Can Circulation Types be a proxy for flooding risk in Europe?

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Abstract

This paper evaluates whether Circulation Types Catalogues (CTCs) can inform on the occurrence of floods in Europe, and if the same few Circulation types (CTs) are systematically associated with floods. Two local indicators were used measuring if a CT occurs more frequently than usual prior/during a flood and if the persistence of a CT is followed by a flood. A measure of the spatial coherence of CT was used to compare the relative performance of CTCs. Antecedent conditions and time-lag of catchments were accounted for in calculating the indicators on a range of durations up to 10 days preceding a flood.

Relationships between flood occurrence on 488 river basins and CTCs were explored using 64 catalogues developed within COST733 Action, all defined from automatic algorithms using ERA-40 mslp patterns. Results showed that at the river basin scale, some CTs have significant positive frequency anomalies with flood occurrence, and persistence of the same CT has strong relationships with floods. At the scale of Europe, the same CTs showed the strongest links with flood occurrence. The number of classes of CTCs is of lesser importance than the algorithm used, and depending whether global frequency or persistence of CT were analysed, could give contrasting results. Results obtained from an objective Grosswetterlagen classification were consistent with previous research but performance was lower than other automatic algorithms (e.g. WLKC and TPCAC). Results showed seasonal variation, possibly due to differences in flood generation mechanisms in different regions and seasonal CT frequency.

Keywords

Circulation Type Classification, Flood, Synoptic climatology, Grosswetterlagen, Europe, Automatic atmospheric circulation classification

1. Introduction/ Background

Global and regional atmospheric processes are very variable in time and space, in particular in mid-latitude ocean-margins regions such as Europe, and the resulting weather usually described as 'chaotic' as it is constantly changing, sometimes from hour to hour, and at other times from day to day (Lutgens and Tarbuck, 2007). However, some main features have been observed near Europe, two of the most famous being a high pressure centre (anticyclone) generally near the Azores Islands, and a low pressure centre (depression) over Iceland. The strength and the exact position of these centres have an effect on the direction and speed of the wind, the rise of humid air, and where and when humid air reaches the western coast of Europe and falls as precipitation. The North Atlantic Oscillation index is a measure of the change in strength of these two centres, and has been shown to be linked to some of the variations in temperature and precipitation in Europe, but do not explain all the observed variability. Alternatively, recurrent weather patterns around specific dates have been observed and used as basis for long-range weather forecasting (O'Hare et al., 2005).

Circulation type classifications (CTCs, also sometimes referred to as weather types classification) have been developed to summarise and characterise the daily variability of the climate in a number of atmospheric circulation patterns which occur most frequently. These patterns, also called circulation types (CTs) aim to discriminate typical atmospheric phenomenon observed within a region, and have become useful tools for describing and analysing climate conditions and corresponding weather. Subjective classifications have developed through recognition of the recurrence of the atmospheric circulation in certain modes (El-Kadi and Smithson, 1992). The Lamb catalogue (the manual original catalogue extends from 1861-1997) (Lamb, 1972) is a classification scheme designed for the British Isles which has bee used to study hydroclimatology relationships (see review by El-Kadi and Smithson, 1992). The Grosswetterlaggen classification characterises European weather types is another well known subjective classification with a manual catalogue dating back from 1881 (Hess and Brezowsky, 1977). With the increase of computing facilities and the availability of digital atmospheric data such as reanalyses, a range of automatic classification algorithms have been developed and many circulation types catalogues are now available.

The study of the relationships between the atmospheric circulation and the surface environment shows great potential for basic and applied research (Yarnal, 1993). An example is the analogue weather forecasting, where past synoptic patterns and accompanying weather are matched to current synoptic patterns and forecasts are made according to these past weather (O'Hare et al., 2005) and such techniques are used routinely operationally (Obled et al., 2002). A more recent application of CTCs is the verification of the performance of General Circulation Models (also called Global Climate Models GCMs; e.g. (Anagnostopoulou et al., 2009; Goodess and Palutikof, 1998), the analysis of possible changes in atmospheric circulation, and the downscaling of GCM outputs (Wilby, 1997), using automatic Circulation classification procedures. Comparisons of historical CTCs (obtained from

observed pressure fields), GCM-derived CTCs representative of current and future climates help identifying systematic biases in GCM climatology trends and possible future changes.

Links between CTCs and some specific weather-related events have been investigated for many years, for example with cyclone tracks (e.g. Bartholy et al., 2006), flood events (Duckstein et al., 1993) or drought states (Fowler and Kilsby, 2002). In Europe, specific CTs have been shown to be linked to wet/dry periods. For example, the Cyclonic Lamb weather types are described by *'rainy, unsettled conditions, often accompanied by gales and thunderstorms. May represent rapid passage of depressions across the country [UK], or to the persistence of a single deep depression' (O'Hare et al., 2005). When extended to the full catalogue, such empirical relationships can be used to build weather generators conditioned according to CTs (e.g. Fowler et al., 2005; Schubert, 1994; Wilby, 1995).*

Direct links between weather type and extreme floods are, however, rarely investigated at a large spatial scale. The occurrence of extreme floods has always been a peril to human society. Some of the most devastating floods have actually resulted from synchronic flooding over large regions and major rivers, such as for example the catastrophic floods along the Danube and Elbe rivers in summer 2002; central Europe was also under important flooding in summer 2005 and in June 2009, all with devastating consequences. The cost (both monetary and human) associated with such events is enormous: for example, the annual average flood damage in Europe in the last few decades is about €4 Billion per year (Barredo, 2007) and, between 1998-2004 alone, Europe experienced more than 100 major floods resulting in some 700 fatalities. The environment impact is rarely quantified in terms of economic cost, but can be huge. Other indirect impacts include high psychological damage, and high level of emergency responses sometimes requiring international co-operation and the assistance of army forces, transportation disruption and reconstruction time, which makes flooding some of the most traumatic natural disasters. Understanding the atmospheric conditions which trigger such large-scale events would help in to improve preparedness, and have potential to limit damages and to mitigate impacts in enabling better flood-risk assessment and anticipation. This paper aims to fill this research gap, and is a first step towards evaluating whether some large-scale circulation patterns systematically show a strong link with flood occurrence across Europe. It systematically assesses a number of automatic classifications to identify if some show clear discrimination power for flood events. If such relationships can be identified, they could be used as proxy for evaluating flood risks using atmospheric observation, but also, could be used to assess current General Circulation Models and their ability to reproduce flood-generating atmospheric patterns.

2. Aim and objectives

Many algorithms can be used to characterise synoptic patterns, each resulting in different key atmospheric circulation patterns. The European Cooperation in Science and Technology (COST) Action 733 entitled 'Harmonisation and Applications of Weather Type Classifications for European regions' was initiated to compare different classification methods and to evaluate whether algorithm systematically outperforms others which some can be recommended. Within the action, the different methods are tested for their reliability robustness and their ability to discriminate spatial and temporal climate variation in Europe (such as rainfall and temperature), but also if they could prove useful for various applications ranging to the ability to discriminate large scale atmospheric dipoles such as the North Atlantic Oscillation, to local characteristics such as the level of air pollution, to links with resulting events such as wild fires. The paper focuses on exploring links between CTs and flood events in a pan-European study.

Specifically, the paper aims to investigate three specific questions:

- Does a circulation type CT occur more frequently during/before a flood event than usual?
- Is the persistence of a CT followed by a flood event?
- Does the same CT show the strongest links with flooding in all Europe? In other words, is a CT linked to flooding at the European scale?

Following (Duckstein et al., 1993), indicators are calculated to quantify the frequency anomalies and conditional probabilities linked to the persistence of CT preceding a flood event. A new spatial indicator evaluating the spatial coherence of the strongest links across Europe is also developed and applied to a range of CTCs developed within COST733, allowing a quick comparison of skills of 64 catalogues. The evaluation is done for the whole year and by seasons (3-month) to identify if different seasonal flood-generating mechanisms can be identified using CTCs.

Several studies have found no upward trend in the occurrence of extreme floods in Europe in the last century (Barredo, 2007), and no significant longterm trends have been identified in the majority of the objective catalogues used in this study (Cahynová, 2009). It was hence considered that this study would not implicitly look for possible trends in the methodology for assessing relationships between flood and CTs. If some CTCs emerge to be potential candidates to discriminate flood occurrence in Europe, the relationships identified will be thoroughly evaluated, in particular for any possible trends. This is however out of the purpose of this paper, and trends will not be further discussed.

Data and methodology are detailed in the next section, and the results presented in section 4, first illustrated for the subjective classification OGWLSLP, then comparing the results obtained for the whole set of CTCs. The paper finishes with a short discussion and conclusion.

3. Data and methodology

3.1. Data

The study was conducted on 488 river basins across Europe (Figure 1) with good quality data and longest possible records with limited missing periods. The selection of the river basins insured a good geographical spread and

includes a range of catchment areas. Daily river flow data was obtained from the Global Runoff Data Centre (http://grdc.bafg.de/servlet/is/Entry.987.Display/), the European Water Archive (http://ewa.bafq.de/), UK National River Flow the Archive (http://www.ceh.ac.uk/data/nrfa/index.html) and the French Banque Hydro (http://www.hydro.eaufrance.fr/).

Figure 1 – place holder grey print

The links between flood and CT were evaluated using a set of 64 CTCs defined over Europe. All of these were developed and made available through the European COST 733 action (Philip et al., 2009; Tveito and Pasquini, 2005). The set contains 63 automatic CTCs calculated from daily circulation fields (mostly sea level pressure) over a standard domain (for Europe the 30N - 76N and 37W - 56E) and for the periods 1957-2002. The circulation fields are from the ECMWF reanalysis (ERA40, Uppala et al., 2005) for all the automatic classifications. This set uses 18 independent classification methods, including methods based on Thresholds, Principal Component Analysis, Leader algorithms and Optimization algorithms, but applied with different type numbers (closest to 9, 18 and 27 classes). Additionally one subjective CTC was also considered, the automatic version of the Hess-Brezowsky Grosswetterlagen (Gerstengarbe and Werner, 1999) developed within COST733 (OGWLSLP, without time filters forcing a minimum persistence of CT of 3 days, (James, 2007). For complete description, summary table with acronyms and technical references, see Philip et al. (2009).

3.2. Methods

Unlike rainfall events which are point measurements in time and space, flood flows at a river gauge are a consequence of rainfall events occurring within the whole river basin and during a certain period prior to the measurement. This time-lag between a flood-producing rainfall occurrence and the flood occurrence itself is dependant on the river basin conditions, including the state of the soil (is it already saturated or is it very dry?) and the catchment characteristics. This time-lag influence and the antecedent conditions are accounted for in considering CT occurrence for up to 10 days before a flood event.

Flood is generally associated with inundations, where the level of a river is higher than the main river bank and the stream overflows outside the main river channel to flood the major river channel. Such events are usually considered to be associated have a probability of occurrence of 0.5, in other word they are usually expected to occur once every two years. However, most flow series are expressed into discharge, and the moment when the river bursts its bank is rarely mentioned along river flow time series. Instead, hydrologists define flood events as the largest recorded discharges, either during a fixed period of time (generally the year: annual maxima) or during the whole period of record (peak-over-threshold). Regardless of the sampling methodology used to select floods events, floods in a river basin have a very low frequency of occurrence (typically less of 1%), and associated sample are short compared to daily CTs series (which for the smallest have an occurrence of at least 3%). This means that any study aiming to find statistically significant links between will be confronted to the fact that any CT will occur much more frequently than flood events, even for CTCs with a large number of classes. The consequence is that even if some reliable relationships are found between the occurrence of a CT and that of a flood, this relationship will not be one sided, i.e. it is not because this CT occurs that a flood will occur.

Local statistical significance of the relationships can be evaluated, but it is difficult to assess if they any found links are not a consequence of specific samples of events but truly are representative of physical processes, due to the relatively small samples on which the relationships are established. High variability can be observed when looking at relationships between local climate series and CTCs, due for example to variations both among the individual classifications, and to individual data series. One suggestion to overcome this is to use a comparative approach (Cahynová, 2009). Another empirical technique used to increase the sample size is by pooling information from different sources. For example, the Flood Estimation Handbook suggests to pull together raingauge information in order to estimate very rare events (Faulkner, 1999). Similar concept is also used for flood frequency analysis using the index flood method, where flood frequency curves are defined regionally (Hosking and R.Wallis, 1997; Kjeldsen and Jones, 2007). Here, the aim is to evaluate whether some CTs are representative of the atmospheric processes leading to large-scale flooding in Europe as opposed to characterising local floods, which could results to small-scale, localised processes difficult to characterise by European CTCs. In particular, the question is to explore if some CTs occur more often during flood-rich periods than usual, and if yes, if it is generally the same CT that show positive frequency anomalies during these periods.

Here, a flood event is defined from a partial-duration-series, or peak-overthreshold method (Naden, 1993), where the largest n floods are selected, n being proportional to the length of the daily flow series. Here, the criterion is of POT3, i.e. n=3*Y where Y is the number of years of data. The independence criterions defined by Bayliss and Jones (1993) were applied, with a lag time of 5 days.

The methodology follows that developed by Duckstein et al. (1993) and uses similar notation, but applied to 488 catchments over Europe (Figure 1**Error! Reference source not found.**). Two indicators are calculated that evaluate the links between a CT and the occurrence of a flood event at a site. They are also used to evaluate the spatial coherence in the relationships. In order to incorporate the time-lag in the river basins, the indicators are calculated for a set of N* days preceding the flood. Because of the range of river basin geology, soil type and sizes in our sample, it is not possible to define a priori N* which will lead to the strongest relationship. Instead, the indicators are calculated for a period of up to 10 days up to the flood. Because some catchments have a concentration time of less than 1 day, the day of the flood

is also considered in the study, i.e. 10 days up to the flood refers to the day of the flood and the 9 preceding days.

3.2.1 Is a circulation type occurring more frequently during a flood event than usual?

The indicator PI1 (in %) calculates the difference between the frequency of occurrence of a circulation type CTi during a flood event to that for any day, in percent:

PI1(i) = 100 *
$$(\frac{n_1(i)}{n_2(i)} - 1)$$
 i=1,...,C

with $n_1(i)$ the relative number of days with pattern CTi in N* days up to the flood, and $n_2(i)$ is the relative number of days with pattern CTi, and C is the number of classes of CTC. Estimation can be done looking at the entire series (Pl1_{year}) or just concentrate on specific seasons (Pl1_{season}). It is a modified version of Duckstein et al. (1993) and of the effectiveness correlation of Cony et al. (2008): if Pl1(i) is positive (negative), the pattern occurs more (less) frequently before/during a flood than it does normally (i.e. CTi does (does not) contribute much to the flood). For example, Pl1 = -100% when CTi has never occurred during/before an observed flood, while Pl1=800% indicates that the CTi occurred 8 times more often during/before the flood than any other period. The statistical significance of the frequency anomaly for the entire classification (all classes considered together) is evaluated through the χ^2 statistics with, as null hypothesis, 'the frequency of a weather type during floods is the same as for any day'.

3.2.2 Is the persistence of a circulation type followed by a flood event?

The indicator PI2 measures the conditional probability of finding at last k days out of N* with CTi, given that a flood occurred on day zero:

 $PI2(i) = pr(CT = i \text{ for } \ge k \text{ days, } 0 \le k \le N^*) \qquad i=1,...,C$

This indicator measures the persistence of CTi associated with a flood event, important factor in the river basins antecedent conditions: a high Pl2 indicates that CTi has generally been observed for several days before flood events. This conditional probability is compared with the binomial probability of at least *k* days out of N^* of *CTi* using historical frequencies of occurrence.

3.2.3 Does the same CT show the strongest links with flood in all Europe?

Local evaluations of PIs for a CTC can be discussed at the European level by mapping PI(i) at the river basins outlets. While useful to evaluate single CTC, this soon becomes fastidious for a large number of CTCs (in this paper, the 64 studied CTCs correspond to 1159 CTs). Moreover, spatial evaluation is necessary to assess how well CTCs can describe large-scale flooding.

A spatial indicator, RPI (for Regional PI) is defined which evaluates the spatial coherence of the local relationships:

$$RPI(i) = \frac{\sum_{r=1}^{B} Score_{PI}(i, r)}{B} \qquad i=1,...,C$$

with Score_{Pl}(i,r) the score obtained by CTi for river basin r, B the total number of river basins, and C the number of classes of CTC. The scores are given according to the ranked Pl(i,r) standardised by the number of classes to allow comparison of relative performances of CTCs of different number of classes: Score_{Pl}(i,r)= 1/C for the lowest Pl(i) of r, and Score_{Pl}(i,r)= C/C = 1 for the highest Pl(i) of r. For each CTi, there is one RPI per Pl, i.e. for each N* and k combination for both Pl1 and Pl2.

Two RPIs are of particular interest. The maximum RPI measures the spatial coherence of the CTi with the strongest relationship with flood events: RPI(i) = 1 indicates that CTi has systematically the strongest relationship with floods for all 488 river basins, and hence, there is a strong spatial coherence in the flood-generating mechanism described by CTi. Lower RPIs reflect lower spatial coherence for the flood-generating CTi.

The minimum RPI informs on the spatial coherence of the 'flood-poor' CTs: a value of 1/C indicates that the same CTi has systematically the weakest relationship with floods in all 488 river basins, and could be an indicator of potential absence of flood across Europe. Higher values show a weaker spatial coherence in the flood-poor CTi.

4. Results

Due to the very large number of tested CTs, an example of application of the methodology is illustrated only for the OGWLSLP, the automatic version of the well-known Hess-Brezowksy Grosswetterlagen classification without imposed persistence developed for Western Europe (James, 2007).

4.1. Is a circulation type occurring more frequently during a flood event than usual?

Figure 2 (top) shows PI1_{year} obtained with the circulation types OGWLSLP-CT2 and OGWLSLP-CT28, associated with high PI1_{year} for the majority of river basins. CT2 corresponds to the cyclonic westerly type (Wz), one of the four sub-types of the major type 'westerly circulation'. OGWLSLP-CT2 occurs 8.2% of the year, and is characterised by a dipole with low pressures over north Atlantic (West of Island) and high pressures over the Azores (Figure 3). It is known to be associated with flooding in north-west Europe and western Alps both during winter and summer, and was found to be amongst the CT triggering winter floods in Germany by (Petrow et al., 2009). OGWLSLP-CT28 corresponds to the British Islands low (TB), part of the Meridional Group. It is associated with a low pressure centre located over the British Isles, W Iberia, France, S Alps, Italy, W Balkans) and summer flooding over France, the British Isles and W-C Europe, and occurs on average 3.2% of the year.

Contrastingly, PI1_{year} is negative (i.e. CTi never occurred the same day as a flood) or non-significant (i.e no statistically significant relationships between CTi and flood occurrence) for the majority of river basins of Europe (Figure 2, bottom) for OGWLSLP-CT9, the Central High CT (HM); and OGWLSLP-C18, the anticyclonic North-Easterly (NEa), the latter generally associated with no flooding risks in the winter, and some flooding in Eastern European in the summer. This is consistent with river basins with some positive significant PI1_{SON} found in the eastern part of Europe for OGWLSLP-C18.

Figure 2 place holder grey print

Figure 3 place holder grey print

4.2. Is the persistence of a circulation type followed by a flood event?

Persistence of a CT has been identified as a major factor in flood events occurrence by Petrow et al. (2009) and Jacobeit et al. (2006), for example, who analysed CP occurrence respectively up to 3 and 7 days before flooding. Here, persistence is assessed using PI2 for up to 10 days before a flood event. Figure 4 shows the European distribution of PI2_{vear} for OGWLSLP-CT2 for a 7-day period: while the conditional probability of OGWLSLP-CT2 occurring once within 7 days prior and during the flood is significant for over 80% of the considered river basins (i), it is significant for more than 90% of the rivers for a 4-days persistence (ii), and remains significant for about half of the rivers for a 6-days persistence (iii). There is no geographical pattern in the location of the river basins for which Pl2_{vear} is significant. This would suggest that OGWLSLP-CT2 describes an atmospheric pattern likely to generate flooding in any part of Europe, and potentially, synchronous floods. This is consistent with empirical observations of flood occurrence during western cyclonic patterns throughout Europe, and with conclusions of (Petrow et al., 2009) for flooding in Germany.

Figure 4 place holder grey print

4.3. Does the same CT show the strongest links with flood in all Europe?

RPIs were calculated for all 64 CTCs and results for selected indicators are reported here: Figure 5 shows RPI(PI1_{year}) for four durations (1, 2, 4 and 10 days); Figure 6 shows RPI(PI2_{year}) for two periods prior to a flood and two persistence durations each (2 days persistence within 4 days 4lag-2pers; 4 days persistence within 4 days 4lag-4pers; 4 days persistence within 10 days 10lag-4pers; 7 days persistence within 10 days 10lag-7pers); Figure 5c and Figure 6c shows seasonal RPIs. Maximum / minimum RPIs are ordered so that the CTC in the top of the diagrams has the largest spatial coherence. Bar sizes are proportional to RPI, and bar colours symbolise the number of classes of the CTC: \approx 27 (red – dark grey), \approx 18 (orange - grey), \approx 9 types (yellow – light grey), other type numbers (grey), and manual classifications

(blue). The CT associated with the plotted RPI (maximum or minimum) is given with the CTC acronym.

4.3.1 Spatial coherence for PI1

Annual evaluation

When calculated over the whole year, five CTCs have a maximum RPI(PI1_{year}) equal to 1, indicating that for these catalogues, the same CT systematically leads to the largest PI1_{year} for all river basins (Figure 5a). These CTCs belong to two classification algorithms: the Objektive Wetterlagenklassifikation WLKC (Ditmann et al., 1995; and Bissolli and Dittmann; 2003; from Philip et al., 2009) for 9, 18 and 27 classes; and the Principal Component Analysis in t-mode TPCAC (Huth, 2000; from Philip et al., 2009) for 9 and 27 classes. The leader algorithm with optimized patterns technique PETISCOC (Petisco, 2005; from Philip et al., 2009) also shows high spatial coherence for 9 and 18 classes, but does not achieve the maximum score. At the bottom of the diagram (i.e. classifications for which the highest PI1_{year} across Europe are not associated with the same CT) are found the Litynski advection method LITADVE (see Philip et al. (2009) for details) and the Kirchhofer algorithm KHC (Kirchoffer, 1974; from Philip et al., 2009).

Except for the WLKC and TPCAC, greater spatial coherence is achieved with classifications with fewer classes (around nine: yellow – light grey), but classifications with 18 or 27 classes have comparable performances. The subjective OGWSLPC is not amongst the CTCs displaying the greatest spatial coherence in their flood-generating CT (best score of 18th highest RPI(PI1) obtained for a 10-day period).

Generally, for a given CTC, the same CT is associated with the highest PI1 for all considered durations, especially for high RPI: this would suggest that the flood-generating CTs identified with this methodology are associated with rain, and when they remain over Europe for several days, generate more flooding than any other CTs would do.

Figure 5a, place holder grey print]



The minimum RPIs can inform whether some CTs rarely occur before/during a flood event, i.e. they are generally associated with negative/non significant PI1. Figure 5b shows minimum RPI(PI1_{year}) for all CTCs and corresponding CT when unique (CTX when the minimum RPI is associated with several CTs). The CTCs are ordered so that the CTCs with the highest spatial coherence (i.e. the smallest minimum RPI(PI1_{year})) are on top.

No CTC show the highest possible spatial coherence (minimum RPI between 1/40=0.025 and 1/7=0.14 depending on the number of classes) for any considered time window. The Objektive Wetterlagenklassifikation WLKC remains the most spatial coherent CTC (top of diagram) regardless the number of classes for all four durations. This would suggest an ability to discriminate flood-generating from non flood-generating atmospheric patterns.

The spatial coherence of non-flood generating patterns is, however, not as high as that for flood-generating CTi, with a minimum greater than 0.3 from the 5th 'best' CTC. This could be due to the high number of non-flood days: more than 99% of the days are non-flood, frequency never reached for any CT, hence several CTi are likely to be associated with low PI. Note that CTCs with 27 classes (red – dark grey) are generally associated with the smallest minimum RPI (i.e. better spatial coherence), while CTCs with 9 classes (yellow – light grey) show little spatial coherence. This is in contrast with the top CTCs for flood-CT being generally with greater coherence for smaller number of classes.

[Figure 5b; place holder, grey print]

Seasonal evaluation

Despite few CTCs generated seasonally (see Philip et al., 2009 for information on COST-733 CTCs database), it is still possible to evaluate possible links between flood and CT by season. Difference in results could highlight that different flood-generating mechanisms exist for different season (e.g. frontal or convective) and might also have different frequency of occurrence depending on the season. The maximum (Figure 5c) RPI(PI1_{season}(4)) was calculated for all four 3-month seasons of winter (DJF; i), spring (MAM; ii), summer (JJA; iii) and autumn (SON, iv). There is a strong variation in RPIs with the season, with a maximum RPI(PI1) of 1 obtained for 17 CTCs in summer, but only for three CTCs in winter. This might partly reflect that fewer summer flood events are observed in our sample (16.4% of POT3 are in summer, against 34.4% in winter and 30.3% in spring). This could also could reflect the difference in flood-generating mechanism between summer and winter, where summer flooding is generally caused by shortterm, localised extreme rainfall generally poorly described by large-scale atmospheric patterns such as those described by the European-scale classification tested. However, RPI does not inform on how high local PIs are, and if relationships are stronger in particular season. This could be explored in detail for selected CTCs.

For all seasons, TPCAC (except autumn) and WLKC (except summer) score highest for any number of classes. EZ850C is also found amongst the top CTCs for winter and summer, but perform less well in spring and autumn. No real effect in the number of classes can be seen, except maybe for summer where CTCs with large number of classes (red – dark grey) achieve the highest scores.

[Figure 5c, place holder, grey print]

4.3.2 Spatial coherence for PI2

Annual evaluation

RPI(PI2_{year}) reaches the maximum of 1 only for two CTCs (Figure 6a), and WLKC remains one of the best performing algorithms with 3 catalogues amongst the top 5. Interestingly, WLKC09-CT1 has the highest RPI(PI2_{year}) for all four duration/persistence tested, while WLKC09-CT4 has the maximum RPI(PI1_{year}). For shorter persistence (Figure 6a (i) and (iii)), the OGWSLPC-CT2 is associated with a high spatial coherence (RPI(PI2_{year,10lag-4pers}) of 0.94),

but this spatial coherence is reduced for longer persistence (Figure 6a (ii) and (iv): RPI(Pl2_{year,4lag-4pers}) = 0.76 for OGWSLPC-CT2). This result from the algorithm used to derive OGWSLPC which does not force its CTs to remain persistent for at least 3 days. Another objective version of the Grosswetterlagen, the threshold-based Grosswetter-types prototype classification GWTC (Philip et al., 2009), achieves high RPI(Pl2_{year}) and outperforms the 29-classes OGWSLPC for longer persistence indicators regardless the number of classes (Figure 6a (ii) and (iv)). There is generally no significant effect of the number of classes, and the same CTis are often associated with the highest RPI(Pl2_{year}) for all considered duration.

Figure 6a place holder, grey print

By contrast with RPI(PI1_{year}), WLKC is not associated with low minimum RPI(PI2_{year}) (Figure 6b), but other algorithms have CTis with systematic low/non significant links with flood events across Europe for both 4lag-2pers and 10lag-4pers (short persistence test): TPCAC, EZ850C and PETISCOC (for any class number), with the lowest RPI(PI2_{year}) associated with TPCAC09-CT9 (0.12) for 4lag-2pers. For a longer persistence, the spatial coherence reduces (the smallest RPI(PI2_{year}) is 0.23 for TPCAC09-CT9 for 4lag-4pers) and there is no consistency with CTCs with lowest RPI(PI2_{year}) for shorter persistence. The subjective OGWLSPLC only shows higher spatial coherence (minimum RPI(PI2year, 4lag-2pers=0.25) for a 2-day persistence within a 4 day window.

Results suggest that different CTis have few or no links with flood event occurrence. As already mentioned, this could partly be due to the difference between the frequency of flood events (less than 1% if the time for the POT3 samples considered) and the frequency of any CT (of at least few %): there is a large chance for any CT not to have occurred within or before a flood day, and thus, several CT could be show low PI1 and PI2 values for any river basins. These results, however, should not be interpreted necessarily as the lack of CTi linked to dry periods in the tested CTCs. This should be considered by a specific analysis aimed at investigating links between drought occurrence and CTs. This was not the purpose of this paper and will not be discussed further.

[Figure 6b place holder; grey print]

Seasonal evaluation

The seasonal variation of the maximum RPI(PI2_{season}) is more noticeable in the distribution of the top-scoring CTC rather than the score themselves: regardless of the season, only very few CTC-CTi achieve a maximum RPI of 1, but different classification show the greatest spatial coherence for different seasons. Generally, CTCs with fewer classes (9 classes, yellow – light grey) have higher RPI(PI2_{season}), which is very different from the RPI(PI2_{year}) (compare Figure 6c with Figure 6b(iv)) or the seasonal RPI(PI1_{season}).

[Figure 6c place holder grey print]

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5. Discussion and conclusion

Synoptic climatology aims to characterise simply the chaotic nature of atmospheric processes, by describing the main characteristics of large-scale atmospheric circulation in a set of well defined patterns. One of the most common ways to characterise these circulation patterns is by analysing the spatial patterns of one or more climate variables, for example the mean sea level pressure. By finding the circulation patterns reproducing most of the observed variability in the field, catalogues of circulation types (CTCs) are established that could be used to categorise any spatial pattern of the same variables.

One of the uses of such catalogues is to discriminate climatic features so that the analogy of observed climate field with a known circulation pattern (usually called circulation type) can inform on other possible phenomenon found to be associated with them.

This paper evaluates whether CTCs can inform on the occurrence or non occurrence of floods in Europe, and if the same few Circulation types (CTs) are systematically associated with flood events. Two local indicators were used to quantify these relationships, that measure if a CT occurs more frequently than usual prior/during a flood event, and if the persistence of a particular CT is generally followed by a flood event. A measure of the spatial coherence of the CT with highest local indicators was also calculated, helping comparing the relative performance of a number of CTCs. Antecedent conditions and the time-lag of the catchments were accounted for in calculating the indicators on a range of durations up to 10 days leading to a flood.

Relationships between flood occurrence on 488 river basins and CTCs were explored using a set of 64 catalogues developed in the framework of the COST Action 733, all defined from automatic algorithms using ERA-40 mslp patterns. Results showed that at the river basin scale, some circulation patterns had significant positive frequency anomalies with flood occurrence, i.e. they occurred more frequently before and during a flood than in any other period. The persistence of the same CT was also found to have strong relationships with flood events, with some CT occurring more frequently several days before and during a flood than expected by chance alone. At the scale of Europe, the same conclusions could be made, with the same CTis showing the strongest links with flood occurrence throughout Europe. The number of classes used to define the catalogues was found to be of lesser importance that the algorithm used, and depending whether global frequency or persistence of CT were analysed, could give contrasting results. The results obtained from the automatic version of the Grosswetterlagen classification (OGWSLPC) were found in line with previous research made using the subjective catalogues. Comparison of all 64 CTCs showed that OGWSLPC did not contain the most spatial coherent CT in terms if flood relationships than others, and that persistence of its CT was not a good indicator of flooding. By contrast, other algorithms such as used to derive the WLKC and TPCAC were found to generally outperform any other classification, with strong frequency anomalies and persistence for up to 10

days before/during a flood. Spatial coherence in the CT showing the strongest links with flood occurrence was seen to be very variable seasonally. This is likely to be due to the differences in flood generation mechanism in different regions, as well as different in CT occurrence throughout the year.

Flooding is one natural disaster which can occur at a large scale and have devastating consequences both in terms of material and human impacts. The results of this exploratory analysis proved there is potential to use atmospheric field patterns, and in particular, mean sea level pressure, as a tool to define proxy indicator for flood risk occurrence. However, further research is needed, in particular to assess the level of significance of the relationships for the most promising algorithms. If proven reliable, the same automatic and objective algorithms could be used to evaluate the ability of current Global Circulation Models to reproduce flood-generating atmospheric patterns, and to identify any potential bias and systematic failures. This would allow improving current climate modelling, both for medium range and long tern climate predictions. With such evaluation and improvement, there is potential for CTC to be used as tool to assess potential future changes in flood risk in Europe, and the risk of large-scale flooding as triggered by the set of atmospheric conditions.

Further research is also needed to understand why some algorithms seem to systematically fail to show strong relationships between flood occurrence and CT occurrence, and if results are linked to some lack of discrimination of climate variable such as rainfall and extreme rainfall. One possibility is that the pressure patterns they discriminate are not associated with particular rainfall totals over Europe. Some CTCs have showed difficulty to reproduce the historical frequency of some pressure dipoles such as the North Atlantic Oscillation (Monika's paper), known to be sometimes associated with wetter/dryer than usual years.

Comparison of results with associations with other climate-related events such as drought occurrence, air quality, or forest-fire will also help understand if some algorithms have systematic discriminatory powers over others, or if they are more appropriate to be used for certain applications than others. This is one of the objectives of COST733, part if which this research was undertaken.

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Figure captions:

Figure 1. Location of outlets of river basins considered in the study and distribution of the river basin areas (in km2)

Figure 2. Example results for PI1year for OGWLSLP-CT2 and CT28 (top) and PI1September-November (bottom) for OGWLSLP-CT9 and CT18; Size of dots proportional to PI1; black (grey) dots show significant (non significant/negative) results

Figure 3. Composite map of pressure patterns (lines) and associated precipitation total (blue shades, in mm) of OGWLSLP-CT2 (i) and OGWLSLP-CT28 (ii) for winter (Dec-Mar) and OGWLSLP-CT9 (iii) and OGWLSLP-CT18 (iv) for autumn (Sep-Nov)(from COST733).

Figure 4. Example results for PI2year for OGWLSLP-CT2 for the 7days leading to a flood and a persistence of (i) 1 day ; (ii) 4 days; (iii) 6 days; symbols as in Figure 2

Figure 5a. Maximum RPI(PI1year) for all CTCs for (i) 1day; (ii) 2 days; (iii) 4 days; (iv) 10 days. Bar size shows RPI for a given CTC-CTi. Bar colours distinguish classifications with \approx 27 (red – dark grey), \approx 18 (orange - grey), \approx 9 types (yellow – light grey), other type numbers (grey), and subjective classifications (blue)

Figure 5b. Minimum RPI(PI1year) for all CTCs for (i) 1day; (ii) 2 days; (iii) 4 days; (iv) 10 days. Key as in Figure 5a

Figure 5c. Maximum RPI(PI1) for all CTCs for 4days up to a flood in (i) winter; (ii) spring; (iii) summer; (iv) autumn. Key as in Figure 5a

Figure 6a. Maximum RPI(PI2year) for all CTCs for (i) 2 days persistence within 4days (4lag-2pers); (ii) 4days persistence within 4 days (4lag-4pers); (iii) 4 days persistence within 10 days (10lag-4pers); (iv) 7days persistence within 10 days (10lag-7days). Key as in Figure 5a

Figure 6b. Minimum RPI(PI2year) for (i) 2 days persistence within 4days (4lag-2pers); (ii) 4days persistence within 4 days (4lag-4pers); (iii) 4 days persistence within 10 days (10lag-4pers); (iv) 7days persistence within 10 days (10lag-7days). Key as in Figure 5a

Figure 6. Maximum RPI(PI2) for all CTCs for a 7-day persistence within 10 days up to a flood in (i) winter; (ii) spring; (iii) summer; (iv) autumn. Key as in Figure 5a





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