The pivotal nature of cyclone merger and splitting assessed in an ensemble of cyclone tracking methods


abstract The merger and splitting of cyclones are potentially pivotal events in the cyclone life cycle. They can be of critical importance in rapidly consolidating or isolating a vortex and may therefore bring a sudden change to a cyclone’s intensity. A merger or splitting event may also literally serve as a pivot by changing the direction of motion of a cyclone. It is asserted that cyclone diagnostics generated by automated tracking algorithms may show method-related sensitivity to merger and splitting events. For the first time, a study is conducted to compare the response of an ensemble of cyclone tracking methods (a product of the project IMILAST — the intercomparison of mid-latitude storm diagnostics) to cyclone merger and splitting.

Of the cyclone tracking algorithms contributing to the IMILAST project, three explicitly handle cyclone merger and splitting but differ in their approach and cyclone identification field. Despite these differences, we find that broad features of the merger and splitting distribution are robust, and main differences are related to each method’s cyclone density distribution. All three methods agree that merger and splitting frequency increase with cyclone intensity, and that cyclones typically intensify following merger. Solely the method based on vorticity suggests that cyclones also typically intensify for a brief time following splitting.

A selection of cases is presented that undergo a clear merger or splitting. The IMILAST ensemble (including methods that do not explicitly handle merger or splitting) shows divided behaviour over which tracks to continue over a merger or splitting event when one candidate for continuation is most intense, but the other is closer to the the expected position. It is sug-
gested that merger and splitting events can contribute to locally increased method agreement over lysis and genesis locations respectively.

Keywords: cyclone merger, cyclone splitting, storm tracking, uncertainty

1. Introduction

The merger and splitting (MS) of cyclones are potentially pivotal events in the cyclone life cycle. They can be of critical importance in rapidly consolidating (e.g. Ogura and Juang, 1990) or isolating (e.g. Moore and Vachon, 2002) a vortex and may therefore be implicated in the rapid intensification of a storm. In support of this, Inatsu (2009), showed that the averaged growth rate for merged cyclones in the west Pacific and West Atlantic is significantly greater than for the total cyclone population. Furthermore, statistics presented by Hanley and Caballero (2012) suggest a frequent association of MS events with intense, mature storms. A merger or splitting event may also literally serve as a pivot with regard to the direction of motion or changes to the properties of a cyclone (see case studies in Neu et al., 2013).

Given the above, we reason that (i) there is a fundamental interest in detecting and understanding the occurrence of cyclone merger and splitting, particularly for their role in the development of intense cyclones and (ii) cyclone tracks and diagnostics generated by different cyclone tracking algorithms (whether or not they detect merger or splitting) are likely to demonstrate sensitivity (and therefore imply uncertainty) related to the pivotal nature of merger and splitting events combined with small methodological differences in the way that different algorithms form tracks.

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The IMILAST (Intercomparison of mid-latitude storm diagnostics) project (Neu et al., 2013) offers a dataset with which the above mentioned tracking-method related sensitivities may be explored. Initial results of IMILAST (Neu et al., 2013) showed that, despite a wide variety in the 15 cyclone identification and tracking methods considered, a reasonable agreement on tracks and diagnostics of intense cyclones could be reached, at least in the intensifying stage of the life cycle. In contrast, diagnostics of cyclone genesis and lysis showed reduced agreement. We are curious whether method-related uncertainty in the handling of MS events has an influence on the poor agreement on genesis and lysis diagnostics.

The study of cyclone merger and splitting can, in several respects, be considered to be in its infancy. Firstly, as noted by Rudeva et al. (2014), such events are poorly accounted for in modern cyclone tracking algorithms. In the IMILAST project, only three (M13, M14 and M21) of the 15 investigated cyclone detection and tracking algorithms explicitly handle merger and splitting events. Secondly, there are limited studies on the subject. Except for climatological studies introducing the three MS methods above (Hanley and Caballero, 2012; Kew et al., 2010; Inatsu, 2009), studies are mainly limited to cyclone/upper-level vortex case studies (e.g. Juang and Ogura, 1990; Ogura and Juang, 1990; Takayabu, 1991; Tollefson, 2012; Yamamoto et al., 2012; Strahl and Smith, 2001; Lackmann et al., 1997; Hakim et al., 1996) or upper-level vortex climatologies (e.g. Dean and Bosart, 1996; Gaza and Bosart, 1990). Thirdly, the MS methods developed each contain subjective definitions of merger and splitting appropriate for their individual applications. The terminology for the phenomena is also not fixed. For example, splitting is also known as separation (e.g. Inatsu, 2009), bifurcation (e.g. Schuenemann et al., 2008), and fracture (e.g. Dean and Bosart, 1996).
The three MS methods of IMILAST differ from the other IMILAST methods in that they define cyclones as finite regions, instead of single centres. In doing so, cyclones are permitted to contain more than one cyclonic centre, in other words, to exist as a multi-centre cyclones (MCCs). As will become clear later, the use of MCCs and/or finite areas in cyclone definition facilitates the detection of merger and splitting. These are not essential requirements, however. Alpert et al. (1990) and Dean and Bosart (1996), for example, use a technique to detect the merger and splitting of single-centre extrema. To extend a track, single-centre cyclone (SSC) tracking algorithms select the single centre that best satisfies a given criterion, rejecting all other contenders. Typically a nearest-neighbour search is performed (Serreze, 1995; Wang et al., 2006; Zolina and Gulev, 2002; Rudeva and Gulev., 2007; Bardin et al., 2005; Akperov et al., 2007) or, more sophisticatedly, a cost function based on matching cyclone properties is minimised (Sinclair, 1993; 1997; Murray and Simmonds, 1991; Pinto et al., 2005; Hewson, 1997; Hewson and Titley, 2010).

One reason that most tracking methods do not handle merger and splitting could be that multiple centres around a main cyclone centre have been viewed as unwanted artifacts of high resolution data, whose presence (i) leads to spurious track connections or splittings and (ii) are a hindrance to connecting the main cyclone into its correct track. The unwanted centres can be reduced in number by preprocessing the data with a spatial smoothing, but inevitably some of the early or late developmental stages of cyclones of interest, as well as information on mergers and splittings, are lost. Priority is given to one-to-one track connections to retain the dominant cyclone, which may be the largest, most intense or most long-lived.

Although IMILAST SCCs do not detect MS events, they will react to them. For example, if a vortex is absorbed into a larger one’s periphery, the case might be detected as merger by an MCC method, but most SCC’s will continue the track of the larger system, with the merger of the smaller system being interpreted as a lysis (Wernli and Schwierz, 2006). On the other hand, if the small vortex is not absorbed but becomes a small trough as it passes or remains with a larger system, SCC methods may retain both tracks and have no need to consider a merger. Hanley and Caballero (2012) argue, however, that the MCC definition provides the most realistic representation of a mature cyclone’s structure and size development.
Also, if two similar cyclones approach each other and interact, it could be argued that both cyclone tracks should be terminated and a new system with combined characteristics should be generated (Kew et al., 2010).

There are a number of physical causes of merger and/or splitting events. These include (i) secondary cyclogenesis — as noted by Hanley and Caballero (2012), secondary extrema can often develop from instabilities on fronts of mature cyclones and break away from the parent cyclone to form independent cyclones, (ii) wave breaking at the end of the storm tracks, which is marked by the meridional elongation and splitting of upper level vorticity filaments and their associated lower level troughs, and is sometimes aided by lower-level diabatic processes (Morgenstern and Davies, 1999), (iii) orography being instrumental in restructuring cyclones: splitting cyclones, in the case of diffuent flow, or merging cyclones, in the case of confluent flow, around a topographical obstacle, such as the Greenland tip (e.g. Schwierz and Davies, 2003; Wernli and Schwierz, 2006; Schuenemann et al., 2008), (iv) old, occluded cyclones combining with upper-level instabilities to generate new cyclones with different properties (Moore and Vachon, 2002), (v) upper level flow structures such as jet-streaks or coherent potential vorticity anomalies coupling with low level cyclones or troughs, leading to cyclone merger and/or genesis via ‘phasing’ (amalgamation of separate branches of the upper level westerlies) (Gaza and Bosart, 1990) or co-rotation (Ziv and Alpert, 2003), (vi) the co-rotation and mutual attraction of surface lows directly, known as the Fujiwhara effect (Renfrew et al., 1997; Ziv and Alpert, 2003), can also lead to their merger.

Points (i-iii), in particular, tend to be pinned to geographical regions. It is already known that there are preferred regions for the occurrence of merger and splitting (e.g. Inatsu, 2009; Hanley and Caballero, 2012) and therefore we might expect increased disagreement between tracking methods in these regions. In addition, we postulate that different physical reasons behind the merger or splitting may lead to different behaviour in terms of tracking-method related uncertainty.

Our main objective is to investigate how the pivotal nature of merger and splitting events together with methodological differences in handling cyclone merger and splitting can impact the uncertainty in cyclone diagnostics.

First we describe the three MS algorithms (Section 2). We then investigate the impact of their differences on (i) the climatological MS distributions that are obtained when the same
input dataset, output diagnostic, and means of presentation are used (Section 3.1), (ii) the
dependence of MS frequency on cyclone intensity and whether cyclones typically exhibit
changes in intensity after MS events (Section 3.2). In section 4 we present a selection of MS
case studies that illustrate the range of outcomes generated by IMILAST ensemble, including
methods that do not explicitly handle MS events. We comment on the impact of the selected
events on the spread in genesis and lysis locations. The findings are summarised in Section 5.
2. Datasets and Algorithms

2.1. IMILAST dataset

The IMILAST (Intercomparison of mid-latitude storm diagnostics) project (Neu et al., 2013), is motivated by (i) the large range of differences, and therefore uncertainties, in published extratropical storm diagnostics resulting from the use of different input data, methods or analysis techniques (ii) the need to communicate a clear synthesis of these results to insurance companies, risk managers, adaptation planners, the media and the general public. By fixing the data source (initially 20 but now 30 years of ERA-Interim reanalysis plus a set of selected storms) and the analysis technique across a collection of (initially 15, now 16) different cyclone tracking methods, the project focusses on the method-related uncertainties and showing which diagnostics may or may not be considered robust.

The IMILAST tracking output (1979–2009) is generated from the reanalysis dataset ERA-Interim (Dee et al., 2011) at 1.5° × 1.5° at 6 h intervals. We use the same dataset and resolution to detect and select merger and splitting cases.

As for many cyclone climatologies, cyclones that do not surpass a life time criterion (24 hours) are omitted from the IMILAST dataset. A consequence of this with impacts for our study is that the short tracks involved in a merger or splitting are not retained. Some methods retain information on the existence of those shorter tracks e.g. by recording a merger or splitting event on the longer track, others perform a track surgery or iterative track assessment after the removal of shorter tracks, as if they were never there.

A topography mask is also applied in a post processing stage to tracks from all IMILAST methods, such that cyclones intersecting topography higher than 1500 m are removed.

2.2. Algorithms

This section provides a description of the definitions of merger and splitting applied by each of the three tracking methods that explicitly handle MS events. For the motivation behind these definitions, illustrative figures and full details of the respective cyclone identification and tracking algorithms, please refer to Hanley and Caballero (2012) for M13, Kew et al. (2010) and appendix A for M14, and Inatsu (2009) and Inatsu and Amada (2013) for M21.
Method M13

M13 is an extension of Wernli and Schwierz (2006) and likewise uses mean sea level pressure (SLP), as its identification field. All local minima below 1500 m that satisfy a heat-low-eliminating SLP gradient criterion are considered as cyclone centres. To form tracks, first a guess is made of the subsequent position of a cyclone, using a projection derived from its previous motion. Then the closest candidate to the guess point within a threshold distance is chosen to continue the track. Each cyclone is assigned a finite area: An outermost contour is defined such that the subsequent contour is either anticyclonic, encircles the pole or envelops more than three other minima.

Method M13 is unique amongst the IMILAST methods for explicitly recognising multi-centre cyclones (MCCs). M13 defines an MCC as a cyclonic system with 2 to 3 SLP minima within the outermost contour, if the proportion of contours shared by the minima satisfies given criteria.

To assign a unique track to the MCC, the track of the cyclone whose size evolution best matches to the MCC is retained as dominant. Tracks belonging to the remaining MCC minima are truncated. If the truncated track of an inferior minimum reappears beyond the MCC, the situation is treated as a merger followed by splitting, which generates a new cyclone.

Two further situations are classed as merger, for an MCC with two minima and their associated tracks A and B: (i) Only track A has a future branch, in which case A becomes the MMC track, and (ii) track A is the dominant track but terminates within two time steps after joining the MCC, in which case the latter part of track B is joined to the former part of track A by track surgery. In this study, any type ii events will be interpreted as the continuation of A, because it is A that becomes linked to the merged system whilst B appears to be truncated.

One further situation leads to splitting: Only one track, A, has a past branch. If A continues for at least two time steps, A becomes the MCC track. Otherwise, the event is alternatively classed as a ‘track reconnection’, whereby the continuing track B is connected to the past branch of A. The resulting track is smooth with no MS branches.
Method M14

The identification field for M14 is 850 hPa geopotential height (Z850). Cyclones are identified as Z850 minima enclosed by a Z850 contour such that the size of the enclosed area is close to a target area of 170 000 km². If the bounding contour that would be assigned to a particular minimum incorporates the boundary of a stronger minimum, it is reduced in value until the two minima become distinct, resulting in an area reduction of the weaker minimum. The boundary of a strong cyclone is, however, permitted to enclose weaker minima, consequently forming an MCC.

The local wind field is used to advect the identified areas forward to the next time frame, thereby predicting the new locations of the cyclones. Two or more cyclones at time \( t_n \) are said to have merged into a single cyclone at time \( t_{n+1} \) if the advected areas of the former satisfy an overlap condition with the latter. Likewise, splitting is deemed to have occurred when more than one cyclone at time \( t_{n+1} \) satisfies an overlap condition with the advected area of a single cyclone from time \( t_n \).

Unique to M14 is the decision to generate new tracks at merger or splitting if the merging cyclones or split-off cyclones are considered ‘even’ (comparable in size). In the case of an ‘uneven’ merger (splitting), the identity of the largest component (fragment) is transferred to (retained by) the merged (split) cyclone. Otherwise, both merger and splitting constitute genesis and the post-event cyclones receive new identities.

Occasionally there are ‘hybrid’ events where a cyclone has split from one structure and undergoes merger with another. In these cases, either a splitting or a merger is recorded, depending on which process is most dominant.

Method M21

The identification field for M21 is 850 hPa relative vorticity (VORT850), transformed from 850 hPa geopotential height using geostrophy. The relative vorticity field is high-pass filtered (period < 10 days). A cyclone is defined as an independent enclosed area containing relative vorticity greater than or equal to \( 50 \times 10^{-6} \) s⁻¹. The same identity is given to cyclones from temporally neighbouring time frames if their identified areas overlap. Tracks that never satisfy an overlap criterion of 20 000 km² and an area criterion of 40 000 km² during their life time are then filtered out.
Merger is defined as the case when multiple cyclones in one time frame overlap a single cyclone in the next time frame. Splitting is defined as the case when a single cyclone in one time frame overlaps multiple cyclones in the next time frame. M21 also defines a group connection when two or more cyclones from one time frame overlap with two or more in the subsequent time frame.
Handling of event dates and counts

Note that there are some differences between the methods in the handling of event dates and counts as follows:

– Method M14 registers splitting at the date on which the split entities appear, making entries for each split element. This is different to M13 and M21, which register splitting at the time step before it occurs at the location of the parent cyclone, resulting in just one recorded location for each splitting event — effectively the reverse of a merger. To facilitate event selection and comparison with the other methods, the results for M14 are adjusted such that the splitting event is associated with the pre-split structure on the previous time step, as for M13 and M21. Original unadjusted output of M14 is used in the geographical climatologies (Section 3.1).

– In the original output, M14 registers one splitting for every split-off cyclone, whereas M13 and M21 register one splitting per parent cyclone. Splittings generate two or more fragments. M14 splitting counts are therefore originally at least twice as large as the number of splitting parent cyclones (although the post-tracking removal of short-lived fragments failing the lifetime criterion will reduce the count). In Section 3.1, contour intervals for M14 counts are therefore made to be twice those used for M13, to enable an order of magnitude comparison.

– M14 forces any simultaneous merger and splitting events to be classified as one or the other, depending on which process is most dominant (in terms of an area criterion). M13 and M21 count simultaneous events separately and here we exclude them from both merger and splitting counts.

– M13 removes tracks of length 12 h or less before mergers and splittings are identified. M14 also applies a 12 h threshold but only after the tracking is complete. M21 applies no threshold. All are nevertheless subjected to the 24 h criterion imposed by IMILAST.

– MS events involving a short track that is removed post-tracking are still counted, provided the longer-lived branch exceeds the 24 h IMILAST criterion. For this reason, some of the MS method results for the selected case studies (Sect. 4) only have one branch.
3. Intercomparison of climatologies

Merger and splitting occur most often in the cold season (See Inatsu, 2009) and patterns are likely to seasonally shift, e.g. with the storm tracks. The two existing merger and splitting climatologies are for the Northern Hemisphere (NH) winter. To focus and facilitate comparisons, we also choose to limit our study to the NH winter months, December-February (DJF).

3.1. Geographical distributions

In figure 1 we compare DJF merger and splitting climatologies during the years 1979–2009 for the IMILAST tracking methods M13, M14 and M21 — the only three methods providing a record of merger and splitting events. The input data (ERA-Interim, 6-hourly $1.5^\circ \times 1.5^\circ$ resolution) and the plotting field (event counts per $7.5^\circ$ circle per season) is the same for all. A post-tracking lifetime threshold of 24 h is applied, as for all IMILAST output.

Event counts are similar in order of magnitude for M13 and M14, but are of order 2–3 times larger for M21 mergers and around 6 times larger for M21 splittings.

Broad features of the merger distribution are similar for all three methods. Each method shows two regional maxima in the Pacific, one near the Kamtchatka peninsula and one in the Gulf of Alaska. The forms of these maxima are most similar for M13 and M21. All three methods also show a strong signal in the Atlantic between the southern tip of Greenland and Iceland, which extends further east for M13 and M14. M13 has the strongest signal in the Mediterranean, followed by M14 and a very weak signal for M21. M14 has an additional maximum over Baffin Island, that is weak or absent in M13 and M21. M14 and M21 weight the Atlantic signal stronger than the Pacific, whereas for M13 the balance is reversed.

The splitting distribution for M13 and M14 is quite similar in distribution and magnitude, except that M13 shows two regional maxima of similar magnitude in the Atlantic and Barents seas in contrast to one stronger Atlantic maximum for M14. M21 shows one Atlantic maximum, like M14, and also one Pacific maximum around the date line, which is absent for M13 and M14. M21’s signal in the Mediterranean is again very weak. All three methods weight the Atlantic signal stronger than the Pacific.
Differences in the MS distributions partially originate from respective differences in the methods’ distribution of cyclone density (see supplementary material for MS-method cyclone density maps). For example, M21 shows comparatively few cyclone tracks in the Mediterranean, and the Atlantic track maximum of M13 and M14 extends further to the east. M14 shows spurious MS events linked to high frequencies of near-stationary cyclonic features around the Himalayas that are filtered out by the other methods. The MS signals however are distinct from the patterns of cyclone frequency.

Climatologies of MS events based on M13 and M21 have been previously published and invite comparison. M13 cyclone frequency compares very well to Hanley and Caballero (2012), with minor differences attributable to differences in the resolution of the underlying dataset and time span used. Differences in magnitude for MS events can be partly accounted for by our exclusion of simultaneous MS events and application of the IMILAST post-tracking life time criterion in the current analysis. Note that we normalised (not shown) MS frequency by cyclone frequency for comparison with Hanley and Caballero (2012). Both cyclone and MS frequency of M21 show notably larger amplitudes, compared to Inatsu (2009). The time span is the same but the underlying dataset and resolution differ. More importantly, the NEAT algorithm has been updated since 2009 and now uses relative vorticity in place of meridional wind as the identifying field (See Inatsu and Amada, 2013, where the new algorithm is applied to track 300 hPa vorticities).
3.2. Intensity distribution and life cycle composites

The study of Hanley and Caballero (2012) suggested that MCC frequency as well as both merger and splitting event frequency increase with the storm intensity (see their Fig. 7c and Fig. 9). We perform a similar analysis to compare all three MS methods. A land-sea mask is first applied to eliminate potentially spurious MS events over land associated with weak heat-lows. Intensity decile bins are then defined for each method separately, for the population of remaining NH cyclones ($20^\circ$–$90^\circ$N). Resulting histograms of merger and splitting event counts per intensity bin are displayed in Fig. 2. Note that in our figures, intensity increases with intensity percentile from left to right and statistics are computed per cyclone rather than per track. Despite differences in the measure used for intensity, all three MS methods indicate that both merger and splitting events tend to occur more frequently as cyclone intensity increases, except for M21 showing a marked decrease in the final decile bin for both event types. Bin counts for M13 and M14 are of similar magnitude. Counts for M21 are much larger. This could be due to the M21 assigning larger areas to its cyclones, or that the identification parameter of vorticity produces relatively more elongated structures, either of which could increase chances of more frequent MS events.

We stated in the introduction that merger and splitting can be of critical importance in rapidly consolidating or isolating a vortex and we postulated that the events may therefore play a role in the rapid intensification of a storm. To see if this is generally the case, we compute composites of each MS method’s intensity measures, centred at the registered time of the merger or splitting event in a window of 12 hours before the event to 24 hours afterwards. We impose the additional conditions that the tracks included must survive at least the chosen period of the window, and that there are no subsequent mergers or splittings in the 24 hours following the event. For the average merger event, the composites for all three methods suggest that there is indeed an increase in intensity at the time of the event and up to around 12 hours afterwards. The increase shown by the M21 composite is particularly prominent compared to that of M13 and M14. For the average splitting event the M21 composite indicates a brief increase in intensity in the 6 hours following the average event. The interquartile range suggests (but is not conclusive) that the effect might be stronger for stronger cyclones. However, composites for M13 and M14 suggest otherwise, with decreasing intensities throughout the window. The measure of vorticity, related to the second derivative of geopotential, is
known to be more sensitive to and representative of the vortex anomaly strength compared to the measures of pressure and geopotential height, which are influenced by the background flow field (Sinclair, 1993). The results of M21 might therefore hold more weight.
4. Cases studies

In order to single out significant merger and splitting events present in the ERA-Interim 1.5° dataset for case studies, it is necessary either to take reported cases or to use a algorithm that systemically identifies them. Reported cases, however, are limited in region and overlap with the dates used for IMILAST. They are also identified using different underlying data and resolutions which can result in different representations of the events in timing and space. Here, we will make use of the IMILAST methods M13, M14 and M21, each of which contain an objective but different merger and splitting event detection algorithm.

To reduce the population of events to a manageable set of potentially significant cases, we first identify events that at least 2 of the 3 methods agree on. The conditions applied are that at least 2 methods register the event on the same timestep and within 3 latitude degrees of each other. The set size will be sensitive to these conditions. We note that this selection method may reduce the spread in results, by insisting that two out of 16 methods agree that a merger or splitting of their identified cyclones take place — effectively combining their event identification criteria. The resulting set is therefore only partially representative of the variability in the total population of events.

For mergers, we find 58, 68 and 93 cases in common for the pairings M13-M14, M13-M21, M14-M21, respectively, whilst for splittings, we find 11, 37 and 30 cases for the same respective pairings. Of these, there were three merger events and one splitting event found to be detected by all three algorithms. Note that the agreement increases if the strict event timing criterion is relaxed.

From these subsets, we have hand selected a number of cases to present, which are illustrative of the various types of merger and splitting and the variable IMILAST-method response to those events. We comment on the consensus between IMILAST methods on track continuation through the merger or splitting event and the impact the event has on the spread of genesis and lysis locations of those tracks.
4.1. Cases of cyclone merger

Overview and IMILAST consensus

Figure 4 shows four selected merger cases. Case 1 (15-12-1989 12 UTC, Fig. 4a-c) and case 2 (10-02-1981 12 UTC, Fig. 4d-f) both feature a merger near the end of the Pacific storm track of a large, mature cyclone (labelled A) and a co-rotating smaller cyclone (labelled B) that increases in intensity. In both cases, the merged system forms closer to the track of B and is a smoother continuation of B’s motion. In case 1, B also becomes the deeper cyclone just before the merger. Consequently, the majority of IMILAST methods link the track of B to the merged system. However, in case 2, A is still the larger and deeper cyclone, and the IMILAST methods are evenly divided between the continuation of track A, which would ‘win’ on an intensity criterion or track B, which would win on a ‘position’ criterion. Thus despite the synoptic similarity between these cases, differences in consensus between IMILAST methods are reached.

Case 3 (03-12-1992 06 UTC, Fig. 4g-i) features twin cyclones closer to the beginning of the Pacific storm track, near the west Pacific peak in climatological merger frequency. Twin cyclones are known to be common in this region (Yamamoto et al., 2012, and references therein). Leading up to their merger, cyclones A and B have a similar size, intensity and pace. In the last moments, A accelerates and B decelerates in a co-rotation, and B is absorbed into A’s rear. The majority of the SCC methods agree that cyclone A is the one to continue. The MS methods M14 and M21, however, connect cyclone B to the merged cyclone instead. They register the merger when the two cyclones become close enough to be defined as an MCC, but whilst they are still of similar size and intensity. The other methods (including M13) retain information on the individual centres long enough to determine the dominance of A. This illustrates a mechanism by which MS methods can arrive at different choices to SCC methods.

Case 4 (19-12-1993 18 UTC, Fig. 4j-l) features a merger in the mid-Atlantic storm track of two minor cyclones. There is minimal co-rotation in the strong westerly steering flow. The cyclones are initially weak and poorly defined compared to other cases, but the merged cyclone quickly intensifies into a coherent centre. The IMILAST ensemble is fairly divided
over the history of the merged complex, with 8 methods making a connection from A and 5 methods from B.
Merger-associated lysis

When cyclones merge, two or more tracks are reduced to one, with the consequence that at least one track must be terminated. Merger can therefore be associated with lysis. There can be high agreement over the lysis location if (i) there is high consensus between methods on which cyclone to terminate (ii) the merger is sudden (iii) the terminating cyclone is relatively stationary. In case 1, both (i) and (ii) are satisfied and a tight cluster of lysis points can be seen (Fig. 4b). In other cases, there is greater spread in lysis locations due to a poor ensemble consensus (case 2 - but with local clustering due to (iii), Fig. 4e), and the slow absorption of B into A (case 3, Fig. 4h), allowing differences in cyclone definition to control the spread in lysis locations as the cyclone is slowly absorbed. In case 4, an example with weaker systems, there are few merger-associated lyses because only a few methods capture or retain both cyclones until merger. Perhaps a cyclone lifetime did not meet the IMILAST 24 hr criterion or was too weak for a method’s cyclone definition.

Merger-associated genesis uncertainty

The ensemble spread in genesis locations of the merged complex, C, may also be affected by the ensemble consensus on whether C was previously connected to A or B, that is if A and B originate from different areas, in addition to the usual spread related to method-differences in cyclone definition which can have an impact whether or not a merger takes place.

For example, in case 1, the ensemble consensus is that the merged complex C is connected to B. The moderate spread in the genesis points of B is likely due to method differences in cyclone definition over B’s early life as a trough, but is limited by B’s relatively short pre-merger lifetime. The merger event has little impact on the spread in genesis points for this case. In case 2, however, there is split ensemble consensus over which cyclone should be connected to the merged system, and the spread of genesis locations is enlarged due to the different origins of A and B. For the merger of twin cyclones A and B of case 3, the ensemble links the origins of C mainly to A, along the long track of Typhoon Gay, but a couple of members place the origin in cyclone B, with one track emanating from eastern Mongolia.
4.2. Cases of cyclone splitting

**Overview and IMILAST consensus**

Figure 5 shows four selected splitting cases. Case 1 (04-02-1980 12 UTC, Fig. 5a-c), features a typical event near the end of the Pacific storm track. A mature cyclone, C, develops a trough on its leading edge (Fig. 5a), which separates as cyclone B, leaving a core, A, behind (Fig. 5b). The majority of IMILAST methods continue with cyclone A, which is the oldest and largest, and provides the smoothest continuation of the trajectory of the pre-split cyclone. Cyclone B’s separation distance from the pre-split cyclone centre is quite large and possibly fails the distance criteria for track continuation by most SCC methods. Both A and B, however, follow similar post-split paths, which we frequently observed in cases of this type. Following the split, A initially increases in intensity but B quickly makes landfall and initially weakens.

Case 2 (24-02-2003 18 UTC, Fig. 5d-f), features a complex mid-Atlantic event. Splitting does not occur from one coherent centre, but from an MCC containing 2 centres (Fig. 5d), created by a merger 6 hours earlier between a fast moving long lived Atlantic cyclone and a newly formed centre from a weak trough. The combined complex then splits with 9 IMILAST methods following one element (A) moving northwards towards Iceland and 5 methods following the other (B) that remains close to the site of splitting. We would expect the SCC’s not to notice the merger, and instead to continue the tracks of the 2 centres individually (see Hanley and Caballero, 2012, for several examples of such SCC vs. MCC behaviour). The small separation of the centres and possibly the buffeted trajectory of the weaker centre, however, causes spurious track connections by some methods. For example, two methods effectively treat the process as a splitting without merger, and another effectively as a merger only.
In contrast to the first two cases, case 3 and 4 feature cyclones that elongate and split perpendicular to their previous motion. In both cases, the IMILAST ensemble is very divided over which centre to continue. This situation has the potential to be very divergent, if the centres continue to separate. The mechanisms behind the behaviour differ, however. In case 3 (10-12-2004 06 UTC Fig. 5g-i), the parent cyclone develops in a deepening Atlantic trough, under the influence of an upper level potential vorticity streamer. It splits into a northward moving centre A and a southward moving centre B, as the streamer extends longitudinally (Fig. 5g). However, multiple splittings and mergers as a streamer develops are likely: A subsequent splitting of B brings the majority of tracks back towards A and they merge, forming cyclone A’ (Fig. 5h). The tracks originating in A and B thus approach each other again.

In case 4 (19-01-2002 06 UTC, Fig. 5j-l), the topography of Greenland and Iceland is influential in blocking the parent cyclone C’s motion. Similar behaviour can be observed at the end of the Pacific storm track, where the North American mountain chains form a perpendicular barrier. Two new centres form at either end of C’s longer axis and split apart (Fig. 5k). Blocked by Greenland, cyclone A remains fairly stationary, but B moves quickly away towards Norway, merging with another cyclone. The intensity of the split systems are initially weaker, but A re-intensifies and B generally decays.

Splitting-associated genesis

When a cyclone splits, the number of tracks must increase from one to two or more. Splitting can therefore associated with track genesis. There can be high agreement over the genesis location if (i) there is high consensus between methods on which tracks must be generated (ii) the splitting is sudden (iii) the generated cyclones are initially not very mobile. Case 1 satisfies (i) but not (iii) resulting in the cluster of genesis points being somewhat spread out in the direction of motion. The other three cases do not satisfy (i) but do show local clustering of genesis around the two separate fragments. Case 2 and 3 suffer from some spurious connections - where fragment A or B is erroneously connected, not to the parent cyclone, but to another pre-existing centre. These generally act to decrease consensus over the splitting-associated genesis location.
Splitting-associated lysis uncertainty

Splitting can lead to a diverging ensemble tracks and lysis locations if (i) there is a lack of consensus on which cyclone is the continuation of the initial track and (ii) if the cyclones increase their separation after the splitting. Lysis locations will be related to method-differences in cyclone definition plus specifics relating to the region or circulation, independent of splitting.

Case 2, for example, satisfies both (i) and (ii). Lyses of the parent cyclone associated with fragment B are clustered close to the splitting event in the east Atlantic, but fragment A moves rapidly and coherently North, with most lyses occurring beyond Novaya Zemly in Northern Russia. In case 1 on the other hand, A and B follow very similar trajectories, which we observe for several (not shown) but not all cases studied in this region. The trajectories intertwine across Alaska, where there is a lysis cluster, separate on reaching the Arctic Ocean, and approach each other briefly again near the pole, where there is another lysis cluster. Thus, although the lysis points are spread over a great distance, the splitting itself has a comparatively small influence on the spread.

5. Summarising remarks

For the first time, a study has been conducted to compare the response of an ensemble of cyclone tracking methods to cyclone merger and splitting events. Three (M13, M14 and M21) of the 16 tracking methods, made available by the IMILAST intercomparison project, explicitly define and register merger and splitting (MS) events. They each effectively include multicentre cyclones (MCCs) in their cyclone definition, which lends itself to the detection of MS events, in contrast to other IMILAST methods that employ a single-centre cyclone (SCC) identification. The MS methods however differ in their identification field (sea level pressure, 850 hPa geopotential height and 850 hPa relative vorticity) and in their tracking methodology.
A comparison of merger and splitting climatologies for the three MCC-methods revealed broadly similar geographical distributions. The most obviously differing features were also present in a comparison between the methods’ cyclone density climatologies. We also sought to explore and compare the relations between MS events and cyclone intensity and life cycle. We showed that merger and splitting frequency generally increase with cyclone intensity for all MS methods. Composites of cyclone intensity, centred at the time of merger/splitting and capturing 36 hours of the life cycle, indicated that (i) cyclones do typically intensify after a merger event (ii) cyclones may also typically undergo a brief intensification after a splitting event, but the supporting evidence comes from M21 alone and is therefore non-conclusive.

Despite the differences in identification field and algorithms, it is possible for the MS methods to detect the same events. A number of these events were further explored using the IMILAST ensemble, focussing on the impact of MS events on (i) method (dis)agreement over the track continuations and (ii) genesis and lysis uncertainty.

We find very divided IMILAST method decisions when one candidate for track extension is the most intense, whilst the other is closest to the (predicted) position of the post-merged or pre-split cyclone (e.g. merger case 2). This is a reflection of the balance, within the IMILAST ensemble of methods, in the types of criteria (intensity versus positional) used to find the likely candidate for track continuation. There is hardly any disagreement between SCC methods if position and intensity track-continuation criteria are satisfied by the same candidate cyclone (e.g. merger case 1).

We make two observations regarding differences between MCC and SCC-method behaviour: (i) MCC methods generally register a merger (splitting) some time ahead of (beyond) the convergence (divergence) of the branches of the IMILAST ensemble. This can result in a different choice of the continued track between MCC and SCC methods, due to changes in the relative strengths of the individual cyclone centres in this intermediate time. Such relative changes frequently occur precisely over this time, when the two centres are close enough to interact (interference). M13 retains information on the individual centres inside an MCC, and therefore has an advantage over M14 and M21 in this respect.
(ii) The separation distance need not be (very) small for two centres to be joined in an MCC and thus accepted as candidates for MS events. As the separation increases, more SCC methods are likely to exclude the most distant centre as a candidate for track extension and the greater the chances of agreement between SCC-methods (e.g. splitting case 1).

Where cyclones merge, two or more tracks are reduced to one, whereas where a cyclone splits, the number of tracks must increase from one to two or more. Merger can therefore be associated with lysis, and splitting with genesis. Whether or not there is a consensus between methods on which cyclone track to continue, there will be a cluster of lysis points from discontinued tracks to a merger event, and a cluster of genesis points from tracks generated close to a splitting event. The clustering becomes stronger if there is consensus over the continued cyclone and if the transition between an SCC and MCC configuration or vice versa occurs rapidly (see e.g. merger case 1). Contrary to initial intuition, MS events may actually contribute to increased method agreement in the (euclidean climatological) location of lysis and genesis events respectively, relative to the average method agreement over lysis and genesis locations for cyclones in general, provided all cyclones involved in an MS event are readily identified by the majority of IMILAST methods. Topography, however, can also have a role in clustering genesis or lysis events for the IMILAST ensemble.

On the other hand, merger-associated genesis (i.e. remote origins of tracks that become connected to the merged cyclone) and splitting-associated lysis (remote termination points of tracks emanating from splitting events) have the potential to increase genesis and lysis method-related uncertainty respectively in the Lagrangian sense. That potential is realised if the origins (ends) of the merging (splitting) cyclones are initially very separated, compared to mean lysis/genesis spread for cyclones in general, and if the IMILAST methods are very divided over which cyclone track to continue.

Returning to the potentially pivotal nature of MS events, we note from the composites and/or cases explored, that (i) merger often leads to an increase in cyclone intensity, (ii) splitting may cause larger changes in track divergence, especially where splitting is due to orography or wave breaking. Both merger and splitting introduce sensitivity into the ensemble spread for cyclone intensity and position respectively, in the sense that small differences in tracking method criteria can have a large impact on cyclone diagnostics surrounding these events.
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APPENDIX A: Method 14

Method 14 is an adaptation of Kew et al. (2010) by SFK and tracks geopotential height minima on near-surface isobaric levels.

A1 The original method

The original method of Kew et al. (2010) was developed for tracking upper-level flow anomalies in the form of coherent potential vorticity (PV) maxima on tropopause-intersecting isentropic surfaces. In the quasi-adiabatic flow near tropopause level, PV anomalies are quasi-conserved quantities on isentropic surfaces. Their position at a time \( t + \Delta t \) is therefore well predicted by the advection of the anomalies by the local isentropic wind field (see Fig. 4d of Kew et al. (2010)). The method identifies anomalies as closed PV contours surrounding a local PV maximum, with the size of the enclosed area being constrained to be close to a specified target area. The overlap at \( t + \Delta t \) between observed and advected anomalies from time \( t \) was used to (re)assign identity and thereby connect anomalies that continue from one time step to the next into tracks.

A2 The adapted method

As isentropes in the mid-latitudes do not lie parallel to the earth surface but intersect it at an angle, the original method that tracks PV maxima on isentropic surfaces is not appropriate for tracking the low-level component of mid-latitude storms. We instead use the geopotential height field on a standard near-surface pressure level. The level 850 hPa is chosen, rather than the lower 1000 hPa that is likely to frequently intersect the surface. The isobaric wind is used to advect geopotential height minima forward, to predict the location of cyclonic structures at the next timestep. Unlike PV, geopotential height is not a materially conserved quantity on
the surface chosen for tracking, so we do not expect the tracking method to be as successful as for the original version. Therefore a small envelope of 1° is added to the advected structures, to effectively increase the search radius, before considering the overlap between the observed and advected cyclonic structures.
References


Fig. 1. Frequency density plots, with units of events per 7.5° circle per DJF for the years 1979 – 2009, of cyclone merger (a,c,e), and cyclone splitting (b,d,f) as for IMILAST methods M13 (a,b), M14 (c,d) and M21 (e,f).
Fig. 2. Merger (a) and splitting (b) frequency as a function of NH cyclone intensity, defined in decile bins for each method separately, using percentiles of SLP for M13, Z850 for M14 and VORT850 for M21. Intensity increases with intensity percentile from left to right.
Fig. 3. Composites of intensity measures in a time window of 36 hours, with time expressed relative to the MS event. Top row shows composites for merger, and the lower row for splitting. Results for M13, M14 and M21 are presented left to right, using the intensity measures prescribed by each method. Note that the vertical axes for M13 and M14 are reversed, so that the cyclone intensity increases upwards for all three methods. The black line gives the composite mean intensity and the grey shading indicates the interquartile range of intensities at each 6 hour interval.
Fig. 4. Cases 1 (top row) to 4 (lowest row) of merger. The SLP field is contoured at intervals of 2 hPa and tracks are plotted up to time of field shown (columns 1 and 2). Third panel for each case shows complete tracks of cyclones involved. Green (Magenta) tracks are those that are continued through (terminated due to) the main merger event. Cyan: tracks that join the post-merger cyclone but do not connect to pre-merger component cyclones. Purple: tracks that follow pre-merger components but loose them before the main merger case. Geneses (Lyses) points are shown by white (black) circles. Labels A and B indicate the pre-merger cyclones, and C the merged complex. The approximate merger location is marked by a red dot.
Fig. 5. Cases 1 (top row) to 4 (lowest row) of splitting. Third column for each case shows complete tracks of cyclones involved. The SLP field is contoured at intervals of 2 hPa and tracks are plotted up to time of field shown (columns 1 and 2). Third panel for each case shows complete tracks of cyclones involved. Green (Magenta) tracks are those that are continued through (generated due to) the main splitting event. Cyan: tracks that survive the splitting event but do not connect to post-splitting component cyclones. Purple: tracks that join post-splitting components but do not originate from the pre-splitting cyclone. Geneses (Lyses) points are shown by black open (closed) circles. Labels A and B indicate the post-splitting cyclones, and C the parent cyclone/MCC. The approximate splitting location is marked by a red dot.
‘The pivotal nature of cyclone merger and splitting assessed in an ensemble of cyclone tracking methods’

by Sarah F. Kew, Rodrigo Caballero, John Hanley and Masaru Inatsu.

Fig. 1. Cyclone frequency for IMILAST methods M13 (a), M14 (b) and M21 (c) expressed in cyclone counts per DJF season per 7.5° circle, for the years 1979 – 2009.