Objective identification and tracking of multicentre cyclones in the ERA-Interim reanalysis dataset

John Hanley\textsuperscript{a}\textsuperscript{*} and Rodrigo Caballero\textsuperscript{b}

\textsuperscript{a}Meteorology and Climate Centre, School of Mathematical Sciences, University College Dublin, Ireland
\textsuperscript{b}Department of Meteorology and Bert Bolin Centre for Climate Research, Stockholm University, Stockholm, Sweden

*Correspondence to: J. Hanley, Meteorology and Climate Centre, School of Mathematical Sciences, University College Dublin, Belfield, Dublin 4, Ireland. E-mail: john.hanley@ucdconnect.ie

We present a novel cyclone identification and tracking method that explicitly recognizes ‘multicentre cyclones’ (MCCs), defined as a cyclonic system with two or three sea-level pressure minima within its outermost contour. The method allows for the recognition of cyclone merger and splitting events in a natural way, and provides a consistent measure of the cyclone extent. Using the ERA-Interim reanalysis dataset, we compute a climatology using this method and show that MCCs occur in about 32% of all cyclone tracks and are much more prevalent in more intense storms. We also show that the method permits reconnection of tracks that would have been spuriously split using a conventional method. We present spatial maps of cyclone mergers, splitting, genesis and lysis using the method and also compute statistics of precipitation falling within cyclones, showing that it is strongly concentrated in the most intense cyclones. Copyright © 2011 Royal Meteorological Society

Key Words: cyclone identification; cyclone tracking; multi-centre cyclones

Received 10 December 2010; Revised 18 July 2011; Accepted 2 September 2011; Published online in Wiley Online Library 31 October 2011


1. Introduction

Mobile synoptic-scale cyclonic systems play a central role in the weather and climate of the midlatitudes. The increasing availability of multiyear gridded observational or model-derived datasets has spurred the development of methods for the automatic identification and tracking of such systems (Lambert, 1988; Alpert et al., 1990; Murray and Simmonds, 1991; Keonig et al., 1993; Hodges, 1994; Serreze, 1995; U and U, 1996; Blender et al., 1997; Sinclair, 1997; Trigo et al., 1999; Sickmoller et al., 2000; Gulev et al., 2001; Klawa and Ulbrich, 2003; Hanson et al., 2004; Pinto et al., 2005; Benestad and Chen, 2006; Bengtsson et al., 2006; Wernli and Schwierz, 2006; Raible et al., 2008; Hewson, 2009; Inatsu, 2009). That this is still an evolving field despite this substantial body of work testifies to the intrinsic difficulty and subjectivity involved.

Common to most methods is a two-step approach. Cyclone centres are first identified at each time step, most commonly as minima in sea-level pressure (SLP) or extrema in relative vorticity (though other choices are possible, see e.g. Hoskins and Hodges, 2002); these centres are then connected together across time steps to form tracks. An important difficulty is that there is often no one-to-one relation between local SLP or vorticity extrema and individual, fully formed synoptic cyclones; rather, a cyclonic system may contain several local extrema. This is especially true for large, mature cyclones, where multiple local extrema often appear around the main cyclone centre. Secondary extrema also often develop along fronts (Hewson, 2009) and sometimes break off from their parent to spawn independent cyclones, a process known as secondary cyclogenesis. Multiple extrema create uncertainty in how to connect cyclone centres properly at the tracking stage, leading to short, spuriously truncated tracks. The problem becomes more acute the greater the resolution of the underlying dataset.

One way to mitigate this problem is to apply some form of spatial smoothing to eliminate shallow extrema (Sinclair, 1997; Anderson et al., 2003). With a noisier field such as
vorticity this can be done without removing smaller-scale features that are of interest; when using SLP, however, such features may be unintentionally removed. Some of the most extreme storms to affect Europe are fairly small-scale systems, which achieve their maximum destructiveness while embedded in a strong, large-scale background pressure gradient. Archetypal of such systems is the ‘Lothar’ storm of December 1999 (Wernli et al., 2002). The presence of a strong background flow makes the cyclone appear in the surface-pressure field as a shallow trough (see for instance figures 2 and 4 of Wernli et al., 2002). When using an SLP field, smoothing can easily remove this shallow trough, and once there is no local minimum the feature can no longer be tracked. Moreover, the removal of secondary extrema, through smoothing or otherwise, means that we lose information about how often cyclones are generated through secondary instability of a parent cyclone, which is of interest in itself. We similarly lose information on how often cyclones merge to form a single cyclone or how often a cyclone splits into two separate cyclones.

Here, we present a method that recognizes explicitly situations in which a single cyclone has up to three SLP minima, allowing cyclones to be tracked robustly from genesis to lysis without recourse to spatial smoothing. Crucially, the explicit recognition of ‘multicentre cyclones’ (MCCs) confers the method with capabilities not available to most other tracking methods, specifically the identification of cyclone merger and splitting events, as well as providing a natural measure of cyclone shape and size. Methods to measure the extent of a cyclone system have also been proposed by Simmonds (2000), Simmonds and Keay (2000) and Rudeva and Gulev (2007) (using a radial search from the cyclone centre to the point at which the radial derivative of SLP falls to zero), as well as Sinclair (1997) (whose method searches radially from the centre to the point where either the vorticity becomes zero or the radial vorticity gradient changes sign, whichever occurs first) and Wernli and Schwierz (2006). As discussed in Wernli and Schwierz (2006, henceforth WS06), ‘interference’ between neighbouring cyclones can lead to dramatic changes in their outermost boundary over the course of their life cycle; explicit consideration of such ‘interference’ in our method helps stabilize cyclone size, leading to a more accurate and reliable estimation of area-integrated quantities such as the precipitation within each storm.

The method, described in section 2, is an extension of that proposed by WS06. After identifying all local minima in the SLP field, the method computes contours around each minimum. When two or more minima are found within a closed contour an explicit criterion is invoked to decide whether the system is a MCC—i.e. a single cyclone with several minima—or whether each minimum should be considered as an independent ‘single-centre cyclone’ (SCC). Previous work that considers cyclones with more than one minimum includes that of Inatsu (2009). Our method allows us to compile statistics on cyclone merging and splitting. The problem of systems merging and splitting has been addressed in relation to tracking convective cloud systems (Chetverikov and Verestoy, 1999; Morel and Senesi, 2002; Vila et al., 2008) as well as particular cyclone case studies (Hakim et al., 1995; Strähl and Smith, 2001) and cyclone climatologies (Inatsu, 2009). In our results section, we compare our results on cyclone merging and splitting with those obtained by Inatsu (2009). Examples involving MCCs are discussed in section 3.

We apply the method to create a climatology of Northern Hemisphere winter storms using the ERA-Interim reanalysis product (Simmons et al., 2007). As discussed in section 4, we find that MCCs occur most frequently in mature storms, and are more likely to occur in the most intense storms. We present statistics of merger and splitting events, and find that these also occur most often for intense, mature storms. The method provides an outermost closed contour as a natural measure of cyclone extent; we compute precipitation integrated over this area and find that it is strongly concentrated in the most intense cyclones.

The paper is structured as follows: section 2 outlines the method, including (1) identification of cyclone centres, (2) tracking, (3) contouring and identification of MCCs and (4) track surgery, i.e. mergers, splits and reconnections. Section 3 gives example cases illustrating track reconnection, track merging and track splitting. Section 4 details statistics on the frequency of MCCs, track reconnections, cyclone merging and splitting for our winter climatology. Section 5 discusses our conclusions.

2. Method

Following WS06, our method is based on features in the SLP field. The method proceeds in four stages. Briefly, local minima in the SLP field are first identified at all time steps. Next, the minima are connected together across time to form tracks. Thirdly, contours are computed around each cyclone centre and MCCs are identified. Finally, a ‘track surgery’ stage uses information on MCCs to reconnect some of the tracks and to count cyclone merger and splitting events. These steps are described in detail below. The algorithm was designed and calibrated using six-hourly ERA-Interim data at full T255 resolution, interpolated on to a regular 0.75° × 0.75° grid. ERA-Interim was chosen over ERA-40, as improvements in both the assimilation system and the underlying model allow ERA-Interim to capture intense synoptic cyclones much more realistically than ERA40, even when the ERA40 system is run at the same resolution (Dee et al., 2011). All steps of the method are carried out on the full SLP field. It has been shown that removal of a large-scale background field can help in the identification of synoptic-scale systems (Anderson et al., 2003), but we do not do this here as it would affect the relative depths of SLP minima; as discussed in section 2.3 below, these relative depths are crucial to our definition of MCCs.

2.1. Identification of cyclone centres

A grid point in the SLP array at a given time step is considered a cyclone centre if its SLP value is less than that at the eight neighbouring grid points. If carried out on the native latitude–longitude grid this simple identification is subject to bias, since the convergence on the meridians implies a greater effective zonal resolution with increasing latitude (Sinclair, 1997). To counteract this effect, we first transform the SLP field on to a regular grid on a Lambert projection centred at the North Pole. This area-preserving projection ensures uniform mean resolution (equal number of grid points per unit area) over the entire domain. Further technical details on this procedure and its impact are relegated to Appendix A. The SLP minima identified on the Lambert projection are
then mapped back to the original cylindrical map projection to the nearest grid point before proceeding to the tracking stage.

The weak condition of a minimum being defined as less than its eight neighbours leads to the identification of around 80 SLP minima over the Northern Hemisphere at each time step. Over land, many of these minima are shallow heat lows of no interest. These are removed using an SLP gradient test. The minimum average SLP gradient we require over a 1000 km radius is 7.5 hPa; this value was determined after performing a sensitivity study of varying values from 0–10 hPa. The SLP gradient was estimated by averaging the gradient between points 1000 km north, south, east and west of the cyclone centre. SLP minima with gradients less than this value are deemed heat lows and eliminated, while the rest are considered cyclone centres and retained. Pressure minima above 1500 m are also deemed to be spurious, due to the error associated with calculating a relative sea-level pressure corresponding to this height, and are also eliminated.

2.2. Tracking

Cyclone centres from consecutive time steps are now linked together to form cyclone tracks. We do this following a standard tracking method, specifically the ‘first-guess’ method of WS06. The first-guess location is a reduced linear continuation of the track in geographical longitude–latitude coordinates: \( x^*(t_{n+1}) = x(t_n) + 0.75(x(t_n) - x(t_{n-1})) \), where \( x \) is a latitude–longitude coordinate pair, \( t_n \) is the time at time step \( n \) and the factor 0.75 allows for deceleration as the cyclone progresses through its life cycle. A cyclone centre located at \( x \) at time \( t_{n+1} \) is regarded as a candidate to continue the cyclone track \( x(t_1), \ldots, x(t_n) \) if the distance between \( x(t_{n+1}) \) and the first-guess location \( x^*(t_{n+1}) \) is less than a certain threshold distance \( D \). WS06 used \( D = 1000 \) km, but after some experimentation we found it preferable to use \( D = 500 \) km for tracks less than 12 h old and \( D = 840 \) km for older tracks. This smaller search radius reduces the chances of mistakenly joining up distinct trajectories; examination of a large number of sample trajectories overlaid on SLP fields (as in the examples shown later in Figures 4–5) shows that obviously unnatural connections occur very rarely. If two or more cyclones at time \( t_{n+1} \) are potential candidates to extend the cyclone track, the cyclone that is closest to the guess point is chosen. It could be argued that a better first guess could be obtained by extrapolating along a great-circle path instead of separately along latitude and longitude. The difference between the two extrapolations increases with the latitude and with speed of the cyclone, but remains below 200 km even for very fast-moving cyclones at high latitudes, a distance much less than the search radius for candidate cyclones.

It is not possible to perform a first guess of the track position at the first time step of the track. WS06 take the initial position of the cyclone as the first guess. We take a slightly different approach, instead considering all cyclone centres at the second time step that are within 720 km of the position of the cyclone at the first step. We note all cyclone centres that meet this criterion at the second time step and perform a first-guess projection to the third time step for each. We do not decide at this point which centre to choose as the continuation of the track; instead we wait until the third time step and search for a cyclone centre that falls within the distance \( D \) of one of these projections. If we find such a centre, we have identified our true track and the alternative tracks are disregarded. If more than one candidate lies within the distance \( D \), the closest is chosen.

Once all tracks have been identified, we remove any tracks of length 12 h or less. Various quantities along the remaining tracks, including time, position and SLP value, are then archived.

2.3. Contouring and identification of MCCs

At this point, SLP contours are computed around each surviving cyclone centre at each time step, using a contour interval of 2 hPa. The contouring method is described in Appendix B. Contouring proceeds outwards from the cyclone centre, and continues at 2 hPa intervals until an outermost contour–defined such that the subsequent contour is either anticyclonic, encircles the pole or encircles a total of more than three other minima–is found. SLP contours that envelop a deleted heat low are also removed.

SLP contours are then examined to establish the existence of MCCs. If the outermost contour is found to contain two minima, we compute the ratio \( N_{\text{shared}}/N_{\text{max}} \) where \( N_{\text{shared}} \) is the number of ‘shared’ contours, i.e. those encircling both minima, and \( N_{\text{max}} \) is the number of contours between the lowest minimum and the outermost contour. As illustrated in Figure 1, this is equivalent to computing the ratio between the maximum depth of the system and the depth of the saddle point separating the two minima. If this ratio exceeds 50%, we say that the two SLP minima constitute an MCC. If not, then each constitutes a separate SCC; in this case, the shared contours are deleted. For three minima, the percentage of shared contours common to all three minima is required to be 70%. Both of these values have been tuned subjectively. Sensitivity tests were performed with values lower and higher than 50% for two minima and 70% for three minima. Values less than 50% and 70% respectively resulted in MCCs with SLP centres that were geographically too disparate to constitute a single cyclone–i.e. the condition was not strong enough (this is the same reason why three minima require a greater percentage of shared contours than two). Values greater than 50% and 70% respectively resulted in the exclusion of cases that, on observation, we judged to be MCCs. Note that the number of SLP centres contained within an MCC is limited to three due to computational expense (extending from three to four would dramatically increase computational time), coupled with the fact that MCCs containing four minima are very rarely observed.

Subsequent to the removal of unwanted shared SLP contours, the boundary of each cyclone is defined as the remaining outermost SLP contour. An alternative definition of a cyclone’s boundary, aside from that proposed by WS06, is a radial-gradient approach as outlined by Rudeva and Gulev (2007) and Sinclair (1997). Using such an approach, an MCC containing two minima may be separated into two separate cyclones in which the gradient between the minima drops to zero. In contrast, our method would define the boundary as including both SLP minima, better capturing the size of the MCC. WS06 additionally require each cyclone centre to have at least one closed 2 hPa SLP contour at each time step. We found that in some cases this requirement removed an early part of the storm’s track prior to the formation of a first closed SLP contour. To avoid this, we
situations can arise. Which we shall refer to as track A and track B. The following containing two minima and thus associated with two tracks, system, associated with a unique track. Consider an MCC we would like to interpret an MCC as a single cyclonic two or three tracks passing through it. Physically, however, a distinct cyclone track, meaning that each MCC has either two or three tracks passing through it. Physically, however, we would like to interpret an MCC as a single cyclonic system, associated with a unique track. Consider an MCC containing two minima and thus associated with two tracks, which we shall refer to as track A and track B. The following situations can arise.

(1) Both tracks have past and future branches (Figure 2(a)). In this case, we consider the size of the cyclones associated with each track at the two previous time steps and perform a linear projection of these sizes to the current time step. The cyclone with projected size closest to that of the current MCC is taken as the ‘dominant’ cyclone. If one or both tracks are insufficiently old to compute a size projection, the oldest track is taken as dominant. We then check that the dominant track continues into the future for at least two more time steps. If true, then the dominant track is chosen as the MCC’s track for the current time step (track A’). If the original track B exists beyond the last time step containing an MCC, the remaining track is treated as a new cyclone (track C’). Overall, this sequence of events is interpreted as a merger between A’ and B’ followed by a split that spawns C’. If the dominant track terminates after two time steps, however, track surgery is required. Figure 3(a) illustrates this scenario. Track A is the dominant track and so its track up to the point of MCC formation is taken as the MCC track. On the other hand, Track A cannot serve as the MCC track beyond the next time step and so the remainder of track B is attached to form the new MCC track A’ . Track B is truncated to form track B’. In both cases the outcome effectively constitutes a cyclone merger: two initially separate cyclones come together to form a single system.

(2) Track A has both past and future branches, while Track B only has a past branch (Figure 2(b)). In this case, Track A is naturally chosen as the MCC track. The outcome is a merger event.

(3) Track A has both past and future branches, while Track B only has a future branch (Figure 2(c)). In this case, we check to see whether Track A continues into the future for more than two time steps. If true, then the MCC is assigned to Track A and Track B is taken to start at the next time step. This outcome corresponds to cyclone splitting. If Track A extends less than two time steps into the future, on the other hand, track B is attached to track A at the point of first common contours and the remainder of track A is deleted (Figure 3(b)). This is in effect a track reconnection: two previously separate tracks are joined into a single continuous track. This situation arises when a cyclone develops a secondary minimum that is later reabsorbed into the parent and the conventional tracking algorithm is fooled into spuriously breaking up the track; our ‘track surgery’ acts to reconnect the track, correcting the spurious breakup. Caveats associated with the procedure are discussed in section 4.2.

The remaining possibilities, that both A and B have only past or only future branches, occur very rarely; in both cases, the MCC is simply assigned to the track passing through the deepest minimum.

Subsequent to track surgery, the central pressure for each time step of an MCC is assigned to the minimum pressure within the outermost contour and the position is assigned to the mean position of the identified SLP minima within the system. This is done to ensure the smoothest evolution of track position and central pressure.

3. Examples of reconnection, merger and splitting events

Figure 4 shows a case study illustrating a reconnection event (right column) and compares it with the same case handled using only SCCs, as in SW06 (left column), using ERA-Interim data. A MCC first forms in the second time step shown and survives up to the fourth time step. The MCC’s previous track is taken as the longest-lived track up to its formation, as outlined previously. For the remaining time steps, a single MCC track evolves with an outermost contour of gradually diminishing size. This is in contrast to the SCC-only case, where after the first time step a rather large cyclone collapses into two separate and much smaller SCCs. Our method reconnects the two coexisting tracks of the SCC-only case into a single track at the fourth time step shown in the figure. We argue that our method (right column) offers a more natural description of this cyclone’s complex evolution than the simpler SCC-only case (left column).

A second case study, Figure 5, shows an example cyclone merger. The first time step (1200-11-01-1992) shows two SCCs off the northeastern US seaboard. At the second time step (1800-11-01-1992) the two SCCs have moved closer together but have insufficient common SLP contours to constitute an MCC and so are treated as two separate cyclones. At the third time step (0000-12-01-1992) they
tracks; one is the continuation of the MCC track from the
an MCC. Therefore in the MCC case there are two distinct
longer share a sufficient number of contours to constitute
(0000-14-02-1992) the two neighbouring SLP minima no
remains intact and moves northward. In the final time step
to and including time step 0000-13-02-1992) the MCC
not recorded a merger event. Over the next two days (up
contrast, the SCC method has two separate tracks and has
to form an MCC and records a splitting event. In
step have merged into a single MCC track and thus registers
algorithm recognizes that two tracks from the previous time
contour containing both SLP minima in question. The
of high cyclone density over the Pacific and Atlantic storm
dataset. Only one cyclone centre is counted for each MCC.
grid point.) We then average over all winters in the
great-circle distance less than or equal to 840 km from the
latitude–longitude grid by finding all grid cells lying at a
winter within a region corresponding to a circle on the sphere
centred at the given grid point with radius 840 km, equivalent
to 7.5° latitude. (In practice, this region is identified on the
grid.) We compute the spatial distribution of cyclone frequency
as follows: for each point on the latitude–longitude grid we
count the total number of cyclone centres falling each
winter within a region corresponding to a circle on the sphere
centred at the given grid point with radius 840 km, equivalent
to 7.5° latitude. (In practice, this region is identified on the
latitude–longitude grid by finding all grid cells lying at a
great-circle distance less than or equal to 840 km from the
given grid point.) We then average over all winters in the
dataset. Only one cyclone centre is counted for each MCC.
The resulting density field is rather noisy and the relatively
large 840 km averaging radius is a subjectively optimal
choice, giving a smooth density field highlighting the main
regions of cyclone activity.

The cyclone frequency climatology is shown in
Figure 7(a). As expected, the figure shows broad regions of
high cyclone density over the Pacific and Atlantic storm
tracks and lower density over the continents. At a more
regional scale, the figure shows well-known density maxima
off the east coasts of North America and Asia, a prominent

4. Winter cyclone climatology

We applied the method described in section 2, including
MCCs and track surgery, to the ERA-Interim dataset to
produce a December–February (DJF) cyclone climatology
for the years 1989–1990 to 2008–2009. We used SLP data
at six-hourly time resolution on a regular 0.75°×0.75° grid.
Tracking was restricted to latitudes north of 30°N so as
to focus on the Northern Hemisphere extratropical storm
tracks. Statistics from the climatology are presented below,
with particular emphasis on aspects unique to the present
method.

4.1. Cyclone frequency and MCC occurrence

We find an average of 16 cyclone centres (with only one
centre counted for each MCC) present in the domain at
each given time step, of which six are in the Atlantic sector
(100°W–20°E) and seven in the Pacific (120°E–110°W).
There are 534 cyclone tracks in the average winter, of which
193 are in the Atlantic and 225 in the Pacific.

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Figure 2. Sketch of various track combinations involving MCCs. In the online article, black lines show SCC tracks, blue lines MCC tracks, red dots are
cyclone centres and green lines indicate the outermost SLP contours. In the printed article, black lines show SCC and MCC tracks, grey dots are cyclone
centres and grey lines indicate the outermost SLP contours. (a) Two tracks merging to form an MCC and subsequently splitting. (b) Two tracks merging
to form an MCC. (c) Formation of an MCC and subsequent splitting. This figure is available in colour online at wileyonlineibrary.com/journal/qj

Figure 3. Sketch of situations requiring track reconnection. (a) A merger event where the dominant track expires soon after merging. (b) A situation where a
cyclone develops a secondary minimum, which is later reabsorbed into the parent. This figure is available in colour online at wileyonlinelibrary.com/journal/qj

share sufficient SLP contours to constitute an MCC and so
the two original cyclones have merged. At this time step it is
clear that the two SLP minima in question are embedded in a
single cyclone. The MCC criterion recognizes this and forms
an MCC at this point with a single track and an outermost
contour containing both SLP minima in question. The
algorithm recognizes that two tracks from the previous time
step have merged into a single MCC track and thus registers
a merger event at this time step. A clear contrast between
the two methods can be seen by comparing the respective
images at the third time step; the SCC method considers
the two minima embedded within the larger system as two
separate cyclones, each with their own track and outermost
contour, and fails to recognize the merger event.

Finally, Figure 6 shows an example of cyclone splitting
off the coast of northern Japan. In the first time step
(0000–11–02–1992) the two neighbouring SLP minima share
a sufficient number of SLP contours to constitute an MCC.
As in the merger example, the algorithm recognizes that
two tracks from the previous time step have now merged
into a single MCC track and records a merger event. In
contrast, the SCC method has two separate tracks and has
not recorded a merger event. Over the next two days (up
to and including time step 0000–13–02–1992) the MCC
remains intact and moves northward. In the final time step
(0000–14–02–1992) the two neighbouring SLP minima no
longer share a sufficient number of contours to constitute
an MCC. Therefore in the MCC case there are two distinct
tracks; one is the continuation of the MCC track from the
previous time step, while the other is a new track. The
algorithm recognizes that an MCC from the previous time
step has split into two distinct tracks and records a splitting
event. This is contrast with the SCC example, which does not record a splitting event.
Figure 4. Evolution of a North Atlantic cyclone tracked using the SCC-only method, as in WS06 (left column), and the present method including MCCs and track surgery (right column). Time flows from the top down in six-hourly steps, with time and date shown above each panel. In the online article coloured lines show SLP contours at 2 hPa intervals, with colder colours indicating lower pressure. In the printed article, grey lines show SLP contours at 2 hPa intervals. The outermost contour for each cyclone is shown in bold black. Thin black lines show cyclone tracks, with dots indicating the position of the cyclone centre at each time step. Tracks are plotted only so long as they are active and are removed after cycloysis. This figure is available in colour online at wileyonlinelibrary.com/journal/qj
maximum in cyclone frequency over the Irminger Sea off southeastern Greenland and secondary maxima over the Hudson Bay, the northern North Atlantic between Greenland and Norway and the Mediterranean.

For a qualitative assessment of our method’s performance, we compare these results with those obtained using a variety of different methods: one closely related to ours (WS06, their figure 4(a)), another based on SLP but with very different identification and tracking (figure 5(a) of Hoskins and Hodges, 2002) and other methods using both different identification and tracking strategies and other fields, namely 1000 hPa geostrophic vorticity (figure 9(a) of Sinclair, 1997) and 850 hPa vorticity (figure 2(a) of Bengtsson et al., 2006). Considering the different methods, datasets and time periods covered, we find a remarkable consistency in the structure of the density fields across all studies, with the regional maxima outlined in the previous paragraph appearing in all the cases. (We do not perform a quantitative comparison, since different studies use different units and some report track densities rather than cyclone frequencies.) There is, however, one region where our results depart qualitatively from the others: all the other studies cited above show a lobe of enhanced cyclone frequency over the Great Lakes region of North America with intensity comparable to that over Hudson Bay, while in our results this lobe is missing. We attribute this difference to our use of a heat-low filter (section 2.1), which is not employed by the other studies. While continental heat lows may be expected to be rare in winter, they are actually quite common in the Great Lakes region when cold Arctic air masses surge over the relatively warmer waters of the lakes. Detailed studies of this effect (Weiss and Sousounis, 1999) show about 30 such Great Lakes heat lows per year on average, which would be roughly enough to explain the difference between our results and those in other studies (our Figure 7(a) shows a difference of about 30 cyclones per winter between the Great Lakes and Hudson Bay).

Turning to MCC statistics, we find that MCCs occur rather frequently: 32% of all cyclone tracks contain an MCC at some point in their life cycle. Figure 7(b) shows the spatial distribution of relative MCC frequency. This relative frequency is defined as the MCC frequency (computed analogously to cyclone frequency, but counting only those cyclones that are MCCs) divided by the cyclone frequency field shown in Figure 7(a). The figure should thus be interpreted as showing the mean fraction of all cyclones in a given region that are MCCs. The figure is presented in this way so as to highlight regions that are favourable to MCCs independently of the overall level of cyclone activity. The relative MCC frequency distribution is fairly uniform in the Pacific and western Atlantic sectors, with ~9–12% of cyclones being MCCs there. The eastern Atlantic, by contrast, shows areas of enhanced MCC activity: directly over Iceland, over northern Scandinavia and over the Mediterranean, MCCs account for 15–20% of all cyclones.

We suggested in the Introduction that MCCs would be more likely to occur in strong, mature cyclones, so it is of interest to examine how MCC frequency depends on cyclone intensity. To this end, we use a very simple measure of intensity, the minimum central pressure attained by the cyclone over its life cycle. We partition the cyclone population into intensity decile bins and compute statistics within each bin. Results are shown in Figure 7(c), which shows that MCCs are much more prevalent in stronger storms: MCCs occur in almost 80% of the top 10% most intense storms but in only ~10% of the weakest 10% of the storm population.

Since MCCs occur more often in more intense storms, we expect that they also occur most frequently during the mature phase of the cyclone life-cycle, when the cyclone is most intense. To address this point, we focus on a two-day window centred around the time step of maximum intensity for each cyclone. The ‘window’ histogram bars in Figure 7(c) (blue in the online article), showing the fraction of tracks with an MCC stage within the window, bear out our expectations. For the top 10% most intense class, around two-thirds of tracks exhibiting MCCs do so within a day of maximum intensity and this fraction grows to 1 for the weakest storms.

4.2. Frequency of track reconnection

Section 2 outlined the conditions under which two tracks may be spliced together into a single track. Figure 8(a) shows the spatial distribution of reconnection event frequency over the Northern Hemisphere, relative to total cyclone frequency (computed analogously to relative MCC frequency as described in the previous subsection). As with relative MCC frequency (Figure 7(b)), the distribution is fairly uniform over the Pacific and western Atlantic, where 2–3% of all cyclone centres correspond to reconnection events; there are also areas of higher frequency (3–5%) over northern Scandinavia and the Mediterranean as well as over the North American continent and parts of northern Eurasia. Compared with relative MCC frequencies, and noting that...
a reconnection event is necessarily associated with an MCC, we see that roughly 20% of MCCs are associated with reconnection events and that this number has very weak geographical dependence.

Figure 8(b) shows the frequency of such reconnection events by storm intensity class. Reconnection frequency increases sharply with storm intensity, roughly proportionally to the increase in MCC frequency (Figure 7(c)), thus roughly two-thirds of MCC tracks in any intensity class contain a reconnection. Approximately 40% of the 30% most intense storms in the population undergo reconnection, with about half of these reconnection events...
occurring within a two-day window centred around the time step of maximum intensity. The relationship between track reconnection and time from maximum intensity is further examined in Figure 8(c), where the solid line shows that reconnection events are strongly concentrated around the time of peak intensity, with approximately half of all reconnections occurring within two days from the peak. The dashed line, showing reconnection frequency normalized by total cyclone frequency, shows the same shape. Overall, these results are consistent with the idea that reconnections are required where the conventional (SCC-only) tracking algorithm spuriously breaks up a track in the presence of MCCs, which preferentially occur in mature storms.

However, it is also possible that our algorithm may incorrectly join up two tracks belonging to genuinely distinct cyclones. As is clear from the sketch in Figure 3(b), track reconnections can only occur where the end of one track lies close to the beginning of another; if the two tracks are genuinely distinct then this situation would correspond to cyclolysis fortuitously occurring in the vicinity of a cyclogenesis event. To estimate the frequency of such spurious reconnections, the central SLP profiles of each track that required reconnection in the 1989–1990 season were examined manually. This was done by examining the evolution of the central SLP in the neighbourhood of each reconnection; if the evolution was smooth and consistent the reconnection was judged a success, otherwise it was judged to be a spurious reconnection. The sample examined is approximately 1/20th of the database and is representative of the database as a whole. On inspection, we found 20% of reconnections to be spurious while 80% were deemed correct. This is a relatively high error rate and is indicative of the inherent difficulty in reconnecting tracks in this manner. We feel, however, that the improvement gained in those tracks where reconnection was of benefit outweighs the error associated with the spuriously reconnected storms.

### 4.3. Frequency of cyclone mergers and splits

As discussed in section 2, our method explicitly recognizes cyclone merging and splitting events. In fact, we find that cyclones can exhibit multiple merger and/or splitting events over their life cycle. We refer to cyclone tracks containing a merger or split event as ‘branching’ tracks and to tracks that neither merge nor split as ‘non-branching’. We further subdivide branching tracks into three classes: those containing one or more mergers but no splits (merger-only), those containing one or more splits but no mergers (split-only) and those containing both mergers and splits.
Overall branching statistics are shown in Table I. By far the largest proportion of tracks (76%) are non-branching, while merger-only tracks are the most common type of branching track, closely followed by merger-and-splitting tracks. Figure 9 shows a breakdown of branching statistics by intensity class. The proportion of branching tracks increases as storm intensity increases. Interestingly, more than half of the 10% most intense storms undergo a merger or merger-split event.

Figure 10 shows density plots of track merger and splitting frequencies, normalized by cyclone frequency. Figure 10(a) shows sharp peaks in merger frequency off the coast of Japan and over the Mediterranean, together with broader maxima at the western ends of both the Pacific and Atlantic storm tracks. Splitting frequencies (Figure 10(b)) show rather similar overall geographical distribution in the Atlantic region but less in the Pacific.

Inatsu (2009) has recently presented a tracking method that also recognizes mergers and splits, but using an entirely different approach from ours. Qualitatively, our merger frequency plot (Figure 10(a)) agrees well with Inatsu (2009, his figure 3(b)) over the Pacific; in the Atlantic, there is less agreement with the notable difference of a strong merger signal in the Mediterranean in our figure, which is absent from the corresponding figure in Inatsu (2009). Quantitatively, Inatsu (2009) shows a maximum of four mergers over the Pacific, in a region where the track density is approximately 15: thus mergers make up 27% of the sample. In the same region of our Figure 10(a) we see a maximum of 6% of tracks with a merger event. Comparing splitting events, we see little qualitative agreement between Figure 10(b) and figure 3(b) of Inatsu (2009) and a large quantitative difference; the maximum number of splits according to Inatsu (2009) is 12 in a region of track density of 24, resulting in a splitting fraction of 0.5. In contrast, Figure 10 shows a maximum fraction of 0.047. The most likely explanation for this difference is in the treatment of short-lived split tracks. As mentioned by Inatsu (2009), during the occlusion stage of a cyclone minor fragments may separate from the main body of the eddy to form short-lived split tracks. Inatsu (2009) does not impose a minimum lifetime on such split tracks and so every short-lived track is counted. Our method, on the other hand, imposes a three-time-step minimum lifetime on every track on the basis that tracks of shorter length cannot be considered to be true cyclones.

### 4.4. Cyclone genesis, lysis and peak intensity

Geographical distributions of cyclone genesis, lysis and peak intensity are shown in Figure 11. Figure 11(a) shows areas of high genesis density off the east coasts of North America and Asia, as expected. There are also prominent cyclogenic regions off southeast Greenland, over the Mediterranean, east of the Rockies in the central USA and western Canada and over the Kamchatka peninsula. Figure 11(b) shows the corresponding density plot for lysis events. Both ocean basins have regions of high lysis density near the ends of the respective storm tracks (along the western North American seaboard in Pacific, west of Norway in the Atlantic). There are also mid-basin lysis regions between Greenland and Iceland and over the Kamchatka peninsula.

As in section 4.1, we can compare these results with those obtained using other methods and fields (WS06; Sinclair, 1997; Hoskins and Hodges, 2002; Bengtsson et al., 2006). All methods concur in showing cyclogensis regions off the east coasts of North America and Asia, east of the Rockies and over the Mediterranean. We note however that while our method and other methods based on SLP (WS06 Hoskins and Hodges, 2002) tend to show enhanced cyclogenesis off southwest Greenland, this signal is weaker in vorticity-based methods (Sinclair, 1997; Bengtsson et al., 2006). While cyclogenesis off the eastern coasts of the continents is readily understood to result from enhanced baroclinicity there, the origin of cyclogenesis off Greenland is somewhat more problematic. It is natural to wonder whether much of the signal there is an artefact of spurious track splitting, especially in view of the coexistence of a strong lysis maximum in the same region. The fact that a strong cyclogenesis signal survives our use of track reconnection suggests that this is a region of genuine cyclogenesis, resulting from lee cyclogenesis over Greenland’s topography and/or vortex shedding downstream of the Greenland tip jet (Petersen et al., 2003). Nonetheless, the lack of consistency with vorticity-based results flags possible problems in this region, which should be borne in mind when interpreting our results.

Figure 11(c) shows a density plot of peak intensity. Peak intensity corresponds to the point of minimum central SLP for a given track. The figure shows areas of high density to the south of Greenland, in the Mediterranean sea, east of the Aleutian Islands and over the sea of Okhotsk, substantially overlapping the regions of peak cyclolysis.
4.5. Cyclone size and precipitation

One of the motivations for developing the present cyclone-tracking method is to have a more consistent measure of the size or spatial extent of cyclones, defined by their outermost closed contour. As illustrated by the example in section 3, the introduction of MCCs produces cyclones with a smoother and more natural size evolution than in the SCC-only case. As mentioned in WS06, ‘interference’ between neighbouring SLP minima in the SCC-only case can lead to dramatic changes in the size of the outermost contour. Explicit consideration of MCCs in our method helps stabilize cyclone size, leading to a more accurate and reliable estimation of area-integrated quantities such as the precipitation within each storm.

Figure 12(a) shows a comparison of the storm precipitation totals captured by the MCC and SCC-only methods. For each cyclone track, precipitation is integrated spatially over the cyclone’s extent at each time step and temporally over the cyclone’s lifetime. The sum within each decile bin is then expressed as a fraction of the total DJF precipitation in the Northern Hemisphere from 30°N–90°N. Across all cyclones, the SCC method captures 27% of this total precipitation while the MCC captures 37%, an increase of more than a third.

Figure 12(a) is also notable for the fact that it demonstrates that a small fraction of storms account for the majority of precipitation associated with cyclones as a whole. The top 30% of storms account for 75% of the total, while the top 10% account for almost half. This is consistent with the notion that latent heat release within cyclones plays an important role in their intensification. The high incidence of MCCs in this population (approximately 60% for the top 30% of storms) further underlines the importance of extending the tracking algorithm to include MCCs.

Figure 12(b) shows cyclone size averaged over the cyclone’s life cycle and averaged within each intensity category. Our use of MCCs leads to greater mean sizes, as could be expected from the examples discussed in section 3. Also of note is that mean cyclone size increases with intensity. This increase is not sharp enough to explain the greater amount of precipitation falling in intense cyclones: mean size drops by about 30% from the first to the second intensity class, while precipitation drops by over 50%, implying that the rain rate per unit area is greater in stronger storms.

5. Conclusions

We have introduced a feature-tracking method explicitly recognizing multicentre cyclones as a solution to the dilemma (when using mean sea level pressure (MSLP)) of choosing between a cyclone-tracking method that uses smoothing but removes some important storms and a non-smoothing method, which can result in tracking error. As well as improving the quality of cyclone tracks, our method also allows for the identification of cyclone merging and splitting events, which would not be possible had smoothing been performed prior to cyclone tracking. By extending the definition of a cyclone system, our method allows for a more consistent evolution of cyclone size, which is of importance when measuring physical quantities such as precipitation and wind associated with each cyclone. We showed that the frequency of MCCs increases with storm intensity, with a MCC frequency of approximately 60% for the top 30% most intense storms. We also showed that the frequency of track reconnection (i.e. of tracks that would
have been spuriously split using a conventional, SCC-only scheme) increases with storm intensity, with approximately 40% for the top 30% storms requiring reconnection. Using a representative sample, we investigated the legitimacy of track reconnections and found that reconnections that could be deemed spurious made up about 20% of the total; we believe this is a reasonable price to pay for increased accuracy in tracking the remaining 80% of the sample. We presented statistics on the frequency of cyclone merging and splitting, along with track-density plots of various stages of cyclone development, showing good agreement with previous work. We found that the top 30% of cyclones accounted for 75% of the precipitation associated with cyclones. We also found that the MCC method captured over a third more precipitation than the SCC method and we attributed the difference to ‘interference’ from neighbouring SLP minima.

Acknowledgements

The authors gratefully acknowledge Colm Clancy’s contribution in proof-reading original drafts of this paper and offering helpful suggestions on improving the text. This research has been funded by Science Foundation Ireland, research grant GEOF252.

A. Appendix: Effect of map projection on identification

The ERA-Interim data we use are provided on a regular latitude–longitude grid on a cylindrical map projection. There is a known problem with identification on this grid: because of the convergence of the meridians, spatial resolution increases to infinity in the zonal direction as the Pole is approached, leading to a bias towards greater cyclone-centre counts at higher latitudes (Sinclair, 1997). This is a particularly delicate point in our case, since the extra minima identified are also likely to bias MCC counts.

The problem can be mitigated by selectively smoothing the high latitudes (Sinclair, 1997) or by transforming on to a map projection in which a regular grid gives more homogenous resolution throughout the domain (Simmonds et al., 1999). We follow the latter path, choosing the area-preserving polar Lambert projection, which guarantees uniform mean resolution (equal number of grid points per unit area on the sphere) over the entire domain. Zonal and meridional resolutions are not separately conserved but the inhomogeneity is modest: zonal resolution decreases by about 15% from 30° latitude to the Pole while meridional resolution increases by about the same amount. Other authors (Simmonds et al., 1999) have used a polar stereographic projection, a conformal projection in which both zonal and meridional resolutions decrease by about 30% from 30° latitude to the Pole. The Lambert projection is marginally better, but the difference is probably negligible.

We interpolate the original SLP field on to a regular equispaced grid on the polar Lambert projection with an average grid spacing of about 80 km, which is compatible with the 0.75° resolution of the native grid. To assess the

Figure A1. Comparison of MCC frequency for the original method versus the updated Lambert method. (a) shows the frequency for the entire lifetime, (b) the frequency within 48 h of maximum intensity (24 h either side of the point of maximum intensity). This figure is available in colour online at wileyonlinelibrary.com/journal/qj
impact of identifying cyclones on the transformed grid instead of the original, we have included Figures A1 and A2.

Figure A1 shows a comparison of MCC frequency between the two methods: Figure A1(a) shows the comparison for tracks as a whole, while Figure A1(b) shows the comparison within a window of 48 hours around maximum intensity. Both figures show a clear reduction in MCC frequency when using the Lambert projection, but the qualitative results do not change. Similarly, Figure A2 shows a comparison of track reconnection between the two methods; again, Figure A2(a) shows track reconnection frequency for tracks as a whole, while Figure A2(b) shows the frequency in a window of 48 hours around maximum intensity. Again, as in Figure A1, the Lambert projection shows a clear reduction in track reconnection frequency, but the qualitative results do not change.

B. Appendix: Contour-searching technique

For each cyclone centre identified, we wish to trace out closed SLP contours at a contour interval of 2 hPa. Our method for doing this differs from that of WSO6. If a closed contour exists for the contour value we are searching for, we are guaranteed to intercept this contour if we start at the centre and move radially out from this point. Figure B1(a) demonstrates this point: we start at the centre of the cyclone and step northward until the contour value in question is bracketed by two grid points. Using simple linear interpolation, we can compute the position of the contour, as circled in Figure B1(a).

We then construct a unit square by including the two neighbouring grid points, as shown in Figure B1(b). In the majority of cases, the contour will cut this unit grid square twice, as shown. Our method steps along the perimeter of the unit grid, identifying where the contour is bracketed by two grid point values. As with the first point, it then uses simple linear interpolation to find the location of the contour. If we consider the unit grid in Figure B1(b), we have already found the first point in step 1 (Figure B1(a)) of the method; with the second point identified, we can compute the direction in which to step and continue searching for the contour in this manner. We then construct a new unit grid and repeat the process until we arrive back at our original starting point.

In some cases, the contour may cut the perimeter of our unit grid more than twice. In these cases, we sort the points on the contour within the unit grid in a clockwise direction and use the final point identified in this sorted list as the new direction in which to step to the next unit grid.

References


