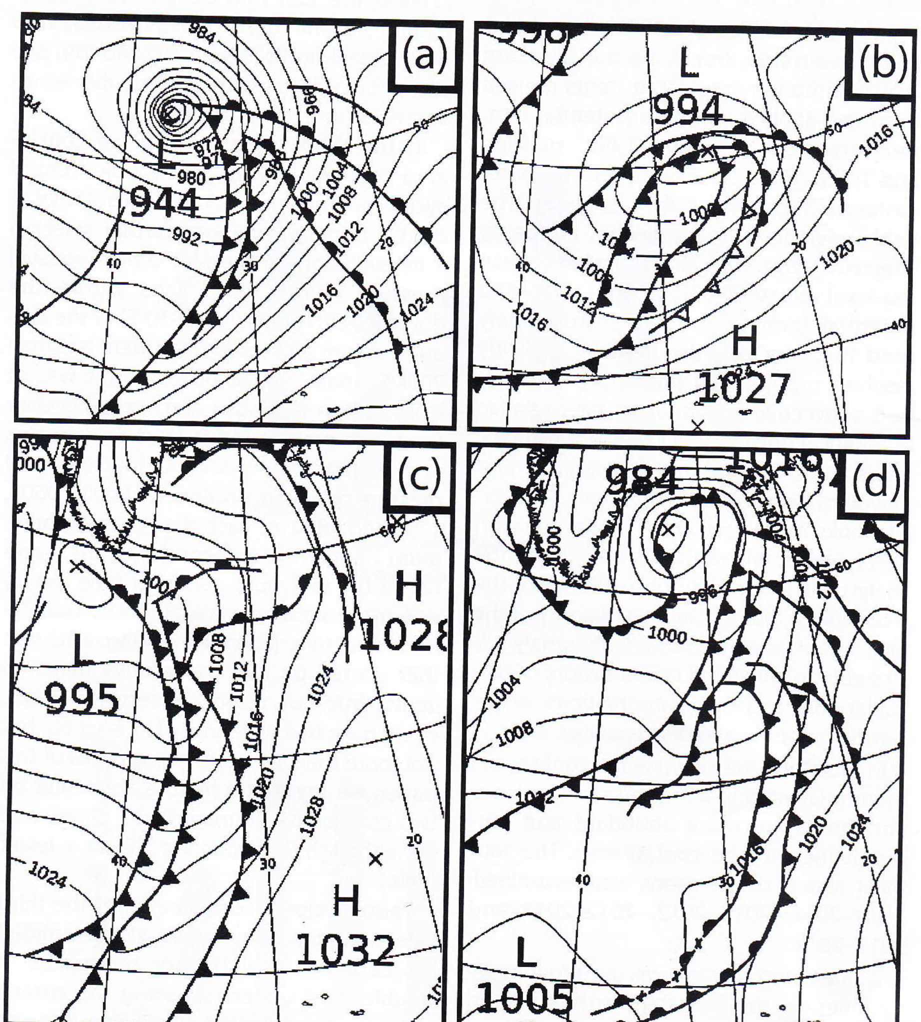

Figure 2. Examples of non-classic multiple-front cyclones from Met Office sea-level pressure charts: (a) 0000 UTC on 26 January 2013, (b) 0000 UTC on 18 November 2012, (c) 1800 UTC on 27 November 2012, and (d) 0000 UTC on 15 January 2013. (Images courtesy of wetter3.de and Crown copyright.)

Perhaps an initial reaction is to dismiss these 'octopus cyclones' (because of their many radiating fronts from the low centre) as too inconsistent with the Norwegian cyclone model, too inappropriate, too difficult to understand, or unclassifiable (Mass, 1991). Such reactions though reduce the users' confidence in the Met Office sea-level pressure charts as a useful tool for understanding the weather. For example, Prichard (2006) lamented the lack of consistency of features analysed on Met Office charts. Rather than dismiss these analyses, our research is aimed at understanding these non-classic structures taken at face-value from the analyses. As an initial step, this article focuses on a class of cyclones from these charts: those with two warm fronts, two cold fronts, or both two warm fronts and two cold fronts (hereafter all three are classified as *double-front cyclones*). Figure 2(a) epitomises these types of cyclones in their most simple form.

Such double fronts have been observed occasionally in the literature. Even the Norwegians recognised the existence of multiple fronts (Bjerknes, 1930, his figures 3, 5, 10 and A3–A5). Browning *et al.* (1995)

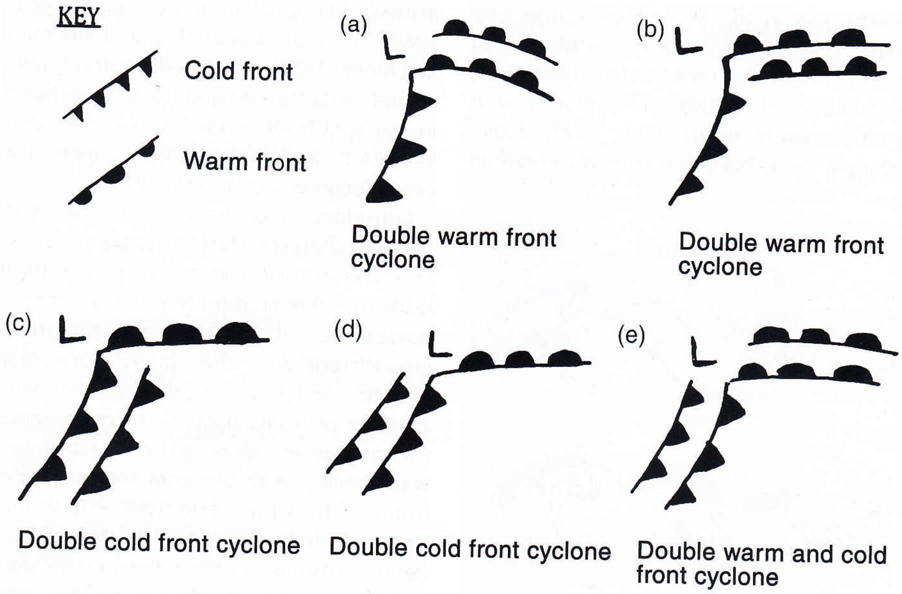

Figure 3. Diagrams representing double-front extratropical cyclones on Met Office sea-level pressure charts. (a) A double warm-front cyclone with a secondary warm front located ahead of the primary warm front. (b) A double warm-front cyclone with a secondary warm front located behind the primary warm front. (c) A double cold-front cyclone with a secondary cold front located ahead of the primary cold front. (d) A double cold-front cyclone with a secondary cold front located behind the primary cold front. (e) A double front cyclone with both a secondary warm front and a secondary cold front.

studied a cyclone with two cold fronts during the FRONTS 92 field programme. Parker (1998, his figure 1, from T. Hewson) showed a schematic of a frontal wave inside a cyclone's warm sector that yielded a cyclone with two warm and two cold fronts. Schultz (2005) discussed prefrontal troughs and wind shifts, features that could be represented as fronts on surface charts.

The questions we want to examine in this study are how common these non-classic cyclones are and how they evolve. We will examine four cool seasons of Met Office sea-level pressure charts, classifying them as single-front cyclones or double-front cyclones. We will produce a classification scheme for double-front cyclones and describe common structures and evolutions. This study has three goals. First, we aim to provide some guidance for interpreting Met Office sea-level pressure charts with non-classic cyclone structures. Second, we wish to bring a greater appreciation to the variety of cyclone structures and evolutions present in the atmosphere. Third, we want to show that the Met Office sea-level pressure charts are more sensible than they may seem at first from a cursory glance at a single chart.

Data and methods

Our data are the six-hourly sea-level pressure charts for the North Atlantic Ocean and western Europe produced by the UK Met Office and archived at wetter3.de. Production of the charts at the Met Office begins with background fields from a previous model run, typically 6h forecasts from the Met Office global forecast model. In the next step, fronts are initially hand drawn, although automated fronts derived from the 850hPa wet-bulb potential temperature field (Hewson, 1998; Hewson and Titley, 2010) are available to the forecaster to supplement their analyses. The fields referenced by the analyst are partly subjective, but they always include mean sea-level pressure and 850hPa wet-bulb potential temperature. Other commonly used fields include the model's explicitly resolved precipitation rate and parameterised convective-precipitation rate, relative humidity at one or more lower-tropospheric levels, 1000–500hPa thickness and surface dewpoint temperature. The analyst generally looks for discrepancies compared with observations. Where these clearly exist, the analyst will follow the observations not the model fields, but for the vast majority of the time, the model is followed. The analyst is also able to follow the recent history of particular ship and buoy observations, which can be helpful when discrepancies arise.

In this study, we examine the cool-season months October to March because cyclones and fronts are more abundant and better defined in the cool season. The four most recent cool seasons were examined: 2010–2011, 2011–2012, 2012–2013 and 2013–2014.

A three-step process was used to identify cyclones. In the first step, we considered just the existence of cyclones. A cyclone was selected for consideration if it had one or more closed isobars, had a central sea-level pressure lower than 995hPa, was located within the North Atlantic region (40°N–70°N, 50°W–10°E), and was isolated from other cyclones (i.e. no double-barrelled low-pressure centres). This process yielded 217 cyclones in our dataset.

In the second step, the 217 cyclones were classified into either single-front or double-front cyclones. Single-front cyclones had a single warm front, single cold front, and a possible occluded front throughout their time within the domain described above. Nominally, these could be Norwegian cyclones or Shapiro–Keyser cyclones, or even another type of evolution. Double-front cyclones had either a double warm front, double cold front, or both, at some point in their evolution within the domain. There were 94 single-front cyclones and 123 double-front cyclones.

The basic structures of these 123 double-front cyclones are displayed in Figure 3. A double-front cyclone consisted of a cyclone with connected warm and cold fronts passing through the centre of the cyclone (the primary fronts), with an additional front or fronts nearby the cyclone (the secondary front or fronts). The 123 double-front cyclones consisted of 63 cyclones (51% of the 123) with double warm fronts (Figure 3(a) and (b)), 37 (30%) cyclones with double cold fronts (Figure 3(c) and (d)), and 23 (19%) cyclones with both double warm and cold fronts (Figure 3(e)).

In the third selection step we considered the evolution of the double-fronted cyclones. From the 123 cyclones above, a double-front cyclone was further selected if its evolution on the Met Office sea-level pressure charts took place within the domain (40°N–70°N, 50°W–10°E), if the secondary front and the cyclone were less than 200km apart, the secondary front was at least 500km in length and the secondary front was present for at least 6h (appears on two maps 6h apart). As four sea-level pressure charts are produced, at 0000, 0600, 1200 and 1800 UTC each day, 6h is the minimum duration of a secondary front – and hence the minimum period of time during which the cyclone maintained its double-front structure. (Strictly speaking, a feature that existed on two consecutive maps 6h apart, but not three consecutive maps, could have had a lifetime of at least 6h, but not more than 18h. For the purposes of this paper, we say that a feature appearing on two consecutive 6h maps had a duration of 6h, although we recognise this as a lower limit.)

Those cyclones remaining after the third selection step above were also examined for common evolutionary sequences. A double-front cyclone meeting the criteria above was considered classifiable if it was possible to understand how the double front formed based on the evolution displayed on the sea-level pressure charts.

Through this process, it became evident that double-front cyclones underwent a small number of classifiable evolutions, allowing for the construction of a classification scheme. A cyclone was considered unclassifiable if its double-front evolution could not be easily recognised from the sea-level pressure charts. Doswell (1991) expressed the importance of having an unclassifiable category, stating that it *leaves open the possibility that someone might find a way to classify them in the future*. With these additional criteria, the number of classifiable cyclones was 53 (43% of the 123 cyclones) and the number of unclassifiable cyclones was 70 (57%).

Climatology

The distribution of the 123 double-front cyclones shows only a slight preference for some cool-season months over others (Figure 4). For example, a relative maximum of 26 events (6.5 events per month) occurs in January compared with a relative minimum of 16 events (4 events per month) in November. Given that only four cool seasons were examined, the possibility of the small sample size of the classifiable cyclones producing a different result for a different set of years because of interannual variability precludes further analysis of this graph.

Nevertheless, Figure 4 does show that double-front cyclones on Met Office sea-level pressure charts are relatively common, averaging about five per cool-season month. Indeed, within our dataset of cyclones, double-front cyclones are more commonly analysed than Norwegian cyclones on the Met Office charts.

The distribution of the durations of the secondary fronts in the 53 double-front cyclones is plotted in Figure 5. Although some double-front cyclones existed for only 6h, others existed for as many as 54h (Figure 5). The mode of the distribution is 12h, with 15 out of 53 cases occurring for this length of time. The mean is 18.7h, and the median is 18h. Thus, double fronts were not isolated features that appeared for a limited period of time only, but were often long-lived and persistently analysed structural features of the cyclones.

Classification

Our classification scheme produced four broad categories of double-front cyclones at some point in their evolution within our analysis domain: A, B, C and D. Category A cyclones started out with both a double cold and double warm front within our analysis domain (Figure 6): in our dataset, 43 cyclones (81.1% of 53) were classified as category A. Five different evolutions were identified within category A, four of which involved the loss of a front, presumably by merger or frontolysis. Type A1 represents cyclones with two cold fronts where the secondary cold front was located ahead of the primary cold front: 2/53 (3.8%) cyclones formed by this evolution. Type A2 also had two cold fronts, but the secondary cold front was located behind the primary cold front: they were the second most common type of evolution, with 16/53 (30.2%) cyclones. Next, A3 cyclones had two warm fronts where the secondary warm front was located ahead of the primary warm front: they were the most common type of evolution, with 18/53 (34.0%) cyclones. The A4 cyclones also had two warm fronts, but the secondary warm front was located behind the primary warm front: 3/53 (5.7%) cyclones formed by this evolution. Finally, A5 represented double-front cyclones with both a double warm and a double cold front throughout the evolution of the cyclone: four (7.5%) cyclones underwent this evolution.

Category B cyclones started out as a classic Norwegian cyclone with a single cold front and a single warm front, but with an occluded front to the north that became emplaced on the cyclone, producing either a double cold- or double warm-front cyclone (Figure 7). This evolution is similar to a conceptual model proposed by Metz *et al.* (2004, their figure 7) for the formation of multiple warm-front-like baroclinic zones within extratropical cyclones east of the Rocky Mountains: attachment of a northern baroclinic zone to a pre-existing cyclone. In our dataset, four cyclones (7.5% of 53) were classified as category B. Type B1 evolved into a cyclone characterised by only a double cold front (2/53, 3.8%), and B2 evolved into a cyclone characterised by only a double warm front (2/53, 3.8%) (Figure 7). Interestingly, this evolution did not produce any cyclones with both a double cold front and a double warm front (although the small sample size of four cyclones could be a factor).

Category C cyclones began life as a cyclone with both a surface warm front

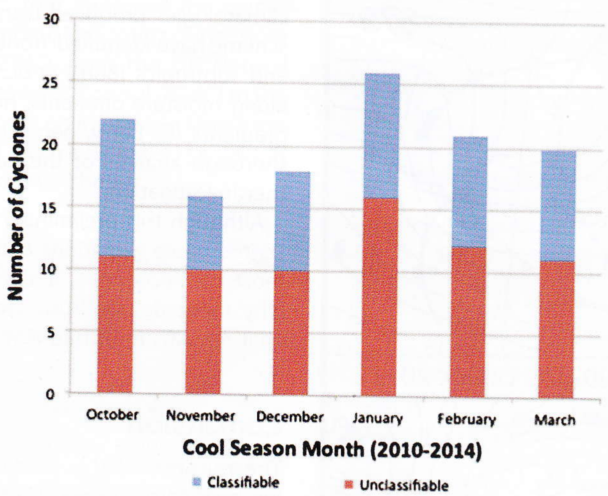

Figure 4. A stacked bar chart showing the annual cycle of 53 classifiable and 70 unclassifiable double-front extratropical cyclones from the four cool seasons (October–March) of 2010–2011 to 2013–2014.

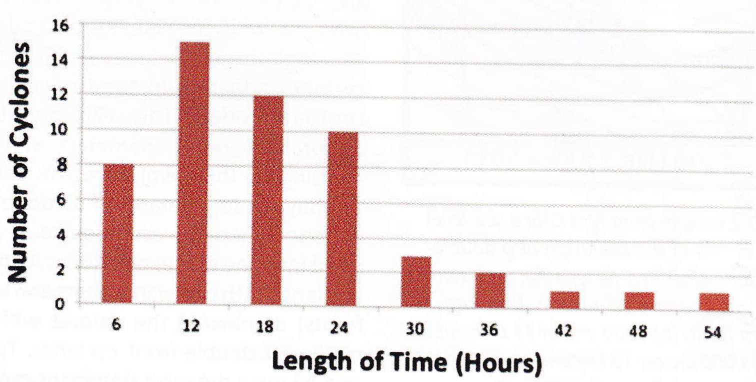

Figure 5. Duration (in hours) of secondary fronts in 53 double-front cyclones.

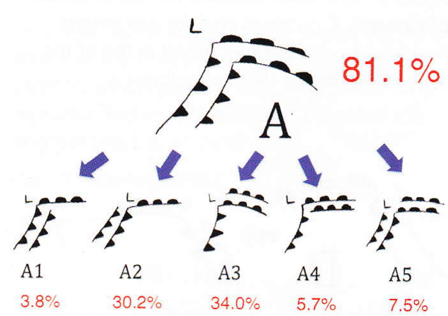

Figure 6. Schematic diagrams for the five possible evolutions of category A cyclones and the percentage (rounded to one decimal place) in red of the 53 cyclones fitting that behaviour.

and an upper-level warm front (Figure 8). At some point in the cyclone's evolution, the analyst changed the upper-level warm front to a surface warm front, producing a cyclone with two analysed warm fronts (C1). In our dataset, three cyclones (5.7% of 53) were classified as category C.

Finally, the fourth classification, category D cyclones, had a trough behind the primary cold front. At a later time in the evolution of the cyclone, that trough became analysed as a secondary cold front (Figure 9). In our dataset, three cyclones (5.7% of 53) were classified as category D.

To summarise, the most common evolutions were those in the A classification, specifically types A2 and A3. These two evolutions involve either the weakening of a warm front (A2) or a cold front (A3), leaving a secondary cold or warm front outside of the warm sector (B1, B2, C1, D1). Evolutions leaving fronts within the warm sector (A1, A4 and A5) were relatively uncommon.

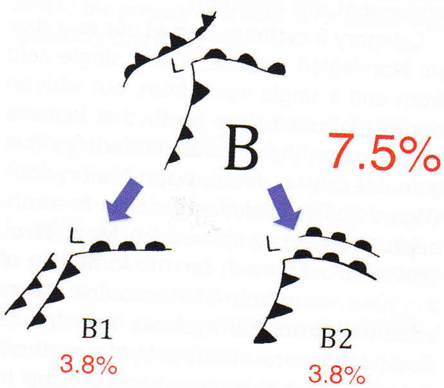

Figure 7. Schematic diagrams for the two possible evolutions of category B cyclones and the percentage (rounded to one decimal place) in red of the 53 cyclones fitting that behaviour.

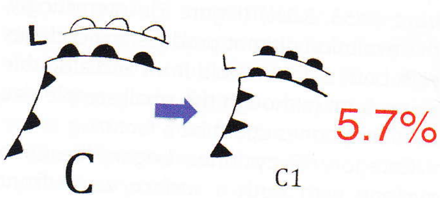

Figure 8. Schematic diagram for the evolution of category C cyclones and the percentage (rounded to one decimal place) in red of the 53 cyclones fitting that behaviour.

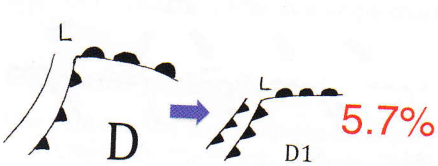

Figure 9. Schematic diagram for the evolution of category D cyclones and the percentage (rounded to one decimal place) in red of the 53 cyclones fitting that behaviour. The solid line represents a trough (see text for definition).

Discussion

The natural question to ask is where the double-front structure that began the evolution in category A came from. Examination of these events indicated that in many cases the innermost cold and warm fronts to the warm sector resulted from the attachment of an open-wave warm sector at a lower latitude (perhaps associated with the subtropical anticyclone) to a more eastwardly mobile extratropical cyclone at a higher latitude. Figure 10 illustrates one of these evolutions of a cyclone in our dataset classified as type A2. As the mobile cyclone passed and deepened from 992 to 960hPa in 24h, it attached to the southernmost 1002hPa open-wave cyclone and became a double cold-front and double warm-front cyclone (Figure 10). This evolution is similar to the conceptual model proposed by Metz *et al.* (2004, their figure 6). As the cyclone neared the UK, the leading warm front lost its identity, probably due to a merger with the leading warm front (Figure 10(b) and (c)).

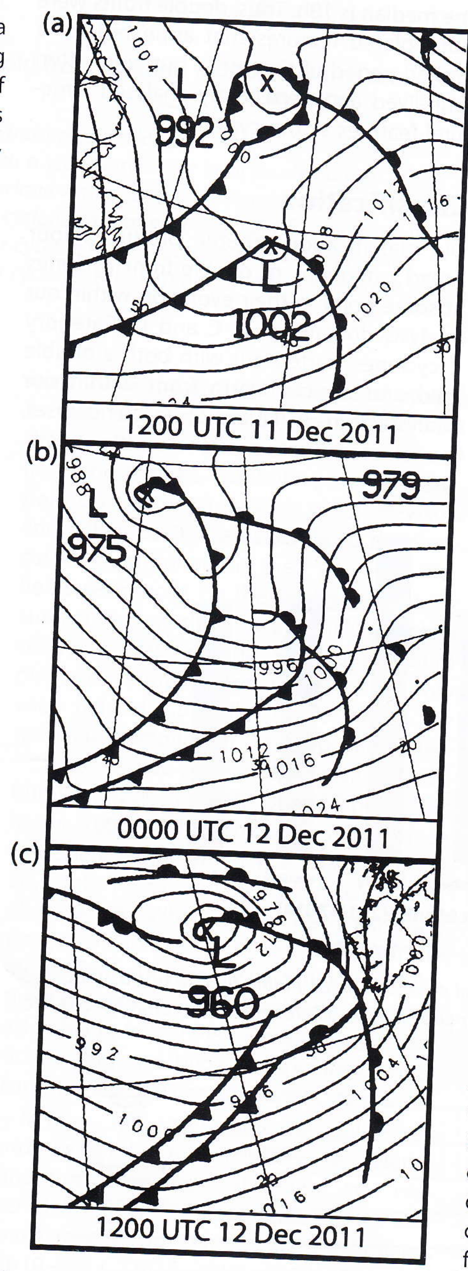

Figure 10. Example from Met Office sea-level pressure charts of the evolution of a double-front cyclone classified as type A2, with two warm fronts and two cold fronts, that loses one warm front: (a) 1200 UTC on 11 December 2011, (b) 0000 UTC on 12 December 2011 and (c) 1200 UTC on 12 December 2011. (Images courtesy of wetter3.de and Crown copyright.).

Another question is why these charts had such an abundance of analysed double fronts compared with charts produced by other agencies (National Oceanic and Atmospheric Administration, Deutsche Wetterdienst). We suggest that one reason may be the use of 850hPa wet-bulb potential temperature (θ_w). As gradients in θ_w result from gradients in both potential temperature and humidity mixing ratio, some 'fronts' may actually have been moisture gradients. Sanders and Doswell (1995), Sanders (1999), Schultz (2009, p. 355) and Schultz and Blumen (2015) have discussed the importance of analysing fronts as a function of temperature. Although a mask for potential-temperature gradients was available for the forecasters (Hewson and Titley, 2010), comparing some analysed cases with gridded-model output indicated that this might have been a factor for some cases, but not all. Indeed, global frontal climatologies produced using the same θ_w scheme have identified 'fronts' in the tropics and subtropics (Berry *et al.*, 2011) that lay along moisture gradients, not temperature gradients (G. Berry, pers. comm.). A more thorough analysis of this issue awaits further investigation.

Although this preliminary study has presented these evolutions and described the most common ones, it does not describe why these double-front cyclones happen. That remains for future research.

Conclusion

The purpose of this study was to examine how common non-classic double-front cyclones are and how they form. Analysing Met Office sea-level pressure charts from four cool seasons between 2010–2011 and 2013–2014 identified 123 double-front cyclones (<995hPa), exceeding the 94 single-front cyclones (which include cyclones adhering to the Norwegian conceptual model). The 123 double-front cyclones were re-examined, specifically focusing on their evolution. This additional scrutiny led to a dataset of 53 double-front cyclones where the evolution could be classified into one of four categories. Category A (cyclones with two warm fronts and two cold fronts) dominated the dataset with 81.1% of the 53 double-front cyclones. Types A2 and A3 were the most dominant evolutions, with 30.2% and 34.0% of 53 double-front cyclones forming from these evolutions, respectively. Specifically, type A2 cyclones evolved to a cyclone with a secondary cold front, and A3 cyclones evolved to a cyclone with a secondary warm front.

This paper highlights the relative abundance of double-front cyclones in reality and suggests that such cyclones are not rare or a result of errors by the analysts. Instead, *they are common structures with recurring classifiable patterns* that are displayed on published Met Office sea-level pressure charts. Moreover, they are more common than single-front cyclones. Therefore, forecasters and researchers should be aware that such double-front cyclones can occur and usually relate to sensible weather on the ground. Although the single-front conceptual models (i.e. Norwegian and Shapiro–Keyser conceptual models) continue to provide a useful framework for many cyclones, this paper adds to a growing body of literature demonstrating that important structural and evolutionary differences exist among real-world cyclones.

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