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Serial clustering of extratropical cyclones: a review of where, when and why it occurs

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Serial clustering of extratropical cyclones describes the passage of multiple cyclones over a fixed location within a given time period. Such periods often result in high precipitation totals and accumulated wind damage, leading to large societal and financial impacts. Here, we define the terminology to differentiate between several types of cyclone clustering and review multiple approaches used to quantify it. We provide an overview of current research activities including a review of serial cyclone clustering climatologies used to identify where clustering occurs. We review the dynamical mechanisms determining when and why serial cyclone clustering occurs for different timescales of interest. On daily timescales, serial cyclone clustering is often associated with a cyclone family and secondary cyclogenesis mechanisms. At longer timescales, active or inactive seasons are often associated with persistent large-scale flow patterns and their interaction with successive Rossby wave-breaking events. Finally, we discuss the knowledge gaps and current research opportunities.

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INTRODUCTION

The weather conditions in the mid-latitudes are largely determined by the absence or presence of extratropical cyclones, whose passage typically leads to changes in temperature, winds, precipitation and cloud cover. Frequent passage of cyclones over the same location in quick succession can lead to accumulated impacts such as flooding and wind damage. In over 100 years of research into extratropical cyclones, sequences of cyclones were recognised as being of particular importance from the earliest studies^{1,2}. For example, Bjerknes and Solberg³ described a series of cyclones forming along the same surface frontal feature as a 'cyclone family'. They observed that during each cyclone family, typically four individual cyclones can be observed in succession at a fixed location, but noted that this number varies considerably from one family to another. They also found that the individual members of a cyclone family were usually at different stages of their development when they passed over. The first cyclone to develop (cyclone A in Fig. 1, referred to as the primary or parent cyclone) usually forms far to the west of Europe and has travelled for several days before arriving at the western coast of the continent; therefore, it is usually in its decaying phase over Europe. The later members (cyclones B–D in Fig. 1, referred to as secondary or frontal wave cyclones) each form on the trailing cold front behind its predecessor and thus typically form further south and east than the previous cyclone, nearer to Europe and show increasing intensity during their passage over Europe.

In the past 20 years there has been a renewed interest in the mechanisms leading to the formation and development of cyclones occurring over short periods (e.g. 1 week). In recognition of the fact that not all of these cyclones conform to the Bjerknes and Solberg model of cyclone families, the phrase 'cyclone clustering' has been used to describe these periods. A common understanding of cyclone clustering is a period of time during which a certain location is affected by an anomalously high number of cyclones, sometimes leading to large cumulative impacts. For example, between December and February 2014, a

total of 57 cyclones passed close to the British Isles⁴. This unprecedented number of storms was associated with exceptionally wet and windy conditions, which led to widespread coastal and inland flooding, wind damage and considerable disruption in infrastructure and transportation^{5,6}. Indeed, precipitation over England and Wales amounted to 435 mm from December to February, the largest ever value in the time series which started in 1766⁷. Priestley et al.⁴ also showed, for the period 6–13 February, that the storms were members of the same cyclone family and discussed the role of the persistent large-scale conditions and of stalling of cyclones over the British Isles to the accumulated precipitation and its related impacts. The cyclone series of this winter resulted in a total insured loss above 3 billion USD (www.perils.com)

Over the past few decades, a considerable body of literature has used the concept of extratropical cyclone clustering (or certain aspects of it) to understand where, when and why sequences of cyclones occur and to quantify its implications (e.g. cumulative impacts). Multiple meanings attached to the generic term cyclone clustering has led to difficulties when comparing and contrasting the results from different studies. This article aims to provide clarification of the methods and terminology used in the literature, thus allowing easier comparison of results. Therefore, we first outline the general frameworks used to analyse clustering, before focusing on where, when and why cyclone clustering occurs in the atmosphere.

The structure of the article is as follows: section 'Types of cyclone clustering' defines some terminology to differentiate between different types of cyclone clustering. Section 'Metrics of serial cyclone clustering' reviews the different kinds of metrics used to define serial cyclone clustering. Section 'Climatology and timescales of serial cyclone clustering' analyses the climatology and the different timescales of serial cyclone clustering, and 'Section Dynamics associated with serial cyclone clustering' describes the dynamics associated with clustering. Finally, in

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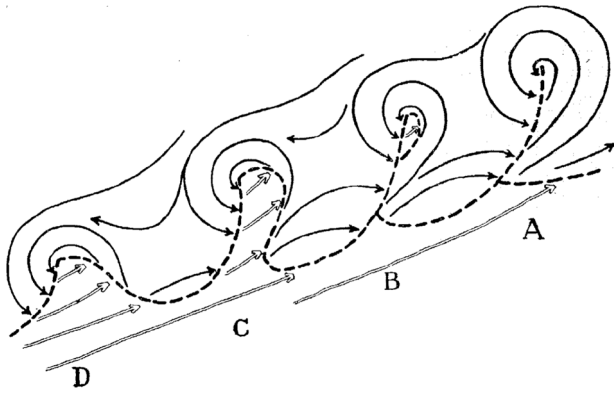


Fig. 1 Schematic snapshot of a cyclone family forming on a front between cold and warm air masses, taken from Bjerknes and Solberg³ (their Fig. 10). Cyclone A is the primary cyclone and cyclones B–D are secondary cyclones forming on the trailing cold front behind their respective predecessor. The dashed line depicts the frontal surfaces showing cyclone A in the decaying phase of its lifecycle with an elongated occlusion, cyclone B in its mature phase with a seclusion at the centre and cyclones C and D in their developing phases. Black and white arrows depict the motion of relatively cold and warm air, respectively.

section ‘Gap analysis’ in the literature and priority areas for future research.

TYPES OF CYCLONE CLUSTERING

The word ‘cluster’ has multiple meanings in maths and statistics and thus also when used in conjunction with cyclones. There are three general ways in which spatio-temporal cyclone data can be split into cyclone clusters⁸. In this paper, we refer to these methods as cyclone clustering by locality, similarity and seriality.

Cyclone clustering by locality

Cyclone clustering by locality describes the location or set of locations occupied by cyclones in a given time or set of times. This means that in this type of analysis cyclones are clustered according to their track location, orientation or genesis region. For example, cyclones travelling in similar locations can be used to identify the major storm tracks⁹. Furthermore, within a single storm track, cyclones can be clustered according to whether they travel preferentially in a zonal, tilted or meridional orientation¹⁰. An early example of this approach is the cyclone paths based on early weather data/charts^{11,12}. van Bebber¹² related particular cyclone paths with specific weather impacts, most notably meridionally travelling Mediterranean cyclones (Vb cyclones), which can lead to heavy precipitation in the Alpine region. More recently, clustering by locality has been applied to cyclone tracks to analyse their links to the large-scale flow^{10,13,14}. For example, Gaffney et al.¹³ found that, in reanalysis data, wintertime North Atlantic cyclone tracks occurring during the positive phase of the North Atlantic Oscillation (NAO) are preferentially in the SW-NE orientated cluster, whereas for the negative NAO phase they are typically more zonal and slower moving.

Cyclone clustering by similarity

Cyclone clustering by similarity describes the set of cyclones that are present at a given location or set of locations at a given time or set of times. In this analysis, cyclones are clustered according to their similar characteristics to help understand the variability in cyclone structure, strength and development. Examples include clustering by cyclone cloud features using satellite imagery¹⁵ or cyclone airflows such as a warm conveyor belt¹⁶ or dry intrusion¹⁷. Cyclones have also been clustered according to their synoptic

cyclogenesis mechanism^{18–20}, upper-level features such as Rossby wave-breaking (RWB)²¹ or cyclone intensification rates^{22,23}. For more details on cyclone clustering by similarity, see the review article by Catto²⁴ and references therein.

Cyclone clustering by seriality

Cyclone clustering by seriality describes the time or set of times that cyclones occupy a location. In this type of analysis, cyclones are clustered according to their frequency of occurrence at that location, quantifying the tendency to occur in groups²⁵. For example, the number of cyclones occurring in a given region per winter can be used to identify particularly stormy seasons in a time series. The concept of clustering by seriality is often used by the insurance industry that is interested in the estimation of the associated accumulated insured losses. Specific examples of serial cyclone clustering are described in detail in sections ‘Climatology and timescales of serial cyclone clustering’ and ‘Dynamics associated with serial cyclone clustering’.

These three general ways to define clustering are often used in combination, for example, by selecting cyclones with specific characteristics, which cross a certain area. In this review article, we will focus on the serial clustering of extratropical cyclones, even though some aspects of clustering by location and/or similarity are sometimes considered in combination. We will also not discuss serial clustering of related phenomena like hurricanes and convective storms, even though the type of metrics and approaches are similar^{26,27}.

METRICS OF SERIAL CYCLONE CLUSTERING

There are several metrics used in the literature to identify serial cyclone clustering. In this section, we review the most common serial cyclone clustering metrics, ranging from simple counts of cyclone occurrence to more complex cyclone impact metrics.

Absolute frequency metrics

Absolute frequency metrics determine the number of cyclones occurring in a given region in a given time period. For time periods of a day, week or month, a moving sum of cyclone occurrences in the time period is typically calculated, centred about the time of interest. This results in a time series of cyclone counts, which is the same length as the number of times in the original dataset. Alternatively, to determine the number of cyclones occurring in a given region for longer sampling periods such as a season, year or decade, a total sum is often calculated. This results in a time series of cyclone counts which is the same length as the number of sampling periods (e.g. seasons) in the dataset.

For both moving or total sum cyclone occurrences, serial cyclone clustering periods are defined using fixed absolute frequency thresholds. For example, weekly serial cyclone clustering can be defined as ≥ 4 cyclones per week travelling over a region²⁸. The advantage of absolute frequency metrics is that they are intuitive to interpret and link to our perception of particularly stormy periods. The main disadvantage is that cyclone numbers are very sensitive to the methods used to identify cyclones, the climatological number of cyclones at a given location and the spatial resolution of the underlying data²⁹. This has implications also for the estimation of cyclone clustering³⁰. Therefore, absolute frequency thresholds used to define serial cyclone clustering need to be tuned for each cyclone dataset and potentially for each location. In addition, different absolute frequency thresholds are necessary to define clustering for different aggregation periods.

Relative frequency metrics

Since the climatological number of cyclones differs regionally and absolute frequency thresholds depend on the length of the time

period studied, relative frequency metrics have often been used to define serial cyclone clustering. Relative frequency metrics compare the variability in cyclone occurrences to the mean (or expected value) of cyclone occurrences in a given region. For example, several studies have used the concept of a Poisson process to describe the temporal clustering of storms²⁵. It is assumed that the storms occur at random and can be described by a homogeneous Poisson process with a constant rate of occurrence (λ)³¹. This implies that for any time interval, T , the number of storms is Poisson distributed with an expected value (μ) and variance (σ^2) of λT . Deviations from this behaviour indicate that the number of events per time interval is not random, but rather overdispersive (if $\sigma^2 > \mu$) or underdispersive (if $\sigma^2 < \mu$). Following Mailier et al.²⁵, the dispersion statistic (ψ) is given by:

$$\psi = \left(\frac{\sigma^2}{\mu} \right) - 1. \quad (1)$$

Positive dispersion indicates that σ^2 is larger than μ , and thus cyclones tend to occur in clusters; negative dispersion means that σ^2 is smaller than μ , and thus cyclones tend to occur at regular intervals; finally, dispersion values near zero indicate that μ and σ^2 have similar magnitudes and cyclones occur randomly. An alternative approach to quantify dispersion uses the concept of fractional Poisson processes³², which are based on long-term memory and permits the estimation of non-exponential return time distributions. These estimates can then be used to quantify clustering. For more details see Blender et al.³².

The advantage of relative frequency metrics is that the threshold used to define serial cyclone clustering is typically independent of location and length of the time sets analysed, thus enabling easy comparison between different cyclone tracking methods^{29,30}. The main disadvantage is that a region can show overdispersion by chance if a short time period is analysed, making interpretation of relative frequency ambiguous³³. The same is true for regions with small cyclone numbers.

Impact metrics

More indirect measures of serial cyclone clustering have been designed to measure the accumulated impact of cyclones over a given period. For example, a proxy for wind damage is given by the storm severity index (SSI). SSI is a measure of the wind speed at a given location (V_{ij}) exceeding the 98th percentile value of the local climatology (V_{ij}^{98}) (or some minimum threshold) summed over a given region^{34,35}.

$$SSI = \sum_{i=1}^{N_i} \sum_{j=1}^{N_j} \left(\frac{V_{ij}}{V_{ij}^{98}} - 1 \right)^3. \quad (2)$$

The method was originally developed to estimate insured building losses, and V^{98} is the threshold above which wind damage is expected to occur³⁴. Typically, the spatially aggregated value of the maximum SSI values within a 72 h time period for each land grid point is calculated (or other impact metric). The 72 h SSI is used as a proxy for the damage associated with a cyclone over a given region. The largest 72 h SSI in a year is referred to as the occurrence exceedance probability (OEP) and the total sum of 72 h SSI in a year is referred to as the annual exceedance probability (AEP). The ratio of OEP to AEP is often used as an impact measure of clustering in the insurance industry³⁶. When OEP/AEP is close to 1 the season is dominated by the impact of a single very large event and thus non-clustered. When the OEP/AEP value is small, multiple cyclone events contribute significantly to the AEP, and thus the season is defined as clustered. However, multiple small cyclone events may be uniformly or randomly separated in time, thus not clustered according to the dispersion statistic. Thus, whether or not a particular region or time period is clustered may be metric

dependent. The estimation of impact metrics is important for the insurance industry, as they must regularly demonstrate the resilience of their business to the regulators (European Union Solvency II directive).

Another hazard associated with extratropical cyclones is damage related to precipitation. While the precipitation damage from individual cyclones may be small, accumulated precipitation from multiple cyclones in succession can cause rivers to overflow leading to flooding^{4,6}. Some studies have investigated the serial clustering of extreme precipitation events using relative frequency metrics^{37,38}, but to our knowledge, there are no widely used impact metrics used as a proxy for precipitation-related damage. Furthermore, multiple hazards associated with extratropical cyclones, such as extreme precipitation, storm surge, high winds and snowmelt, may occur simultaneously or in succession. Analysis and prediction of such compound events is a newly emerging topic of research³⁹.

The advantage of impact metrics is that they can be used as a proxy for insured loss if location-dependent population or building information weighting is added. The main disadvantages are that wind gusts/heavy precipitation can be generated locally by features that are not associated with cyclones, the fixed time window can contain the impact of multiple cyclones making interpretation difficult and results can be sensitive to the minimum threshold used. Nevertheless, these metrics are of particular interest for insurance companies⁴⁰.

CLIMATOLOGY AND TIMESCALES OF SERIAL CYCLONE CLUSTERING

Cyclone clustering by seriality can either be analysed in a given time, to determine where cyclone clustering occurs, or in a set of times to study the drivers of serial cyclone cluster variability, allowing analysis of when and why serial cyclone clustering occurs. Given a defined aggregation time (e.g. a year), cyclone statistics are analysed typically over long time periods (e.g. 30 or more years), thus enabling the computation of a climatology of serial cyclone clustering. This approach can be used to determine regions in which clustering occurs preferentially in climatological terms both for present-day and future climates and therefore any projected changes.

Present-day climatology of serial cyclone clustering

Several studies have analysed the representation of serial cyclone clustering based on reanalysis data^{25,41,42}. Mailier et al.²⁵ first identified that serial clustering of extratropical cyclones does not occur uniformly over the mid-latitudes, but only in specific areas, namely the exit region and flanks of the North Atlantic storm track and over the central North Pacific. The schematic in Fig. 2 shows these regions for the North Atlantic/European region, together with some representative storm tracks. Despite using datasets with different resolution, different aggregation periods, different time periods to calculate the dispersion statistic ψ ^{32,33,36,41–43} and different cyclone tracking algorithms³⁰, all of these studies reproduce this general pattern with a region of regular cyclone activity (underdispersion, blue colour in Fig. 2) at the entrance to the North Atlantic storm track and clustered cyclone activity (overdispersion, red colour) on the flanks and exit region of the North Atlantic storm track. Much of the spread in ψ values in the above-mentioned literature is associated with the total number of cyclone counts and their variance identified by each cyclone tracking method³⁰. However, serial cyclone clustering is statistically significant for almost all methods across the red area in Fig. 2, and thus it is a robust feature. While the spatial pattern of clustering over the North Atlantic is well established, this is not the case for the other large ocean basins. Only two studies have analysed clustering in the North Pacific^{25,32}. The different

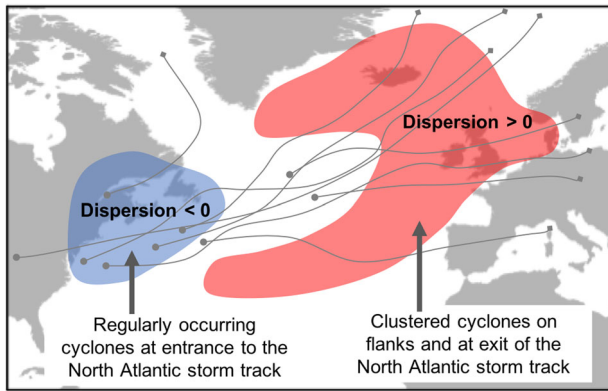


Fig. 2 Schematic of serial cyclone clustering in the North Atlantic (determined using the dispersion statistic described in section ‘Relative frequency metrics’). Areas with regular cyclone activity (underdispersion) in blue, and with clustered cyclone activity (overdispersion) in red. The representative cyclone tracks shown in grey. Summarised from figures in Maillier et al.²⁵ (Fig. 5), Kvamstø et al.⁴³ (Fig. 3), Pinto et al.⁴² (Fig. 3), Economou et al.³³ (Fig. 2), Pinto et al.³⁰ (Fig. 4) and Priestley et al.³⁶ (Fig. 1).

approaches used to quantify clustering in these two studies make a direct comparison difficult, but both studies agree on the identification of serial cyclone clustering on the flanks of the North Pacific storm track, notably over the central North Pacific and close to the Bering Strait and Alaska. For the Southern Hemisphere, only one study exists³², which identified areas of regularly occurring cyclones (underdispersion) in the entrance region of SH storm track region (notably 30–150°E), and regions of serial cyclone clustering near South America (60°W) and close to the Antarctic continent. Further studies for the North Pacific and Southern Hemisphere are necessary to investigate the robustness of these patterns.

In addition, several authors have analysed whether differences in the clustering of cyclones occur for cyclones of different intensities (i.e. clustering by similarity^{18,20,22,24}). For example, Vitolo et al.⁴¹ provided evidence that intense cyclones tend to cluster more (higher ψ values) than the whole sample of cyclones. Later studies confirmed this result using different reanalysis datasets and/or a different tracking method^{33,42}.

Future climatology of serial cyclone clustering

General circulation models (GCMs) and more recently Earth system models (ESMs) are commonly used to determine the possible evolution of the Earth’s climate given a pre-described forcing and boundary conditions. The resulting cyclone statistics and characteristics can be used to analyse the variability and long time changes of cyclone activity under recent and future climate conditions^{44–46}. Several studies^{33,36,42,43} have investigated how well the identified characteristics of serial cyclone clustering can be reproduced by climate models. Based on a simulation for recent climate conditions, Kvamstø et al.⁴³ showed that the ARPEGE GCM has considerable deviations from reanalysis in terms of the numbers and variance of cyclones over their study area, leading to a substantial underestimation of serial cyclone clustering over the Eastern North Atlantic. Other studies^{33,42} provided evidence that GCMs are able to provide a similar spatial pattern of clustering over the North Atlantic compared to the reanalysis, in spite of several biases such as a more zonal storm track. Sample uncertainty due to short time periods is often a major caveat when estimating clustering from both reanalysis and single model simulations. A large GCM ensemble can allow the assessment of more robust return periods for serial cyclone

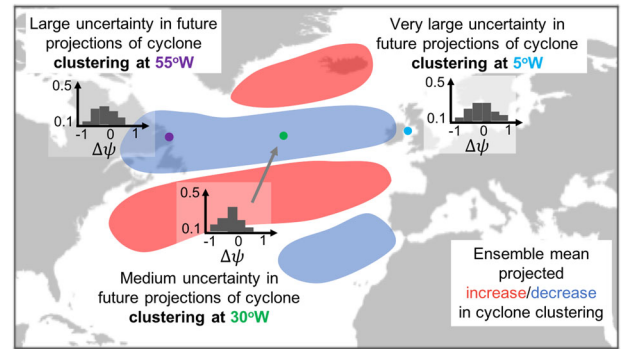


Fig. 3 Schematic of projected changes in serial cyclone clustering in the North Atlantic in a future climate (determined using changes in the dispersion statistic, $\Delta\psi$, described in section ‘Relative frequency metrics’). Due to the large spread in projected changes over Europe between models, there is low confidence regarding potential changes in serial cyclone clustering (see inserted histograms and text). Summarised from figures in Economou et al.³³ (Figs. 4 and 5) and Pinto et al.⁴² (Figs. 5 and 6).

clustering. For example, Karremann et al.⁴⁷ demonstrated a strong reduction in uncertainty in their estimates of storm return periods over Germany when using over 4000 years of GCM simulations.

When considering future climate projections, Pinto et al.⁴² analysed a large ensemble of GCM simulations and concluded that clustering may decrease over large parts of the North Atlantic and European sector, but noted that the changes are small and associated with large uncertainties (see Fig. 3). Similarly, Economou et al.³³ analysed a multi-model CMIP5 (Coupled Model Intercomparison Project fifth phase) ensemble with a different tracking method. They found that while some future changes in serial cyclone clustering were identified, and concluded that the results were inconsistent across models (cf. Economou et al.³³, their Fig. 4 and summarised in Fig. 3). The authors attributed these differences primarily to the large sampling uncertainty identified for the analysed 30-year periods. Using the same large ECHAM5 GCM ensemble data as Pinto et al.⁴², Karremann et al.⁴⁸ followed a different approach and investigated how far the return periods of storm series affecting Europe and associated return levels in terms of losses (SSI) may change in a warming world. Shorter return periods for storm series are identified for Western Europe, but a large sample uncertainty is present. When considering changes in the return levels, which combines the effects of clustering and the intensity of the single events, shorter return periods are found for most European countries. While the results by Karremann et al.⁴⁸ are not directly comparable to studies focussing on cyclone statistics^{33,42}, they provide a view of possible changes in clustering closer to the impacts.

In addition to the sample uncertainty, a potential caveat for climate models may be the deficient representation of the physical processes associated with clustering (see section ‘Dynamics associated with serial cyclone clustering’). However, there is evidence that high-resolution climate simulations show smaller biases: Priestley et al.³⁶ showed, based on an ensemble of high-resolution GCM simulations (90 km in the mid-latitudes), that high-resolution GCMs are able not only to simulate comparable cyclone and clustering statistics to reanalysis, but that the associated key processes such as RWB are well reproduced. Given that such high-resolution simulations are more frequent in CMIP6 compared to CMIP5, it is expected that they may enable a major step forward in the understanding and quantification of serial cyclone clustering for recent and future climate conditions.

Varying timescales of serial cyclone clustering

When cyclones are clustered, information about their variability can be analysed and the drivers of this variability can be studied. This allows questions about why serial cyclone clustering occurs to be answered. Serial cyclone clustering has been analysed for aggregation periods varying from sub-weekly to decades, but the relevant drivers typically depend on the chosen aggregation period (see section 'Dynamics associated with serial cyclone clustering'). Some studies focus on clustering at the synoptic scale and on the occurrence of cyclone families, thus they use aggregation periods of about week to quantify clustering^{28,49} (see section 'Secondary cyclogenesis and cyclone families'). Other authors have chosen to analyse longer aggregation periods, ranging from a month to a full year^{25,33,42,50,51} (see sections 'Relationship between cyclone clustering and teleconnection patterns' and 'Jet stream and Rossby wave'). Several studies have also analysed clustering on decadal to multi-decadal time-scales^{52,53}. Some studies relate years with above (below) average storm activity to teleconnection patterns like the NAO^{45,54}. Note that longer clustering periods, such as a season or a full year, typically consist of multiple cyclones that are unrelated to each other, thus not fulfilling the criteria of a cyclone family (see section 'Secondary cyclogenesis and cyclone families'). This often causes confusion as to what serial cyclone clustering means and how it should be quantified.

Vitolo et al.⁴¹ have performed the only detailed analysis investigating how the amount of serial cyclone clustering (quantified as ψ) over the North Atlantic and Western Europe changes when varying the length of the chosen aggregation period from 4 days to 6 months. The authors conclude that ψ increases quasi-linearly with the logarithm of the length of the aggregation time period. A small decrease is found for longer (6-month) aggregation periods. They also examine the relationship between clustering on different timescales and teleconnection patterns (see section 'Relationship between cyclone clustering and teleconnection patterns' for details).

The total length of the time series is also important when estimating the magnitude of clustering^{33,55}. Better estimates of ψ are achieved using longer datasets due to a strong reduction of the sampling uncertainty. As mentioned above, Karremann et al.⁴⁷ provided evidence that the estimated return periods of storm series affecting Germany, quantified based on cumulative SSI, have much lower uncertainties when considering a large ensemble of simulations, thus achieving more accurate estimates. Similarly, using almost 1000 years of historical GCM data, Priestley et al.³⁶ have shown that for return periods of 3–200 years, the accumulated seasonal loss (based on SSI) is between 5 and 20% larger than the accumulated seasonal loss from a set of random re-samples of the data. Given that the average loss is over USD 2 billion for windstorm in Europe⁵⁶, this implies an underestimation of average losses by USD 100–400 million if clustering is not properly addressed. The results described in this section show how important it is to define the aggregation timescale for which clustering is quantified and the length of the time series, and how the obtained answer may depend on these choices. The next section will focus on the dynamics associated with clustering.

DYNAMICS ASSOCIATED WITH SERIAL CYCLONE CLUSTERING

In the previous section, we reviewed when and where cyclones often cluster in time. There are multiple reasons why cyclones might cluster in time³³. These include: (a) interaction between cyclones and the large-scale patterns of variability; (b) interaction between successive cyclones in a cyclone family; (c) by chance—even if cyclone occurrences happen at random, some will occur in clusters. In this section, we review the literature analysing the

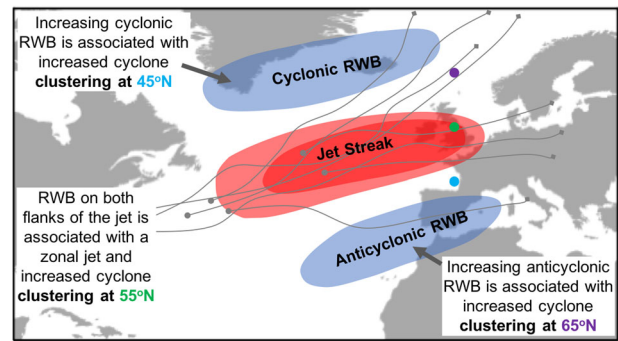


Fig. 4 Schematic showing the position of the jet maxima (red) and Rossby wave-breaking (RWB) (blue) on both north and south flanks during periods of increased serial cyclone clustering in the British Isles (55°N, green dot). Increasing amounts of anticyclonic RWB to the south of the jet is associated with a more tilted jet and increased serial cyclone clustering in the Norwegian Sea (65°N, purple dot). Increasing cyclonic RWB to the north of the jet is associated with a more southerly jet position and increased serial cyclone clustering in the Bay of Biscay (45°N, cyan dot). The representative cyclone tracks shown in grey. Summarised from figures in Benedict et al.⁸⁹ (Figs. 3 and 5), Gomara et al.²³ (Fig. 8), Pinto et al.²⁸ (Fig. 7) and Priestley et al.⁴⁹ (Fig. 2).

different drivers of serial cyclone clustering from synoptic to longer timescales.

Jet stream and RWB

Given that the development of cyclones is closely associated with the jet stream, it is logical to investigate the relationship between the jet stream and cyclone clustering. Pinto et al.²⁸ investigated four periods of intense serial cyclone clustering and concluded that such episodes for the British Isles (55°N, 0°E, green dot in Fig. 4) are characterised by persistent, zonally orientated and extended jet stream conditions over the Eastern North Atlantic. Several studies have documented that such conditions can endure for several days if supported by RWB on both sides of the jet stream, anticyclonic to the south and cyclonic to the north^{23,49,57,58}, see Fig. 4). Even though the jet stream is not always in the same position on the day-to-day scale (Pinto et al.²⁸, their Fig. 3), the RWB occurrences on both sides of the jet constrain its latitudinal variation. The largest RWB event typically corresponds to the first cyclone in a cyclone family (primary cyclone, see 'Introduction'), which sets up the environment for the following cyclones by contributing to a strengthening of the jet stream and reducing low-level stability^{49,59}. The physical interpretation is that RWB enhances the thermal gradients at the jet level, thus accelerating the jet and leading to a downstream extension⁶⁰, which ultimately foster the occurrence of the cyclone family. For more details see section 'Secondary cyclogenesis and cyclone families'.

Priestley et al.⁴⁹ further analysed how far clustering periods in regions North (65°N, purple dot in Fig. 4) or South (45°N, cyan dot) of the British Isles confirm or differ from this pattern. For 45°N, cyclonic RWB on the north side of the jet is dominant, and anticyclonic RWB is strongly reduced. This leads to a strongly zonal jet stream across the North Atlantic and Western Europe, with enhanced storm activity and clustering periods in Iberia and France. Conversely, anticyclonic RWB is dominant for clustered periods in the 65°N region, deflecting the jet stream northward and enhancing the SE–NW tilt. This leads to enhanced cyclone activity and clustering episodes near Scotland, Norway and nearby Northern Seas. Independent of the latitude, Priestley et al.⁴⁹ identified a positive correlation between the jet stream speed at the exit region and the occurrence of clustering periods. A similar relationship was also identified for RWB activity and clustering, but

with a larger spread. Unfortunately, no dynamical analysis of the physical processes leading to serial cyclone clustering is available either for the North Pacific or for the Southern Ocean.

Secondary cyclogenesis and cyclone families

Secondary cyclones form along the fronts of pre-existing primary cyclones and tend to be small and develop rapidly⁶¹. Due to their small scale, the dynamics of secondary cyclones can differ from the baroclinic growth mechanism^{62,63}, which dominates for primary cyclones. Secondary cyclogenesis is often initiated by moist processes at low levels^{64–66}. Latent heat release (LHR), due to condensation, occurs when moist air ascends. This LHR can impact the wind field at low levels and thus influence the cyclone's evolution. Potential vorticity (PV) is a useful means for identifying the dynamical feedbacks associated with LHR since high PV, generated by LHR, is associated with cyclonic flow in the NH. LHR occurring in ascending frontal updrafts can thus generate a low-level PV strip along the frontal surface^{67,68}. If this PV strip breaks up into individual anomalies, the cyclonic circulation associated with these anomalies can lead to the formation of shallow frontal waves forming along the cold front^{69–71} or occasionally the occluded front^{72,73} of a parent cyclone. If a low-level PV anomaly couples with an upper-level Rossby wave (or trough), both the upper-level Rossby wave and low-level frontal wave can amplify. This amplification can lead to RWB at upper-levels (see section 'Jet stream and RWB') and the evolution of surface frontal surfaces described in Fig. 1. Cyclones influenced by LHR (diabatic heating) are known as type C cyclones^{71,74,75} (or diabatic Rossby waves) and they often form in regions of low static stability^{20,76}. Their intensification is sensitive to the magnitude of low-level PV during their development phase^{77,78}. Occasionally, secondary cyclones may also intensify upon crossing the jet stream, even without a clear upper-level trough feature^{72,79}.

Priestley et al.⁵⁹ linked clustering of primary and secondary cyclones to the large-scale environmental flow described in section 'Jet stream and RWB'. Figure 5 shows a typical cyclone family and their associated tracks at the surface. The primary cyclone (A, cyan) forms in the western North Atlantic and tracks towards Iceland. The secondary cyclone (B, green) forms on the cold front of cyclone A in the central North Atlantic, and tracks further south towards the British Isles⁸⁰. The third cyclone (C, purple) forms on the cold front of cyclone B in the eastern North Atlantic and also tracks over the British Isles. Following the genesis of a primary cyclone (A), the authors⁵⁹ have shown that RWB increases (upper level in Fig. 5), leading to an increase in jet speed and a decrease in low-level stability. This can concentrate more

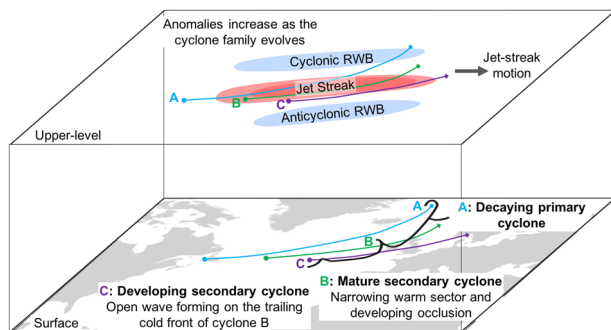


Fig. 5 Schematic linking jet and RWB anomalies to a cyclone family. A typical cyclone family (grey) and their associated tracks are shown at the surface. At upper-levels, the cyclone family is associated with evolving jet and RWB anomalies, which move eastward with the surface cyclone family. For more details see text. Adapted from Bjerknes and Solberg³ (Fig. 10), Pinto et al.²⁸ (Fig. 7) and Priestley et al.⁵⁹ (Fig. 9b).

secondary cyclones over a certain location, thus leading to clustering (cyclones B and C in Fig. 5). Since secondary cyclones typically move faster than upper-level Rossby waves, they can further enhance upper-level anomalies due to successive RWB, which constricts the jet latitude, thus steering subsequent cyclones to the same area. Consistent with Dacre and Gray²⁰, they found that secondary cyclogenesis commonly occurs in a region of low stability, close to the European continent. During clustered periods over the United Kingdom, they found an increase in secondary cyclogenesis near western Europe. Accordingly, the proportion of secondary cyclones passing over the United Kingdom increases from approximately a third during non-clustered periods to almost half during highly clustered periods. However, the total number of secondary cyclones in the wider North Atlantic does not actually increase. Thus, the large-scale environment appears to redistribute secondary cyclones during periods of clustering rather than increasing the total number of secondary cyclones.

Similarly, Weijenborg and Spengler⁸¹ found limited influence of RWB in the development of a single family of cyclones in the North Atlantic. Thus, it appears that while successive RWB may be favourable for steering cyclones over the same location, thus increasing clustering, it does not necessarily increase secondary cyclogenesis. On the other hand, more local mechanisms such as diabatic heating may lead to increased secondary cyclogenesis or stronger cyclones⁸², but not necessarily clustering of cyclones in the same location. The role of successive cyclones in re-enforcing the large-scale flow pattern is not well understood and the interaction with low-level diabatic heating requires more research.

Relationship between cyclone clustering and teleconnection patterns

In this section, we discuss the relationship between the large-scale atmospheric patterns and periods of serial cyclone clustering. Extratropical variability on timescales >10 days (low frequency) is often described in terms of persistent large-scale patterns of surface pressure or geopotential height and circulation anomalies known as teleconnection patterns. For example, the NAO describes the normalised pressure difference between Iceland and the Azores and is related to the large-scale flow pattern over the North Atlantic⁸³. Similarly, the Pacific North American (PNA) pattern describes the pressure difference between the Aleutian Islands, Hawaii and Southeastern USA and is related to the large-scale flow pattern over the Pacific and North America⁸⁴. Distinct weather regimes are associated with positive and negative NAO and PNA indices. One of the earliest studies linking cyclone activity and these indices was performed by Bradbury⁸⁵, who showed that a positive NAO index is associated with more frequent cyclones in the north eastern Atlantic ocean, usually poleward of the mean storm track. A negative NAO index gives the inverse picture, with higher frequency of cyclones off the east coast of North America, Central North Atlantic and in the Mediterranean. Similarly, there are more frequent cyclones north of 50°N over the Pacific Ocean during negative PNA index circulations and a reduction south of 50°N. These relationships between absolute frequency metrics and teleconnection indices are largely driven by changes in the location of storm tracks⁸⁶. Indeed, the phase shifts (from positive to negative indices) in a particular pattern are related to whether cyclones travel in one or another direction, and thus affect one or another area. Therefore, a persistence in the phase of the large-scale pattern is determinant on whether a period of clustering occurs or not at a given location⁸⁷.

Many studies have investigated the usefulness of teleconnection patterns for explaining the variability in extratropical storminess at given locations^{10,45}. Often, regression models are used to determine the strength of the relationship between relative

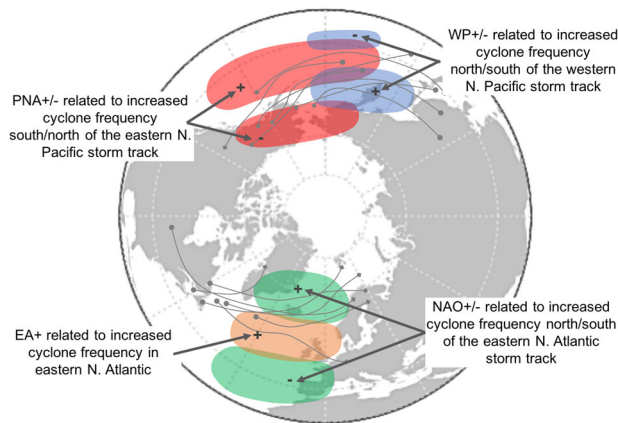


Fig. 6 Schematic showing regions in which the dominant large-scale patterns are related to cyclone frequency in the North Atlantic and North Pacific. North Atlantic Oscillation pattern (NAO, green), East Atlantic pattern (EA, orange), Pacific North American pattern (PNA, red) and West Pacific pattern (WP, blue). +/− refers to positive/negative indices of the large-scale patterns, respectively. The representative cyclone tracks shown in grey. Summarised from figures in Maillier et al.²⁵ (Figs. 8 and 9), Economou et al.³³ (Fig. 8), Pinto et al.³⁰ (Figs. 7 and 8) and Walz et al.⁵⁰ (Fig. 3).

frequency metrics (dispersion statistic) and dominant time-varying teleconnection indices (NAO, PNA, East Atlantic (EA) and West Pacific (WP) patterns). Many studies have investigated the relationship between monthly cyclone counts and teleconnection indices in reanalysis and climate models^{25,33,41,50}. Consistent with Bradbury⁸⁵, they showed that variability in the dominant pattern, the NAO, leads to additional variance in monthly cyclone counts on the flanks of the North Atlantic storm track and hence increased clustering (overdispersion) in these regions (green regions in Fig. 6). This result was confirmed by Pinto et al.³⁰, who found that the NAO index variability explained between 20 and 60% of the monthly clustering variability for the ERA-interim reanalysis, depending on the cyclone tracking algorithm used.

Specifically, Vitolo et al.⁴¹ investigated the relationship between clustering and teleconnections not only for the monthly scale but also for timescales from 4 days to 6 months. They found that on timescales >2 weeks the frequency of clustering in Europe is related to teleconnection indices like the NAO and the Scandinavian Pattern. The strongest relationship was found for 3-monthly time periods due to the seasonal persistence of some of the analysed teleconnection patterns. The authors suggest that teleconnection indices could thus be a good predictor of active and inactive seasons, that is, more/fewer cyclones than average. On decadal timescales, periods with multiple stormy years (e.g. early 1990s) or reduced cyclone activity (e.g. 1960s) have been related to the dominant NAO phase^{45,88}.

However, the statistical analysis performed in these studies does not allow the determination of causes and effect. For example, in the North Atlantic, the large-scale NAO pattern can act to 'steer' cyclones further north or south. However, it can also interact with transient cyclones and their associated synoptic-scale Rossby waves (see section 'Secondary cyclogenesis and cyclone families'). These Rossby waves can break and help maintain the NAO phase^{87,89}, breaking anticyclonically for the positive phase and cyclonically for the negative phase. For both phases, the persistent NAO pattern is therefore supported by the successive breaking of upstream Rossby waves (as discussed in sections 'Jet stream and RWB' and 'Secondary cyclogenesis and cyclone families'). Subsequent RWB has also been shown to reinforce atmospheric blocking patterns, which similarly play a role in steering cyclone tracks⁹⁰. However, potential links between

serial cyclone clustering and the occurrence of blocking has not so far been addressed in the literature. In the North Pacific, the low-frequency patterns interact with both quasi-stationary and transient cyclones, which contribute to the maintenance of the pressure anomalies. The dominant low-frequency pattern in the North Pacific is the PNA, which is related to east Pacific cyclone frequency⁹¹, shown as red regions in Fig. 6. The exact balance of the two-way interaction between the large-scale and synoptic-scale circulations remains an area of active research.

GAP ANALYSIS

In the previous sections, several not-yet explored or under-explored aspects were reported. In general, they can be classified into three groups: topics related to the data used, the research methods chosen or the analysis performed. In this section, we discuss these aspects and identify areas in which key questions remain.

Data used

Several aspects of the data used to study serial cyclone clustering have been limited, such as the location, type and length of the datasets. First, our knowledge is almost solely based on the North Atlantic Basin and Europe. In fact, only two studies have analysed the North Pacific Basin^{25,32}, and to our best knowledge, only the latter has analysed conditions in the Southern Hemisphere. The same is true regarding the dynamical analysis of serial cyclone clustering, as all the available studies have focused on the North Atlantic/European region (see section 'Jet stream and RWB'). It is crucial to address serial cyclone clustering in other basins. Second, the type of data used to identify serial cyclone clustering typically comes from reanalysis, GCMs and ESMs. While low-resolution models are suitable for representing large-scale circulation patterns and synoptic-scale cyclones, they cannot capture the mesoscale processes acting on fronts and microscale diabatic and frictional processes are entirely parameterised. For example, low-resolution models may fail to capture the correct dynamics of RWB events⁹². Given the dependence of secondary cyclogenesis to smaller-scale processes (see section 'Secondary cyclogenesis and cyclone families'), analysis of the interaction between successive cyclones in a cyclone family in reanalysis and higher-resolution models is required. Finally, the length of the datasets used in the literature tends to be too short due to limited data availability. Longer datasets are needed to reduce uncertainties (see section 'Varying timescales of serial cyclone clustering'). Longer datasets are particularly important for estimating the impact of rare storm series (200-year return period), which are of interest to the insurance industry.

Research methods

In order to identify clustering, several research steps are combined. These include identification and tracking of cyclones²⁹; choice of a metric defining clustering; and specification of aggregation timescale to be analysed. With respect to the impact of different tracking algorithms, this was addressed for the North Atlantic by Pinto et al.³⁰. Regarding the choice of clustering metrics used, the majority of the literature uses either absolute or relative frequency metrics to define clustering varying on a monthly seasonal timescale, but generally only one metric, making comparisons difficult. Moreover, while it is useful to study where and when serial cyclone clustering occurs, they are not the most relevant metrics for many practitioners. For example, the insurance industry is most interested in serial clustering of cyclones and their potential damage, in particular the relationship between AEP and OEP (see section 'Varying timescales of serial cyclone clustering'). Thus, more attention should be paid to the impacts of clustering. Finally, while serial cyclone clustering has

been studied for various aggregation periods, the focus has often been on monthly to seasonal variability (see section 'Varying timescales of serial cyclone clustering'). However, it is of crucial importance to assess how different cyclone clustering is for long and short aggregation time periods, and if clustering must be distinguished between different timescales. For example, only a few studies have linked slow oscillations in cyclone activity to ocean variability⁹³ or internal variability of the climate system⁵⁴. On shorter aggregation timescales, more analysis of clustering on daily-weekly timescales is required to answer questions regarding the onset and end of cyclone families forming along the same frontal feature.

Analysis

Analysis of clustering has dealt primarily with where and when serial cyclone clustering occurs. However, our understanding of why serial cyclone clustering occurs is still incomplete. For example, the role of successive cyclones in re-enforcing the large-scale flow pattern is not well understood or the link between blocking and serial cyclone clustering. Similarly, the interaction of low-level diabatic heating in enhancing the occurrence and strength of secondary cyclogenesis is very pertinent and requires more research. The ability of GCMs and ESMs to represent these interactions has not been fully investigated, and poorly resolved or incorrectly parameterised processes may limit the ability of models to predict how climate change will affect serial cyclone clustering. There has also been relatively little analysis of whether serial cyclone clustering, on the full range of timescales, can be predicted. Vitolo et al.⁴¹ and others provided evidence that the frequency of seasonal clustering for locations across northern Europe is strongly related with teleconnection indices, suggesting that they could be a good predictor of active and inactive seasons. However, other authors^{25,94} found that time-lagged indices do not have much predictive skill because of their limited persistence 1 month ahead, but noted that time-lagged indices might be expected to show more skill in the seasonal range. On weekly timescales, it would be particularly relevant to estimate the probability of development of a cyclone family based on the characteristics of the primary cyclone and the large-scale environment in which it develops, as this could provide an added value for weather forecasters. Moreover, possible influences by indirect drivers like sea surface temperatures, stratosphere, Arctic and sub-tropical variability have not yet been quantified.

Key questions

In this review, we have provided an overview of current research activities into serial cyclone clustering over different space and timescales. The following questions have been identified as being key for future research and should be understood as suggestions for future research opportunities. They are framed as overarching questions and associated topics:

1. Can we predict the onset and duration of cyclone families from the characteristics of the large-scale atmospheric flow and/or primary cyclone?

This is important for predictability of high impact events on timescales ranging from daily to long-term climate change, including sub-seasonal, seasonal and decadal timescales. Depending on the timescale, the focus will be on single clustering periods or aggregated statistics over years/decades. In particular, it is important to understand the nature of the two-way interaction between cyclones and the environment, which can act to maintain the jet position and baroclinicity necessary for serial cyclone clustering to occur in a certain location. Among the potential large-scale drivers, the role of strong stratospheric vortex episodes for the maintenance of persistent zonal weather regimes is of strong interest.

2. What are the relative properties of primary and secondary cyclones?

A detailed analysis of possible differences over large climatologies of cyclones is required. Studies into whether secondary cyclones are smaller in scale and more influenced by diabatic processes than primary cyclones will be key to advancing our physical understanding. Another aspect is to investigate is whether secondary cyclones lead to higher precipitation accumulations because they typically originate closer to the moist subtropics than primary cyclones.

3. What are the characteristics of serial cyclone clustering globally?

Most of our knowledge about serial cyclone clustering is based on studies about the North Atlantic/European region. A detailed analysis of serial cyclone clustering in the Southern Hemisphere is called for. Moreover, more studies on the dynamics of serial cyclone clustering for the North Pacific and the Southern Ocean will surely lead to new insights.

4. Can we quantify the cost of serial cyclone clustering for the insurance and re-insurance industry?

The insurance industry must regularly demonstrate to the market regulators their capacity to deal with unexpected events that may lead them out of the market (European Union Solvency II directive). For natural catastrophe insurance, the accumulated loss of a 200-year return period 'extreme event' is taken as the benchmark. Given the nature of the re-insurance contracts, the situation is particularly critical if multiple very large events occur within the same year. Extended datasets and new methodologies (like synthetic event sets) are essential to properly quantify the role of serial cyclone clustering at such long return periods (high return levels).

5. How will climate change affect serial cyclone clustering?

The current climate change studies on serial cyclone clustering show large sampling uncertainties. One key question remaining is how far the different projections of serial cyclone clustering between models are associated with differences in storm track latitude/orientation, or the spatial resolution of the model data. Multi-model and multi-method evaluations of CMIP6 data will be useful here.

While we have named here some knowledge gaps, we acknowledge that huge advances in our understanding of extratropical cyclones have already been made by the studies included in this review, and many others that could not be included. We hope that this review article provides clarification of the terminology associated with serial cyclone clustering and a framework into which future studies can be placed, allowing easier comparison of results irrespective of the research direction.

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COMPETING INTERESTS

The authors declare no competing interests.

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