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TITLE OF THE THESIS: Flash Heat and Flash Cold during the 20th century in Europe

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Título: Fenómeno Flash Heat y Flash Cold a lo largo del siglo XX en Europa

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Resumen

El fenómeno atmosférico conocido como Flash Heat fue propuesto por primera vez por [4] tras analizar dos episodios de rápida advección de aire extremadamente cálido y seco que afectaron Barcelona (España) el día 27 de agosto de 2010 y Heraklion (Grecia) el día 23 de marzo de 2008. La rápida advección conllevó un incremento de la temperatura máxima en más de 5ºC para ambas ciudades. Sin embargo, ninguno de estos dos episodios puede ser considerado una ola de calor o un 'heat burst' debido a que tuvieron lugar en una escala temporal de menos de dos días (escala temporal mínima para una ola de calor) pero de más de unos pocos minutos (escala temporal para un 'heat burst'). Esto motivó la definición del fenómeno Flash Heat. Análogamente, el fenómeno Flash Cold fue propuesto posteriormente por [5].

Siguiendo las investigaciones llevadas a cabo por [5], quienes analizaron los fenómenos Flash Heat y Flash Cold acontecidos a lo largo del siglo XX en la Península Ibérica, este proyecto desarrolla su investigación extendiendo el análisis al sur, centro y norte de Europa.

Por lo tanto, el objetivo de este proyecto es estudiar cómo se han distribuido los fenómenos Flash Heat y Flash Cold por Europa entre los años 1900 y 2000. Para desarrollar la investigación, se han utilizado datos relativos a la temperatura máxima y mínima diaria así como la precipitación diaria para un total de 26 estaciones meteorológicas repartidas por todo Europa.

La memoria incluye un análisis basado en la evolución de los Flash Heat y Flash Cold para cada estación meteorológica a lo largo del siglo pasado, un estudio sobre su distribución según la estación del año así como un análisis para determinar si existe relación alguna entre la evolución en el número de episodios registrados de estos fenómenos, la temperatura media y la precipitación media. Finalmente, se estudia la influencia de las masas de aire y la distribución de los distintos tipos propuestos de Flash Heat y Flash Cold por Europa.

Una vez se haya procesado y analizado todos los datos, se presentarán las conclusiones de la investigación y se propondrá trabajo futuro en este tema.

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Overview

The atmospheric event named Flash Heat was first proposed by [4] after analyzing two rapid advection events of extremely warm and dry air which affected Barcelona (Spain) on the 27th August 2010 and Heraklion (Greece) on the 23rd March 2008. The rapid advection led to an increase of the maximum temperature by more than 5ºC in both cities. However, none of the two events could be classified as neither a heat wave nor a heat burst due to a time scale of less than two days (minimum temporal scale for a heat wave) but more than few minutes (temporal scale for a heat burst). This is what motivated the Flash Heat definition. Analogously, the Flash Cold phenomenon was later proposed by [5].

Following the research done by [5], where the Flash Heat and Flash Cold phenomena along the 20th century in the Iberian peninsula was analyzed, this paper develops their investigation by extending the analysis to southern, central and northern Europe.

Thus, the aim of this paper is to study how the Flash Heat and Flash Cold phenomena have distributed over Europe between 1900 and 2000. To develop the research, maximum and minimum daily temperature and precipitation data has been used for a total of 26 different meteorological stations across Europe.

The paper includes an analysis based on the evolution of Flash Heat and Flash Cold for each station throughout the last century, a study on its seasonal distribution and an analysis to determine if there is any relationship between the evolution in the number of episodes registered of these phenomena, mean temperature and mean precipitation. Finally, the influence of air masses will be assessed and the distribution of different Flash Heat and Flash Cold types over Europe will be quantified.

Once all the data processed and analyzed, the conclusions of the research will be presented and future work on this topic will be proposed.

First and foremost, we would like to express our sincere gratitude to the director of our thesis Prof. David Pino for the continuous support, for his patience, motivation and knowledge. His guidance helped us in all the time of research and writing of this thesis.

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Last but not the least, we would like to thank our families for being a constant source of love, patience, support and strength. This journey would not have been possible if not for them, and we dedicate this thesis to them.

INDEX

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

A heat wave is defined by the World Meteorological Organization (WMO) as a period of five or more days in which there is an exceedance of at least 5ºC in the average daily maximum temperature with respect to the period 1961-1990 (see [1]).

On the contrary, the National Weather Service (NWS), an agency of the United States government, defines a heat wave as an event which lasts two or more days that is characterized by abnormally and uncomfortably hot and unusually humid weather (see [2]).

The definition of this atmospheric event presents slight differences according to the national weather service consulted. However, all of them agree when it comes to its duration: for a heat wave to happen there must be at least two consecutive days with abnormal temperature values.

When moving to a smaller temporal scale, a heat burst is defined as a rare atmospheric event which consists of a sudden temperature rise and a fall in relative humidity with a duration of less than an hour, usually lasting a few minutes (see [3]).

In between these two events, having significant different temporal scales, there is a phenomenon occurring at intermediate temporal and spatial scales, which has been named Flash Heat (see [4]). Analogously, the Flash Cold concept has also been introduced by further investigation (see [5]). Flash Heat (FH) and Flash Cold (FC) phenomena are associated to a sudden increase or decrease of temperature, respectively, for a period of time ranging from 1 to 24 hours.

The main purpose of this project is to use daily data from several weather stations across Europe (South, Central and North) dating from 1900 until 2000 to analyze the different patterns in Europe of these types of phenomena and the tendency observed during the last century.

The project will consist of the following three sections:

I. In Chapter 1, a definition for the FH and FC phenomena will be given and their three proposed types will be introduced.

II. In Chapter 2, the data of interest for the analysis to be carried along this project and the sources from which the data has been obtained will be presented. Besides, the treatment done to this data will also be explained in detail.

III. In Chapter 3, the results of analyzing the data will be presented for both FH and FC and for each climate type existing in Europe. Later on, the influence of season, mean temperature, mean precipitation, air masses and FH and FC type's distribution will be exposed.

CHAPTER 1. THEORETICAL STUDY

1.1. Flash Heat

The definition of the FH phenomenon comes from the need to define an observed event, which consists of a sudden increase of temperature that happens in between heat wave and heat burst temporal and spatial scales. A comparison of heat bursts, FH and heat waves is presented in **Table 1.1**.

Table 1.1 Temporal and spatial differences of heat burst, FH and heat wave phenomena (see [4]).

	Temporal Scale	**Spatial Scale**	**Driving mechanism**
Heat burst	Few minutes	Micro-β,γ (<2km)	Thunderstorms
Flash heat	1-24 hours	Meso-β,γ (20-200km)	General atmospheric circulation, Foehn effect
Heat wave	From 2 days to few weeks	Meso-α (200-2000km)	General atmospheric circulation

A FH can be defined as a meteorological event that happens when there is an increase of temperature of 5ºC or more and a decrease in relative humidity, lasting for up to 24 hours maximum and taking place within an area from 20 to 200km (see [4]).

FH events are believed to have an impact on human health, economic activities such as agriculture and the quality of the air. Given the fact that this temperature increase happens suddenly within a short temporal scale, it is difficult to adopt preventive measures to mitigate its effects (see [4]).

According to the classification proposed by [5], FH are split into three different categories depending only on the maximum temperature difference from the previous and later day. The FH types are shown in **Table 1.2**.

Table 1.2 FH types.

FH type	**Temperature difference from the previous and later day**
1	+5ºC to +7ºC
2	+7ºC to +9ºC
3	+9ºC or more

1.2. Flash Cold

Analogously to the FH definition and types, the FC phenomenon has been proposed by [5] to name the events in which instead of having a sudden increase of the maximum temperature, there is a sudden decrease of the minimum temperature.

Thus, a FC can be defined as a meteorological event that happens when there is a decrease of temperature of 5ºC or more, lasting for up to 24 hours maximum and taking place within an area from 20 to 200km.

FC are split into three different categories depending only on the minimum temperature difference from the previous and later day. The FC types are shown in **Table 1.3**.

Table 1.3 FC types.

FC type	Temperature difference from the previous and later day
1	-5ºC to -7ºC
2	-7ºC to -9ºC
3	-9ºC or more

CHAPTER 2. METHODOLOGY

2.1. Selected data

The development of this project requires identifying all FH and FC episodes that have occurred throughout Europe for the 20th century. With this objective, the data needed to compute both phenomena are the maximum and minimum daily temperature for each meteorological station taken into consideration.

All this information has been gathered from two different sources. In some cases, it has been directly obtained by contacting directly the corresponding national meteorological services. The other information has been downloaded from the European Climate Assessment and Dataset (ECA&D, see [6]), an extensive dataset of daily meteorological station observation. This dataset is considered to be the first step towards a high-resolution dataset for Europe and the Middle East having a high potential for climate studies (see [7]).

Since the aim of the project is to study the FH and FC phenomenon across Europe, a total of 28 meteorological stations have been chosen in order to cover as much extension as possible. The list of the stations analyzed is shown in **Table 2.1**.

Table 2.1 Meteorological stations across Europe chosen for FH and FC analysis.

	Station	Country	Height (m)	Latitude	Longitude
1	A Coruña	Spain	58	43° 22’ 1” N	8° 25’ 9” E
2	Armagh	Great Britain	62	54° 21’ N	6° 39’ W
3	Athens	Greece	103	37° 58’ 24” N	23° 43’ 5” E
4	Barcelona	Spain	412	41° 25’ 5” N	2° 7’ 26” E
5	Bern	Switzerland	553	46° 59’ 27” N	7° 27’ 50” E
6	Bologna	Italy	53	44° 30’ N	11° 20’ 45” E
7	Bordeaux	France	47	44° 49’ 54” N	0° 41’ 30” W
8	Brindisi	Italy	10	40° 37’ 59” N	17° 55’ 59” E
9	Buzau	Romania	97	45° 7’ 59” N	26° 51’ E
10	Debrecen	Hungary	110	47º29’44” N	21º37’48” E
11	Den Helder	The Netherlands	4	52° 57’ 41” N	4° 44’ 49” E
12	Galway	Ireland	8	53° 16’ 48” N	9° 1’ 12” W
13	Hamburg	Deutschland	11	53° 38’ 6” N	9° 59’ 24” E
14	Helsinki	Finland	4	60° 10’ 48” N	24° 56’ 24” E
15	Jena	Deutschland	155	50° 55’ 36” N	11° 35’ 3” E
16	Karlstad	Sweden	46	59° 21’ N	13° 28’ E
17	Kiev	Ukraine	166	50° 24’ N	30° 31’ 59” E
18	Ljubljana	Slovenia	299	46° 3 ’56” N	14° 31’ 1” E
19	Maastricht	The Netherlands	114	50° 54’ 19” N	5° 45’ 42” E
20	Madrid	Spain	667	40° 24’ 42” N	3° 40’ 41” E
21	Marseille	France	75	43° 18’ 18” N	5° 23’ 48” E

22	Odesa	Ukraine	42	46° 28’ 48” N	30° 37’ 48” E
23	Oxford	Great Britain	63	51° 46’ N	1° 16’ W
24	Paris	France	75	48° 49’ 23” N	2° 20’ 12” E
25	Sodankyla	Finland	179	67° 21’ 57” N	26° 37’ 59” E
26	Stornoway	Great Britain	21	58° 13’ 12” N	6° 19’ 12” W
27	Tartu	Estonia	59	58° 18’ N	26° 43’ 59” E
28	Vilnius	Lithuania	156	54° 37’ 59” N	25° 06’ E

Besides the maximum and minimum daily temperature, two more variables will be further used in this report: the daily amount of precipitation and the mean daily temperature. These variables have also been obtained from ECA&D (see [6]).

2.2. Data treatment

The FH and FC episodes have been found by using the Matlab script developed by Almarza and Cortés (2015) (see [5]). This script analyzes all the databases in search of FH and FC phenomenon. This is done by introducing the base temperature value from which the phenomena are considered to happen. The Matlab program compares the temperature of each day with the temperature of the previous and later day. When the base temperature is matched or exceeded within 24 hours, one of the two phenomena will have been identified.

An example of both FH and FC in Helsinki can be checked in **Table2.2** and **Table 2.3** respectively.

Table 2.2 FH example (Helsinki).

Day	Daily maximum temperature (ºC)
23/07/1945	20
24/07/1945	26.1
25/07/1945	21

Table 2.3 FC example (Helsinki).

Day	Daily minimum temperature (ºC)
10/03/1945	-9.9
11/03/1945	-18.3
12/03/1945	-7.3

In order to ensure a minimum standard of data quality, the script has been modified by adding a new functionality. This extension of the original script looks for missing data values in each station. Its purpose is to ensure that if any decade has more than a 10% of missing daily data, this decade will not be

taken into consideration in the report. The definitive versions of the script are included in **ATTACHMENT A** and **ATTACHMENT B**.
Once this analysis was carried, there were two stations that were eliminated and thus will not be considered further on this report. These stations are Galway (Ireland) and Bordeaux (France), which due to their lack of data affecting different decades have been not considered.

In this sense, two exceptions have been made. This is the case of Athens (Greece) and Brindisi (Italy). Despite having missing data for the first half of the 20th century, both stations will be kept for further analysis. This decision has been taken given the difficulty to find surface air temperature data series for Mediterranean stations before the 1950s.

The meteorological stations that will be considered from now on are displayed in **Figure 2.1**.

Figure 2.1 Meteorological stations analyzed.

Beyond the script explained, two more complimentary scripts have been developed for further analysis. One of these scripts is used to calculate the mean temperature for each decade from the mean daily temperature data for each station (see **ATTACHMENT C**). In a similar way, the other script calculates the mean amount of precipitation for each decade from the daily amount of precipitation for each station (see **ATTACHMENT D**). These scripts will be specifically used for Section 3.3.

CHAPTER 3. ANALYSIS

3.1. Climate classification according Köppen

In order to deeply analyze how FH and FC phenomena occur across Europe, a wide geographical area needs to be studied. With the aim of dealing with such a big amount of climate information, the meteorological stations have been organized into climatic regions with similar characteristics. The final objective is to determine if there is any resemblance in the evolution of these phenomena in places with similarities in their climates.

This stations grouping has been done according to the Köppen climate classification system, which is the most widely used modern climate classification system. This system, which first appeared in 1918 and since then it has constantly been modified and refined by numerous geographers and climatologists, defines each climate type by using temperature and precipitation as the main variables (see [8]).

The Köppen system consists of five major climatic types, which are designated by a capital letter (A, B, C, D and E). A general overview on these climatic types is given in **Table 3.1**.

Table 3.1 The five major climatic types of Köppen classification system (see [9]).

	Climatic type	Brief overview
A	Tropical moist climates	All months have an average temperature above 18ºC. Since all months are warm, there is no real winter season.
B	Dry climates	Deficient precipitation most of the year. Potential evaporation and transpiration exceed precipitation.
C	Moist mid-latitude climates with mild winters	Warm-to-hot summers with mild winters. The average temperature of the coldest month is below 18ºC and above -3ºC.
D	Moist mid-latitude climates with severe winters	Warm summers and cold winters. The average temperature of the warmest month is exceeds 10ºC, and the coldest monthly average drops below -3ºC.
E	Polar climates	Extremely cold winters and summers. The average temperature of the warmest month is below 10ºC. Since all months are cold, there is no real summer season.

According to the classification presented in **Table 3.1**, all the European meteorological stations studied in this report belong either to types C or D, i.e.,

to similar climate types. However, each of these groups is divided into different subcategories according to regional characteristics.
Type C climates, which can be understood as a transitional layer between drier tropical climates and moist mid-latitude climates with severe winters, are spread equatorward along mid-latitudes. This major climatic type is subdivided into Mediterranean (Csa, Csb), Humid Subtropical (Cfa, Cwa, Cwb) and Oceanic (Cfb, Cfc) climates based on precipitation seasonality and summer temperatures (see [8]). This classification is shown in **Table 3.2**.

Table 3.2 Classification for C climates (see [7]).

Letter symbol				
1st	**2nd**	**3rd**	**Climatic characteristics**	**Criteria**
C			Moist with mild winters	Average temperature of coolest month is below 18ºC and above -3ºC
	w		Dry winters	Average rainfall of wettest summer month at least 10 times as much as in driest winter month
	s		Dry summers	Average rainfall of driest summer month less than 4cm; average rainfall of wettest winter month at least 3 times as much as in driest summer month
	f		Wet all seasons	Criteria for w and s cannot be met
		a	Summers long and hot	Average temperature of warmest month above 22ºC; at least 4 months with average above 10ºC
		b	Summers long and cool	Average temperature of all months below 22ºC; at least 4 months with average above 10ºC
		c	Summers short and cool	Average temperature of all months below 22ºC; 1 to 3 months with average above 10ºC

On the other hand, type D climates extend broadly across North America and Eurasia with latitude values ranging from 40ºN to 70ºN. All the places with climate D need to fulfill the condition of having an average temperature below -3ºC in its coldest month. Köppen determined this value of -3ºC after finding out that it was the temperature that marked the southern limit of persistent snow cover in winter for Europe. Thus, D climates are exposed to a great deal of winter snow that stays on the ground for long periods (see [9]).

D climates, based on temperature, are split into Humid Continental (Dfa, Dfb) and subarctic (Dfc) climates. This classification is shown in **Table 3.3**.

Table 3.3 Classification for D climates (see [9]).

Letter symbol				
1st	**2nd**	**3rd**	**Climatic characteristics**	**Criteria**
D			Moist with cold winters	Average temperature of coldest month is -3ºC or below; average temperature of warmest month is greater than 10ºC
	w		Dry winters	Same as under Cw
	s		Dry summers	Same as under Cs
	f		Wet all seasons	Same as under Cf
		a	Summers long and hot	Same as under Cfa
		b	Summers long and cool	Same as under Cfb
		c	Summers short and cool	Same as under Cfc
		d	Summers short and cool; winters severe	Average temperature of coldest month is -38ºC

In **Figure 3.1** a map of Köppen climate distribution system over Europe and the Middle East is shown.

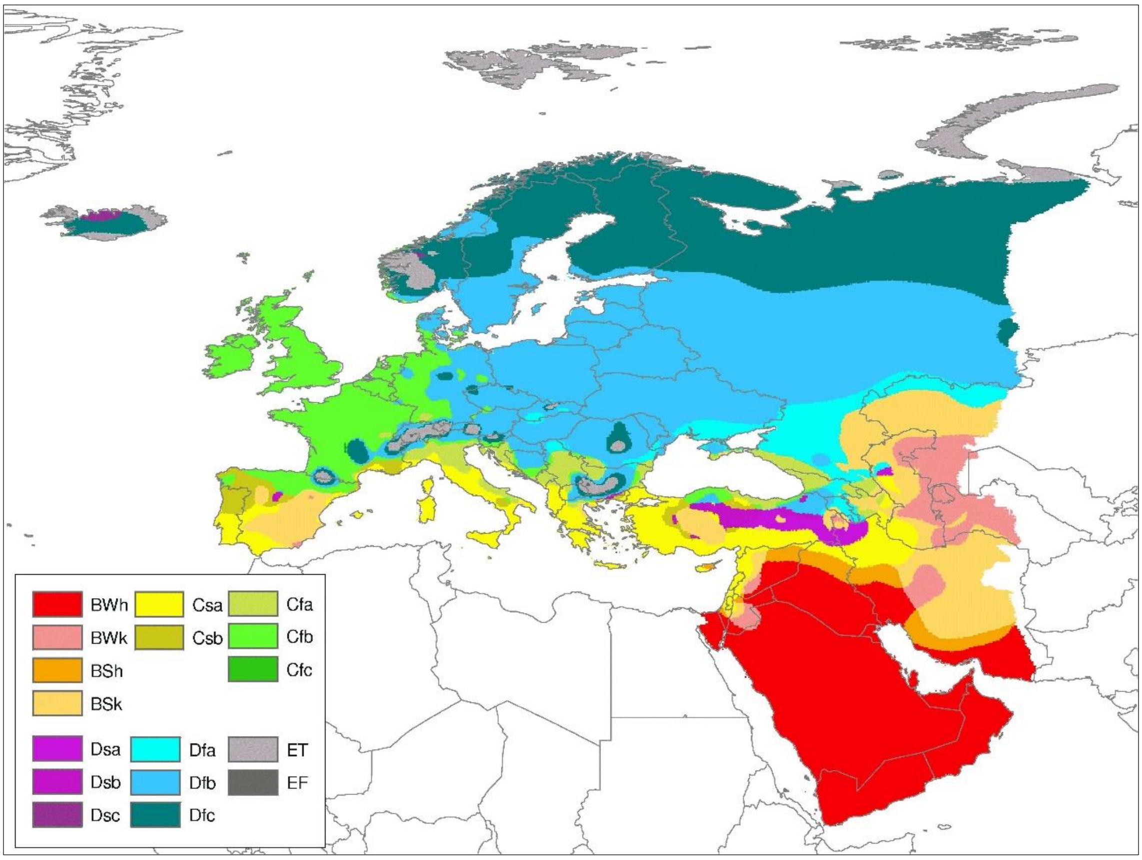

Figure 3.1 Updated Köppen climate classification (see [10]).

3.1.1. Oceanic Climate

Oceanic climates, which are also known as marine west coast climates, extend poleward along western and central Europe. With latitudes between 40º and 60º, these regions are continuously exposed to westerly winds coming from the ocean. This year-round cool maritime influence moderates temperatures leading to extraordinarily temperate climates considering the latitude (see [8]).

Regarding precipitation, oceanic climates are among the wettest of the mid-latitudes again due to the influence of the ocean. The onshore oceanic flow causes a remarkable precipitation frequency all year round in the form of light or moderate rain associated with maritime polar air masses (see [9]).

The stations belonging to this kind of climates are Armagh, Den Helder, Hamburg, Jena, Maastricht, Oxford, Paris and Stornoway. The stations of Bologna and Ljubljana will also be included in this section but taking into account some considerations. Bologna is generally considered to have a humid subtropical climate along with other inland northern areas of Italy. However, the only difference between oceanic (Cfb) and humid subtropical (Cfa) climates is based in cooler summers experienced in the former climates (see [9]). Thus, as the only station featuring Cfa climate is Bologna, it will be studied in this section for simplicity and similarities with Cfb climate. For the case of Ljubljana, it is generally classified as Oceanic Climate despite being placed in a location where humid continental, subarctic and humid subtropical climates regions intersect. This is because Ljubljana belongs to the Carpatho-Balkan-Dinaric region, which due to its large extent and the presence of the Carpathians, the Balkans and the Dinaric Alps is known to have a very diverse climate. Air temperature, precipitation or snow cover change substantially depending on the specific region and orographic factors such as elevation, mountain slope angle or exposure (see [11]).

FH in Oceanic Climate

In this section, the evolution of FH phenomenon has been analyzed for the stations having an Oceanic Climate.

It is important to remember that for some stations there is a lack of data available (the decade of 1900 for Den Helder and Maastricht and the decade of 1920 for Ljubljana). In order to have an idea of what the real total amount of FH episodes could be and only with the purpose of checking if this would change its position inside the ranking in **Table 3.4**, the following approximation has been used: the mean FH per decade has been computed with the available decades and it has been added to the missing decades.

Table 3.4 Classification of stations with Oceanic climates according to the mean annual precipitation and temperature (with data from 1982 until 2012 obtained from [12]), latitude, longitude, number of FH registered for the 20th century and height. Stations are grouped according to their longitude and FH number into stations with east longitudes and 108 FH episodes or more (in gray) and stations with west longitudes and 84 FH episodes or less (in orange).

Mean annual precipitation (mm, high to low)	**Mean annual temperature (ºC, low to high)**	**Latitude (southward)**	**Longitude (eastward)**	**FH total**	**Height (m)**
Ljubljana (1290)	Stornoway (8.1)	Stornoway	Ljubljana	Jena 298	155
Stornoway (1151)	Hamburg (8.5)	Armagh	Jena	Maastricht 242 (269*)	114
Armagh (887)	Jena (8.6)	Hamburg	Bologna	Paris 211	75
Maastricht (790)	Armagh (8.9)	Den Helder	Hamburg	Den Helder 186 (201*)	4
Bologna (774)	Den Helder (8.9)	Oxford	Maastricht	Hamburg 176	11
Den Helder (765)	Maastricht (9.8)	Jena	Den Helder	Ljubljana 156	299
Hamburg (738)	Oxford (9.8)	Maastricht	Paris	Bologna 108	53
Paris (637)	Ljubljana (10.4)	Paris	Oxford	Oxford 84	63
Oxford (631)	Paris (11.3)	Ljubljana	Stornoway	Armagh 55	62
Jena (565)	Bologna (14)	Bologna	Armagh	Stornoway 26	21

**Total FH value with the approximation for missing decades (1900 for Den Helder and Maastricht and 1920 for Maastricht)*

From **Figure 3.2** and **Table 3.4**, it is possible to divide the stations into two separate groups. These two groups are proposed according to the total amount of FH, the evolution in the number of FH per decade and their longitude similarity. However, altitude, the total amount of precipitation and latitude of the stations do not play any role in this classification.

On the one hand, there are the stations situated on western longitudes, particularly Oxford, Armagh and Stornoway, which have been highlighted in **Table 3.4** in color orange. These stations are characterized by a low number of FH with values of no more than 10 episodes per decade in general (with the exceptions of the decades of 1930 and 1950 for Oxford station with 11 and 12 episodes respectively) and less than 100 episodes in the whole century.

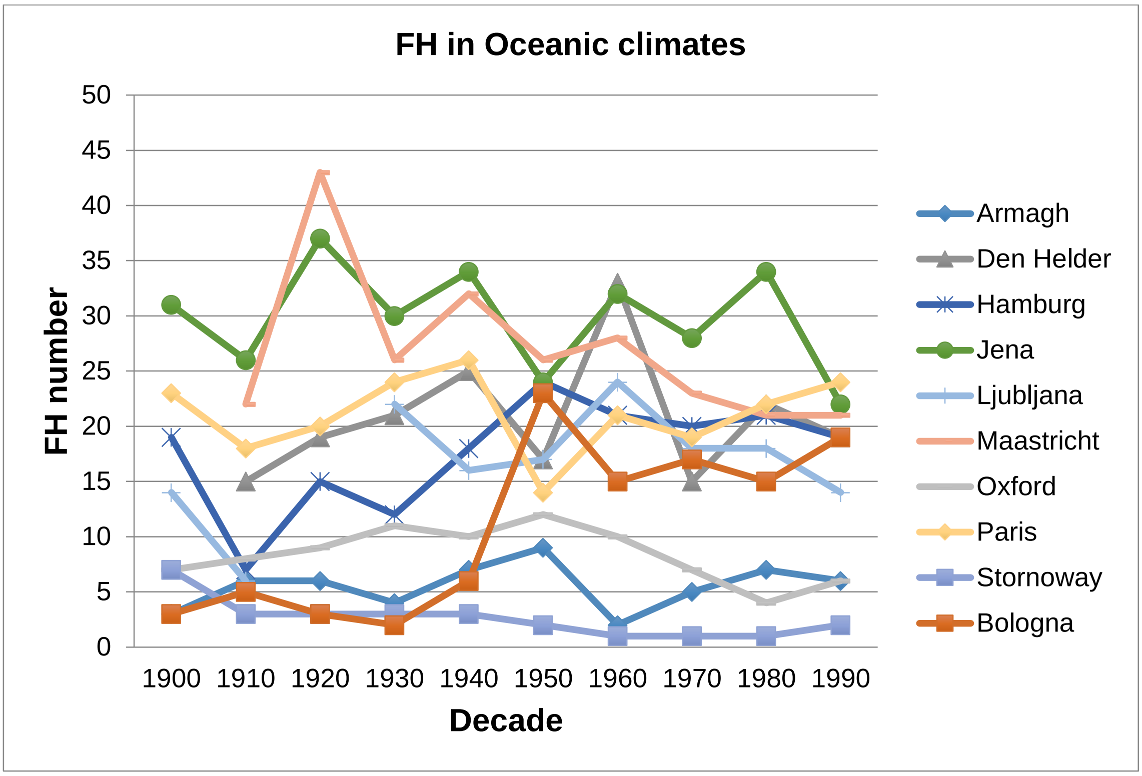

Figure 3.2 Evolution in the number of FH episodes registered every decade in stations with Oceanic Climate for the period 1900-2000.

On the other hand, there are the stations situated on eastern longitudes, particularly Jena, Maastricht, Paris, Den Helder, Hamburg, Ljubljana and Bologna. These stations are characterized by having a higher number of FH with values oscillating from 15 to 35 episodes per decade and from 108 to 298 episodes in the whole century.

This difference between western and eastern stations with an Oceanic Climate, could be explained by the influence the Atlantic Ocean and the North Sea have over the United Kingdom and Ireland. For this precise geographical area, which is highly exposed to the North Atlantic Drift, the ocean influence moderates temperatures leading to narrower temperature fluctuations. This narrowing prevents the appearance of temperature extremes that could cause a FH. As you approach the continental coast and especially the further inland you go (eastward), the more mitigated the ocean influence will be.

Thus, given a sudden advection of a warm and dry air mass northward that eventually reaches the British Islands, the high influence exerted by both the North Sea and the Atlantic Ocean will moderate the impact of this air mass with a higher probability than other regions situated further from the coast.

However, nowadays the contribution of the North Atlantic Drift to the temperature moderation is a matter of dispute. Some recent publications point that the influence of atmospheric waves bringing subtropical air northwards have a deeper impact on the temperature differential than thermohaline circulation has (see [13], [14] and [15]).

FC in Oceanic Climate

Similarly to FH, the evolution of FC phenomenon has been analyzed for the stations having an Oceanic Climate. Again, the lack of data for some specific decades (same than mentioned in Section 3.1.1.1) has been approximated and quantified exactly in the same way than explained for FH.

Table 3.5 Classification of stations with Oceanic climates according to the mean annual precipitation and temperature (with data from 1982 until 2012 obtained from [12]), latitude, longitude, number of FC registered for the 20th century and height. Stations are grouped according to their FC number into stations with 115 FH episodes or more (in gray) and stations with 40 FH episodes or less (in orange). Ljubljana and Bologna, in white, are treated separately and thus are not included in neither of the groups.

Mean annual precipitation (mm, high to low)	Mean annual temperature (ºC, low to high)	Latitude (southward)	Longitude (eastward)	FC total	Height (m)
Ljubljana (1290)	Stornoway (8.1)	Stornoway	Ljubljana	Jena 218	155
Stornoway (1151)	Hamburg (8.5)	Armagh	Jena	Stornoway 185	21
Armagh (887)	Jena (8.6)	Hamburg	Bologna	Hamburg 154	11
Maastricht (790)	Armagh (8.9)	Den Helder	Hamburg	Oxford 134	63
Bologna (774)	Den Helder (8.9)	Oxford	Maastricht	Armagh 115	62
Den Helder (765)	Maastricht (9.8)	Jena	Den Helder	Ljubljana 107 (119*)	299
Hamburg (738)	Oxford (9.8)	Maastricht	Paris	Den Helder 40 (44*)	4
Paris (637)	Ljubljana (10.4)	Paris	Oxford	Bologna 23	53
Oxford (631)	Paris (11.3)	Ljubljana	Stornoway	Paris 20	75
Jena (565)	Bologna (14)	Bologna	Armagh	Maastricht 9 (10*)	114

**Total FC value with the approximation for missing decades (1900 for Den Helder and Maastricht and 1920 for Maastricht)*

From the information shown in **Table 3.5**, stations can be divided into two separate groups according to the total amount of FC. However, no relationship can be established between FC and altitude, total amount of precipitation, longitude or latitude of the stations. Thus, the classification proposed for the FH analysis in Oceanic climates cannot be used for the FC phenomenon.

The stations of Armagh, Oxford and Stornoway (highlighted in orange color in **Table 3.5**) are among the ones with a higher FC register. According to the explanation given before for the FH phenomenon, the British Islands and Ireland are highly exposed to the influence of the Atlantic Ocean and the North Sea leading to mild temperatures. However, these FC values can be mainly explained by two factors: winter anticyclones and the invasion of polar air masses.

An anticyclone, also known as a high pressure area, is defined by the United States National Weather Service (see [16]) as a large-scale circulation of winds around a central region of high atmospheric pressure, clockwise in the Northern Hemisphere, which are characterized by bringing stable conditions and clear skies. During the winter nights, the absence of clouds implies that the heat radiated from the surface escapes. This rapid cooling of the ground leads to a lowering in temperature which, if strong enough, can end up in a FC episode.

Besides, England and Ireland are sometimes invaded by polar air masses that can cause a decrease in temperature of more than 5ºC within a period of 24 hours. Thus, this becomes the second reason that explains this high number of FC episodes.

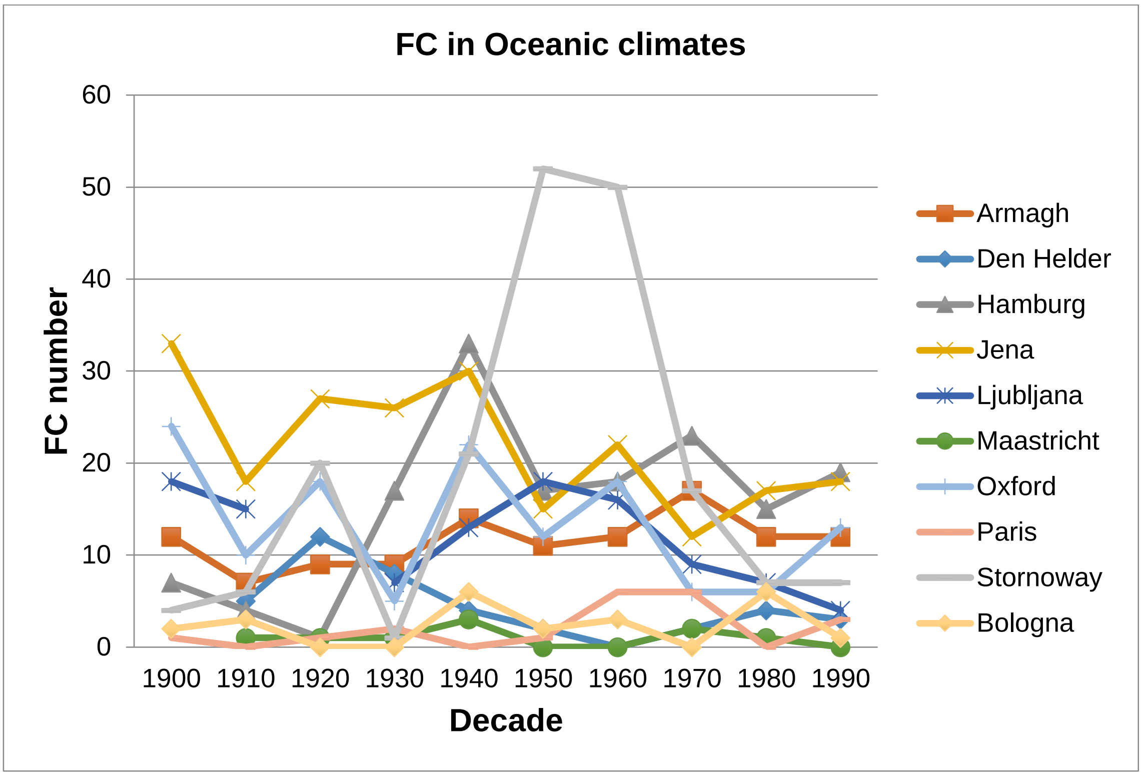

Figure 3.3 Evolution in the number of FC episodes registered every decade in stations with Oceanic Climate for the period 1900-2000.

Regarding the evolution of the FC events throughout the century in **Figure 3.3**, it is important to highlight the discontinuous evolution experienced by Stornoway. It first increased from 1 FC in the decade of 1930s up to 52 FC in the decade of 1950s, in just twenty years. Later on, the number of FC suffered an abrupt decrease in a period of ten years, from 50 FC in 1960s down to 17 episodes in 1970s. These oscillations may be explained by specific local factors that will not be analyzed in this report.

On the other hand, far eastward are located the stations of Den Helder, Maastricht and Paris (gray in **Table 3.5**), with similar FC evolution as shown in **Figure 3.3**. These locations, which share a close longitude, are still greatly influenced by the Atlantic Ocean which contributes to have mild winters and cool summers with small temperature fluctuations. Thus, these areas are not prone to have FC.

Further to the East, the stations of Hamburg and Jena (orange color in **Table 3.5**) maintain high FC records experiencing a similar evolution from the decade of 1940s onwards as can be seen in **Figure 3.3**. According to their position, Hamburg and Jena are influenced by both the North Sea and Baltic Sea. The absence of remarkable orography on the way from the coast of northern Germany up to Jena, causes this city to still receive the influence from the sea. However, as explained before, the further inland, the less impact experienced. This explains the lower FC register in Hamburg in comparison to Jena.

It is important to take into account the difference in the temperature of the different water masses. In this sense, the Atlantic Ocean on the West of the British Islands is warmer than the North Sea which at the same time is warmer than the Baltic Sea. An example of the sea surface temperature is shown in **Figure 3.4**.

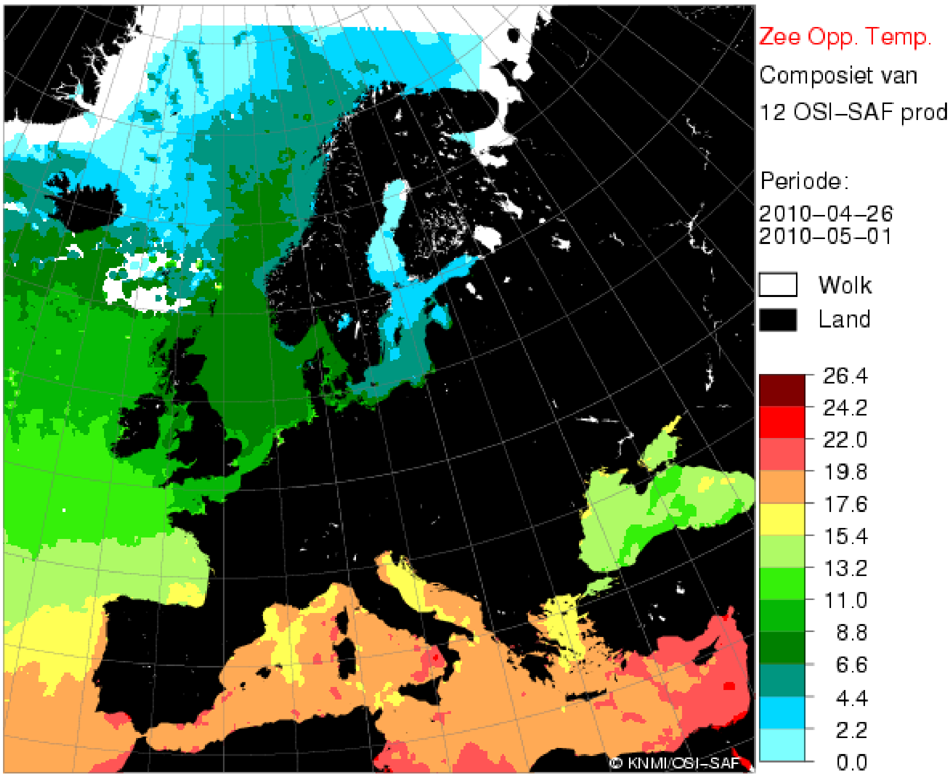

Figure 3.4 Mean sea surface temperature from 26th April until 1st May 2010 (see [17]).

According to these differences, the stations mainly influenced by the Baltic Sea will have colder temperatures in winter in comparison to those exposed to the influence of the North Sea or Atlantic Ocean. The cooler the sea mass, the less capability of moderating temperatures will have. This may also help to explain the difference in FC episodes experienced by Paris or Den Helder with the FC episodes occurred in Hamburg. As an example, the mean temperature distributions throughout the year for Hamburg, Paris and Maastricht can be seen in **Figure 3.5**.

Again for this case, these stations will be influenced by the invasion of polar air masses and the so-called Siberian Highs during the winter, that is, continental high-pressure areas originated to the East. Polar air masses bringing low temperatures and Siberian Highs carrying colder drier weather mitigate the warming influence of sea masses. Under these conditions temperature can easily drop and lead to a FC episode.

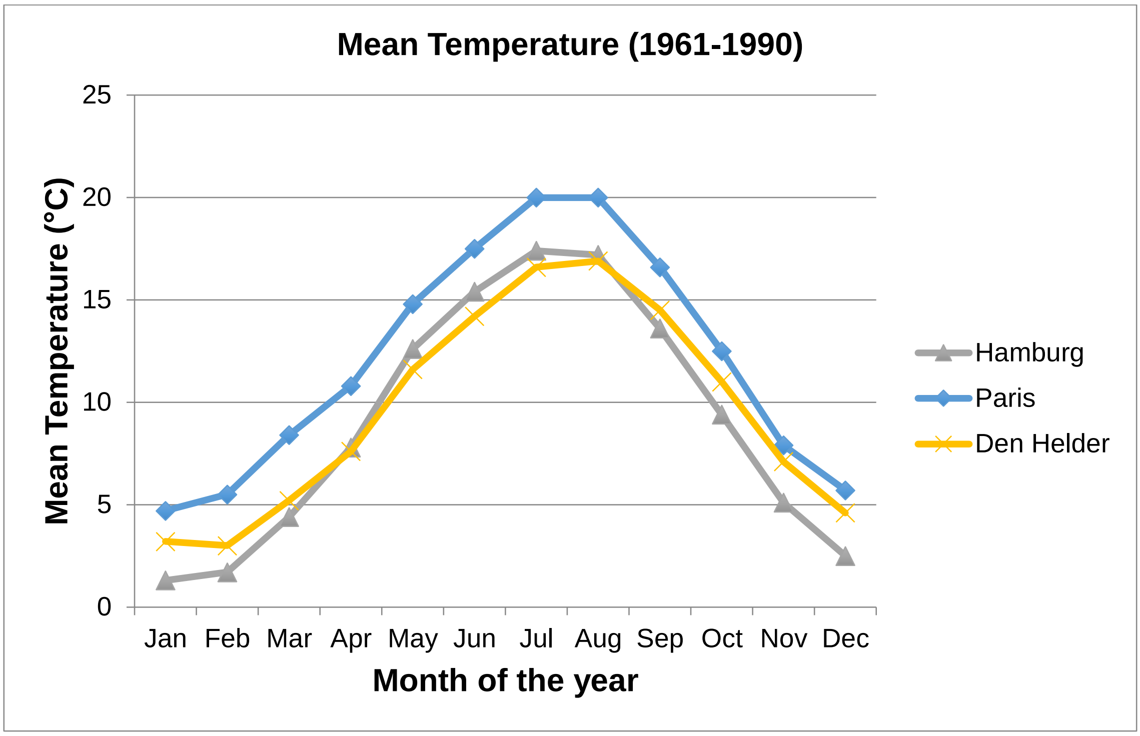

Figure 3.5 Mean temperature throughout the year for the period 1961-1990 for the stations of Hamburg (in gray), Paris (in blue) and Den Helder (in yellow) (see [18]).

Finally, the stations of Bologna and Ljubljana are analyzed separately. For the station of Bologna, which despite its location is little influenced by the sea, the number of FC decreases to 23 episodes for the whole period from 1900 until 2000. Thus, along with Paris and Maastricht, constitute the group with the lower amount of FC registered for this type of climate.

In the case of Ljubljana the registered FC is similar to the one obtained for Hamburg or Jena. Inside the wide variety of climates in Slovenia, Ljubljana is considered to have an Oceanic Climate. Furthermore, its specific geographical situation within the Ljubljana Basin, between the Alps and the Karst, has a direct influence in the weather of the city. During winter months, Ljubljana is affected by a meteorological phenomenon known as temperature inversion (see [19]). This phenomenon can help to explain the more than one hundred FC events registered in the city for the last century.

3.1.2. Mediterranean Climate

Moving equatorward of Oceanic Climates (Cf) implies starting a transition to Mediterranean Climates (Cs). According to the Köppen system abbreviations, this shift from one climate to the other implies changing a ‘f’ by an ‘s’. In other words, instead of having precipitation all year round, Mediterranean Climates will experience clear, dry conditions during summer due to the greater influence of the subtropical highs (see [9]).

Mediterranean climates are found on latitudes centered at about 35ºN and 35ºS. Despite being present in regions of North and South America, Africa and Australia, the only extensive area for this kind of climate is found around the Mediterranean Sea (see [8]).

The stations with a Mediterranean Climate are A Coruña, Athens, Barcelona, Brindisi, Madrid and Marseille. All stations except of A Coruña, which experiences a warm-summer Mediterranean climate (Csb), are classified as hot-summer Mediterranean climate (Csa). Csb is usually associated to the influence of a cool ocean current and upwelling, a process in which deep and cold water rises toward the surface of oceans. Csa coastal areas have milder summers and winters than inland areas as a result of sea breezes and frequent coastal advection fog.

FH in Mediterranean Climate

In this section, the evolution of FH phenomenon has been analyzed for the stations having a Mediterranean Climate.

According to the results obtained in **Table 3.6**, it does not exist an apparent link between the total number of FH episodes and the rest of variables. Moreover, the differences observed in the FH registered are not significant.

The tendencies observed throughout the century in **Figure 3.6** show a slight difference between the amount of FH episodes experienced by A Coruña and Brindisi and the amount registered by the rest. Barcelona, Brindisi, Madrid and Marseille show a similar behavior with the exception of the sustained growth observed between the 1950s and 1980s in Barcelona. However, after reaching the maximum of 12 FH episodes on the decade of 1980, the tendency shown is to decrease this number and recover FH values similar to the observed in other comparable stations such as Marseille. Similar growths are also observed for both A Coruña and Brindisi, between the decades of 1950 and 1970 for Brindisi and the decades of 1970 and 1980 in A Coruña. Immediately after, from the 1980s onwards, all stations show a common lowering tendency in the number of FH.

Table 3.6 Classification of stations with Mediterranean climates according to the mean annual precipitation and temperature (with data from 1982 until 2012 obtained from [12]), latitude, longitude, number of FH registered for the 20th century and height.

Mean annual precipitation (mm, high to low)	Mean annual temperature (ºC, low to high)	Latitude (southward)	Longitude (eastward)	FH total	Height (m)
A Coruña 1025	Madrid 13.7	Marseille	A Coruña	A Coruña 139 (154*)	13
Barcelona 612	Marseille 14.2	A Coruña	Madrid	Brindisi 100 (200*)	16
Brindisi 598	A Coruña 14.2	Barcelona	Barcelona	Marseille 61	13
Marseille 588	Barcelona 16.5	Madrid	Marseille	Barcelona 42 (47*)	20
Madrid 450	Brindisi 16.5	Brindisi	Brindisi	Madrid 37	676
Athens 397	Athens 18.1	Athens	Athens	Athens 14 (28*)	87

**Total FH value with the approximation for missing decades (1900 for Barcelona, 1910 for A Coruña and 1900 to 1940 inclusive for Athens and Brindisi)*

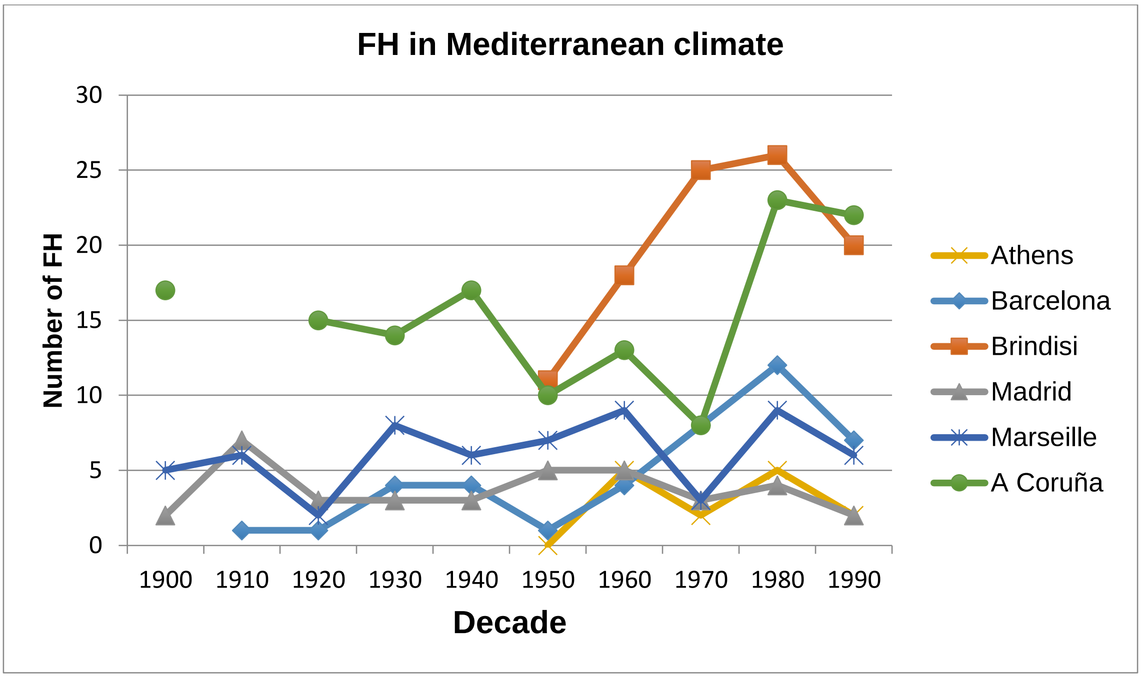

Figure 3.6 Evolution in the number of FH episodes registered every decade in stations with Mediterranean Climates for the period 1900-2000.

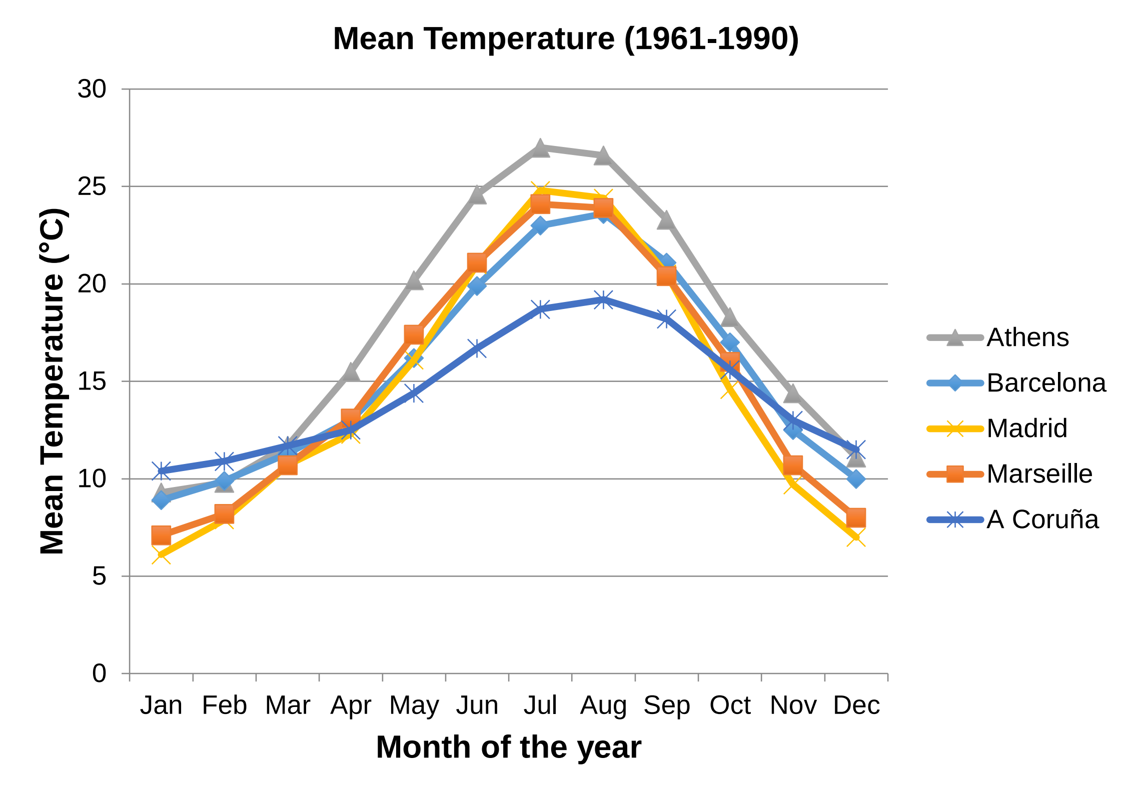

Figure 3.7 Mean temperature throughout the year for the period 1961-1990 for the stations of Athens (in gray), Barcelona (in light blue), Madrid (in yellow), Marseille (in orange) and A Coruña (in dark blue) (see [18]).

Marseille, Barcelona, Madrid and Athens have similar mean temperatures as can be seen in **Figure 3.7**. However, when going more into detail, it is observed that Athens clearly has the highest temperatures throughout the year. This could help to explain why this is the city with the lower number of FH episodes. Possibly, in the event of a sudden advection of a warm and dry air mass, the higher the temperature of the city, the less probability of reaching the threshold of 5ºC temperature increase needed by definition to have a FH episode.

The cases of A Coruña and Brindisi shall be commented separately. Brindisi must be analyzed by taking into account the topography around the city. The Apennines is a mountain range that extends along the whole length of the Italian peninsula as can be seen in **Figure 3.8**, being Brindisi just behind the so-called Meridional Apennines. Given this topography, the western flows need to go through the Apennines before reaching Brindisi, giving place to the phenomenon known as Foehn Effect or Foehn winds. The case of A Coruña may be also influenced by the Foehn Effect when southerly winds prevail and move across the Galician Massif. Moreover, A Coruña location on the shores of the Atlantic Ocean, gives this city milder temperatures than those influences by the Mediterranean Sea (see in **Figure 3.7**). Conversely to the case of Athens, when being influenced by a warm and dry air mass, A Coruña will be more likely to see an increase of 5ºC and thus experience a FH. This can help explaining the high temperature register obtained in this station.

Figure 3.8 Relief map of the Apennines, Italy (see [20]).

A Foehn wind appears when an air mass with sufficient water content is forced to ascend over the windward mountain slope. As it keeps ascending, it cools at the dry adiabatic lapse rate and eventually it might become saturated if the dew-point temperature is reached. From that moment on, condensation begins, clouds appear and rain may happen. Once at the top of the mountain, the air will have reached its minimum temperature and will have lost a significant amount of its water content. Finally, the air starts descending being heated at the moist adiabatic lapse rate until it reaches again the dew-point temperature. After this, it continues the descent heated by the dry adiabatic lapse rate finally getting to the foot of the mountain at a higher temperature than on the windward slope (see [21]). When the resulting warm and dry winds, named Foehn winds, move through an area, the temperature increases sharply with increments up to 20ºC or more in less than an hour (see [9]).

The sharp temperature increase caused by the flow of these winds may explain the high FH register obtained in Brindisi for the second half of the 20th century.

FC in Mediterranean Climate

Similarly, the evolution of FC phenomenon has been analyzed for the stations having a Mediterranean Climate.

Table 3.7 Classification of stations with Mediterranean climates according to the mean annual precipitation and temperature (with data from 1982 until 2012 obtained from [12]), latitude, longitude, number of FC registered for the 20th century and height. Stations are grouped according to their FC number into the only station with 126 FC episodes (in gray) and stations with 41 FC episodes or less (in orange).

Mean annual precipitation (mm, high to low)	**Mean annual temperature (ºC, low to high)**	**Latitude (southward)**	**Longitude (eastward)**	**FC total**	**Height (m)**
A Coruña 1025	Madrid 13.7	Marseille	A Coruña	Marseille 126	75
Barcelona 612	Marseille 14.2	A Coruña	Madrid	A Coruña 41 (46*)	58
Brindisi 598	A Coruña 14.2	Barcelona	Barcelona	Brindisi 31 (62*)	10
Marseille 588	Barcelona 16.5	Madrid	Marseille	Madrid 18	667
Madrid 450	Brindisi 16.5	Brindisi	Brindisi	Barcelona 7 (8*)	412
Athens 397	Athens 18.1	Athens	Athens	Athens 1 (2*)	103

**Total FC value with the approximation for missing decades (1900 for Barcelona, 1910 for A Coruña and 1900 to 1940 inclusive for Athens and Brindisi)*

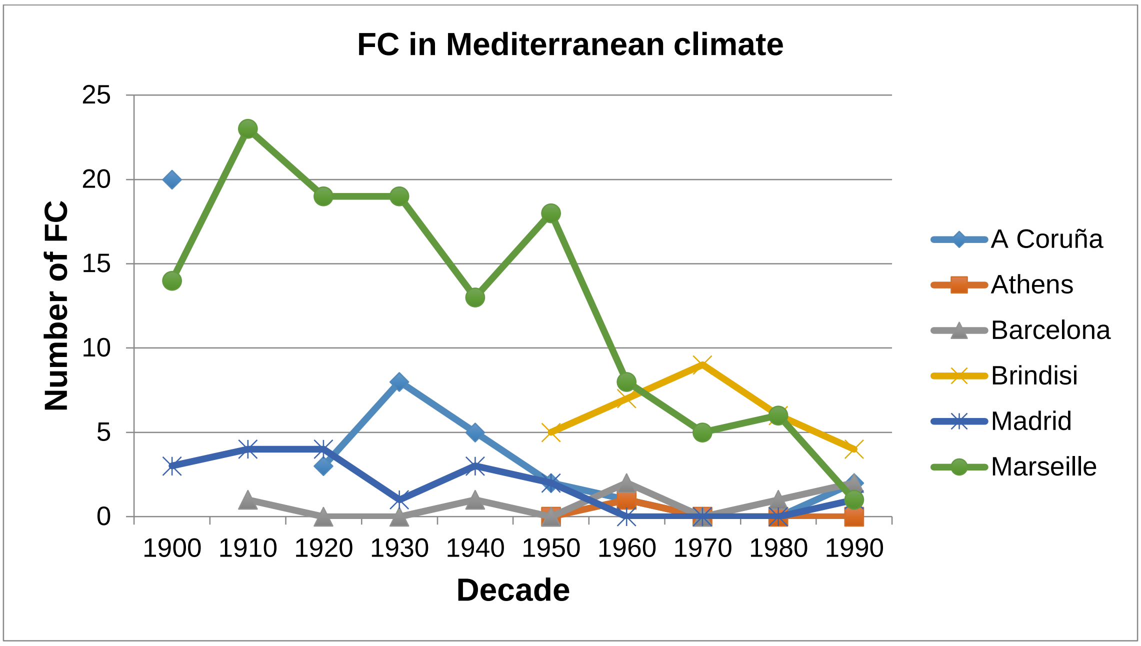

Figure 3.9 Evolution in the number of FC episodes registered every decade in stations with Mediterranean Climate for the period 1900-2000.

From the evolution observed in **Figure 3.9** and the total FC register in **Table 3.7** Marseille stands out from the others, followed far behind by A Coruña and Brindisi. However, it is significant the converging tendency all these stations show for the last decades of the 20th century. Marseille is the station which experiences the highest decrease throughout the decades going from its maximum of 23 FC episodes in the 1910s down to only 1 FC registered in the decade of 1990.

Again, local factors will help to explain the register of 126 FC episodes obtained in Marseille. The FC phenomenon is more likely to happen in this city rather than any of the others because of the influence of the Mistral wind. The mistral refers to a violent, cold and generally dry wind that develops and accelerates along the Rhône and the Durance valleys to the coast of the Mediterranean (see [22]). **Figure 3.10** shows the extension of the Mistral wind and the main directions it follows. The continuous incidence of this type of wind, which is especially common during winter, implies a descent in the temperatures that could fill the conditions for having a FC episode. Thus, mistral wind seems to have an impact on the number of FC episodes experienced in Marseille.

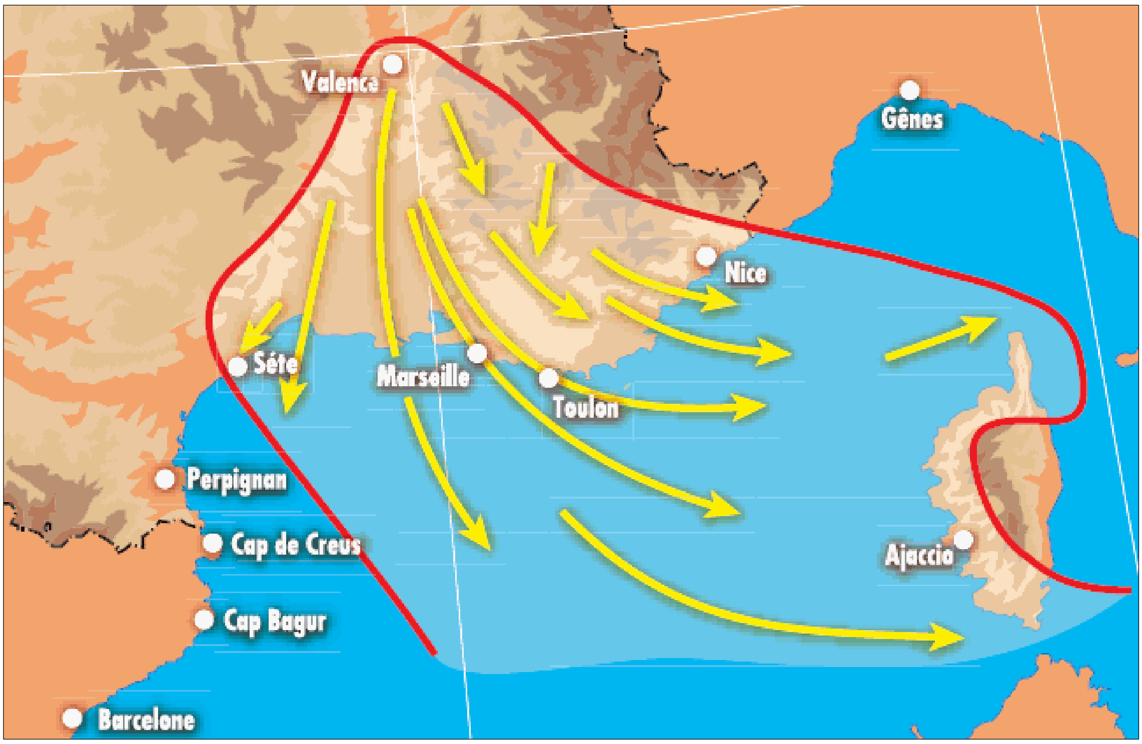

Figure 3.10 Mistral wind extension and main directions (modified from [23]).

3.1.3. Humid Continental and Subarctic Climates

The Humid Continental climate is spread over a large area of northern and northeastern Eurasia, with latitudes ranging from 35º to 60ºN. Humid Continental climates are grouped into two groups depending on their summer temperatures. This report will only cope with the so-called Humid Continental with long cool summers (Dfb, according Köppen system abbreviations). In this climate, the average temperature of the warmest month is below 22ºC and at least four months have a monthly mean temperature above 10ºC (see [9]). Westerlies have a large influence throughout the year over this type of climate, leading into frequent weather changes associated with the passage of migratory pressure systems, especially in winter (see [8]).

In contrast with the conditions mentioned for Humid Continental climates, when winters are severe and summers short and cool, with only one to three months having a mean temperature exceeding 10ºC, the climate is named Subarctic or Subpolar (see [9]). The low temperature during winter allows for little moisture in the air, and anticyclonic conditions predominate (see [8]).

Both humid continental and subarctic climates will be studied together in this section due to their similarities. The stations to be included in this section are Bern, Buzau, Debrecen, Helsinki, Karlstad, Kiev, Odesa, Tartu, Vilnius and Sodankyla.

FH in Humid Continental and Subarctic Climates

In this section, the evolution of FH phenomenon has been analyzed for the stations having either Humid Continental or Subarctic Climates.

Table 3.8 Classification of stations with Humid Continental and Subarctic climates according to the mean annual precipitation and temperature (with data from 1982 until 2012 obtained from [12]), latitude, longitude, number of FH registered for the 20th century and height. Stations are grouped according to their FH number into stations with 160 FH episodes or more (in gray) and stations with 75 FH episodes or less (in orange). Bern, Sodankyla and Debrecen, in white, are treated separately and thus are not included in neither of the groups.

Mean annual precipitation (mm, high to low)	Mean annual temperature (ºC, low to high)	Latitude (southward)	Longitude (eastward)	FH total	Height (m)
Bern 911	Sodankyla -1.1ºC	Sodankyla	Bern	Vilnius 215 (239*)	156
Vilnius 655	Tartu 5ºC	Helsinki	Karlstad	Odesa 196 (245*)	55
Helsinki 650	Helsinki 5.1	Karlstad	Debrecen	Kiev 181	166
Karlstad 644	Karlstad 5.8	Tartu	Helsinki	Bern 175	553
Kiev 640	Vilnius 6.4	Vilnius	Vilnius	Sodankyla 172 (191*)	179
Tartu 599	Kiev 7.7	Kiev	Sodankyla	Tartu 161	59
Debrecen 581	Bern 8.8	Debrecen	Tartu	Buzau 160 (229*)	97
Buzau 533	Debrecen 10.1	Bern	Buzau	Debrecen 113	110
Sodankyla 515	Odesa 10.2	Odesa	Kiev	Helsinki 75	4
Odesa 495	Buzau 10.5	Buzau	Odesa	Karlstad 59 (74*)	46

**Total FH value with the approximation for missing decades (1900 for Sodankyla, 1910 for Vilnius, 1900 to 1910 inclusive for Karlstad, 1900 to 1940 inclusive for Odesa and 1910 to 1930 for Buzau)*

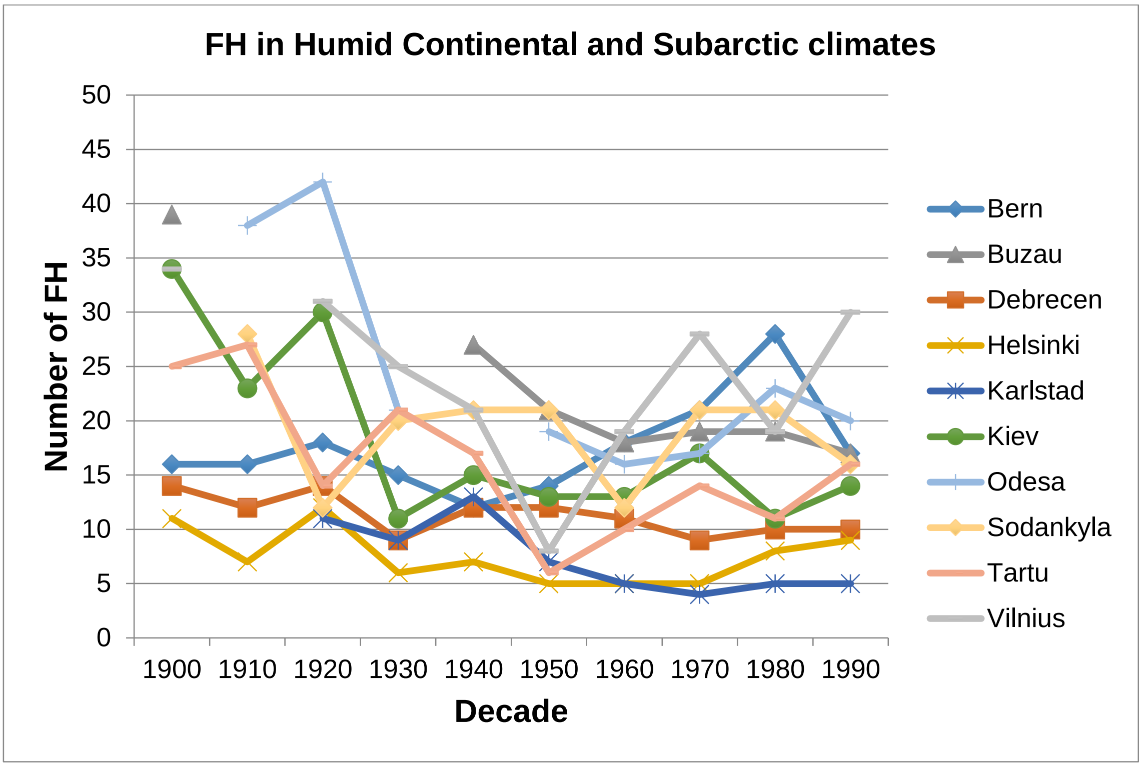

Figure 3.11 Evolution in the number of FH episodes registered every decade in stations with Humid Continental and Subarctic Climates for the period 1900-2000.

The tendencies observed in **Figure 3.11** show a wide variety of patterns depending on the station. Among these patterns, Karlstad and Helsinki show a similar evolution along the century having the lower FH registers. Two more stations showing similarities in their evolution are Buzau and Odesa. Both stations, highly influenced by the Black Sea, show similarities in their evolution especially from the decade of 1950.

In order to complement the tendencies observed from **Figure 3.11**, the stations have been divided into two different groups according to the number of FH events (grey and orange cells in **Table 3.8**). However, no connection has been found between the other variables. The stations of Bern, Sodankyla and Debrecen will be treated separately from the others.

On the one hand, there is the group formed by Vilnius, Odesa, Kiev, Tartu and Buzau with a high FH register. Among these stations, Odesa, Buzau and Kiev have the influence of the Black Sea. As explained before in this report, the further inland a city is, the less influence it receives from the Sea and thus the less mild climate it experiences. However, for the cases of Buzau and Odesa, which are closer to the Black Sea than Kiev, the number of FH events is considerably higher. This could be explained by the vicinity of these two cities to the Carpathian mountain range, as can be seen in **Figure 3.12**. As a consequence, westerly winds need to go through the Carpathians before reaching both cities. This process of going up and down the mountains might lead to the occurrence of the Foehn effect, with higher temperatures on the leeward side of the mountain. The existence of this phenomenon in the region can explain this higher number of FH events.

Figure 3.12 The Carpathian Mountains incursion in Ukraine and Romania (modified from [24]).

When moving to the northeast, there are the stations of Tartu and Vilnius. Estonia is dominated by temperate maritime and continental air masses depending on the season of the year. Besides, it is also occasionally reached by tropical air masses carried far up to the north in summer by southern cyclones (see [25]). Air masses bringing warm temperatures can lead to an increase of temperature that can result into a FH episode. Moreover, its distance from the sea mitigates the temperate effect from the sea. For the case of Vilnius, which is further inland, it presents a higher number of FH than Tartu.

On the other hand, further north the stations of Helsinki and Karlstad are the ones with a lower amount of FH episodes. Both Helsinki and Karlstad are influenced by the Baltic Sea, being Karlstad at a greater distance from it. When westerly winds prevail, the air needs to go through the Scandinavian Mountains resulting into the Foehn effect (see [26]). However, as long as the Scandinavian Mountains are not very high, the resulting Foehn effect will be weaker leading to a small increase of temperature on the leeward side of the mountains. Besides, the moderating effect of the sea is sometimes disturbed by the invasion of continental climate coming from Asia turning into extreme heat in summer (see [26]). These conditions give a low number of FH with a maximum register of 13 and 12 episodes per decade for Karlstad and Helsinki respectively.

Finally, Sodankyla, Debrecen and Bern are analyzed. The station of Sodankyla lies above the Arctic Circle being the only station in this report with a Subarctic Climate. This kind of climate has the largest annual temperature fluctuations in the world which frequently exceed the 45ºC (see [8]). Under these conditions the number of FH registered here is higher than the observed for the Humid Continental stations.

The case of Debrecen is studied separately due to the considerable existing difference in its amount of FH in comparison with Kiev, Buzau or Odesa. Debrecen is located halfway in-between the Atlantic Ocean and the inner parts of the Eurasian continent. This geographical situation causes its climate to be affected by oceanic air masses during summer and continental air masses during winter. The effect of the Mediterranean is felt when southerly winds prevail (see [27]). Besides, it is also important to highlight that Debrecen is surrounded by the Carpathians mountain range. Thus, when continental air masses approach, the Foehn effect may appear.

Finally, the case of Bern is examined. This station is situated far away from any of the other stations mentioned in this section. The city of Bern lies in the Swiss Plateau, between the Jura Mountains and the Swiss Alps, bordered by areas with Tundra, Subarctic and Oceanic Climates. Its location in the Swiss Plateau can be checked in **Figure 3.13**.

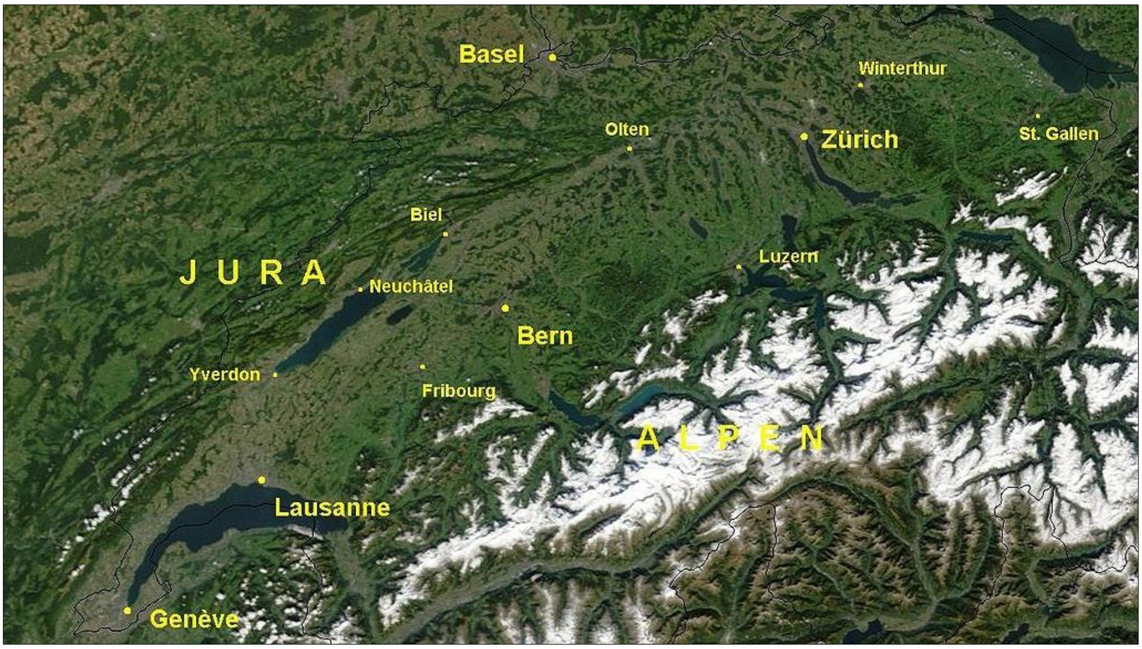

Figure 3.13 Bern location in the Swiss Plateau surrounded by Swiss Alps and the Jura Mountains (see [28]).

The Alps act like a climatic barrier between northern and southern Switzerland, giving place to different climatic regions. Moreover, Foehn effect occurs often in this region. When the wind crosses the Alps, it originates milder and drier conditions on the leeward side, where Bern is located (see [29]). Again, the influence of Foehn effect could explain the high FH registers observed in Bern.

FC in Humid Continental and Subarctic Climates

Similarly, the evolution of FC phenomenon has been analyzed for stations having Humid Continental or Subarctic Climates.

Table 3.9 Classification of stations with Humid Continental and Subarctic Climates according to the mean annual precipitation and temperature (with data from 1982 until 2012 obtained from [12]), latitude, longitude, number of FC registered for the 20th century and height. Stations are grouped according to their mean temperature, latitude and FC number into stations with a mean annual temperature below 6.4ºC, latitudes greater than 54ºN and 208 FC episodes or more (in gray) and stations with a mean annual temperature above 7.7ºC, latitudes smaller than 51ºN and 105 FC episodes or less (in orange). Debrecen and Buzau, in white, are treated separately and thus are not included in neither of the groups.

Mean annual precipitation (mm, high to low)	**Mean annual temperature (ºC, low to high)**	**Latitude (southward)**	**Longitude (eastward)**	**FC total**	**Height (m)**
Bern 911	Sodankyla -1.1	Sodankyla	Bern	Sodankyla 1539 (1710*)	156
Vilnius 655	Tartu 5	Helsinki	Karlstad	Karlstad 449 (561*)	55
Helsinki 650	Helsinki 5.1	Karlstad	Debrecen	Vilnius 353 (392*)	166
Karlstad 644	Karlstad 5.8	Tartu	Helsinki	Tartu 327 (363*)	553
Kiev 640	Vilnius 6.4	Vilnius	Vilnius	Debrecen 294	179
Tartu 599	Kiev 7.7	Kiev	Sodankyla	Helsinki 208	4
Debrecen 581	Bern 8.8	Debrecen	Tartu	Buzau 156 (223*)	97
Buzau 533	Debrecen 10.1	Bern	Buzau	Kiev 105	110
Sodankyla 515	Odesa 10.2	Odesa	Kiev	Odesa 79 (99*)	42
Odesa 495	Buzau 10.5	Buzau	Odesa	Bern 45	46

**Total FC value with the approximation for missing decades (1900 for Sodankyla, 1910 for Vilnius, 1900 to 1910 inclusive for Karlstad, 1900 to 1940 inclusive for Odesa and 1910 to 1930 for Buzau)*

At first sight, Sodankyla clear outstands over any other station in **Figure 3.14** with more than 100 FC episodes per decade. Probably, the Subarctic climate characteristics, its location above the Arctic Circle, the wide annual temperature fluctuation with a mean annual temperature below freezing and the influence of northerly airflows may explain this number of FH.

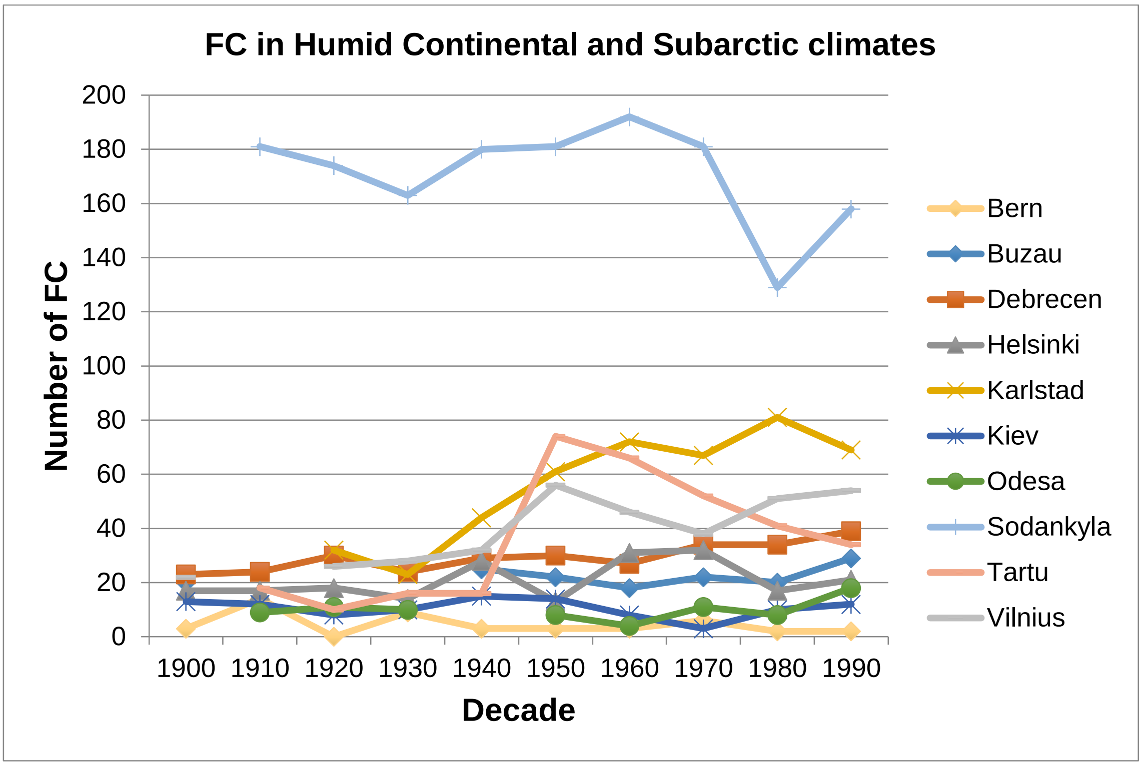

Figure 3.14 Evolution in the number of FH episodes registered every decade in stations with Humid Continental and Subarctic Climate for the period 1900-2000.

Besides this maximum value, by having a look at **Table 3.9**, it is possible to group the stations according to their FC values, latitude and mean annual temperature. Only Buzau and Debrecen cannot be included in the proposed classification.

First of all, there are the stations located at northern latitudes and having the higher FC registers (highlighted in grey in **Table 3.9**). Among them, Helsinki deserves a particular mention due to its lower number of FC in comparison to the other stations. Probably, its location on the shores of the Baltic Sea can explain this difference with Karlstad, which is located at a similar latitude but further inland. The same happens with the stations of Tartu and Vilnius. Being far from the coast they are less influenced by the Sea. This means that Tartu and Vilnius are more exposed to experience the temperature differences needed to have a FC in the event of a continental air mass invasion.

The second group is formed by stations highlighted in orange in **Table 3.9**. In reference to the first group, there is a significant change in terms of FC events, latitude and mean annual temperature. Odesa and Kiev are influenced by the effect of the Black Sea. However, despite Kiev being further inland than Odesa, the number of FC registered is similar. Bern, with its location near the Alps has the lowest number of FC events for this climatic type.

Finally, in between these groups, Debrecen and Buzau show different patterns. They have FC values similar to those obtained in Helsinki or Tartu despite having considerably higher mean annual temperature and an equatorward latitude. Buzau is located further inland than Odesa, at the foot of the Carpathians, what could explain the higher number of FC episodes. However, it does not seem enough to explain such a big difference. Thus, there must exist other local effects that lead into this result. Besides, **Figure 3.14** shows that, from the decade of 1950 the difference in the number of FC episodes between Buzau and Odesa has narrowed. To be more precise, this difference has constantly decreased from 34 FC of difference in the 1950s down to the 11 FC of difference achieved in the 1970s, a value that has remained constant for the following decades.

Debrecen presents a similar amount of FC events to Buzau. Similarly to Buzau, it is also situated at the foot of the Carpathians but on the opposite side. Its distance from both the Mediterranean and Black Sea, facilitate the existence of a FC when a continental air mass arrives. Moreover, the low maritime influence may favor the process of radiative cooling at nights. The tendencies observed in **Figure 3.14** for this station show a sustained increase in the number of episodes since 1960 onwards, reaching its maximum of 39 in the decade of 1990.

3.2. Seasonal variation

This section is devoted to study the FH and FC occurrence on the different seasons for each decade along the 20th century and also to determine which seasons are more representative of each phenomenon.

Almarza and Cortés (2015) (see [5]) determined that, for the particular case of Spain, the FH phenomenon was mostly concentrated during summer and spring. This result was especially relevant for the northern part of the country where the Foehn effect played an important role. On the contrary, FC mainly occur during winter, when the necessary conditions for this phenomenon to happen were more frequent.

Here the distribution of FH and FC events for each of the seasons has been computed and expressed as a percentage. In order to avoid percentages of stations with low number of FH and FC and sometimes with random distributions that have no clear trends, all stations with less than 100 FH or FC episodes have been omitted from this analysis. Moreover, given the variability in the duration of each season depending on the climatic zone, the standard duration of seasons in Spain will be taken as a reference for the whole analysis. Taking into account all these considerations, the seasonal FH and FC distributions are presented in **Figures 3.15** and **3.16**, respectively.

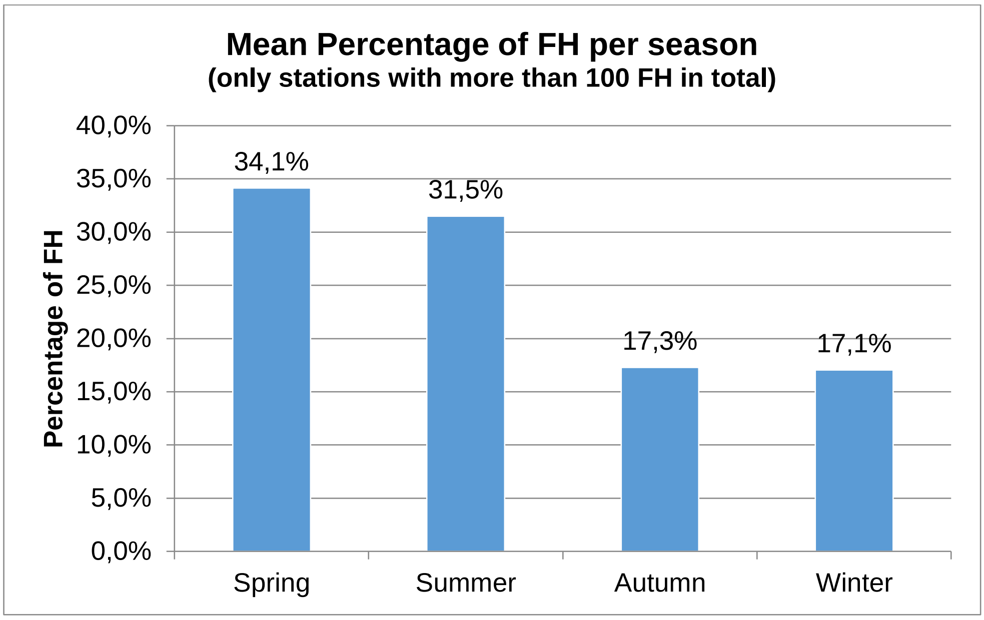

Figure 3.15 Seasonal FH distribution for the period 1900-2000 expressed as a percentage.

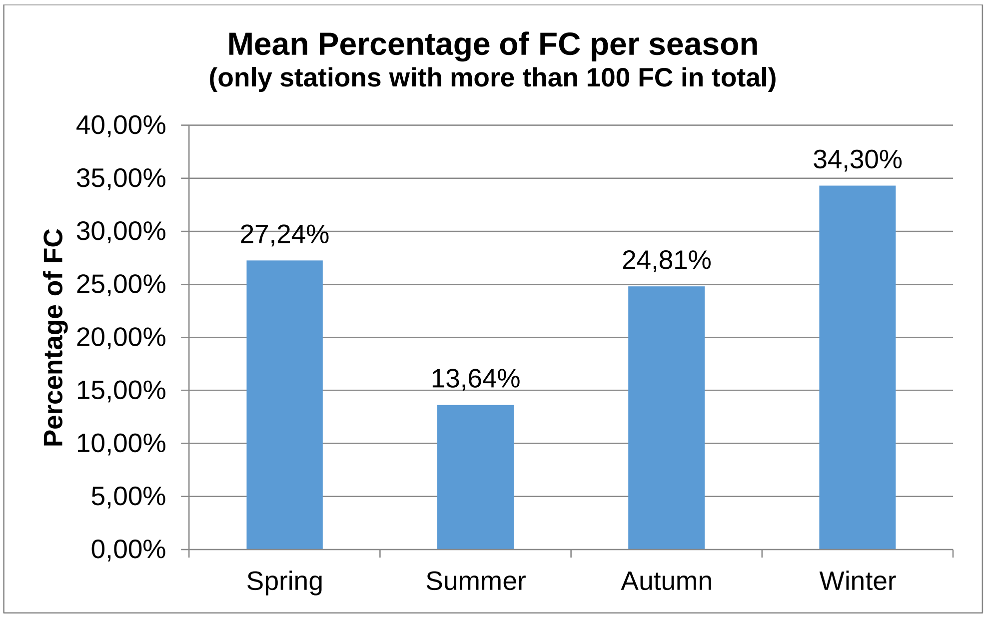

Figure 3.16 Same as Figure 3.15 for FC.

According to **Figure 3.15**, the FH phenomenon is more likely to occur in spring and summer with a 34.1% and a 31.5% of the episodes respectively. The other two seasons, autumn and winter, stay far behind with only the 17.3% and the 17.1% of the episodes respectively.

When focusing on the results shown in **Figure 3.16**, the FC phenomenon clearly prevails in winter with a 34.3% of the results. Spring and autumn are close behind with the 27.24% and 24.81% of the episodes respectively. Finally, the season with the lowest FC register is summer with only a 13.64% of the episodes.

In view of the results, the distributions determined by Almarza and Cortés (2015) for Spain can be extrapolated to a European scale. Thus, for the stations analyzed, it can be concluded that the FH phenomenon is more important during spring and summer while the FC phenomenon mostly happens during wintertime.

The next step is to analyze the distribution of FH and FC over the different seasons throughout the 20th century. With this objective three stations are studied for each phenomenon. All the stations selected for this analysis have the common characteristic of not having any decade with missing data.

3.2.1. FH seasonal distribution

The stations of Hamburg, Paris and Kiev have been chosen and their evolution regarding the number of FH episodes is shown in **Figures 3.17**, **3.18** and **3.19**, respectively.

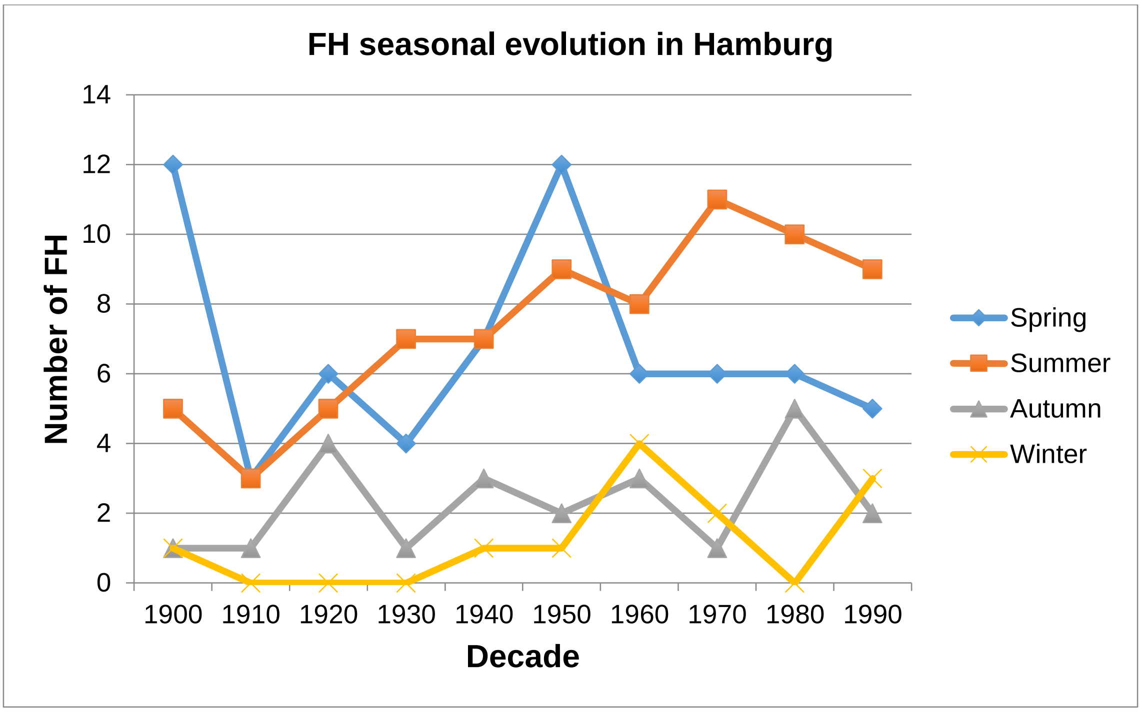

Figure 3.17 FH evolution in Hamburg for the period 1900-2000 for spring (in blue), summer (in orange), autumn (in gray) and winter (in yellow).

Hamburg (see **Figure 3.17**) fits the seasonal distribution observed for the whole Europe. There is a clear predominance of spring and summer with autumn and winter being the seasons with the less amount of FH episodes. This tendency is maintained along the century.

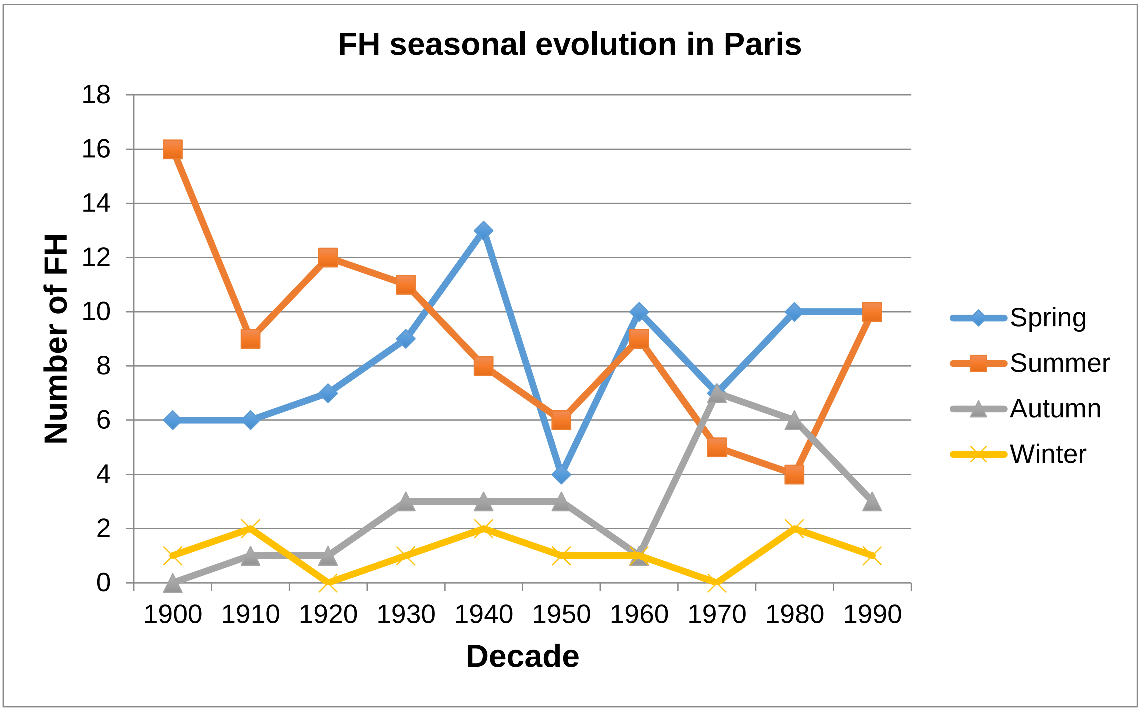

Figure 3.18 Same as Figure 3.17 for Paris.

Paris (see **Figure 3.18**) also fits the distribution shown in **Figure 3.15**. There are only two decades, 1970s and 1980s, when a decrease in the number of episodes registered for spring and summer is observed. This decrease coincides with a substantial increase in the number of episodes occurred in autumn, increasing from 1 FH in the decade of 1960 up to 7 FH in the decade of 1970. However, after these two decades, the predominance of spring and summer are recovered.

The last studied station, Kiev shown in **Figure 3.19**, shows different evolution compared to Hamburg and Paris and also to the global distribution mentioned before. From 1930 onwards, autumn clearly prevails over summer and until the 1970s even over spring. Thus, in this particular case the two prevailing seasons for FH to happen in Kiev are spring and autumn instead of spring and summer. This difference may be explained by local factors.

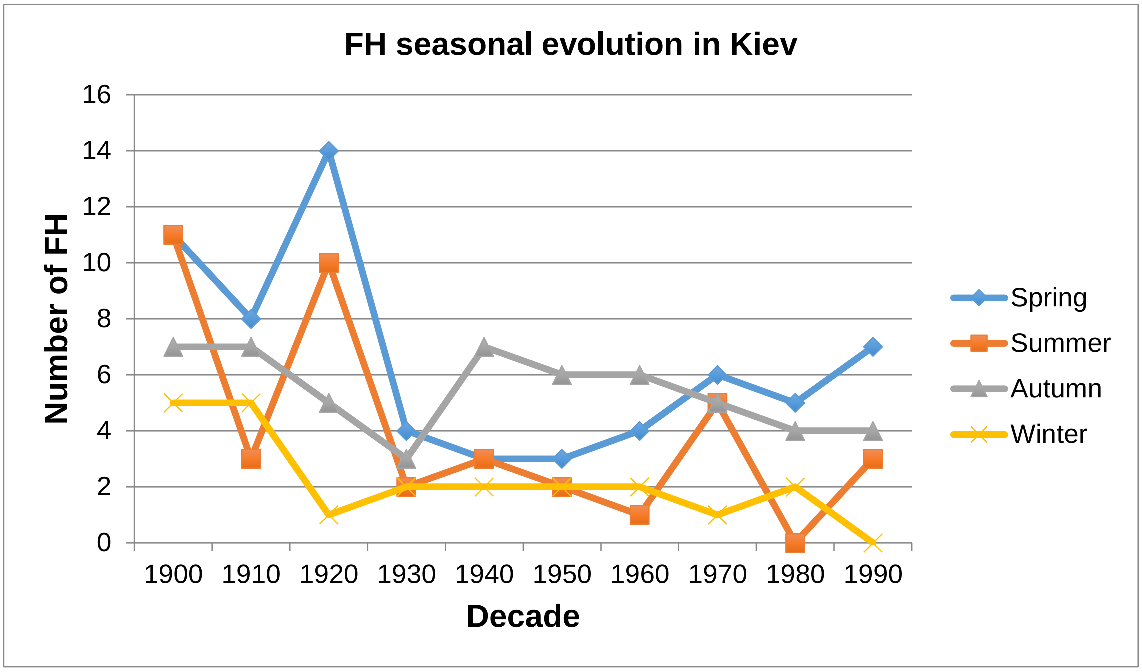

Figure 3.19 Same as Figure 3.17 for Kiev.

3.2.2. FC seasonal distribution

The selected stations for this purpose are Debrecen, Helsinki and Armagh. The FC evolution for each of these stations is shown in **Figures 3.20**, **3.21** and **3.22**.

Debrecen (see **Figure 3.20**), fits the seasonal distribution observed for Europe from the decade of 1940 onwards. Before this date, there are specific points in which spring and autumn slightly overcomes the episodes occurred in winter, contradicting the global patterns shown in **Figure 3.16**. However, these values only exceed the winter registers by 1 or 2 episodes.

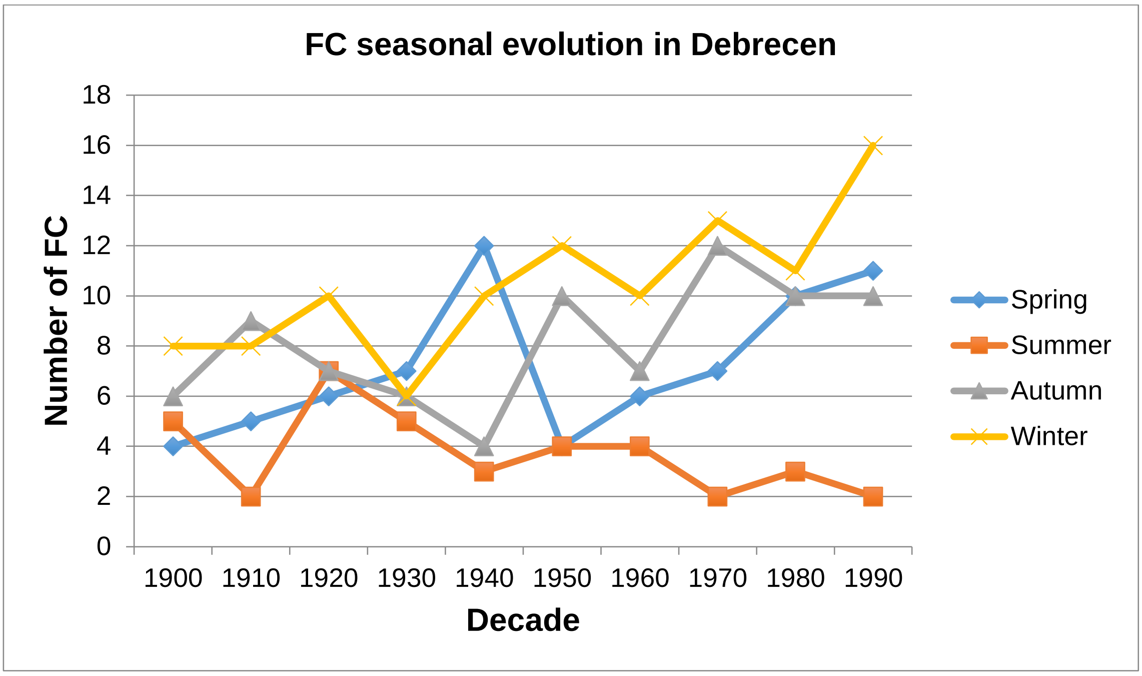

Figure 3.20 FC evolution in Debrecen for the period 1900-2000 for spring (in blue), summer (in orange), autumn (in gray) and winter (in yellow).

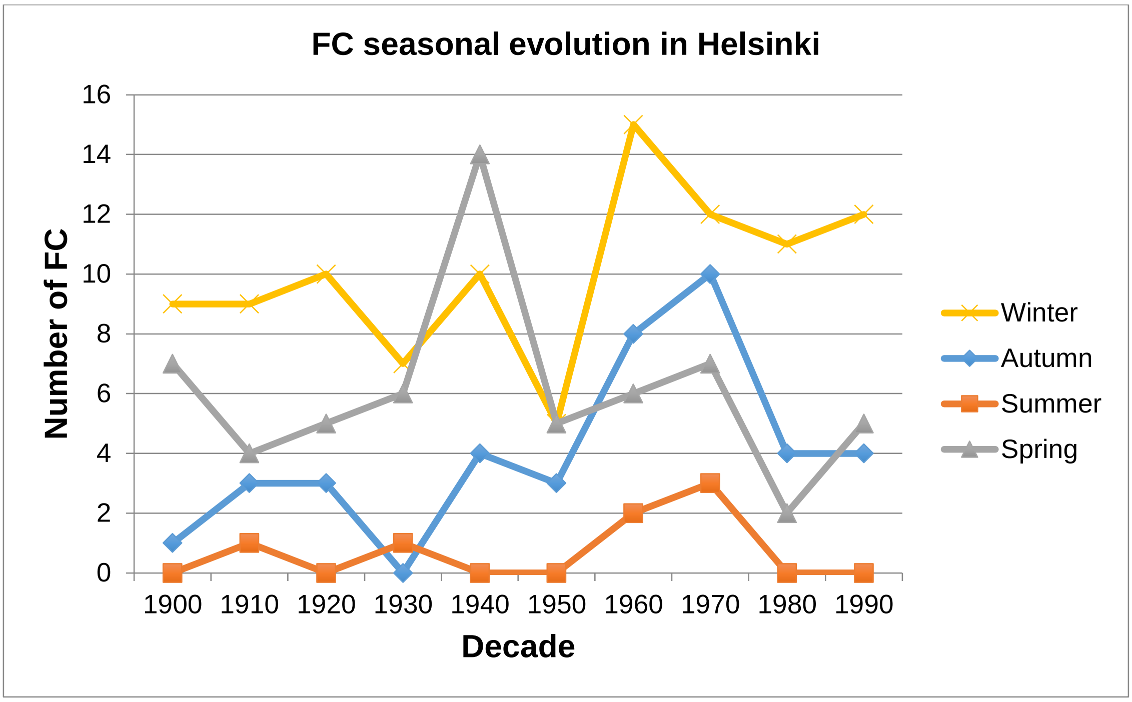

Figure 3.21 Same as Figure 3.20 for Helsinki.

According to the FC evolution throughout the 20th century, Helsinki (see **Figure 3.21**) follows the global percentage distribution with the exception of the period between the 1930s and the 1950s, in which the FH episodes in spring are higher than those in winter. However, generally speaking winter keeps being the predominant season, followed by spring, autumn and further down summer.

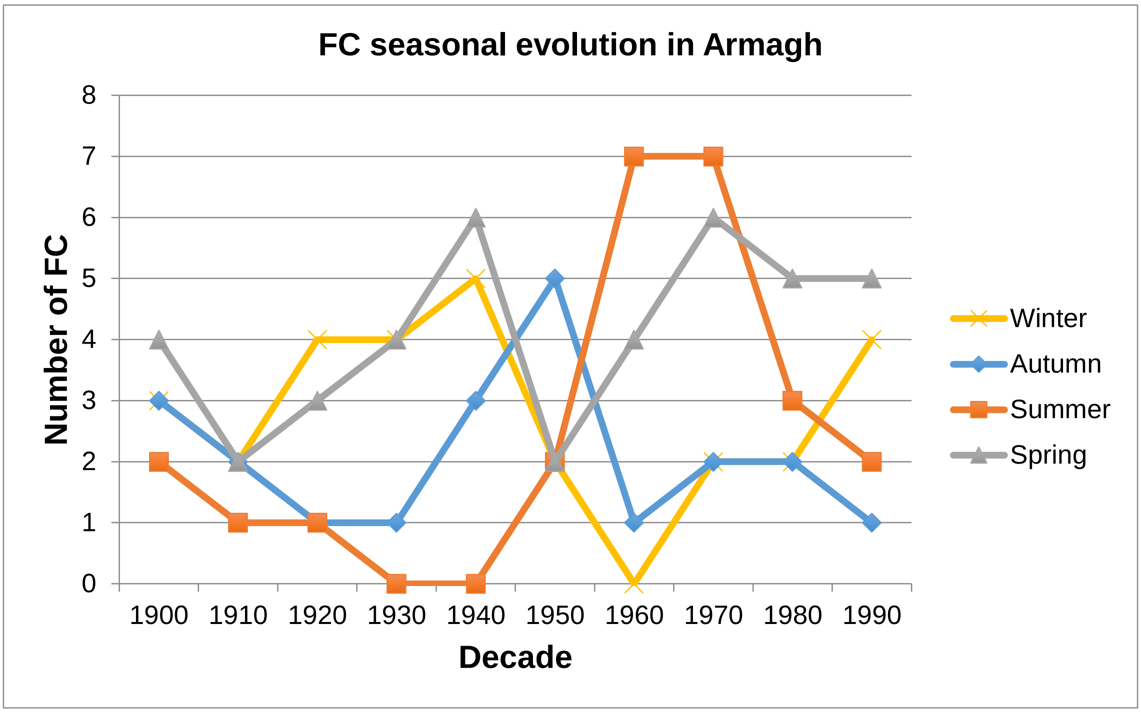

Figure 3.22 Same as Figure 3.20 for Armagh.

Finally, the station of Armagh in **Figure 3.22** shows different evolution from those observed for Debrecen and Helsinki. On the first half of the century, the prevailing seasons are winter and spring, followed by autumn and winter. Thus, up to the 1950s Armagh fulfilled with the distribution in **Figure 3.16**. However, from the decade of 1950 onwards, the seasonal distribution of FC events experience considerable changes. The most remarkable variation is the experienced by summer turning into the prevailing season until the 1970s. From that moment on, summer falls to the third position, leaving winter on the second position and spring on the first. Thus, the last two decades show a tendency to recover the global distribution patterns. This different behavior in comparison to the other stations may be justified by local factors.

3.3. Influence of mean temperature and precipitation on the occurrence of FH and FC

Previously in this report, the distribution of FH and FC based on the climatic conditions has been studied. According to the United Kingdom's Meteorological Office, climate usually refers to a region's long-term weather patterns. This is basically measured in terms of average precipitation, maximum and minimum temperature as well as other variables such as sunshine hours, humidity or the frequency of extreme weather (see [30]).

In order to further analyze the relationship between these events and climate, the evolution of the number of FH and FC throughout the last century will be compared with the evolution of the mean temperature and mean precipitation for this same period. Thus, this section aims to check if a given evolution in temperature and precipitation has an influence in the number of FH and FC episodes.

In this sense, recent studies have demonstrated a significant increase in the annual occurrence of warm nights and a similar proportion of significant decrease in the annual occurrence of cold nights. Regarding precipitation, results suggest complex changes in precipitation extremes but generally showing a global tendency towards a wetter world (see [31]).

The Pearson's correlation coefficient has been used to analyze the influence of mean temperature and precipitation on FH and FC phenomena. This coefficient, denoted by r, is used in statistics to measure the strength of the linear association between two variables. The value of this coefficient ranges between -1 and 1 inclusive, where -1 indicates a strong negative linear correlation and 1 indicates a strong positive linear correlation. If there is no linear correlation between variables, the value of the coefficient will be equal to 0. A positive linear correlation between variables means that if one variable increases, the other variable tends to increase too. Similarly, a negative linear correlation between variables means that if one variable decreases, the other tends to decrease too. As a guideline, the interpretation of the correlation coefficient in **Table 3.10** is generally proposed.

Table 3.10 Strength of the correlation for the absolute values of r (see [32]).

Coefficient, r	Strength of association
0 to 0.19	Very weak
0.2 to 0.39	Weak
0.4 to 0.59	Moderate
0.6 to 0.79	Strong
0.8 to 1	Very strong

The mean temperature and precipitation evolution have been obtained by using the Matlab scripts in **ATTACHMENT C** and **ATTACHMENT D** respectively. Besides, the data needed for computing the evolution is only available for stations belonging to the European Climate Assessment and Dataset (ECA&D). Thus, only stations obtained from this dataset will be used for this section.

3.3.1. Influence of mean temperature and precipitation on FH

First of all, the relationship between the evolution of the mean temperature and mean annual precipitation with the evolution of total number of FH is assessed. With this purpose, the correlation coefficient between these variables for all the stations is shown in **Table 3.11**.

Table 3.11 Value of the correlation coefficient between temperature, precipitation and FH.

	Mean Temperature	Mean Annual Precipitation
Armagh	0.435	0.059
Bologna	0.231	0.722
Hamburg	-0.454	-0.124
Jena	-0.467	-0.444
Karlstad	0.458	-0.231
Kiev	-0.455	-0.663
Ljubljana	0.000	0.259
Maastricht	0.204	-0.441
Marseille	0.214	-0.135
Odesa	-0.499	-0.159
Paris	0.238	-0.140
Sodankyla	-0.386	-0.643
Vilnius	-0.041	-0.338

According to the results obtained in **Table 3.11** for the correlation coefficient with both the mean temperature and the mean annual precipitation, no clear correlation seems to exist for most of the analyzed stations. Regarding the correlation with the mean annual precipitation, the station of Bologna presents a strong positive correlation while, on the opposite side, Kiev shows a strong negative correlation. In between these two values situated in the opposite extremes, there is a wide range of stations with inconsistent correlation values. In the case of temperature, the inconsistency of the results is even higher. In this case, there are no correlation values above or below 0.5 and -0.5 respectively.

3.3.2. Influence of mean temperature and precipitation on FC

Similarly to the procedure followed for the FH phenomenon, the relationship between FC, mean temperature and mean annual precipitation is now studied. As a first step, the correlation coefficient between these variables for each of the stations considered is shown in **Table 3.12**.

Table 3.12 Value of the correlation coefficient between temperature, precipitation and FC.

	Mean Temperature	Mean Annual Precipitation
Armagh	0.283	-0.505
Bologna	-0.291	0.028
Hamburg	-0.065	-0.224
Jena	-0.579	-0.316
Karlstad	-0.717	-0.130
Kiev	-0.418	-0.440

Ljubljana	-0.645	-0.142
Maastricht	0.282	-0.552
Marseille	-0.843	0.208
Odesa	0.590	-0.266
Paris	0.292	0.176
Sodankyla	-0.211	-0.326
Vilnius	0.211	0.493

The results in **Table 3.12** are similar to those obtained for the FH phenomenon. There is a wide range of different correlation coefficients not showing any global trend. Regarding the correlation with the mean temperature, the station showing the highest coefficient value is the city of Odesa with 0.590, which is considered to be a moderate correlation. On the opposite side, there is the station of Marseille with a very strong negative correlation coefficient (-0.843). In between these two extremes, there is a wide variety of other correlation values.

On the other hand, the correlation with the mean annual precipitation is again inconsistent due to the apparent lack of any link between the different correlation coefficients. Among all the values obtained, the one showing a more positive correlation is Vilnius with a moderate positive coefficient of 0.493 while the one showing a more negative correlation is Maastricht with a strong negative coefficient of -0.552. By taking into account the wide variety of correlation coefficients obtained, no clear relation between these variables can be deduced.

3.4. Influence of the movement of air masses

As previously mentioned, advection processes and more particularly the invasion of air masses is pointed as one of the main causes that trigger FH and FC phenomena. In this section, two particular cases will be deeply analyzed to show this influence.

An air mass is a large body of air, generally extending more than 1600km across and several kilometers deep which remains over a uniform land or sea surface long enough to acquire its temperature, humidity and stability characteristics. Air masses are usually classified according to their source region and the associated characteristics. In this sense, the temperature of the air mass is directly linked to the latitude of its source region while the humidity of the air mass depends on the nature of the region surface. This implies that warm to hot air masses will have its origin at low latitudes while cool to cold air masses will origin at high latitudes. Besides, this air mass will be moist when developing over a mass of water or dry when developing over a continental surface (see [8]).

As these air masses move from their source regions, they modify the weather of the regions on its way. This is why an air mass invasion may lead to an increase or decrease of temperature by 5ºC within a period of 24 hours.

3.4.1. Warm air masses producing FH

When a given territory is invaded by a warm air mass it experiences an increase of its temperature. If this increase in the daily maximum temperature amounts to 5ºC or more and happens within a period of less than 24 hours, a FH will occur. An example of a FH event occurred because of the influence of a southern warm air mass took place between the 21st and 23rd April 1998 in Madrid, Paris, Oxford and Barcelona and produced 4 FH episodes.

Figure 3.23 shows a ridge from North Africa that remains concentrated over Morocco, Algeria and Tunis on the 21st April at 06:00 UTC. Six hours later, on the 21st April at 12:00 UTC (see in **Figure 3.24**), the 120m height contour stays exactly over Madrid. The following day at 06 UTC, less than 24 hours later, the same contour line moves away from Madrid as can be seen in **Figure 3.25**. Within this period of time, a FH event took place in Madrid as can be seen by the maximum temperature values provided in **Table 3.13**.

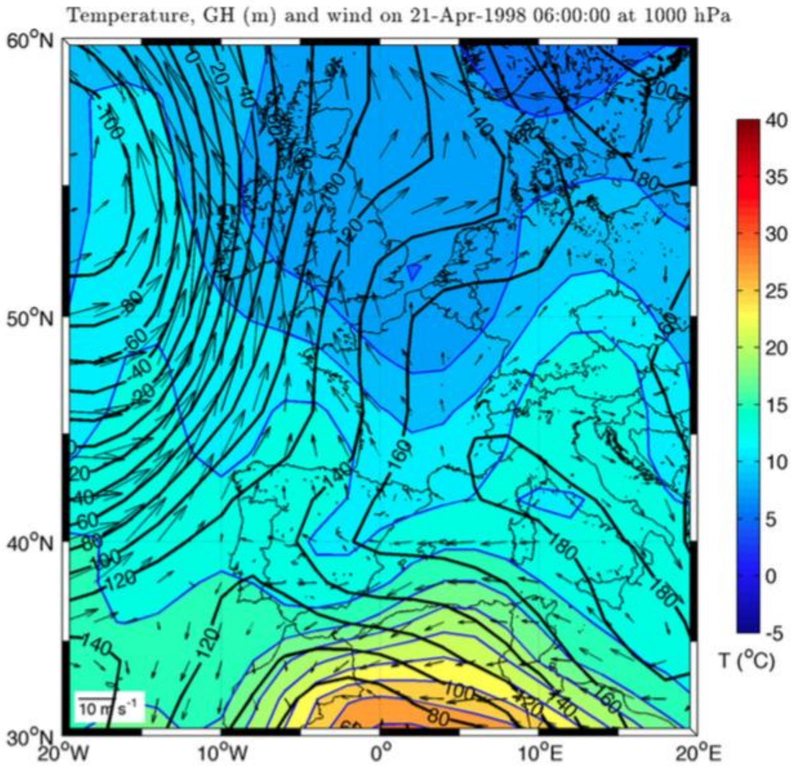

Figure 3.23 Temperature (color contours), GH (black contour lines, m) and wind (arrows) on 21st April 1998 at 06:00 UTC at 1000hPa (see [33]).

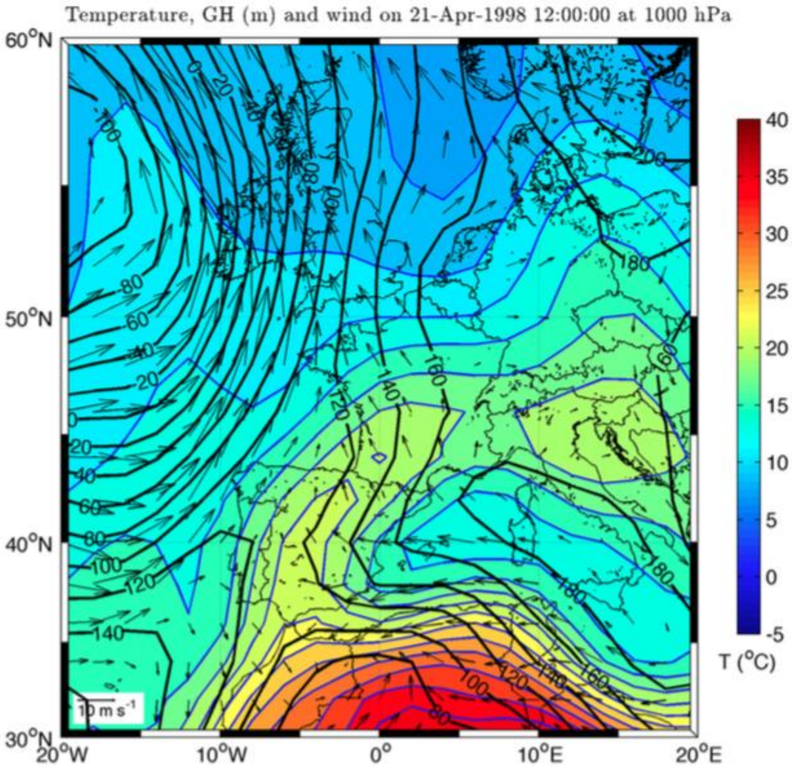

Figure 3.24 Same as Figure 3.23 at 12:00 UTC.

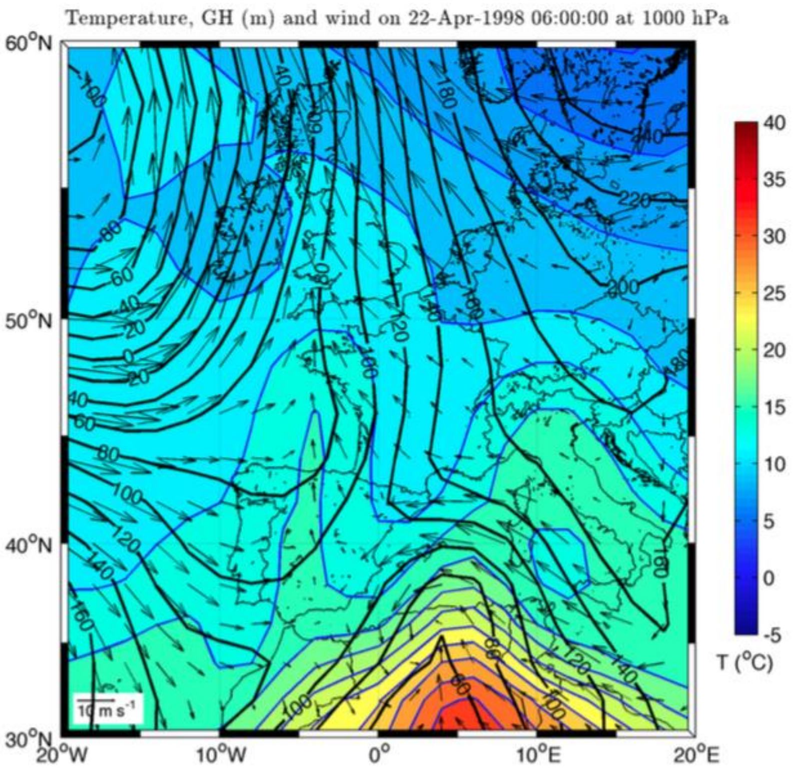

Figure 3.25 Temperature (color contours), GH (black contour lines, m) and wind (arrows) on 22nd April 1998 at 06:00 UTC at 1000hPa (see [33]).

Table 3.13 Daily maximum temperature registers in Madrid from 20th April until 22nd April 1998.

	Daily maximum temperature (ºC)
20th April 1998	19
21st April 1998	24.2
22nd April 1998	16.6

On the 22nd April at 18:00, the air mass moves to the northwest and stays over Paris and Oxford, as seen in **Figure 3.26**. Only 12 hours later, on the 23rd April at 06:00 UTC, the mass of air has receded again such as shown in **Figure 3.27**. During this process a FH episode occurred in Paris and Oxford. The maximum temperature values registered for those days are presented in **Table 3.14**.

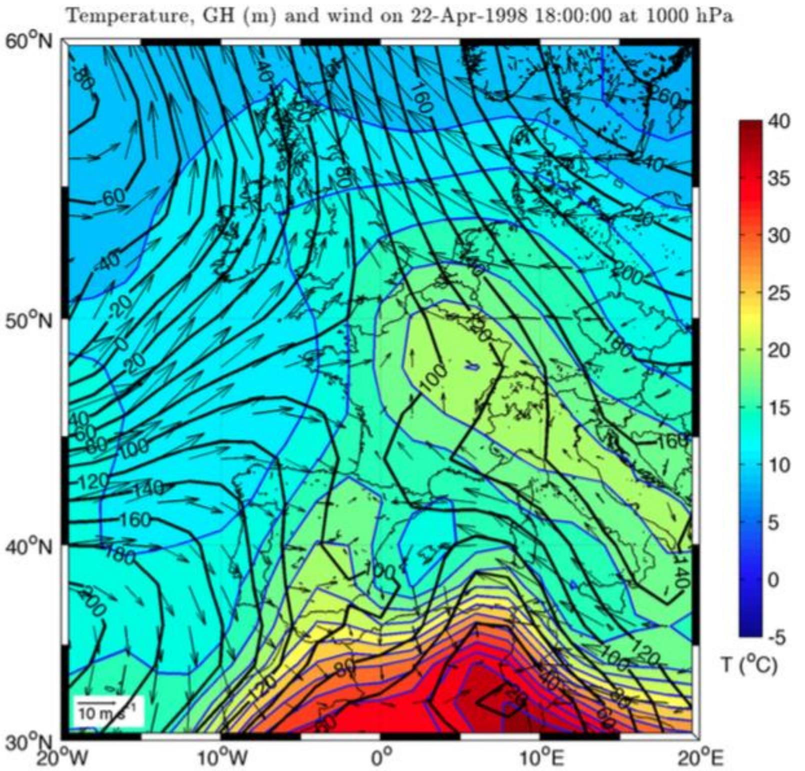

Figure 3.26 Same as Figure 3.25 at 18:00 UTC.

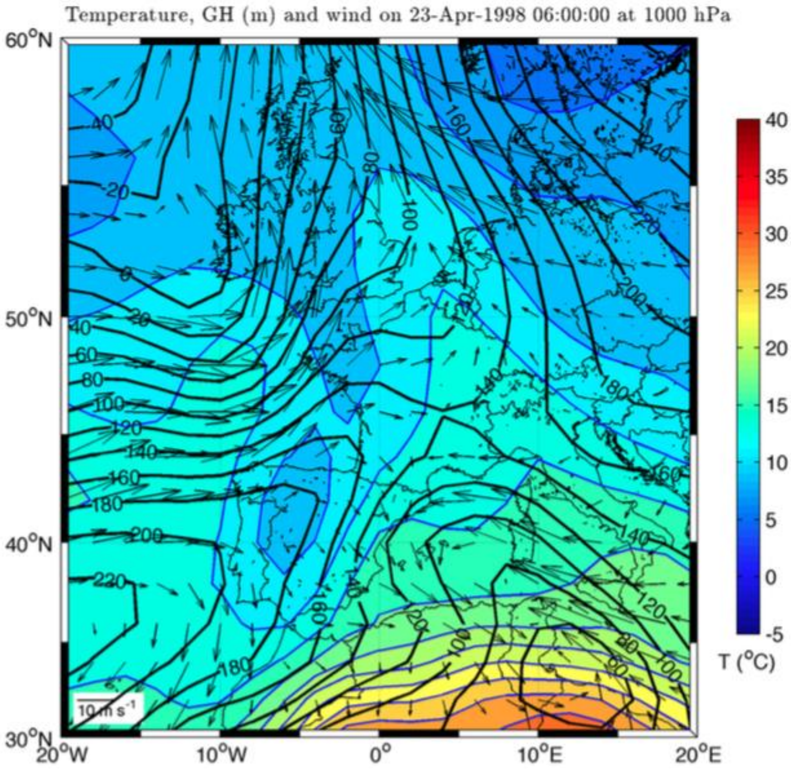

Figure 3.27 Temperature (color contours), GH (black contour lines, m) and wind (arrows) on 23rd April 1998 at 06:00 UTC at 1000hPa (see [33]).

Table 3.14 Daily maximum temperature registers in Paris and Oxford from 21st April until 23rd April 1998.

	Daily maximum temperature (ºC)	
	Paris	**Oxford**
21st April 1998	17.4	12.9
22nd April 1998	24.4	19.3
23rd April 1998	18	13.4

Later on the 23rd April, at 18:00 UTC, the ridge covers again most of the Iberian Peninsula with values around the 20ºC reaching Barcelona (see **Figure 3.28**). Similarly to the previous episodes, this ridge rapidly moves southward again as shown in **Figure 3.29** for the 24th April at 06:00 UTC, where there ridge has receded. This invasion of warm air leaded to a FH episode in Barcelona during the 23rd April. The maximum temperature values registered during those days are shown in **Table 3.15**.

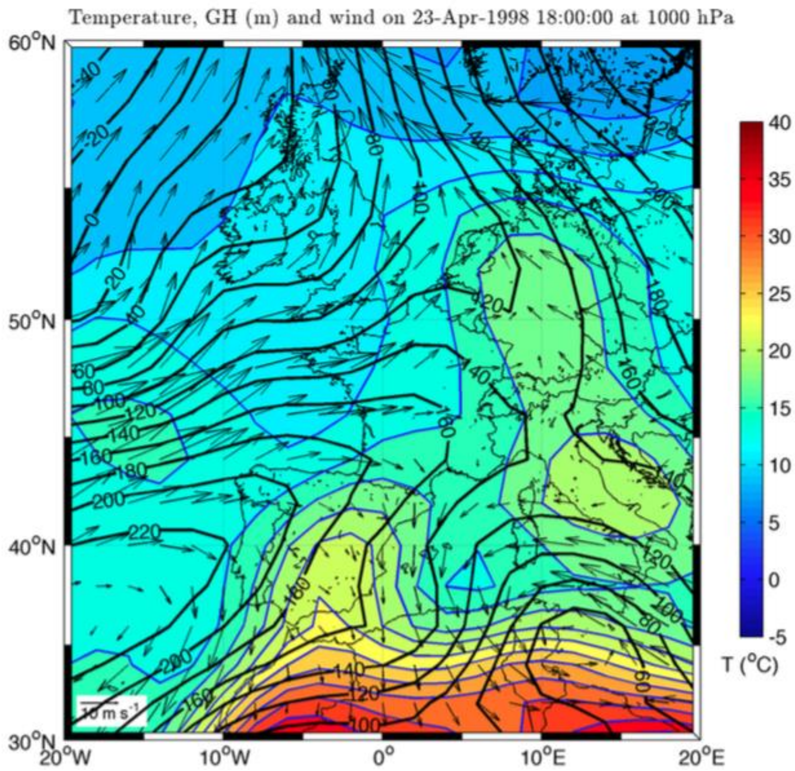

Figure 3.28 Same as Figure 3.27 at 18:00 UTC.

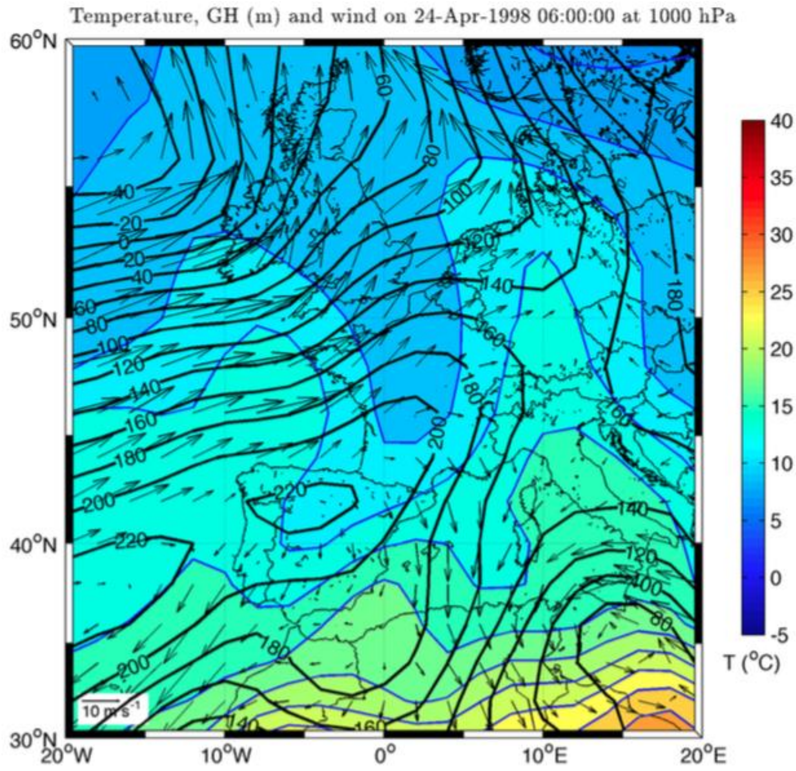

Figure 3.29 Temperature (color contours), GH (black contour lines, m) and wind (arrows) on 24th April 1998 at 06:00 UTC at 1000hPa (see [33]).

Table 3.15 Daily maximum temperature register in Barcelona from 22nd April until 24th April 1998.

	Daily maximum temperature (ºC)
22nd April 1998	18.8
23rd April 1998	24.8
24th April 1998	18.2

3.4.2 Cold air masses producing FC

Similarly, when a territory is invaded by a cold air mass it experiences a decrease of its temperature. If this decrease in the daily minimum temperature reaches a value of 5ºC within a period of less than 24 hours, a FC will occur.
An example of a FC event occurred because of the influence of a cold air mass will be now analyzed. It consists of 2 FC episodes occurred between the 7th and 8th March 1947 in the cities of Oxford and Den Helder as a consequence of a cold air mass coming from the north.

Figure 3.30 shows a polar air mass quietly remains at northern latitudes on the 6th March at 12 UTC. Few hours later, on the 7th March at 06:00 UTC the ridge moves to the southwest until reaching England (see **Figure 3.31)**.

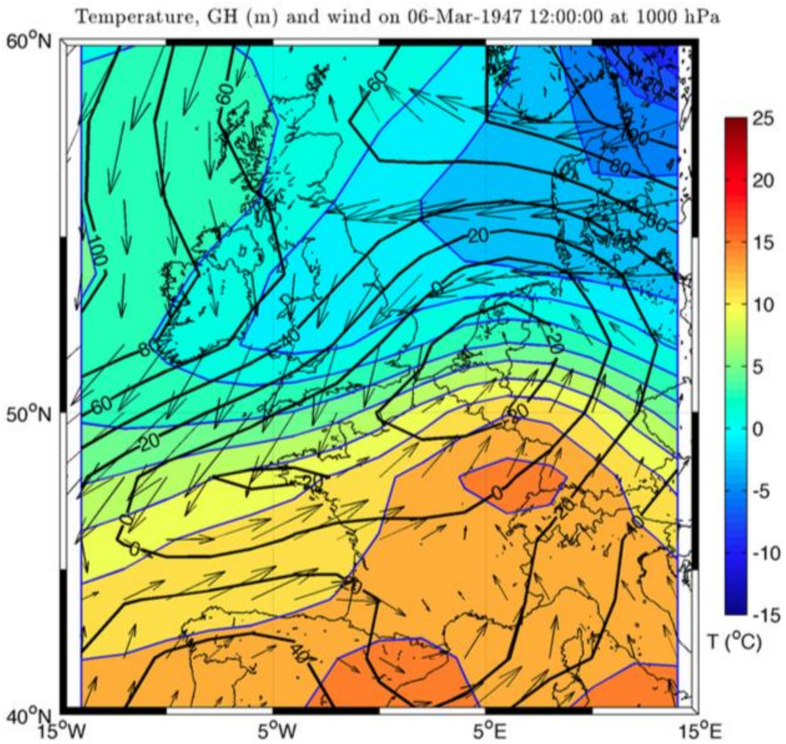

Figure 3.30 Temperature (color contours), GH (black contour lines, m) and wind (arrows) on 6th March 1947 at 12:00 UTC at 1000hPa (see [33]).

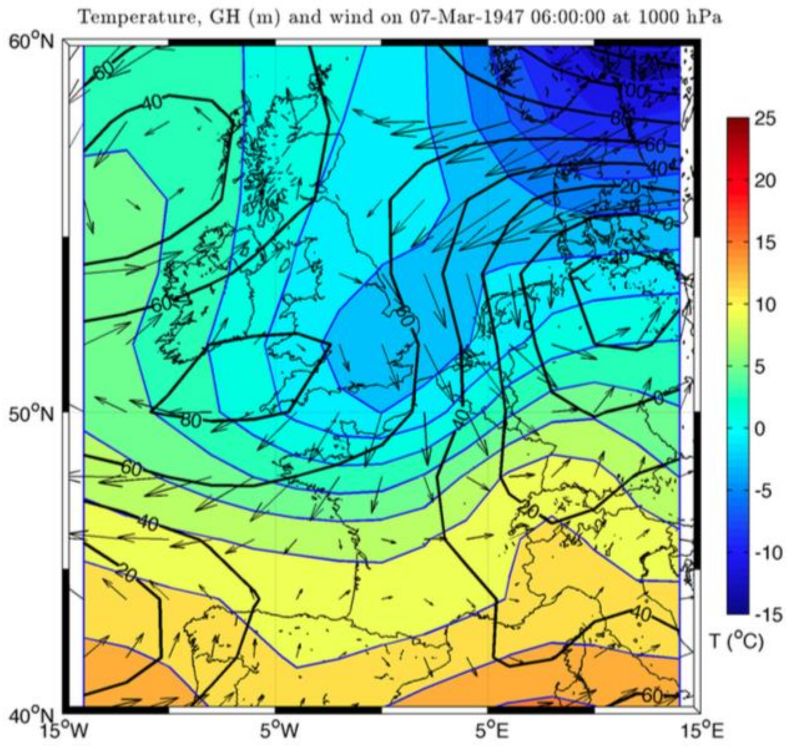

Figure 3.31 Same as Figure 3.30 on 7th March 1947 at 06:00 UTC (see [33]).

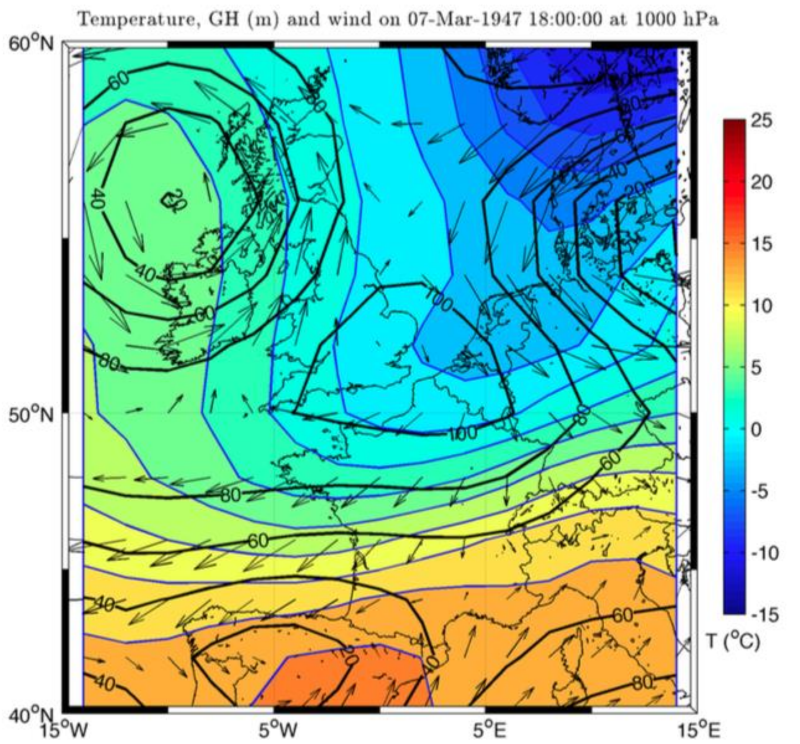

Figure 3.32 Same as Figure 3.31 at 18:00 UTC.

This rapid advection, stronger over southeastern regions of England, vanishes on the same day by 18:00 UTC as seen in **Figure 3.32**. This cold air mass over Oxford for a few hours caused a FC event in the city. The details for this FC episode are shown in **Table 3.16**.

Table 3.16 Daily minimum temperature register in Oxford from 6th March until 8th March 1947.

	Daily maximum temperature (ºC)
6th March 1947	-2.2
7th March 1947	-11.1
8th March 1947	-6.1

On the next day, 8th March at 06:00 UTC (**Figure 3.33**), there is a new brief and rapid movement of this polar air mass affecting most of The Netherlands, Belgium and surrounding territories. This invasion carries air at temperatures between -5 and -10ºC. The polar air stays over these territories for a short period of time and only six hours later, at 12:00 UTC, it starts receding and leaves the area as shown in **Figure 3.34**. As a consequence of this invasion a FC episode occurs in Den Helder on the 8th March. The temperature variation on the days the FC took place is shown in **Table 3.17**.

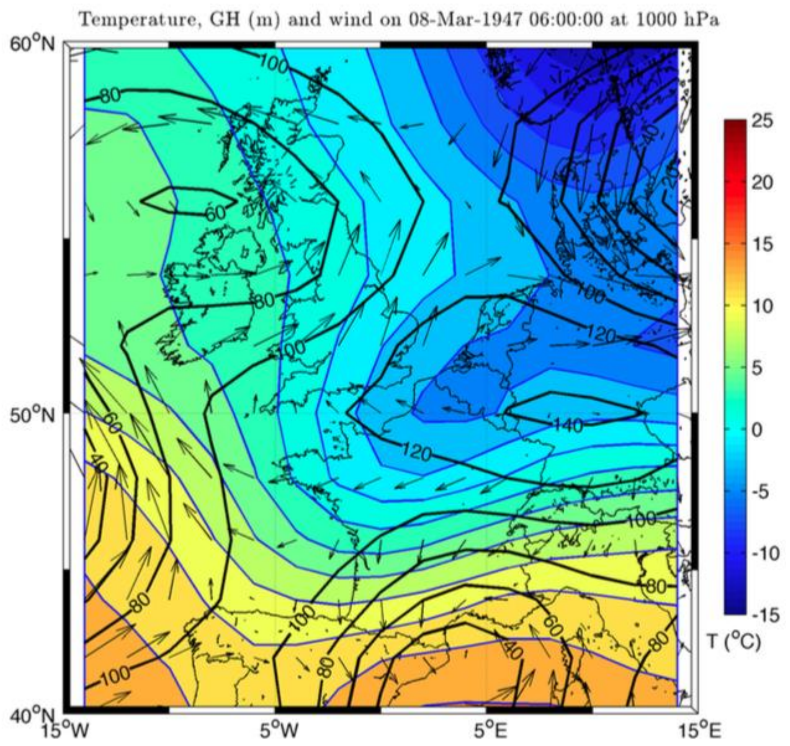

Figure 3.33 Temperature (color contours), GH (black contour lines, m) and wind (arrows) on 8th March 1947 at 06:00 UTC at 1000hPa (see [33]).

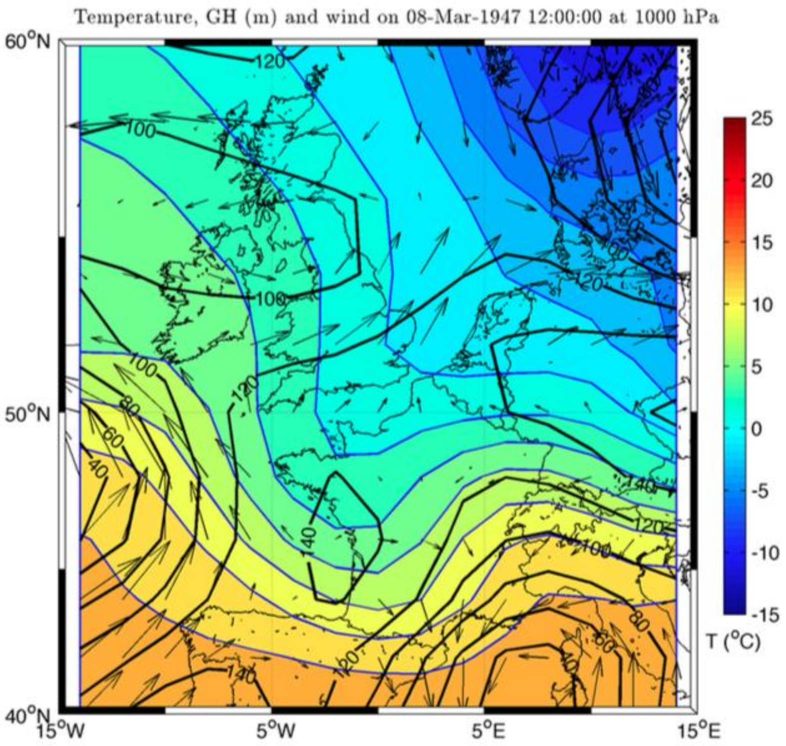

Figure 3.34 Same as Figure 3.33 at 12:00 UTC.

Table 3.17 Daily minimum temperature register in Den Helder from 6th March until 8th March 1947.

	Daily maximum temperature (ºC)
6th March 1947	-4.5
7th March 1947	-12.9
8th March 1947	-6.4

3.5. Distribution of different types of FH and FC in Europe

According to the classification proposed by [5], both FH and FC are split into three different categories. These categories depend only on the temperature difference achieved with the previous and later day. In order to further analyze how the FH and FC phenomena are distributed throughout Europe, all the episodes occurred between 1900 and 2000 will be classified according to these three different categories. In order to avoid distortional results, we consider only those stations having more than 100 episodes in total.

FH and FC distribution in type 1 (absolute temperature difference between 5 and 7 ºC), type 2 (absolute temperature difference between 7 and 9 ºC) and type 3 (absolute temperature difference of more than 9ºC) are shown in **Figures 3.35** and **3.36** respectively.

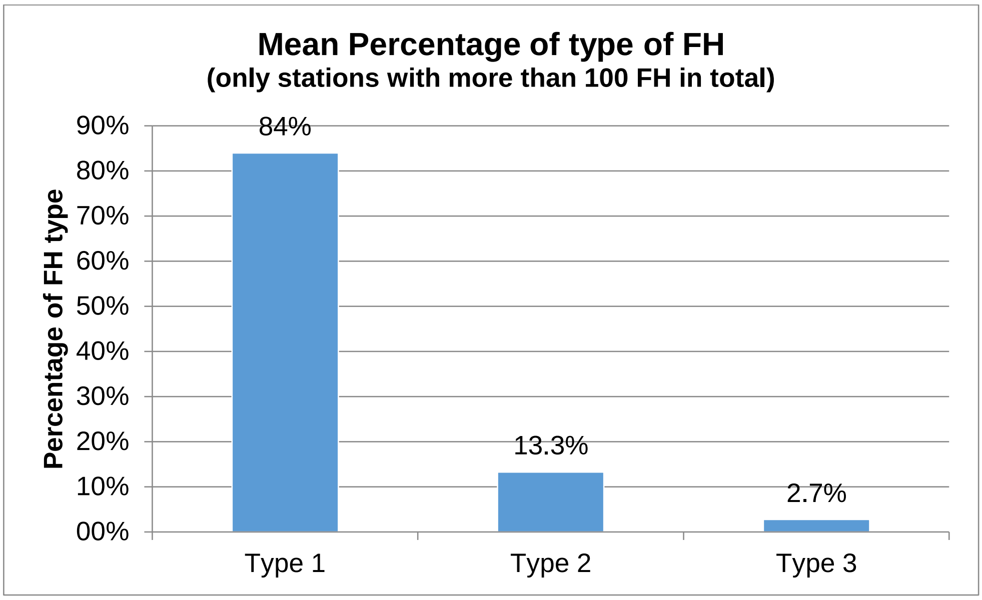

Figure 3.35 FH type distribution for the period between 1900 and 2000 expressed as a percentage

According to the distribution obtained in **Figure 3.35**, the prevailing FH type is 1 with an 84% of the total episodes registered. Types 2 and 3 only represent the 13.3% and 2.7% respectively. This implies that most of the FH are caused by a sudden increase in temperature between 5ºC and 7ºC. Thus, the episodes occurring because of extremer temperature differences only represent a small portion of the total FH.

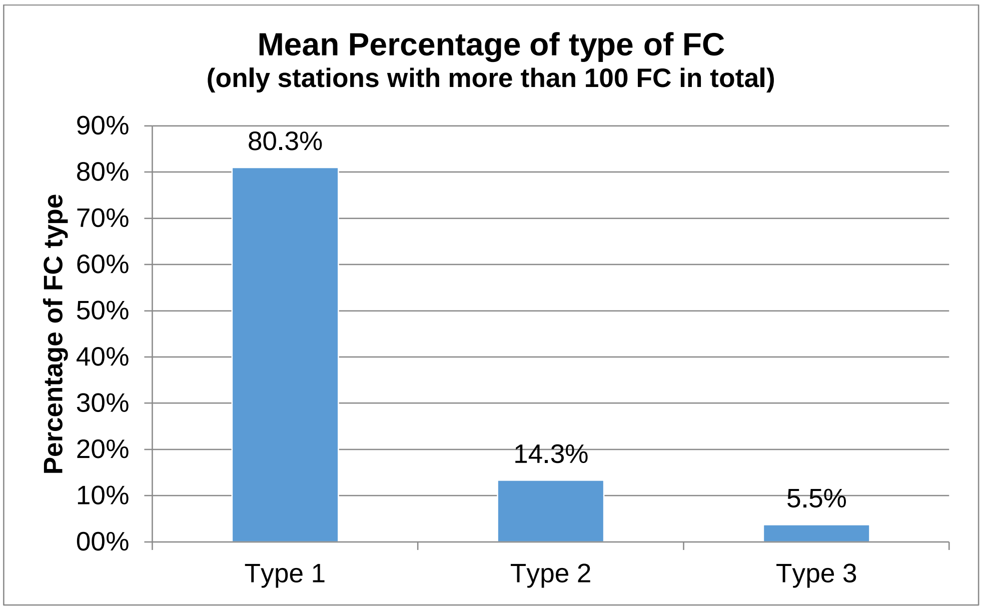

Figure 3.36 Same as Figure 3.35 for FC

From **Figure 3.36**, the percentage distribution of FC types is very similar to the obtained for FH. The prevailing FC type is 1 with an 80.3% of the total episodes registered, followed by types 2 and 3 with the 14.3% and 5.5% respectively. This means that most of the FC are caused by a sudden decrease in temperature between -5ºC and -7ºC.

In conclusion, the FH and FC type distribution over Europe from 1900 until 2000 points towards a predominance of type 1 with sudden temperature variations from 5ºC to 7ºC in absolute value. Type 1 is followed far away by type 2 with only the 13.3% of FH and the 14.3% of FC episodes with temperature variations from 7ºC to 9ºC in absolute value. Finally, type 3 becomes residual with a low register of FH and FC caused by temperature variations of more than 9ºC in absolute value.

CONCLUSIONS

The definition of the flash heat and flash cold phenomena is proposed to name the meteorological event contained between the temporal scales of a heat wave and a heat burst, which range from 2 days to a few weeks for the heat wave to few minutes for the heat burst.

Therefore, the flash heat phenomenon can be defined as a meteorological event that consist of a sudden increase in temperature of at least 5ºC and a decrease in relative humidity that lasts a maximum of 24 hours. Analogously, the flash cold phenomenon can be defined as a meteorological event that consist of a sudden decrease in temperature of at least 5ºC and a decrease in relative humidity that lasts a maximum of 24 hours.

The data analyzed to carry out this project consist of the daily minimum and maximum temperature of 26 different meteorological stations dispersed all over Europe for the 20th century. The FH and FC events have been identified and grouped together by decades and by seasons within each of the stations using a Matlab script.

First, to determine if there is any common trend in the evolution of the FH and FC phenomena across Europe, the meteorological stations have been organized into different climatic regions with similar characteristics using the Köppen climate classification system. Inside each climate region it has been attempted to classify the stations according to the mean annual precipitation, mean annual temperature, latitude, longitude, total number of FH or FC episodes and height. For most cases, it does not exist a clear relationship between the mean annual precipitation, mean annual temperature, height of the stations and the total number of FH or FC. In the case of the stations having oceanic climate, those situated on western longitudes (United Kingdom and Ireland) show a considerably lower number of FH than the stations situated on eastern latitudes. Simultaneously, for the humid continental and subarctic climates, the stations situated on northern latitudes show a higher number of FC than those situated on southern latitudes. As for the stations grouped as Mediterranean climate, the results suggest a converging tendency of the FC episodes for the last decades of the 20th century.

Water masses such as the Atlantic Ocean, the Baltic Sea, the Mediterranean Sea and the Black Sea, and their temperature seem to be a possible influence in the number of FH and FC. The orography around the stations and the invasion of air masses might also be factors in both phenomena. Another possible cause for the FH phenomenon is the Foehn effect. As for the FC, some of the possible causes are temperature inversion and Mistral winds (particularly for the station of Marseille).

Secondly, the seasonal distribution for each decade of the 20th century for both FH and FC have been analyzed. The results obtained show that the FH phenomena during the 20th century occurred more frequently during spring and summer. The FC phenomena took place mainly during winter, followed closely by spring and autumn.

Later, the evolution of the number of FH and FC throughout the last century has been compared with the evolution of the mean temperature and mean annual amount of precipitation. For this analysis, a correlation coefficient has been calculated. The results show a wide range of different correlation coefficients for both temperature and precipitation variables and FH and FC. Therefore, there seems to be no apparent relation between the evolution of the mean temperature and the mean annual amount of precipitation and the evolution of the number of FH and FC.

Next, the influence of air masses has been analyzed by studying two particular cases. In both cases it is shown how an air mas, warm or cold depending on each case, is the cause responsible for a FH or a FC episode in some particular stations.

Finally, the episodes of FH and FC have been classified into three different categories depending on the temperature difference with the previous and later day. The results show that both FH and FC episodes are mostly of type 1 with temperature variations from 5ºC to 7ºC.

FUTURE WORK

This project consists on a first approach to the analysis of FH and FC phenomena occurred in Europe throughout the 20th century, consequently several additional research studies can be done for extending the scope of this work.

On a large scale, a first line of research could be the so called North Atlantic Oscillation (NAO). The NAO is based on the surface sea level pressure difference between the Icelandic Low and the Azores High. A strong positive phase of NAO is associated to above-normal temperatures across northern Europe and below-normal temperatures over southern Europe. Thus, the NAO could have an influence on FH and FC distribution over Europe.

FH and FC main driving mechanism are the general atmospheric circulation and Foehn effect. In this sense, another line of research is to further investigate the role of atmospheric circulation on FH and FC occurrence.

Regarding the Foehn effect, it has been suggested in this project to be responsible for the FH registered in many stations surrounded by mountain ranges. A deeper study on local factors such as the orography or the prevailing winds should be done to those stations presumably affected by Foehn winds to determine its influence. Similarly, a deeper analysis on the occurrence of temperature inversion could be done to those stations susceptible of suffering this phenomenon in order to determine if it has any influence on the occurrence of FC.

On another front, more research needs to be done on the influence of mean temperature and precipitation on the occurrence of FH and FC. The results showed a wide disparity on the linear correlation coefficients obtained for each of the stations. Thus, a deeper study on those stations showing strong correlation coefficients is needed. Also, other types of correlation between these variables should be studied.

Finally, another line of research is to study if there is any difference in the number of FH and FC episodes depending on whether they are in an urban or rural setting. This will be useful to determine if industrialization favors or not the occurrence of FH and FC.

There is clearly much work to be done in the analysis of FH and FC phenomena across Europe. Perhaps the most direct extension of this work is by means of deeply analyzing each of the stations used to better understand the causes and nature of FH and FC distribution over Europe.

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ATTACHMENT A

Main Flash Heat Matlab script:

```
%%%%%%%%%%%%%%%% MAIN FLASH HEAT %%%%%%%%%%%%%%%%
clear all
close all
clc

%% Read the file data  & save it in a struct

% The file is named after the station and a .txt extension
s=readfile('Sodankyla.txt');

%% Find the Flash heat
count=0;
j=1;
x=0;

%the days with a Flash Heat episode are saved into a matrix with the date,
%the temperature and the difference of temperature with the previous and
%the next day

FH=zeros(1,6);
dec=zeros(1,10);
nodata=zeros(1,10);
daysperyear=zeros(1,100);
season=zeros(4,10);% row( 1=spring; 2=summer; 3=autumm; 4=winter);
type=zeros(3,10); %row( 1=type1; 2=type2; 3=type3)
for i=2:(length(s)-1)

    %calculate how many days per year are there in the data (it will be
    %used to determine if there are any missing days)
    daysperyear(1,s(i).year-1900+1)=daysperyear(1,s(i).year-1900+1)+1;

    if(s(i-1).tmax==(-999.9)||s(i-1).tmin==(-999.9)||s(i).tmax==(-
999.9)||s(i).tmin==(-999.9)||s(i+1).tmax==(-999.9)||s(i+1).tmin==(-999.9))
        %if there is no data from the previous day, the current day or the
        %next day we skip the day

         %Calculate the number of days per decade that there is no data
        if(s(i).tmax==(-999.9)||s(i).tmin==(-999.9))
            year=s(i).year;
            nodata(1,fix(year/10)-190+1)=nodata(1,fix(year/10)-190+1)+1;
        end

        continue
    else

        %Calculate the temperature difference between the current day and
```

```
%the previous day and the difference between the current day and
%the next day

difTemp1=s(i).tmax-s(i-1).tmax;
difTemp2=s(i).tmax-s(i+1).tmax;

%A Flash Heat occurs only if the temperature difference is higher
%than 5 degrees celcius
if(difTemp1>=5)
   if(difTemp2>=5)

      %Safe the data of the day where the flash heat happens. The
      %data is saved following: year  month  day  temperature max
      %temperature difference previous day   temp dif next day
      FH(j,1)=s(i).year;
      FH(j,2)=s(i).month;
      FH(j,3)=s(i).day;
      FH(j,4)=s(i).tmax;
      FH(j,5)=difTemp1;
      FH(j,6)=difTemp2;

      %check which type of FH
      type1=0;
      type2=0;
      type3=0;
      if(FH(j,5)>=5 && FH(j,5)<7)
         type1=type1+1;
      elseif (FH(j,5)>=7 && FH(j,5)<9)
         if(FH(j,6)>=7)
            type2=type2+1;
         else
            type1=type1+1;
         end
      elseif (FH(j,5)>=9)
         if(FH(j,6)>=9)
            type3=type3+1;
         elseif (FH(j,6)>=7)
            type2=type2+1;
         else
            type1=type1+1;
         end
      end

      %Decade and season
      year=s(i).year;
      month=s(i).month;
      for i=0:11
         if((1900+i*10)<=year&&(1900+i*10+10)>year)
           dec(i+1)=dec(i+1)+1;
           type(1,i+1)=type(1,i+1)+type1;
```

```
                type(2,i+1)=type(2,i+1)+type2;
                type(3,i+1)=type(3,i+1)+type3;

                if(month>=3&&month<=5)
                   season(1,i+1)=season(1,i+1)+1;
                elseif(month>=6&&month<=8)
                   season(2,i+1)=season(2,i+1)+1;
                elseif(month>=9&&month<=11)
                   season(3,i+1)=season(3,i+1)+1;
                else
                   season(4,i+1)=season(4,i+1)+1;
                end
              end
           end
           j=j+1;
        end
     end
   end
end

%Calculate the number of missing days per year of data
missingdaysperyear=zeros(1,100);
for i=1:100
   if (daysperyear(1,i)==365 || daysperyear(1,i)==366 || daysperyear(1,i)==364)
      continue
   else
      missingdaysperyear(1,i)=365-daysperyear(1,i);
   end
end

%Calculate teh number of missing days per decade of data
missingdaysperdecade=zeros(1,10);
a=1;
decade=1;
for i=1:100
   if(a<=10)

missingdaysperdecade(1,decade)=missingdaysperdecade(1,decade)+missingd
aysperyear(1,i);
      a=a+1;
   else
      decade=decade+1;

missingdaysperdecade(1,decade)=missingdaysperdecade(1,decade)+missingd
aysperyear(1,i);
      a=2;
   end

end
```

ATTACHMENT B

Main Flash Cold Matlab script:

```
%%%%%%%%%%%%%%%%%% MAIN FLASH COLD %%%%%%%%%%%%%%%%%%

cleclear all
close all
clc

%% Read the file data  & save it in a struct

% The file is named after the station and a .txt extension
s=readfile('Oxford.txt');

%% Find the Flash Cold
count=0;
j=1;
x=0;
%we save the days with Flash Cold into a matrix with the data, the
%temperature and the difference of temperature with the previous and the
%next day.
FC=zeros(1,6);
dec=zeros(1,12);
nodata=zeros(1,12);
season=zeros(4,12);% row( 1=spring; 2=summer; 3=autumm; 4=winter);
type=zeros(3,10); %row( 1=type1; 2=type2; 3=type3)

for i=2:(length(s)-1)

   if(s(i-1).tmax==(-999.9)||s(i-1).tmin==(-999.9)||s(i).tmax==(-
999.9)||s(i).tmin==(-999.9)||s(i+1).tmax==(-999.9)||s(i+1).tmin==(-999.9))
      %if there is no data from the previous day, the current day or the
      %next day we skip the day

      continue
   else
      %Calculate the temperature difference between the day to analyse and
      %the day before and the next day.
      difTemp1=s(i).tmin-s(i-1).tmin;
      difTemp2=s(i).tmin-s(i+1).tmin;

      %A Flash Cold occurs only if the temperature difference is higher
      %than 5 degrees celcius
      if(difTemp1<=-5.0)
         if(difTemp2<=-5.0)

            %safe the data of the day where the flash cold happens. The
            %data is saved following: year  month  day  temperature min
            % temperature difference previous day   temp dif next day
```

```
FC(j,1)=s(i).year;
FC(j,2)=s(i).month;
FC(j,3)=s(i).day;
FC(j,4)=s(i).tmin;
FC(j,5)=difTemp1;
FC(j,6)=difTemp2;

 %check which type of FC
type1=0;
type2=0;
type3=0;
if(FC(j,5)<=-5 && FC(j,5)>-7)
   type1=type1+1;
elseif (FC(j,5)<=-7 && FC(j,5)>-9)
   if(FC(j,6)<=-7)
      type2=type2+1;
   else
      type1=type1+1;
   end
elseif (FC(j,5)<=-9)
   if(FC(j,6)<=-9)
      type3=type3+1;
   elseif (FC(j,6)<=7)
      type2=type2+1;
   else
      type1=type1+1;
   end
end

%Decade and season
year=s(i).year;
month=s(i).month;
for i=0:11
   if((1900+i*10)<=year&&(1900+i*10+10)>year)
     dec(i+1)=dec(i+1)+1;
     type(1,i+1)=type(1,i+1)+type1;
     type(2,i+1)=type(2,i+1)+type2;
     type(3,i+1)=type(3,i+1)+type3;
     if(month>=3&&month<=5)
        season(1,i+1)=season(1,i+1)+1;
     elseif(month>=6&&month<=8)
        season(2,i+1)=season(2,i+1)+1;
     elseif(month>=9&&month<=11)
        season(3,i+1)=season(3,i+1)+1;
     else
        season(4,i+1)=season(4,i+1)+1;
     end
   end
end
```

```
            j=j+1;
         end
      end
   end
end
```

ATTACHMENT C

Mean Temperature Matlab script:

```
%%%%%%%%%%%%%%%% MAIN TEMPERATURE %%%%%%%%%%%%%%%%

clear all
close all
clc

%% Read the file data  & save it in a struct

% The file is named after the station and a .txt extension
s=readfileaveragetemp('Karlstad.txt');

%% Find the Average Temperature per decade

%Save the number of days per each decade and the sum of the average
%temperature per decade
numdays=zeros(1,10);
sumtemp=zeros(1,10);

for i=1:length(s)
   %if the data for a given day is missing it is not included
   if (s(i).taverage==-999.9)
      continue
   else
      numdays(1,fix(s(i).year/10)-190+1)=numdays(1,fix(s(i).year/10)-190+1)+1;
      sumtemp(1,fix(s(i).year/10)-190+1)=sumtemp(1,fix(s(i).year/10)-
190+1)+s(i).taverage;
   end

end

%Calculate the mean temperature for each decade
meantemperature=zeros(1,10);

for i=1:10
   if(numdays(1,i)==0)
      continue
   else
      meantemperature(1,i)=sumtemp(1,i)/numdays(1,i);
   end

end
```

ATTACHMENT D

Mean Annual Amount of Precipitation Matlab Script:

```
%%%%%%%% MEAN ANNUAL AMOUNT OF PRECIPITATION %%%%%%%%

clear all
close all
clc

%% Read the file data  & save it in a struct

% The file is named after the station and a .txt extension
s=readfileannualprecip('Vilnius.txt');

%% Find the Average amount of annual precipitation per decade

%Save the number of days per each decade and the sum of the annual
%precipitation per decade
numdays=zeros(1,10);
sumprecip=zeros(1,10);

for i=1:length(s)
   %if the data for a given day is missing it is not included
   if (s(i).annualprecip==-999.9)
      continue
   else
      numdays(1,fix(s(i).year/10)-190+1)=numdays(1,fix(s(i).year/10)-190+1)+1;
      sumprecip(1,fix(s(i).year/10)-190+1)=sumprecip(1,fix(s(i).year/10)-
190+1)+s(i).annualprecip;
   end

end

%Calculate the mean annual precipitation for each decade
meanannualprecip=zeros(1,10);

for i=1:10
   if(numdays(1,i)==0 || numdays(1,i)<=3600)
      continue
   else
      meanannualprecip(1,i)=sumprecip(1,i)/10;
   end

end
```