Extreme Storms in the North Atlantic and Europe –

John Hanley
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John Hanley
This thesis is dedicated to my parents.

Cover image: A cyclone situated close to Iceland.
Photo from: http://en.wikipedia.org/wiki/File:Low_pressure_system_over_Iceland.jpg.

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Abstract

A study of the most extreme cyclones affecting the North Atlantic and Europe is presented with particular focus on extreme windstorms over the densely populated area of Western Europe, whose associated high surface wind speeds are capable of causing extensive structural damage and occasionally a loss of life.

A novel cyclone identification and tracking algorithm is presented which explicitly recognises ‘multi-centre cyclones’ (MCCs), defined as cyclonic systems which contain two or three sea-level pressure minima. The method also recognises cyclone merging and splitting events and reduces the number of tracks which would have been spuriously split at some point in their life-cycle. MCC frequency is shown to increase with storm intensity, with approximately 60% of the top 30% of cyclones constituting MCCs at some point in their life-cycle.

The first findings of the IMILAST (Inter-comparison of MIId-LAtitude STorm diagnostics) project, an intercomparison study of 15 cyclone identification and tracking algorithms, are presented. Each method was applied to a 20 year period of the ERA-Interim dataset and results for cyclone frequency, intensity, life-cycle and track location were compared across the methods.

The relationship between the evolution of the most intense wind storms affecting Western Europe (Britain and Ireland, Scandinavia, and Western Continental Europe) and the large-scale atmospheric flow is investigated using an automated cyclone tracking algorithm and an objective measure of cyclone destructiveness applied to ERA40 and ERA-Interim reanalysis data as well as EC-Earth model output data at two different spatial resolutions. Composite analyses reveal a clear connection between the precise location of upper-level anti-cyclonic wave breaking and cold air intrusion from the north and the position and orientation of an intense jet; this, in turn, plays a crucial role in determining into which region a developing extreme storm will be steered.
List of Papers

This thesis consists of an introduction and the following papers:


IV Hanley, J. and Caballero, R. (2013). Rossby wave breaking and extreme windstorms over Western Europe, Manuscript.

For Papers I, III and IV, I was the main contributor in terms of analysis and writing, with the help of R. Caballero. For Paper II, I contributed analysis from the cyclone identification and tracking algorithm developed in Paper I; lead authorship of the paper was provided by C.C. Raible, S. Gulev, J.G. Pinto, G.C. Leckebusch and X.L. Wang, with additional input from the rest of the members of the collaboration. The original ideas for Papers I and III came from discussions between R. Caballero and myself; Paper IV was a natural
continuation of Paper III. The original idea for Paper II was provided by U. Neu. Reprints were made with permission from the publishers.

The following paper was not included in this thesis:

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1. Introduction

Weather patterns in the midlatitudes are largely dominated by cyclonic systems and their associated winds and precipitation. Through their transport of cold polar air equatorwards and warm sub-tropical air poleward, these cyclonic systems play a crucial role in the transport of energy and moisture across these latitudes. While most of these cyclones produce benign day-to-day weather conditions, a very small subset achieve extremely high surface winds capable of causing extensive structural damage, storm-surge flooding and occasionally a loss of life. Scientific and societal interest in these storms has grown in the wake of a number of extremely high-impact events over the past 30 years, such as the windstorms ‘Daria’ (January 1990), ‘Lothar’ (December 1999) and ‘Kyrill’ (January 2007). ‘Daria’ and ‘Lothar’, in particular, were each responsible for over 100 deaths and inflation-adjusted economic losses in excess of US$ 10 billion, comparable to those caused by a major US hurricane (Berz, 2005).

This thesis focuses on such extreme, high-impact windstorms, particularly over the densely populated area of Western Europe. The thesis consists of four papers, which address two main topics of research:

- Identifying and tracking midlatitude cyclones in either reanalysis data or climate model output data.
- Studying the large-scale atmospheric features associated with the development and intensification of the most destructive windstorms over Western Europe.

Paper I introduces a novel method for identifying and tracking multi-centre cyclones in reanalysis data which also allows for the recognition of cyclone merging and splitting events. Paper II is an intercomparison study of the method-related uncertainties associated with extratropical cyclone identification and tracking algorithms, with most of the main methods of the past 30 years included (including the algorithm presented in Paper I). Paper III is a study of the relationship between upper-level Rossby wave breaking and the evolution of the most destructive windstorms affecting the most densely populated area of Continental Europe. Paper IV is an extension of Paper III, focusing on a wider area of Western Europe as well as investigating how well such
storms, and their associated large-scale features, are captured in a state-of-the-art global circulation model.

Chapters 2–4 of this thesis provide a brief introduction to the topics covered in Papers I-IV, Chapter 5 presents a summary of the main findings of the papers and Chapter 6 gives a outline of possible future work.
2. Midlatitude Cyclones

In this section, we will first give a conceptual description of the life-cycle of a typical midlatitude cyclone before proceeding to briefly outline the theory of midlatitude cyclogenesis, a process primarily driven by baroclinic instability (Charney, 1947; Eady, 1949). Sections 2.2 and 2.3 closely follow chapters 6 and 8 of Holton (2004).

2.1 Conceptual models

The first widely adopted conceptual model of cyclone development was developed by Bjerkness & Solberg (1922) at the Bergen school of Meteorology and was known as the Norwegian cyclone model. This conceptual model originated from detailed analyses of synoptic weather charts, from which the concept of cyclogenesis as a disturbance on a stationary polar front (the boundary where a cold air mass from the north meets a warm air mass from the south) was developed. As this initial disturbance grows, the polar front is deformed in such a way to produce characteristic warm and cold fronts.

Figure 2.1 (a) shows the four stages of development in the Norwegian cyclone model. Stage I shows the cyclone beginning as an initial small perturbation on a stationary front. In stage II, a clearly defined cyclonic circulation advects cold air equatorward and warm air poleward of the cyclone centre, thereby forming cold and warm fronts respectively. In stages III and IV, an occluded front is formed as the faster moving cold front catches up with the warm front (Schultz et al., 1998).

The Norwegian cyclone model served as the primary conceptual model for cyclone development for almost 70 years before being updated by the Shapiro-Keyser model, which was developed based on both observations and numerical simulations (Shapiro & Keyser, 1990). Figure 2.1 (b) shows the four stages of development for this model. If we compare these stages with the Norwegian cyclone model, we see a similar evolution in stages I and II, with the exception of a slightly different angle forming between the cold and warm fronts in stage II; in the Shapiro-Keyser model, the cold front is orientated approximately perpendicular to the warm front. This feature is clearer in stage III, where a ‘frontal T-bone’ has formed (Shapiro & Keyser, 1990). Unlike the Norwegian...
Figure 2.1: From Schultz et al. (1998) [their Figures 2 and 12 combined]. This figure shows (a) the Norwegian conceptual model of cyclone development and (b) the Shapiro-Keyser model. The lower panels show lower-tropospheric potential temperature while the top panels show lower-tropospheric geopotential heights and associated cyclone fronts.

cyclone model, a narrowing warm tongue does not develop in the Shapiro-Keyser model and therefore there is no catch-up; instead, a bent-back front develops with warm-core seclusion (Schultz et al., 1998).

Conceptually, the three dimensional structure of a cyclone can be described in terms of three main airflows or ‘conveyor belts’: the warm conveyor belt (WCB), the cold conveyor belt (CCB) and a dry intrusion (Carlson, 1980). The WCB is a band of warm, moist air which originates at low levels within the warm sector and moves poleward ahead of the cold front, ascending over the warm front where it can often split into two branches; one branch turns cyclonically, forming part of the upper-level cloud head, while the other turns anti-cyclonically joining the westerly jet flow (Browning, 2004; Browning & Roberts, 1994; Carlson, 1980). The WCB can ascend to heights of greater than 7 km, transporting warm, moist air which then forms clouds and precipitation (Browning, 1985).

The CCB is a cold, moist band of air originating at low levels ahead of the warm front and flowing underneath the warm frontal zone (Carlson, 1980). Previous work suggests that after passing underneath the warm frontal zone, the CCB can take one (or both) of two paths: studies prior to 1980 (Schultz, 2001) depict the CCB turning cyclonically around low centre, remaining at low levels behind the cold front; Carlson (1980) demonstrated that the CCB can turn anti-cyclonically and ascend along the cold side of the warm front; while
ascending, it receives moisture from the WCB, leading to the development of a cloud head.

The final airflow is the dry intrusion, an air stream which originates in the upper troposphere or lower stratosphere. This airflow descends on the western side of the upper-level trough before fanning out and ascending over the bent-back front and descending behind the surface cold front (Schultz, 2001). Due to its origins in the upper atmosphere, this airflow usually contains very little moisture and can often be identified in satellite imagery as a dark, cloud-free region behind the cold front.

2.2 Baroclinic Instability

The sphericity of the Earth results in a greater amount of solar radiation incident on those latitudes located close to the equator in comparison with those nearer the pole. This uneven heating creates a meridional temperature gradient which produces a vertical shear of the geostrophic wind; the relationship between a horizontal temperature gradient and an increase in the geostrophic wind with height is described by the thermal wind relationship, which in vector form is given by:

\[
V_T = \frac{\partial V_g}{\partial p} = \frac{\hat{k}}{f} \times \nabla \frac{\partial \Phi}{\partial p}
\]

where \( V_T \) is the thermal wind vector, \( V_g \) is the geostrophic wind vector, \( p \) is the pressure, \( f \) is the Coriolis parameter, \( \Phi \) is the geopotential height and \( \hat{k} \) is the vertical unit vector.

In the presence of a horizontal temperature gradient on a pressure surface and the associated vertical wind shear, the flow is baroclinic and there exists available potential energy which may be extracted by baroclinically growing disturbances and converted into kinetic energy.

The process by which cyclones grow from an initial baroclinic instability was mathematically developed independently by Charney (1947) and Eady (1949). Although both theories describe the main features of cyclogenesis, the focus here will be on the Eady model. Analysis of the Eady model shows that the growth rate of a cyclone is inversely proportional to the static stability (N). For higher static stabilities, a low-level circulation cannot extend as far vertically through the tropopause; therefore, static stability effectively acts to dampen the growth of an initial disturbance. The Eady model also reveals that long waves are baroclinically more unstable than short waves and will grow exponentially with time. The typical cyclone wavelength predicted from the model is of the order of 1000 km with a growth rate of approximately 1 day;
both of these values are reasonable estimates for the growth of cyclones in the
midlatitudes.

A useful description of the mechanism of baroclinic instability is in terms
of potential vorticity (PV), a concept first used by Rossby (1940) and Ertel
(1942). PV is defined as:

\[ PV = \frac{1}{\rho} \zeta \cdot \nabla \theta \]

where \( \rho \) is the density of the air, \( \zeta \) is the absolute vorticity and \( \theta \) the
potential temperature.

Rossby (1940, 1939) first identified large-scale planetary waves (later known
as Rossby waves) as transverse waves with a gradient of potential vorticity
serving as their restoring force. These waves can be excited through interaction
of the mean flow with orography, through surface forcing due to a land–ocean
temperature contrast and in the presence of large-scale baroclinicity.

A description of baroclinic instability in terms of potential vorticity was
first developed by Bretherton (1966a,b) and later added to by Hoskins
et al. (1985). It describes the instability in terms of the interaction of two counter-
propagating Rossby waves. A qualitative overview of this process follows.

PV has the useful property that it is conserved for adiabatic, frictionless
flow, i.e. \( \frac{\partial (PV)}{\partial t} = 0 \), a fact which allows for the movement of air masses to
be traced. Generally speaking, PV in the troposphere is small and positive
whereas PV in the stratosphere is much higher due to stronger vertical potential
temperature gradients; PV can therefore be used to identify air originating from
the stratosphere which has descended into the troposphere.

Another useful property of PV is the ‘invertibility principle’, first intro-
duced by Hoskins et al. (1985); it states that under a suitable balance condition,
such as geostrophic balance, if the full three-dimensional global distribution is
known, the wind and temperature fields can be obtained by inverting this PV
distribution. This principle leads to the concept of ‘action at a distance’, which
describes how a local PV anomaly can induce a circulation at a distance.

Figure 2.2 shows a schematic picture of how PV anomalies lead to cyclone
formation via baroclinic instability. Due to the increase of PV with height and
latitude, a small downwards or southwards perturbation leads to the creation
of a positive PV anomaly. Relative to its surroundings, this high PV air has
both higher relative vorticity (\( \zeta \)) and higher static stability (\( N^2 = \frac{g}{\rho} \frac{\partial \theta}{\partial z} \)). This
positive upper-level PV anomaly has associated cyclonic vorticity which, via
the principle of ‘action at a distance’, creates a weak cyclonic vorticity at the
surface.

This weak surface circulation acts on the surface temperature gradient, cre-
ating a cold temperature anomaly to the west of the upper-level PV anomaly.
and a warm temperature anomaly to the east. Again, via the principle of ‘action at a distance’, the lower-level warm temperature anomaly itself induces an upper-level cyclonic circulation which will then act to reinforce the original upper-level anomaly. The resulting upper and lower level disturbances are slightly out of phase, with the lower-level cyclone ahead of the upper-level cyclone. The two features are now locked together, mutually intensifying each other and forming a baroclinic wave; this process of mutual intensification is known as baroclinic instability and it is the primary mechanism driving the creation of cyclones in the midlatitudes.

2.3 Cyclone life-cycles

The Eady model briefly outlined in Section 2.2 is a linear theory; therefore, strictly speaking, it applies only to small perturbations. Since the atmosphere is a non-linear system, extending the theory into the non-linear regime has been the focus of research over recent decades. In particular, Thorncroft et al. (1993) outlined two paradigms of non-linear cyclone development. The first paradigm was denoted LC1, which consists of a normal mode perturbation on the basic state westerly jet. At the surface, a strong cold front dominates a much weaker warm front while at upper levels the associated tropopause PV wave ‘breaks’ anticyclonically at the moment of occlusion – this results in the cyclone decaying to cycolysis. The second paradigm, denoted LC2, forms with the addition of a barotropic contribution to the zonal flow. At the
surface, this results in a low pressure system dominated by a strong warm front and weak cold front, while at upper levels the associated tropopause PV wave ‘breaks’ cyclonically at the moment of occlusion – this results in a cut-off cyclone which does not decay.

2.4 Cyclone development and planetary-scale flow

The theoretical models of baroclinic instability outlined in Section 2.2 represent midlatitude cyclones as disturbances superimposed on a zonal flow that varies only with latitude and height. While this viewpoint is useful in understanding the underlying mechanisms driving cyclogenesis, it is only a first approximation to the reality of synoptic-scale disturbances in the atmosphere. Part of the additional complexity is due to the fact that developing cyclonic systems in the midlatitudes are embedded in a large-scale flow which is itself baroclinic. This planetary-scale flow, with wavelengths of the order of 1,000 – 10,000 km (compared with approximately 100 - 1,000 km at the synoptic scale), is itself highly influenced by highly longitudinal-dependent factors such as the presence of orography and continent-ocean heating contrasts. These planetary-scale waves are relevant to Papers III and IV of this thesis.

Planetary waves in the atmosphere are identifiable as large-scale meanders in the upper-level flow. This leads to the creation of upper-level ridges and troughs which accelerate and decelerate the upper-level flow respectively; thus, the poleward-flowing sections of the upper-level flow will form jet streams with lifetimes of the order of a few days. Accelerating flow (the passing of the flow from a trough to a ridge) is associated with divergence which results in convergence at the surface and falling pressure. Thus, locations downstream of an upper-level trough are associated with areas favourable for cyclogenesis.

The time-averaged zonal wind component for December, January and February on the 200-hPa surface in the Northern Hemisphere is shown in Figure 2.4 and gives a guide to the typical zonal flow in which synoptic-scale eddies are embedded. It shows strong zonal wind maxima (jets) just off the east coasts of North America and Asia and north of the Arabian peninsula. As outlined, synoptic-scale eddies tend to develop preferentially in regions of maximum zonal winds associated with these jets and propagate downstream, approximately following the jet axes, to produce the Atlantic and Pacific storm tracks.

2.5 Latent heating

Recent work has shown that latent heat release can play an important role in the rapid intensification of a cyclone (Moore & Montgomery, 2005; Parker &
Figure 2.3: Mean zonal wind at the 200-hPa level for December-February averaged for years 1958–1997 [taken from Holton, Fig 6.2, fourth edition]. Contour interval 10 m s$^{-1}$ (heavy contour, 20 m s$^{-1}$). (Based on NCEP/NCAR reanalysis after Wallace, 2003.)

As discussed in Section 2.1, the structure of a cyclone can be described in terms of three main airflows; the warm conveyer belt, the cold conveyer belt and a dry intrusion. The warm conveyor belt consists of a band of warm, moist air which cools as it ascends ahead of the low pressure centre. As the air cools, the moisture within it condenses out to form clouds and precipitation. As the moisture changes phase from gas to liquid, it releases latent heat. This local heating results in a positive PV anomaly being created below, which then enhances the circulation of the surface cyclone (Martin, 2006).

Recent modeling studies have studied the affect this latent heating has on the rapid intensification of some historically well-known storms; for example,
Wernli et al. (2002) performed a sensitivity study using mesoscale model simulations of the December 1999 extreme windstorm ‘Lothar’. Simulations of ‘Lothar’ were made with diabatic components in the model turned on and off and these simulations were compared with ECMWF analysis and observations. Figure 2.4 shows the time evolution of the minimum core sea-level pressure of ‘Lothar’ from these four sources. Clearly, latent heating appears to be playing a crucial role in ‘Lothar’s rapid intensification.

![Figure 2.4: Time evolution of the minimum sea-level pressure in the core of the cyclone, from observations (German Weather Service DWD), ECMWF analyses, and HRM mesoscale hindcast simulations (moist and dry). [taken from Wernli et al. (2002), Figure 6].](image)

More recently, Fink et al. (2012) applied a modified form of the pressure tendency equation (PTE) to ERA-Interim reanalysis data to quantify the contribution of latent heating to the deepening of five well-known recent historical windstorms, namely; ‘Lothar’ and ‘Martin’ in December 1999, ‘Kyrill’ in January 2007, ‘Klaus’ in January 2009 and ‘Xynthia’ in February 2010. They found diabatic processes played an important role in the intensification of ‘Xynthia’, ‘Klaus’ and ‘Lothar’ but they had a less prominent role in the intensification of ‘Kyrill’ and ‘Martin’ – these storms appeared to be primarily
driven baroclinically.
3. The relationship between cyclones and the large-scale flow

3.1 Overview

As outlined in Section 2.4, planetary-scale flow can influence the growth and development of synoptic-scale disturbances. Papers 3 and 4 in this thesis explore the role of this large-scale flow in the evolution of the most destructive windstorms over Western Europe, with particular focus on their interaction with the dominant large-scale mode of variability in the region, the North Atlantic Oscillation (NAO, Walker (1924)). This chapter gives a brief overview of the NAO before considering planetary-scale flow in general. Some recent statistical findings will also be presented.

3.2 NAO

The NAO is the dominant mode of variability in the North Atlantic and refers to the redistribution of atmospheric mass between the Arctic and the subtropical Atlantic (Hurrell, 1995; Hurrell et al., 2003). Swings from one NAO phase to another correspond to changes in the strength and position of a semi-permanent dipole over the North Atlantic, characterised by a low pressure system located over Iceland (the Icelandic Low) and a high pressure system located over the Azores (the Azores High), which in turn produce large changes in the mean wind speed and direction over the Atlantic. These changes in wind speed and direction influence the heat and moisture transport into the North Atlantic and Europe, as well as the frequency and intensity of midlatitude cyclones (Hurrell et al., 2003).

A positive phase of the NAO corresponds to a deeper Icelandic low and stronger Azores high; the increased pressure gradient results in an increase in the frequency and intensity of midlatitude cyclones. It also shifts the storm track to a more northerly orientation, resulting in warm, wet, stormy weather over Northern Europe and cool, dry weather over Southern Europe. A negative phase of the NAO corresponds to a shallower Icelandic low and weaker Azores high, which results in a decreased pressure gradient over the North Atlantic.
and Europe. This reduced gradient leads to a decrease in the frequency and intensity of midlatitude cyclones in the region and a shift in the storm track to a more zonal direction, which reverses the main airflows over Europe compared with the positive phase of the NAO.

3.3 Upper-level Rossby wave breaking

Recent work has revealed that the NAO can be dynamically interpreted in terms of upper-level Rossby wave breaking (Benedict et al., 2004; Kunz et al., 2009; Rivière & Orlanski, 2007; Woollings et al., 2008) and that the onset of midlatitude blocking episodes can also be associated with these type of wave breaking events (Pelly & Hoskins, 2003).

Figure 3.1 shows a composite of potential temperature over 10 positive NAO events. The dark shading highlights strong anti-cyclonic wave breaking (defined as a reversal in the north–south potential temperature gradient) in the days preceding, and during, peak positive NAO events. The lighter shading shows a simultaneous strong intrusion of cold polar air originating over the North American continent. This intrusion of cold air collides with the warm air intrusion associated with the strong anti-cyclonic wave breaking, creating an extremely intense, focused upper-level jet and a region of high baroclinicity in the mid-Atlantic.

3.4 Recent statistical findings

The relationship between the phase of the NAO and the frequency and intensity of extreme windstorms over the North Atlantic and Europe has been documented in previous studies (Serreze et al., 1997). More recently, Pinto et al. (2009) demonstrated that extreme cyclones in the North Atlantic occur more (less) frequently during strong positive (negative) NAO phases while the occurrence of extreme European storms is associated with moderately-positive phases of the NAO. Raible (2007) also demonstrated a correlation between an positive NAO-like pattern in the 500 hPa geopotential height and the occurrence of extreme cyclones over Northern Europe.

The association of large-scale atmospheric flow in general with windstorms over Europe has been extensively examined in previous studies, a summary of which can be found in Donat et al. (2010). Recently, Leckebusch et al. (2008) performed a ‘k-means’ clustering algorithm on 3-day MSLP development and found that four primary storm clusters were associated with 72% of historical extreme storm events over Continental Europe. Using an objective scheme for daily flow classification based on Jones et al. (1993), Donat et al. (2010)
Figure 3.1: A composite of potential temperature fields over 10 positive NAO events [taken from Benedict et al. (2004), Figure 3]. The contour interval is 5 K, with the 320–K line emboldened to emphasize the low–over–high structure, the anticyclonic wave breaking, and the SW–NE title. Darker (lighter) shading denotes positive (negative) t values that exceed the 98% confidence level. The corresponding lag days are shown to the right of each panel. The wind vectors are denoted by arrows.

showed that approximately 80% of storm days in Continental Europe, and most of the severe historical storms (e.g. ‘Daria’ (January 25/26, 1990), ‘Weibke’ (February 28, 1990) and ‘Anatol’ (December 3, 1999; cf. Ulbrich et al. (2001))) are associated with a westerly flow. A corresponding MSLP pattern showed that this flow was associated with an anomalous low pressure pattern centred over Scandinavia.

Rivière & Joly (2006) investigated the tendency of midlatitude cyclones to explosively deepen in specific specific areas relative to the large-scale flow, such as the jet-exit regions. They show that the strongest deepening rates of midlatitude cyclones developing in the northeast Atlantic tend to occur down-
stream of the baroclinicity maximum, in the jet-exit region. This suggests that large baroclinicity is a necessary condition for their development but does not give any information on the location of explosive growth. Rivière & Joly (2006) demonstrate that this explosive deepening is the result of the interaction between the developing cyclone and the upper-level jet as the cyclone ‘crosses the jet’.
4. Cyclone identification and tracking

4.1 Overview

Extratropical cyclones exhibit a wide range of physical characteristics: their scale can vary by an order of magnitude from small-scale initial disturbances of less than 100 km in diameter to large-scale mature systems of over 1000 km in diameter; their three-dimensional structure can vary from those cyclones confined to the lower troposphere to those which extend throughout the troposphere; they can remain stationary for long periods of time or they can have translational velocities of greater than 100 km/hr; and they can merge, split and re-merge during their lifecycle. As a result, identifying and tracking these features, a seemingly straight-forward task, is extremely challenging. A testament to the complexity involved is the fact that no single commonly agreed definition of what exactly constitutes a midlatitude cyclone exists within the scientific community (Neu et al., 2012).

4.2 Historical evolution

The identification and tracking of midlatitude cyclones began in earnest in the mid 19th Century with the first simultaneous surface observations, made possible by the arrival of the electric telegraph. These observations allowed for the first synoptic weather charts to be drawn, from which features such as surface cyclones could be manually detected. The first studies of midlatitude cyclones which utilized these new synoptic charts included Köppen in 1881 and VanBebber in 1891 who recognized the key role of cyclones in synoptic-scale variability (Raible et al., 2008). Cyclone identification and tracking remained a laborious and time-consuming task for over 100 years, before the development of increasingly power computers allowed for the process to be eventually automated.
4.3 Modern analysis

Modern analysis of synoptic-scale variability from reanalysis data has typically taken the form of an Eulerian or Lagrangian measure. One common Eulerian measure is the so-called dynamic storm track, which is defined as a region of enhanced standard deviation of the bandpass filtered 500-hPa geopotential height, e.g. Blackmon (1976); Lau (1988). A more common approach over the past 30 years has been to take a Lagrangian approach by considering individual cyclone tracks. The automated methods developed over this period consist of two steps: cyclone identification and cyclone tracking.

The choice of field used for cyclone identification varies according to the features of interest one wishes to capture; the high-frequency vorticity field is more closely related to the wind field, while the central pressure is linked to the mass field and captures the low-frequency scale better (Hodges et al., 2003; Neu et al., 2012). Those methods using sea-level pressure or geopotential height typically identify cyclone centres by searching for local minima in these fields (Blender et al., 1997; Hanley & Caballero, 2012; Wernli & C., 2006), while those methods using the relative vorticity field search for local maxima (Sinclair, 1994). A number of methods combine both fields at the identification stage, by first searching for local vorticity maxima and then searching for an associated ‘open’ or ‘closed’ pressure depression (the terms ‘open’ and ‘closed’ refer to whether pressure depressions have regions of closed sea-level pressure isobars or not) (Hodges, 1994; Murray & Simmons, 1991; Pinto et al., 2005).

Aside from such a wide range of cyclone identification possibilities, the methods employed in cyclone tracking also vary considerably (Raible et al., 2008). Cyclone tracking is further complicated by the issue of cyclone merging and splitting; the choice of what constitutes the most appropriate track in the case of the generation of a new cyclone centre close to an existing one is a particularly difficult problem (Hanley & Caballero, 2012; Neu et al., 2012).

The issue of objectively comparing the large number of existing cyclone identification and tracking methods and their strengths and weaknesses has recently begun to be addressed though an inter-comparison project named IMILAST, which was founded in 2009 with the intention of providing ‘a quantitative comprehensive assessment of all types of uncertainties inherent in the mid-latitudinal storm tracking by comparing different methodologies’. The first set of results to emerge from this inter-comparison project have recently been published (Neu et al., 2012) and this paper constitutes the second paper in this thesis.

1http://www.proclim.ch/imilast/index.html
Figure 4.1: This figure shows the cyclone centres (mean sea-level pressure minima) identified by the Hanley & Caballero (2012) algorithm from a mean sea-level pressure snapshot over the North Atlantic region. The cyclone centres are denoted with red dots while mean sea-level contours are plotted at intervals of 2 hPa.
5. Summary of papers

5.1 Paper I

Paper I introduces a novel cyclone identification and tracking algorithm based on mean sea-level pressure (MSLP) which recognises ‘multi-centre cyclones’ (MCCs); a ‘multi-centre cyclone’ is defined as a cyclonic system which contains two or three MSLP minima within its outermost MSLP contour. This method was developed as a solution to the problem of choosing between a cyclone tracking algorithm which applies spatial smoothing to the MSLP field prior to cyclone identification, but which may remove small-scale features of interest as a result, and an algorithm which does not apply such spatial smoothing, but which may have difficulty in correctly tracking the increased number of identified MSLP minima (particularly MSLP minima in close proximity to each other). By recognising such ‘multi-centre cyclones’, the method allows for a more consistent evolution of cyclone size, while also reducing the number of cyclone tracks which would have been spuriously split as a result of neighbouring, short-lived MSLP minima. The method also recognises cyclone merging and splitting events, allowing statistics on these phenomena to be gathered.

The relationship between the frequency of MCC occurrence and cyclone intensity is investigated. MCC frequency is shown to increase with storm intensity, with approximately 60% of the top 30% of cyclones constituting MCCs at some point in their life-cycle. This result is of particular importance for Papers III and IV which focus on extreme cyclones. The frequency of track reconnection (those tracks which would have been spuriously split using a conventional single-centre method) is also shown to increase with storm intensity, with approximately 40% of the top 30% of cyclones requiring reconnection. The error rate of this track reconnection is estimated to be approximately 20%; this high error rate is considered a reasonable price to pay for the improvement in tracking associated with the remaining 80% of re-connected tracks. Statistics on the frequency of cyclone merging and splitting events are also presented, along with track density plots of cyclones at various stages of development.
5.2 Paper II

Paper II presents the first findings of the community project IMILAST (Intercomparison of Mid-LAtitude STorm diagnostics), an intercomparison study of 15 cyclone identification and tracking methods (including the method presented in Paper I). These 15 methods are compared using the same input data (20 years of ERA-Interim data with a spatial resolution of 1.5 degrees and a temporal resolution of 6 hours) to assess their similarities and differences. All methods were run in their ‘standard form’, with the only standardization applied the condition of a 24 hour minimum cyclone lifetime. The methods were applied to both the Northern and Southern Hemispheres.

Differences between the various methods are explored by comparing results for cyclone frequency, intensity, life-cycle and track location. Comparisons of the geographical distribution of cyclone centre densities for the winter season reveals a good qualitative agreement amongst the methods in both hemispheres. Despite this agreement, there are relatively large differences in the total number of cyclones identified; in the Northern Hemisphere, the total number of winter cyclones varies from 6,000 to 21,000 while in the Southern Hemisphere, the total number of summer cyclones varies from 5,000 to 28,000.

Analysis of life-cycle characteristics reveal a reasonable agreement across the methods while there is good agreement with regards to cyclone interannual variability, the distribution shape for many life cycle characteristics, and geographical patterns of strong trends. Consistency amongst the methods is generally higher for deep (or strong) cyclones compared with shallow (or weak) ones. Aside from differences in total cyclone numbers, large disparities also exist with respect to the detection of weak cyclones and cyclone distribution over some densely-populated regions. Two case studies of intense cyclones, one in each hemisphere, reveal a close agreement in the identification of the most intense part of the cyclone’s life cycle but with considerable differences with regards to the development and dissolution phases.

5.3 Paper III

Paper III investigates the interaction between large-scale planetary waves and the most extreme wind storms affecting Western Continental Europe (WCE). Applying the tracking algorithm presented in Paper I to the ERA-40 43-year reanalysis dataset, a climatology of cyclones is generated over the Northern Hemisphere, from which the most destructive WCE wind storms are selected using a destructiveness measure. A ranking of the top 100 most destructive wind storms in the region shows an exponential-like distribution, with the top
25 storms dominating; these 25 storms are then selected, with the goal of assessing what characteristics, if any, they share. This subset also contains most of the major named European windstorms of the period (1958–2001), lending confidence that both the tracking algorithm and the method for measuring destructiveness are performing well.

Detailed analysis of each one of these 25 storms reveals that 22 of them can be considered as having a similar trajectory and evolution. These 22 storms are subsequently grouped together, with the term ‘embedded storms’ introduced to identify them. Temporal composites reveal that these storms typically occur during persistent, moderately-positive North Atlantic Oscillation (NAO) events which peak approximately 2 days before maximum destructiveness. The evolution of spatial composites of mean sea-level pressure reveal an eastward shift of the NAO dipole pattern which results in a large-scale low positioned over Scandinavia at the moment of maximum destructiveness. This creates a strong MSLP gradient over WCE, on top of which the storms superimpose their own MSLP gradient, resulting in extremely destructive winds in the region.

For a dynamically oriented perspective on the evolution of these ‘embedded storms’, temporal composites of $\theta_{PV2}$ (potential temperature on the nominal tropopause, the 2-PVU surface) are computed. They reveal that the eastward NAO dipole shift observed at the surface can be associated with concurrent cyclonic and anti-cyclonic wave breaking in the mid-Atlantic penetrating much further eastward compared with climatological high NAO events. These contemporaneous wave breaking events serve to intensify and elongate an extremely strong, zonally-orientated upper-level jet which plays an important role in the explosive intensification of pre-existing cyclones while also steering these cyclones into WCE; this is in contrast to climatological high NAO events where the upper-level jet steers cyclones on a path close to Iceland.

5.4 Paper IV

Paper IV is a natural continuation of the research contained in Paper III. Here, the regions of Scandinavia and Britain and Ireland are also included along with WCE. Analyses are performed on the ERA-40 and ERA-Interim reanalysis data sets (at resolutions of T159 and T255, respectively) as well as EC-Earth model output (run in AMIP mode) at two different spatial resolutions (T159 and T511). A similar approach to Paper III is taken, where the top 25 most destructive storms in each region in each dataset are selected from a Northern Hemisphere cyclone climatology.

Before considering the evolution of these destructive storms, an assessment of how well both model resolutions capture the extreme winds in each
region compared with the reanalysis data sets is performed. The EC-Earth model at T511 resolution shows a very similar distribution to that obtained using ERA-Interim data, while the T159 resolution model exhibits large biases, particularly along coastal regions. Ranking the top 25 most destructive storms in each region in each dataset reveals an exponential-like distribution, similar to that obtained in Paper III.

Temporal composites of the NAO index reveal that these storms typically occur during persistent, moderately-positive NAO events which peak approximately 2 days before maximum destructiveness in the case of WCE and between 1–3 days before maximum destructiveness in the case of Britain and Ireland. The most extreme storms over Scandinavia typically occur during static, neutral NAO events.

MSLP composites reveal a similar large-scale pattern observed in Paper III for WCE, with an eastward shift of the NAO dipole pattern resulting in a large-scale low pressure system located over Scandinavia at the moment of maximum destructiveness; ERA-Interim shows a similar evolution to ERA40 while both model resolutions also broadly agree with the reanalysis data, although the T511 resolution is in closer agreement. For the most extreme storms over Britain and Ireland, a similar evolution is observed, but without the same eastward shift of the NAO dipole. In Scandinavia, a large-scale, persistent blocking over Europe dominates and deflects eastward propagating cyclones northwards into Scandinavia.

\( \theta_{PV2} \) composites reproduce the results of Paper III for the WCE region. In Britain and Ireland, we see similar concurrent wave breaking in the mid Atlantic compared with WCE, but without the same eastward penetration – this orients the upper-level jet in a northeastward direction while also positioning it further north, which results in eastward propagating cyclones being steered into Britain and Ireland. In Scandinavia, anti-cyclonic wave breaking is observed much further north compared with WCE, helping to reinforce the strong blocking observed in the surface composites – this orients the upper-level jet to the west of Scandinavia, helping to steer cyclones into this region. Overall, a clear connection is drawn between the precise location of anti-cyclonic wave breaking and cold air intrusion from the north and the position and orientation of an intense upper-level jet; this, in turn, plays a crucial role in determining into which region a developing extreme storm will be steered. \( \theta_{PV2} \) composites computed using model output data show a good, qualitative agreement with the reanalysis data, with the exception of a positive bias of between 10–15 K and 5–10 K most likely due to a lower tropopause height in the model.
6. Outlook

This thesis has focused on the identification and tracking of midlatitude cyclones as well as the role planetary-scale waves play in the evolution of extreme windstorms over Western Europe.

As outlined in Section 4.1 of the thesis and in Papers I and II, the identification and tracking of cyclones in reanalysis and model output data remains an extremely challenging topic. A number of approaches could be explored to improve the method introduced in Paper I, in particular to address the issue of the smooth tracking of a cyclone as it transitions from a single-centre system to a multi-centre one (and vice-versa). One approach to this issue is to consider the centre of a multi-centre cyclone as being the geographical point which minimises the distance to the cyclone’s boundary; this has the potential drawback, however, of locating the instantaneous location of the cyclone at a position unrelated to minima or maxima in the local MSLP and vorticity fields (areas typically considered as the cyclone’s centre). Another possible approach is to extend the algorithm to include the identification of vorticity maxima and to denote the centre of a cyclone as the nearest identified vorticity maximum in situations where there is more than one MSLP minimum (i.e., an MCC).

Paper II constitutes a first step in an ongoing collaborative effort to measure the similarities and differences of commonly used automated cyclone tracking algorithms. The next steps of this project include a comparative study of the variability in results across the different methods in identifying and tracking a set of selected historically notable windstorms over Europe from the past 30 years, and a number of studies focusing on particular themes such as cyclone merging and splitting.

Papers III and IV established a clear link between the evolution of the most extreme windstorms over Western Europe and planetary-scale waves; the dynamical mechanisms underlying the observed wave breaking behaviour were not explored, however, and remain a topic for future research. One possible mechanism is the propagation of exceptionally high-amplitude Rossby waves from the Pacific to the Atlantic [Feldstein 2003, Franzke et al. 2004, Strong & Magnusdottir 2008]. Another possibility is the upscale cascade of energy from high-frequency synoptic scale disturbances through increased merging in the mid-Atlantic; the ability of the method presented in Paper I to identify cyclone merging events could be used to generate statistics on merging frequency
in the build-up to the observed wave breaking events.

As outlined in Paper III, some of the most destructive storms of the past 30 years over Europe have had the remarkable feature of being separated by as little as 2–3 days. Our results may help to explain this by demonstrating that a particular set of large-scale conditions persist for longer-than-synoptic timescales, creating an environment which amplifies several pre-existing, smaller-scale perturbations that might have otherwise developed into more benign systems. It is also possible that the very strong baroclinicity generated by the wave breaking events spawns its own small-scale instabilities. This remains a topic for future research.
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