The Spatial Distribution and Evolution Characteristics of North Atlantic Cyclones

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(Manuscript received 13 December 2007, in final form 28 May 2008)

ABSTRACT

A climatology of extratropical cyclones is produced using an objective method of identifying cyclones based on gradients of 1-km height wet-bulb potential temperature. Cyclone track and genesis density statistics are analyzed and this method is found to compare well with other cyclone identification methods. The North Atlantic storm track is reproduced along with the major regions of genesis. Cyclones are grouped according to their genesis location and the corresponding lysis regions are identified. Most of the cyclones that cross western Europe originate in the east Atlantic where the baroclinicity and the sea surface temperature gradients are weak compared to the west Atlantic. East Atlantic cyclones also have higher 1-km height relative vorticity and lower mean sea level pressure at their genesis point than west Atlantic cyclones. This is consistent with the hypothesis that they are secondary cyclones developing on the trailing fronts of preexisting “parent” cyclones. The evolution characteristics of composite west and east Atlantic cyclones have been compared. The ratio of their upper- to lower-level forcing indicates that type B cyclones are predominant in both the west and east Atlantic, with strong upper- and lower-level features. Among the remaining cyclones, there is a higher proportion of type C cyclones in the east Atlantic, whereas types A and C are equally frequent in the west Atlantic.

1. Introduction

Extratropical cyclones play a large role in determining the day-to-day weather conditions in western Europe through their associated wind and precipitation patterns. Thus, their typical spatial and evolution characteristics are of great interest to meteorologists. The aims of this paper are to compare cyclone statistics produced using the Hewson method of cyclone identification (Hewson 1997, 1998a,b), based on low-level gradients of wet-bulb potential temperature, with previous climatologies and to calculate the spatial distribution of cyclone characteristics and the evolution of these characteristics in composite cyclones.

Many climatologies of Northern Hemisphere extratropical cyclone activity have already been produced, each identifying regions of maximum cyclone track density (or frequency density) and genesis density. Cyclone track density is generally defined as the number of cyclones passing through a given area in a given time and genesis density is defined as the number of cyclones with a genesis point in a given area in a given time. Cyclones can be identified by a variety of methods, most often as mean sea level pressure (MSLP) minima or relative vorticity maxima, and can be tracked both manually and automatically. Despite the differences in datasets, data periods, cyclone identification, and tracking methods used to create these climatologies, some consistent features appear in the cyclone track density and genesis density statistics.

One of the first extratropical cyclone climatologies produced was by Whittaker and Horn (1984) for the four midseason months during the period 1958–77. Cyclones were identified and tracked manually using MSLP. They found a maximum in the January track density close to the North American continent with an extension northeastward across the North Atlantic. In the European area a maximum was located over the north-central Mediterranean. Similar patterns of cyclone track density have been observed in climatologies for different data periods by Sinclair (1997), Sickmölleer et al. (2000), Hoskins and Hodges (2002), Anderson et al. (2003), Pinto et al. (2005), Wernli and Schwierz (2006), and Raible et al. (2008).

Whittaker and Horn (1984) also calculated genesis
density statistics, where a genesis point was defined as the point where the first closed isobar formed. They found major genesis regions in the lee of the Rockies, off the east coast of North America and in the Gulf of Genoa, showing the influence of mountain ranges and east coastal areas in providing environments favorable for cyclone development. Again these genesis regions are identified in the climatologies of Roebber (1984), Sinclair (1997), Sickmöller et al. (2000), Hoskins and Hodges (2002), Anderson et al. (2003), Pinto et al. (2005), and Wernli and Schwierz (2006).

These later studies have located cyclones using search algorithms to find either minima in pressure or 1000-hPa geopotential height (Blender and Schubert 2000; Sickmöller et al. 2000; Gulev et al. 2001; Geng and Sugi 2001; Hoskins and Hodges 2002; Wernli and Schwierz 2006; Trigo 2006; Raible et al. 2008), maxima in the Laplacian of the pressure or 1000-hPa geopotential height (Murray and Simmonds 1991; Pinto et al. 2005), low-level vorticity maxima (Sinclair 1997; Hoskins and Hodges 2002; Anderson et al. 2003), or a hybrid of MSLP minima and low-level vorticity maxima (König et al. 1993). MSLP minima and 1000-hPa geopotential height minima methods perform well when the cyclone has reached maturity but generally fail to locate cyclones early in their life cycle, as a flat wave may not be associated with a pressure minimum (identified by a closed isobar). Identifying maxima in the Laplacian of the pressure enables the inclusion of “open depressions” (i.e., without a closed isobar) and hence enables the tracking of cyclones from the early stages of cyclone development. Vorticity maxima methods are better at identifying smaller-scale cyclones than MSLP methods, but vorticity maxima are not always connected with a local pressure minima and vorticity fields tend to be noisy at high resolution so some smoothing or reduction in resolution is often needed, which leads to a loss of small-scale features (Sinclair 1997). The objective Hewson method of cyclone identification used in this study is well suited to locating a feature during the period from genesis through to maturity [see cyclone life cycle examples in Hewson (1997)]. As we are interested in cyclone development it is important to capture the early stages of the cyclone life cycle.

Cyclone development has been studied extensively, but this analysis has been largely limited to case studies as opposed to the analysis of climatological data (e.g., Petterssen and Smebye 1971; Carlson 1980; Browning and Roberts 1994; Deveson et al. 2002). Such case studies have contributed heavily to the generation of conceptual models of cyclones that provide a framework for understanding the dynamical evolution of cyclones. For example, Deveson et al. (2002) studied the evolution of dynamical forcing mechanisms responsible for cyclone development. They classified the 14 cyclones observed during the Fronts and Atlantic Storm Track Experiment (FASTEX) according to the relative contributions to the midlevel vertical motion of the quasigeostrophic forcing from upper and lower levels ($U/L$ ratio)—upper-level forced vertical velocity dipole $U$ determined within a 600-km radius of a feature point and the strength of the lower-level forced vertical velocity dipole $L$ determined within a 300-km radius of a feature point—and the horizontal separation between their upper-level trough and low-level cyclone (tilt). They found three types of cyclones: type A cyclones, which are predominantly low-level forced and have constant tilt; type B cyclones, which are predominantly upper-level forced, with low-level forcing that increases with time and a tilt that decreases as the cyclone intensifies; and type C cyclones, which have strong upper-level forcing (of a similar magnitude to type B cyclones), but very weak low-level forcing and a tilt that remains constant or increases as the cyclone intensifies. [Type A and B cyclones were first categorized by Petterssen and Smebye (1971)].

Gray and Dacre (2006) applied the threefold classification scheme of Deveson et al. (2002) to a climatology of extratropical cyclones. Cyclones were classified using the ratio of their upper-level to lower-level quasigeostrophic forced midlevel vertical velocity averaged over their intensification period (average $U/L$ ratio). The cyclogenesis regions of the different types of cyclones were analyzed and preferred regions of cyclogenesis were found to exist. Type A cyclones dominated in the cyclogenesis region to the east of the Rockies. Type B cyclones dominated in the cyclogenesis region near the east coast of the United States. Type C cyclones were more common over the oceans. However, the $U/L$ ratio of cyclones often changes throughout their cyclone life cycle (Deveson et al. 2002). Thus, an average $U/L$ ratio, although the simplest method for classification purposes, does not give information about the evolution of dynamical forcing throughout the cyclone life cycle. This study aims to analyze the evolution of dynamical forcing and other cyclone characteristics throughout the cyclone life cycle by compositing cyclone diagnostics, thus extending the method of Gray and Dacre (2006).

Cyclone compositing provides more generality than individual cyclone case studies. The compositing studies so far have averaged cyclone structure relative to thickest cloud (Lau and Crane 1995; Klein and Jakob...
Considerable effort has been spent validating the cyclone tracks produced by the tracking algorithm. It was found that many of the cyclonic feature points identified over regions of steep orography could not be validated. Thus, a mask was placed over Greenland prior to

1999), cyclone center (Wang and Rogers 2001; Field and Wood 2007), or maximum warm and cold sea surface temperature advection (Chang and Song 2006). However, all of these studies, with the exception of Wang and Rogers (2001), produce composites that do not distinguish between the different stages of cyclone evolution. Thus, although they are useful for determining average spatial cyclone characteristics they are unable to provide information on the evolution of composited cyclone structure. The cyclone database used in this study allows cyclone characteristics to be tracked throughout the cyclone life cycle, thus, enabling a temporal evaluation for a large number of cyclones.

In this paper, a feature-tracking algorithm is applied to a cyclone database, that has been generated using the Hewson method of cyclone identification, to produce a climatology of extratropical cyclones. This enables the evaluation of the characteristics of cyclone evolution for systems forming in different genesis regions. The paper is structured as follows. The cyclone database, tracking algorithm, and density statistics are described in section 2. Results are given in section 3 for the cyclone density statistics. The spatial distribution of cyclone characteristics are given in section 4 and the evolution of these characteristics in composite cyclones is examined in section 5. Finally section 6 contains further discussion and conclusions.

2. Method

a. The cyclone database and tracking algorithm

The cyclone database (compiled by Hewson) contains single point diagnostics for objectively identified cyclonic features from the hydrostatic global Met Office Unified Model for January 2000–July 2002 and the nonhydrostatic global Met Office Unified Model for November 2002–January 2006. The output is interpolated from the global model (0.55° latitude × 0.83° longitude) onto a limited-area domain (0.44° latitude × 0.44° longitude) covering a region from the east coast of the United States to the Black Sea and from northern Africa to northern Greenland (as marked in Fig. 2a) with a grid spacing of approximately 50 km.

Cyclone feature points are objectively identified from the model output at 0000 and 1200 UTC and single point diagnostics of each feature point form the database. Thus, use of the database is constrained by the diagnostics included. Feature points are identified at the cyclonic intersections of 1-km height objectively defined warm and cold fronts (frontal wave cyclones), at points on fronts characterized by local maxima in the 1-km height vorticity of the cross-front wind (potential wave cyclones), and also at the intersections of zero contours of two orthogonal 1000-hPa geopotential height gradient components (nonfrontal cyclones). Very weak frontal wave and potential wave cyclones were not used (defined by thresholds in wet-bulb potential temperature gradients, rate of change of wet-bulb potential temperature gradients, and rate of change of potential temperature gradients). The equations and thresholds used to define the feature points are given in Hewson (1998a,b, 2001). The cyclone database is described in more detail in Gray and Dacre (2006). The individual cyclone feature points are joined up into cyclone tracks so that the cyclone characteristics can be analyzed over cyclone life cycles. The tracking was performed using the automated system of Hodges (1994). Constraints on the minimum lifetime threshold (36 h), the maximum distance between successive feature points in a track (9°), and on the local track smoothness are described in Gray and Dacre (2006).

An example of the position of the diagnosed cyclone feature points in the cyclone database relative to MSLP and 850-hPa relative vorticity features over a 36-h period is given in Fig. 1. In general the cyclone features correspond to regions of either MSLP minima and/or relative vorticity maxima. Several distinct synoptic weather features evolve during this period and two contrasting features are described here [see Gray (2003) for a detailed analysis]. The mature and partially occluded (according to Met Office surface analyses, not shown) low pressure system (center at 59.5°N, 32.5°W in Fig. 1a) interacts with a weaker low pressure center initially to the north as it crosses the northern coast of Iceland during this period (this is diagnosed as an actual frontal wave in Fig. 1a, a barotropic low in Figs. 1b,c, and there is an actual frontal wave marked in the vicinity of the decaying system in Fig. 1d). A frontal wave forms on the trailing cold front of the mature low (first seen as a slackening of the pressure gradient in the 12-h forecast at 53°N, 22.5°W, Fig. 1b). This evolves into an elongated low pressure region not associated with a closed contour of MSLP in these figure panels but associated with an increasing relative vorticity maximum (Figs. 1c,d) and tracks northeastward. This feature is diagnosed as an actual frontal wave in all figure panels with potential frontal waves diagnosed along the tail end of the relative vorticity strip associated with the cold front along which the frontal wave forms.
evaluating the tracks. This is a less severe constraint than is used in Gray and Dacre (2006) (who did not consider feature points north of 60°N) and appears to effectively remove spurious tracks at high latitudes. Cyclones are classified into developing and nondeveloping cyclones, such that developing cyclones are those that become intense (defined as those for which the maximum relative vorticity $\geq 1.2 \times 10^{-4}$ s$^{-1}$).

b. Cyclone diagnostics

The cyclones were analyzed using density statistics and by the spatial distribution and evolution of their characteristics. Density statistics have been produced for the distribution of cyclone tracks. Track density measures the number of cyclones within a 564.2-km radius of a given point. This radius was chosen as it enables calculation of densities $(10^6$ km$^2$)$^{-1}$ for comparison with other climatologies. Genesis density gives a measure of the number of cyclones first identified within a 564.2-km radius of a given point. The density statistics are displayed per month to allow direct comparison with other studies (results in section 3).

Using the cyclone database and the tracking algorithm, it is possible to calculate a cyclone’s characteristics at each point along its track. The cyclone’s characteristics at its genesis point give us information about the environment in which the cyclone formed. By averaging the genesis characteristics of all cyclones gen-

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**Fig. 1.** Met Office global model mean sea level pressure (4-hPa contour interval) and 850-hPa relative vorticity (only positive values between 0.5 and $3.5 \times 10^{-4}$ s$^{-1}$ shaded) from (a) 0000 UTC 2 Sep 2000 operational analysis and (b) 12-, (c) 24-, and (d) 36-h forecasts overlaid with positions of potential frontal waves (P), actual frontal waves (A), and barotropic lows (L) diagnosed in the cyclone database at these times using this analysis and the operational version of this forecast.
generated within a $10^6$ km$^2$ area we can calculate the spatial distribution of cyclone genesis characteristics over the entire domain (results in section 4).

To study the evolution of the developing cyclones we need to calculate the temporal variation of characteristics associated with each cyclone along its track. To do this several steps were carried out. First, the cyclones were centered such that their time of maximum relative vorticity was aligned at time zero. This allows a direct comparison between the intensifying and decaying stages of cyclone evolution for cyclones with different lifetimes. Second, the cyclones were grouped according to their lifetime (e.g., all cyclone tracks that were 48 h long were grouped together). Finally, for each group, the average cyclone characteristics were calculated at each 12-h interval along the track (results in section 5).

3. Cyclone density statistics

a. Track density

The cyclone track density is plotted in Fig. 2a. There is a region of maximum track density extending northeastward from the east coast of North America into the North Atlantic, with some cyclone tracks [$>4$ cyclones $(10^6$ km$^2)^{-1}$ (month)$^{-1}$] reaching the United Kingdom and northern Europe. This is the North Atlantic storm track. There is also a localized region of maximum track density over northern Italy. The pattern of track density compares well with the track density (or frequency density) produced in other climatologies (e.g., Sinclair 1997; Sickmoller et al. 2000; Hoskins and Hodges 2002; Wernli and Schwierz 2006). The values obtained in this study are within the large range of values spanned by the other studies. Consistent with those studies, we also find higher track densities in the Atlantic region than in the Mediterranean region (not shown).

b. Genesis density

Figure 2b shows the genesis density for the cyclones in the cyclone database. Regions of maximum genesis are found to the east of the Rocky Mountains, off the east coast of North America, and southeast of Greenland. Regions of weaker genesis density are found over the northern Mediterranean and in the east Atlantic. The pattern of genesis densities in Fig. 2b generally compares well with the genesis regions produced in other climatological studies. The five main genesis regions that exist in the domain are marked on Fig. 2b. The high genesis density along the left-hand edge of the domain (in the North American region) is due to cyclones generated farther west traveling into the domain and so is not a real region of genesis. The maximum genesis density in the Mediterranean region is located over the alpine ridge. This is slightly downstream of the “Gulf of Genoa” maximum genesis location found in Trigo (2006) using the 40-yr European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-40) winter reanalysis data. However, the monthly analysis of Trigo et al. (1999) using ERA-15 reanalysis data shows that the Mediterranean genesis region moves during the year. Our maximum location is more consistent with the Mediterranean genesis density maximum in Trigo et al. (1999) for the spring months (March–May) suggesting that our findings may in part relate to preferential identification of cyclones during the spring and summer months. However, it is also possible that our results in this region may be con-
TABLE 1. Comparison of the maximum genesis densities for selected regions from different studies. Dacre and Gray (2006) (a) is for all cyclones identified in cyclone database and Dacre and Gray (2006) (b) is for developing cyclones only. Different reanalysis datasets are used by Trigo (2006) (a) and (b). The genesis regions, marked in Fig. 2b, are west Atlantic (w Atl), east Atlantic (e Atl), Greenland (Gre), and Mediterranean (Med). The cyclone locating methods are minima in the MSLP field (MSLP), maxima in the cyclonic gradient wind vorticity at 1000 hPa ($\zeta_{p}$), and Mediterranean (Med). The cyclone locating methods are minima in the MSLP field (MSLP), maxima in the relative vorticity at 850 hPa ($\xi_{850}$), maxima in the Laplacian of the MSLP ($\nabla^2 p$), and identification using the gradient of wet-bulb potential temperature ($\nabla \theta_a$). Genesis densities are in cyclones month$^{-1}$ (10$^6$ km$^2$)$^{-1}$.

<table>
<thead>
<tr>
<th>Authors</th>
<th>Max genesis density</th>
<th>Unit area (km$^2$)</th>
<th>Data period</th>
<th>Lifetime threshold (h)</th>
<th>Spatial resolution dataset</th>
<th>Cyclone-locating method</th>
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<tr>
<td>Whittaker and Horn</td>
<td>2.2</td>
<td>0.23 x 10$^6$</td>
<td>Jan (1987–77)</td>
<td>24</td>
<td>Manual</td>
<td>MSLP</td>
</tr>
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<td>Roebber (1984)</td>
<td>3.1</td>
<td>0.13−0.24 x 10$^6$</td>
<td>Annual (1980)</td>
<td>24</td>
<td>Manual</td>
<td>MSLP</td>
</tr>
<tr>
<td>Trigo (2006) (a)</td>
<td>3.8</td>
<td>0.2 x 10$^6$</td>
<td>Dec−Mar (1958–2000)</td>
<td>24</td>
<td>Manual</td>
<td>$\zeta_{1000}$</td>
</tr>
<tr>
<td>Trigo (2006) (b)</td>
<td>1.9</td>
<td>0.2 x 10$^6$</td>
<td>Dec−Mar (1958–2000)</td>
<td>24</td>
<td>Manual</td>
<td>$\zeta_{1000}$</td>
</tr>
<tr>
<td>Pinto et al. (2005)</td>
<td>0.3</td>
<td>2.2 x 10$^6$</td>
<td>Oct−Mar (1958–98)</td>
<td>24</td>
<td>Manual</td>
<td>$\nabla^2 p$</td>
</tr>
<tr>
<td>Dacre and Gray (2006)</td>
<td>2.0</td>
<td>1 x 10$^6$</td>
<td>Annual (2000–06)</td>
<td>36</td>
<td>0.4 x 0.4</td>
<td>$\nabla \theta_a$</td>
</tr>
<tr>
<td>Dacre and Gray (2006)</td>
<td>1.6</td>
<td>1 x 10$^6$</td>
<td>Annual (2000–06)</td>
<td>36</td>
<td>0.4 x 0.4</td>
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<tr>
<td>Hoskins and Hodges</td>
<td>1.8</td>
<td>1 x 10$^6$</td>
<td>Annual (1979–2000)</td>
<td>48</td>
<td>2.5 x 2.5</td>
<td>$\xi_{850}$</td>
</tr>
<tr>
<td>Hoskins and Hodges</td>
<td>1.6</td>
<td>1 x 10$^6$</td>
<td>Annual (1979–2000)</td>
<td>48</td>
<td>2.5 x 2.5</td>
<td>MSLP</td>
</tr>
<tr>
<td>Sinclair (1997)</td>
<td>1.0</td>
<td>1 x 10$^6$</td>
<td>Oct−Mar (1980–86)</td>
<td>48</td>
<td>2.5 x 2.5</td>
<td>$\xi_{850}$</td>
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<tr>
<td>Mean</td>
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<td>1 x 10$^6$</td>
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taminated by spurious features over the steep alpine orography (this problem led to a mask being placed over Greenland prior to evaluating the tracks—see section 2b).

The maximum magnitudes of genesis in four regions (excluding the partially spurious North American region) have been quantitatively compared with a range of studies and possible reasons hypothesized for differences seen. The maximum genesis density magnitudes have been estimated from the largest contour of genesis found in the papers in Table 1 and have been normalized to represent the number of cyclones (10$^6$ km$^2$)$^{-1}$ (month)$^{-1}$. (The “unit area” given in this table is that used to produce the genesis density plots in the respective studies.) The spatial resolution of the dataset given in Table 1 represents the spatial resolution of the gridded data on which cyclone identification was performed, that is, the spectral National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis dataset used by Trigo (2006) [labeled as (a) in Table 1] and Pinto et al. (2005) was interpolated onto a 2.5° × 2.5° latitude–longitude grid. Note that Pinto et al. (2005) further transformed the data to a finer grid (0.8° latitude × 0.8° longitude) before performing identification. This procedure does not add any information to the original data, but it permits cyclones with cores to be located between the original grid points. The spectral ERA-15 reanalysis dataset used by Hoskins and Hodges (2002) and Sinclair (1997) was interpolated onto a 2.5° × 2.5° latitude–longitude grid and the high-resolution spectral ERA-40 reanalysis dataset used by Trigo (2006) [labeled as (a) in Table 1] was interpolated onto a 1.1° × 1.1° latitude–longitude grid. The data used by Hewson to compile the cyclone database used in this study is from the Met Office global model with a spatial resolution of 0.55° latitude × 0.83° longitude, it was interpolated onto a 0.44° × 0.44° latitude–longitude grid before identification was performed. Note that some studies, such as Wernli and Schwierz (2006), have been excluded from Table 1 because of their different method of identifying cyclones as an area rather than as a point. Reasons for the differences in the genesis densities between the different studies that apply to all four regions include the following:

1) The spatial resolution of the dataset upon which the detecting and tracking algorithm is applied. Decreasing the spatial resolution of a dataset results in a similar distribution of cyclones but with reduced density (Blender and Schubert 2000; Zolina and Gulev 2002; Pinto et al. 2005; Trigo 2006; Raible et al. 2008). Pinto et al. (2005) showed that this reduction in density is result of less weak systems being identified. In addition, a reduction in the resolution of the orography and sea ice can lead to fewer cyclones being identified (Raible et al. 2008).

2) The minimum lifetime threshold. If there is no minimum lifetime threshold on the cyclone tracks, thermal lows that grow and decay daily lead to prominent maxima in the statistics (Wernli and Schwierz 2006). Pinto et al. (2005) showed that cyclones with lifetimes of less than 1 day tend to be weak (core pressure above 1010 hPa). Thus, increasing the mini-
maximum lifetime threshold acts to remove weaker systems.

3) The different identification methods used. As described in section 1, MSLP or 1000-hPa geopotential height methods favor larger-scale systems and hence often identify cyclones later in their life cycle; this can result in fewer cyclones being identified when combined with a minimum lifetime threshold. The Laplacian of pressure or low-level vorticity methods tend to identify smaller-scale systems and hence this method increases the number of cyclones identified (cf. Hoskins and Hodges (2002) [labeled as (a) in Table 1]. Note the exception of Pinto et al. (2005) but see point 5. The Hewson method of cyclone identification, based on gradients of low-level wet-bulb potential temperature, is designed to identify the early stages of cyclone development and so may also result in larger genesis densities.

4) Any constraints/thresholds applied to the cyclone tracks. These constraints include the removal of cyclones over high ground (often applied as vorticity maxima and lows are sometimes introduced into the data because of extrapolation below high ground) and a minimum intensity threshold (often applied as spurious or artificial lows are mostly characterized by low values of vorticity). These constraints vary from study to study and affect the number of cyclone tracks identified.

5) The size of the unit area over which density statistics are calculated. A larger unit area leads to a reduction in peak densities as averaging is performed over a wider region [e.g., Pinto et al. (2005) calculate their genesis statistics over a larger unit area than other studies]. This results in much smaller maximum genesis densities in all genesis regions.

6) The seasonality of the dataset (i.e., whether statistics are calculated for a dataset that has been split into individual seasons or calculated for the whole year). Whittaker and Horn (1984) showed that oceanic regions experience a maximum of cyclone frequency in the cooler seasons, whereas the cyclone frequency over continental areas is relatively greater in the warmer seasons.

First, the genesis densities in the west Atlantic region are compared. It can be seen that the largest genesis density is identified by Trigo (2006) [labeled (a) in Table 1] using a high-resolution dataset ($1.1^\circ \times 1.1^\circ$). This study also has a short lifetime threshold (24 h). In general, with the exception of Pinto et al. (2005), the longer the lifetime threshold the fewer the number of cyclones identified in the west Atlantic. However, our study, Dacre and Gray (2006) [labeled (a) in Table 1], identifies more genesis in the west Atlantic than Trigo (2006) [labeled (b) in Table 1] even though it has a longer lifetime threshold. This is possibly due to a combination of the fact that we use a higher resolution dataset and an identification method that identifies more nondeveloping cyclones. When we remove the nondeveloping cyclones (cyclones for with the maximum $\xi < 1.2 \times 10^{-4} \text{s}^{-1}$) from our climatology (Dacre and Gray (2006) [labeled as (b) in Table 1] the genesis density reduces to a magnitude below that of Trigo (2006) [labeled as (b) in Table 1].

Next, the genesis densities in the east Atlantic region are compared. The highest genesis density is seen in the manually analyzed study of Whittaker and Horn (1984). This is surprising as it was expected that observations in the middle of the North Atlantic may be sparse and hence lead to an underestimation of east Atlantic cyclones. Again, the study by Trigo (2006) [labeled as (a) in Table 1] using a high-resolution dataset and short lifetime threshold identifies a relatively large number of cyclones. However, the Dacre and Gray (2006) [labeled as (a) in Table 1] study has a comparable genesis density in the east Atlantic. The studies by Hoskins and Hodges (2002) [labeled as (b) in Table 1] and Sinclair (1997) have significantly lower genesis densities in the east Atlantic region than the other studies. Hoskins and Hodges (2002) [labeled as (b) in Table 1] use MSLP to identify cyclones and so may be identifying cyclones later in their life cycle (potentially removing short lived cyclones due to the long lifetime threshold). Sinclair (1997) removes cyclones that already have considerable circulation at their first track point from their climatology. Cyclones forming in the east Atlantic often form on the trailing fronts of preexisting “parent cyclones.” These fronts have vorticity strips associated with them and hence east Atlantic cyclones have statistically higher vorticity at their genesis point than west Atlantic cyclones (see section 5.) The circulation threshold imposed by Sinclair (1997) may remove these cyclones from their climatology. These hypotheses may explain the lower east Atlantic genesis densities found by Hoskins and Hodges (2002) [labeled as (b) in Table 1] and Sinclair (1997).

The genesis densities in the Greenland region are now compared. There is a very large spread in the genesis densities observed in this region. The largest densities are found by Trigo (2006) [labeled as (a), (b) in Table 1]. All of the automated studies, except Trigo (2006), remove cyclone tracks over high orography [Pinto et al. 2005; Dacre and Gray 2006, labeled as (a), (b) in Table 1] or apply a distance threshold that eliminates cyclones that fail to move a significant distance during their lifetime [Hoskins and Hodges 2002, la-
beled as (a), (b) in Table 1; Sinclair 1997], thus effec-
tively removing the slow moving cyclones that form in
the lee of Greenland from their climatologies. This may
explain why the studies by Trigo (2006) identify so
many more cyclones in the Greenland genesis region.
Finally, the genesis densities in the Mediterranean
region are compared. The highest densities are seen in
the high resolution Trigo (2006) [labeled as (a) in Table
1] study who find genesis densities that are twice as
large as in any other studies. Trigo (2006) showed that
Mediterranean cyclones have shorter lifetimes relative
to their North Atlantic counterparts. Cyclones have an
average lifetime of 2.5 days (n Atl) versus 2.1 days
(Med) for DJFM cyclones. This suggests that cyclone
identification in the Mediterranean region is particu-
larly sensitive to the minimum lifetime threshold. How-
ever, Hoskins and Hodges (2002) also claim that the
relatively small-scale cyclones frequent in the Mediter-
ran region are particularly sensitive to resolu-
tion of the dataset and the identification method
used. This may explain why the studies using vorticity
methods [Hoskins and Hodges 2002, labeled as (a) in
Table 1; Sinclair 1997] find relatively high genesis den-
sities in the Mediterranean region. Our peak Medi-
terranean genesis density is within the large spread re-
ported in the literature. When we restrict our attention
to developing cyclones only [Dacre and Gray 2006, la-
beled as (b) in Table 1] we find a significant drop in the
peak genesis density in this region (the greatest per-
centage drop of all the regions we consider). This sug-
gests that Mediterranean systems are more likely to be
nondeveloping relative to other regions. This is consist-
tent with the respective distributions of the minimum
pressure tendency in the North Atlantic and Medi-
terranean regions shown in Fig. 6 of Trigo (2006), which
shows an enhanced skew to faster deepening rates for
the North Atlantic.
To summarize, the genesis densities in this study are
within the large spread found in previous studies for all
the regions examined although they exceed the mean
values in all regions except the Mediterranean when
both developing and nondeveloping cyclones are con-
sidered. The relatively high genesis densities suggest
that this study identifies more cyclones than other stud-
ies with intermediate lifetime thresholds and annual
datasets due to a combination of a higher-resolution
dataset and the Hewson method of cyclone identifica-
tion that identifies either more nondeveloping cyclones
or identifies cyclones at an earlier stage of their life
cycle (so increasing the likelihood of cyclones satisfying
the minimum lifetime constraint).
Figures 3a,b show the genesis density for developing
and nondeveloping cyclones, respectively. Figure 3a
shows that most of the cyclones that develop are gen-
erated over the sea. This may be because they need a
source of moisture to develop, and also because friction
over the sea is lower than over land. Figure 3b shows
that although nondeveloping cyclones are identified ev-
everywhere in the domain, there are regions with more
nondeveloping cyclones. These regions lie in the lee of
the Rocky Mountains, over the Alps, and east of
Greenland. Cyclones in the lee of the Rockies and Alps
may fail to develop as they are over land and so there
is an insufficient source of moisture and surface friction
is large. The region of nondeveloping cyclones identi-
fied east of Greenland could be a result of the limited
area of the domain used in this study. Investigating the
number of tracks generated east of Greenland for
which the end point is within 990 km (=9° latitude, the
maximum distance allowed between two track points)
of the domain boundary it has been found that up to
47% of the Greenland genesis cyclone tracks may be
shortened because of the edges of the domain. This
figure is an upper bound because usually the distance
between successive feature points is less than 990 km
and also, some of the tracks may naturally end within
990 km of the domain boundary. However, it has been
found that only 5% of these Greenland cyclone tracks
have their maximum relative vorticity within 990 km of
the domain edge. This implies that most of the cyclones
that are cut short by the domain edges are in their
decaying stage. Therefore, it appears that while the do-
main edge can shorten Greenland cyclone tracks, it
does not result in the misclassification of as many de-
veloping cyclones as nondeveloping cyclones.
Figure 3c shows the maximum intensification rate
density for developing cyclones. The maximum inten-
sification rate location for a cyclone is defined as the
point at which the cyclone’s MSLP begins to decrease
by the most, within a 12-h period, along its track. The
regions in which this density is greatest are located
slightly downstream of the regions of highest genesis in
agreement with Pinto et al. (2005). MSLP was chosen as
the measure of development to compare with Roebber
(1984), Sinclair (1997), Wang and Rogers (2001), and
Trigo (2006) who all studied explosive cyclones. Explo-
sively intensifying cyclones, “bombs,” are defined as
cyclones whose MSLP falls by more than 1 Bergeron
(Sanders and Gyakum 1980), where 1 Bergeron = 24
(hPa day$^{-1}$)$\sin(\phi)$/$\sin(60^\circ)$, and $\phi$ is the latitude of
the cyclone center. The explosive intensification rate den-
sity for cyclones generated between January 2000 and
January 2006 is shown in Fig. 3d. In this study the ex-
plosive intensification rate location for a cyclone is de-
fined as the point at which the cyclone’s MSLP begins
to decrease by 1 Bergeron. There were 352 explosive
developing cyclones in the cyclone database. The regions in which most explosive intensification occurred are over the ocean, off the east coast of the United States and in the middle of the North Atlantic. Both the regions in which maximum explosive intensification occurred and the density of cyclones undergoing explosive intensification in these regions are consistent with the results of Sanders and Gyakum (1980), Roebber (1984), Sinclair (1997), Wang and Rogers (2001), and Trigo (2006).

c. Cyclone tracks

It is noted by Whittaker and Horn (1984) that mean cyclone tracks can be misleading in that relatively few systems ever travel the entire length of the storm track; most dissipate before the end of the track is reached while others may form along the track and move to the end. With this in mind, cyclone density statistics have been produced for cyclones that originate in the different genesis regions marked in Fig. 2b, similar to the method used by Hoskins and Hodges (2002). For each separate genesis region, the corresponding lysis densities were calculated.

Figure 4a shows the lysis density for cyclones that originate in the North American genesis region. North American cyclones generally reach the end of their life cycle in the east of North America, rarely penetrating into the North Atlantic. This is consistent with the findings of Hoskins and Hodges (2002) for cyclones generated in the lee of the Rockies. Many of these cyclones are nondeveloping cyclones (Fig. 3b). Most of the cyclones that originate off the east coast of the United States, in the west Atlantic, travel northeastward across the North Atlantic and decay in a broad region covering the whole of the North Atlantic. A small number of the cyclones that originate in the west Atlantic region turn northwestward and decay to the west of Greenland (Fig. 4b). Approximately 0.1 cyclones (10^6 km^2)^{-1} month^{-1} originating in the west Atlantic region reach the end of their lifetime over western Europe. Most of the cyclones that reach western Europe originate in the east Atlantic region (Fig. 4c). This agrees with the findings of Wernli and Schwierz (2006, see their Fig. 10f). The east Atlantic genesis region corresponds to a region in which the west Atlantic cyclones decay. Thus, it is hypothesized that some east Atlantic cyclones may
form on the trailing fronts of decaying west Atlantic cyclones (as reviewed by Parker 1998).

Figure 4d shows the lysis density for cyclones that form in the Mediterranean region. These cyclones mostly travel eastward, decaying in a broad region covering eastern Europe. Although it has been shown that these cyclones are often nondeveloping, (Fig. 3b), it is unlikely that many of these cyclones are cut short because of the limited-area nature of the domain as their maximum lysis region does not lie along the edge of the domain. Conversely, the maximum lysis region for cyclones that originate southeast of Greenland lies parallel to the northern edge of the domain (Fig. 4e). This indicates that these cyclones tracks are being cut short by the northern boundary of the domain, as discussed in section 3b.

In conclusion, the North Atlantic storm track is a composition of many shorter tracks and most of the cyclones that reach western Europe originate in the east Atlantic. Figure 5 shows a schematic of the main tracks for cyclone activity in the North Atlantic identified in this study. It shows many of the same tracks identified by Whittaker and Horn (1984) and Hoskins and Hodges (2002).

4. Spatial distribution of cyclone characteristics

The method of calculating the spatial distribution of cyclone characteristics is described in section 2b. This
method allows us to determine whether cyclones that originate in different parts of the domain are generated in different environmental conditions. Throughout the remainder of this paper we will focus on a comparison of developing cyclones forming in the east and west Atlantic regions because, as shown earlier, cyclones generated in the North American and Greenland regions are close to the domain edges (which may affect average cyclone characteristics), and there are too few cyclones in the Mediterranean region to create meaningful composites.

The spatial distribution of MSLP at the genesis point of developing cyclone tracks is plotted in Fig. 6a. The MSLP at the cyclone genesis points decreases with latitude. This is consistent with climatological mslp charts (see online at http://www.ecmwf.int) that show low pressure near Greenland and high pressure in the Azores. Compared to climatology, the MSLP at the cyclone genesis points are on average 10–15 hPa below the climatological average with the largest differences (>20 hPa) occurring in the east Atlantic indicating that east Atlantic cyclones have anomalously low MSLP at their genesis points. The spatial distribution of 1-km height relative vorticity at the genesis points of developing cyclone tracks is plotted in Fig. 6b. In general, the relative vorticity at the genesis point of east Atlantic cyclones is higher than for west Atlantic cyclones. The anomalously low MSLP and high relative vorticity at the genesis points of east Atlantic cyclones supports the hypothesis that cyclones in this region are forming on the trailing fronts of preexisting cyclones, hence in regions of lower MSLP (due to their proximity to a pre-existing cyclone) and on the low-level vorticity strips often associated with these fronts.

Figure 6c shows the 1-km height wet-bulb potential temperature gradient in the frontal zone at the genesis point of developing cyclone tracks. The wet-bulb potential temperature gradient in the frontal zone at the point of maximum intensification (largest 12-h increase in relative vorticity, not shown) shows a similar pattern and magnitude to the wet-bulb potential temperature gradient in the frontal zone at the genesis point (Fig. 6c). Hence, we restrict our analysis to the conditions at the genesis point. The wet-bulb potential temperature gradient in the frontal zone represents a location approximately 35 km from the front in the direction in which the local thermal gradient is increasing most rapidly. It is used, in this study, as a proxy for the strength of the low-level front associated with the cyclone [see Hewson (1998a) for method of calculation]. Thus, cyclones forming in the west Atlantic have stronger fronts at their genesis point than east Atlantic cyclones. This is surprising considering the hypothesis that east Atlantic cyclones are secondary cyclones developing on the trailing fronts of preexisting “parent” cyclones. However, it has been shown by Bishop and Thorpe (1994), Renfrew et al. (1997), Rivals et al. (1998), Chaboureau and Thorpe (1999), and Dacre and Gray (2006) that secondary cyclone development often occurs when the deformation strain acting on a preexisting front begins to weaken. This results in a relaxation of the frontal temperature gradient when secondary cyclone development occurs and may explain why east Atlantic cyclones form in a region with weaker low-level wet-bulb.
potential temperature gradients than west Atlantic cyclones. The stronger frontal temperature gradients in the west Atlantic indicate that cyclones that form there form in an environment of stronger baroclinicity than those forming in the east Atlantic.

The spatial distribution of the low-level static stability at the genesis point of developing cyclones is plotted in Fig. 6d. The static stability is calculated from 900 to 700 hPa. The static stability is slightly weaker in the east Atlantic than in the west Atlantic in agreement with Wang and Rogers (2001). They suggest that strongly developing east Atlantic cyclones are more convectively unstable as a result and hence develop faster than west Atlantic cyclones. The spatial distribution of the sea surface temperature (SST) gradient at the genesis point of developing cyclones is plotted in Fig. 6e. The largest SST gradients are found along the east coast of North America, extending eastward into the North Atlantic. There is also a region of large SST gradient off the southeast coast of Greenland. These areas of large SST gradients are located in the same regions as maximum genesis over the sea confirming the results of Colucci (1976), Whittaker and Horn (1984), Roebber (1984), and Sinclair (1997) that large SST gradients are also important for cyclone genesis. The cyclones that form in the east Atlantic form in a region of much weaker SST gradients than west Atlantic cyclones.

Thus, in summary, west Atlantic cyclones form in a
The method of calculating composite cyclone characteristics is described in section 2c. This method assumes that the characteristics of developing cyclones with the same lifetime follow the same evolution. Table 2 shows the number of cyclones in the west and east Atlantic used for each lifetime composite. There are more west Atlantic cyclones than east Atlantic cyclones used in the composites for all lifetime classes. There are 428 west Atlantic developing cyclones and 249 east Atlantic developing cyclones in total. Composites are only calculated for cyclone groups containing >20 cyclones.

It was shown in section 4 that cyclones generated in the west Atlantic develop in different environmental conditions to those that develop in the east Atlantic. As a result, it is hypothesized that their evolution may be different. Figure 7 shows the evolution of several cyclone characteristics for both west and east Atlantic cyclones. Comparing the 1-km height relative vorticity of west Atlantic and east Atlantic cyclones, Fig. 7a, we see that the relative vorticity evolution of the cyclones is similar. However, the relative vorticity of east Atlantic cyclones at the genesis point is generally higher than for west Atlantic cyclones, as discussed in section 4. The second difference between east Atlantic cyclones and west Atlantic cyclones is the period of intensification (from genesis point to time of maximum relative vorticity) for east Atlantic cyclones is shorter (mean 29.5 h, standard deviation 19.3 h) compared to west Atlantic cyclones (mean 35.1 h, standard deviation 21.6 h), a difference that is significant at the 99% level according to the Student’s t test. This is consistent with the results of Wang and Rogers (2001) who found that explosively developing east Atlantic cyclones had a faster evolution and shorter life cycle compared to explosively developing west Atlantic cyclones.

Figure 7b shows the evolution of MSLP for west Atlantic and east Atlantic cyclones. Again the overall evolution is similar. However, the MSLP at the genesis point is lower for east Atlantic cyclones and remains lower throughout the cyclone life cycle. This is partly because the east Atlantic genesis region is located slightly farther north than the west Atlantic genesis region. It may also be due to east Atlantic cyclones forming in the vicinity of a preexisting decaying cyclone and hence forming in a region of lower MSLP than west Atlantic cyclones. Wang and Rogers (2001) showed that a parent cyclone northeast of the incipient low is essential for producing extreme explosive cyclogenesis in the east Atlantic.

Figure 7c shows the evolution of potential vorticity (PV) at 1 km for west Atlantic and east Atlantic cyclones. For both genesis regions the PV increases as the cyclone develops and then decreases as the cyclone decays. The PV at 1 km reaches higher values, by the time of maximum deepening, for long-lived west Atlantic cyclones. This low-level PV may be generated by friction in the boundary layer (Stoelinga 1996; Adamson et al. 2006), or by latent heat release (Hoskins and Berrisford 1998); Reed et al. 1993; Plant et al. 2003), or a combination of the two. However, it is not possible to determine the dominant process responsible for the creation of PV using the diagnostics available in the cyclone database and hence it is not possible to ascertain why west Atlantic cyclones have higher low-level PV than east Atlantic cyclones.

The contribution of forcing from upper- and lower-levels to cyclone development can be calculated by using a height-attributable solution to the quasigeostrophic omega equation (Clough et al. 1996). Following Deveson et al. (2002), the lower and upper layers are defined as 1050–750 and 650–50 hPa, respectively, and the vertical motion forced from both layers is calculated at 700 hPa (the typical level of maximum vertical motion in cyclones). The strength of the vertical velocity dipole is defined as the average magnitude of the maximum and minimum values of vertical velocity $|w_{max} + |w_{min}|$. The diagnostics available in the cyclone database include the strength of the upper-level forced vertical velocity dipole, $U$, determined within a 600-km radius of a feature point, and the strength of the lower-level forced vertical velocity dipole, $L$, determined within a 300-km radius of a feature point. These radii were chosen to reflect the characteristic scales of the upper- and lower-level forcing regions. [See Fig. 1a in Gray and Dacre (2006) for a schematic of the upper- and lower-level forcing.] The $U/L$ ratio allows us to determine the relative contribution of the upper- and lower-level features to the cyclone development. The evolution of the vertical velocity at 700 hPa attributable to upper-level quasigeostrophic for-
ing is shown in Fig. 7d. The upper-level forcing for both west Atlantic cyclones and east Atlantic cyclones increases as the cyclone intensifies and then decreases as the cyclone decays. The upper-level forcing for west Atlantic cyclones and east Atlantic cyclones is similar during all stages of cyclone evolution suggesting that vorticity advection is important for both west and east Atlantic cyclones (since this process is assumed to dominate the upper-level forcing.)

Figure 7e shows the vertical velocity at 700 hPa at-

FIG. 7. Composite of west and east Atlantic cyclone diagnostics. The intensifying and decaying time periods, marked in (a), refer to the stage of cyclone evolution. (a) Average relative vorticity at 1 km, (b) average MSLP, (c) average potential vorticity at 1 km, (d) average vertical velocity at 700 hPa attributable to quasigeostrophic forcing above 650 hPa (upper-level forcing), (e) average vertical velocity at 700 hPa attributable to quasigeostrophic forcing below 750 hPa (lower-level forcing), and (f) average ratio of upper- to lower-level forcing ($U/L$ ratio). Plotted for west Atlantic cyclones (gray dashed) and east Atlantic cyclones (black solid) with lifetimes of 36, 48, 60, 72, 84, and 96 h. Shading represents ±1 standard deviation from the mean in (a)–(c) and the 16–84th percentiles in (d)–(f) for west Atlantic cyclones with lifetimes of 48 h.
tributable to lower-level quasigeostrophic forcing. The evolution of lower-level forcing is similar for west and east Atlantic cyclones, but the magnitudes of low-level forcing are different. The low-level forcing for west Atlantic cyclones is larger than for east Atlantic cyclones throughout the whole of the cyclone life cycle. This suggests that low-level thermal advection is more important for the development of west Atlantic cyclones than east Atlantic cyclones (since this process is assumed to dominate at low levels).

The U/L ratio is shown in Fig. 7f. Schematic plots of the evolution of this ratio and the 900-hPa relative vorticity for idealized type A and B cyclones and a type C cyclone case studies are given in Deveson et al. (2002, their Figs. 4, 5, and 8, respectively). The pattern of evolution found here (a reduction in U/L ratio as the cyclones intensify) is similar for west and east Atlantic cyclones and is typical of type B cyclogenesis. This ratio generally has a lower value for west Atlantic cyclones (at a given time relative to the time of maximum intensity). This suggests that, although type B cyclogenesis is important in both regions, there may be a higher proportion of type C cyclones in the east Atlantic; this is consistent with the thresholds established by Gray and Dacre (2006) for mean U/L ratio during the intensification stage of 2 and 4 for the boundaries between type A and B and type B and C cyclones, respectively. Indeed, if this intensification stage average U/L ratio is calculated for the developing cyclones in this database then it is found that type A, B, and C cyclones account for 24%, 51%, and 25%, respectively, of the west Atlantic cyclones and 11%, 50%, and 39%, respectively, of the east Atlantic cyclones. This distribution is consistent with the conclusions of Gray and Dacre (2006) based on a subset of the cyclone database used here.

6. Discussion and conclusions

Cyclone track density and genesis density statistics have been analyzed for a climatology of extratropical cyclones produced using a cyclone database compiled by Tim Hewson using the Hewson method of cyclone identification based on gradients of wet-bulb potential temperature (Hewson 1997, 1998b). The statistics compare well with previous climatologies, reproducing the temperature (Hewson 1997, 1998b). The statistics consistent with the conclusions of Gray and Dacre (2006) for mean U/L ratio during the intensification stage of 2 and 4 for the boundaries between type A and B and type B and C cyclones, respectively. Indeed, if this intensification stage average U/L ratio is calculated for the developing cyclones in this database then it is found that type A, B, and C cyclones account for 24%, 51%, and 25%, respectively, of the west Atlantic cyclones and 11%, 50%, and 39%, respectively, of the east Atlantic cyclones. This distribution is consistent with the conclusions of Gray and Dacre (2006) based on a subset of the cyclone database used here.

The locations of maximum intensification rate are located downstream of the major genesis density regions with explosive intensification (MSLP deepening by >24 hPa in 24 h) occurring in the Gulf Stream off the east coast of the United States, consistent with previous studies.

The lysis densities for five separate genesis regions were produced and it was found that few cyclones track the entire length of the North Atlantic storm track; rather, the storm track is a composition of many shorter tracks. Most of the cyclones that reach western Europe originate in the east Atlantic where the baroclinicity and the SST gradients are weak compared to the west Atlantic. Thus, cyclones that form in the east Atlantic form in a different environment to west Atlantic cyclones. East Atlantic cyclones also have stronger relative vorticity and lower MSLP at their genesis point than west Atlantic cyclones. This is consistent with the fact that some east Atlantic cyclones form on the trailing fronts of preexisting cyclones that often have a strip of relative vorticity associated with them.

A comparison of the evolution of diagnostics associated with west and east Atlantic cyclones has been made. West Atlantic cyclones develop more slowly than east Atlantic cyclones with greater low-level PV generation. The ratio of their upper- to lower-level
forcing indicates that west Atlantic cyclones are predominantly type B cyclones, with strong upper- and lower-level features. East Atlantic cyclones have shorter lifetimes than west Atlantic cyclones, they reach maximum intensity faster and they develop in environments with weaker baroclinicity and lower stability. The ratio of their upper- to lower-level forcing indicates that although they are predominantly type B cyclones, a higher proportion of east Atlantic cyclones are type C cyclones with strong upper-level forcing but weak low-level forcing.

Calculation of the quasigeostrophic upper- and lower-level forcing diagnostics in a larger dataset such as ERA-40 or NCEP–NCAR reanalyses would be a valuable extension to this work. It would allow two-dimensional composites of cyclone diagnostics to be determined, such as produced by Wang and Rogers (2001), for a wider range of diagnostics than are possible using our cyclone database. Regarding cyclone activity in future climate conditions, although the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4; Meehl et al. 2007) shows a lack of confidence in current predictions of future cyclone activity, several studies have shown a possible reduction in midlatitude storms in the Northern Hemisphere. In particular, Bengtsson et al. (2006) and Pinto et al. (2008) found that total cyclone numbers decrease by 10% over the North Atlantic with the exception of the east Atlantic region near the United Kingdom, which features an increased track density and intensity of extreme cyclones. This is the region in which we identify a higher proportion of type C cyclones. Furthermore, they suggest that latent energy seems to play a more important role in the intensification of extreme cyclones in future climate conditions. Thus, it is hypothesized that in future climate conditions there may be more frequent development of type C cyclones.

Acknowledgments. We are grateful to Tim Hewson at the Met Office for supplying us with data from his cyclone database and to Kevin Hodges at the Environmental Systems Science Centre for supplying us with his tracking algorithm. We would also like to thank two anonymous reviewers who helped to significantly improve this paper.

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