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BACHELOR'S DEGREE THESIS

TITLE OF THE THESIS: Meteodiversity Index during the 20th century in Europe

DEGREE: Bachelor's Degree in Air Navigation Engineering

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Overview

The concept of meteorological diversity or Meteodiversity was first proposed by [1], derived directly from the concept of biodiversity. Its main purpose is to characterize the variety of meteorological phenomena in a defined area within a specified period. To quantify this variety, a Meteodiversity Index is proposed in [1].

The aim of this paper is to study how the Meteodiversity Index have distributed over Europe between 1950 and 2000. To develop the research, 7 meteorological variables have been obtained from the data of 23 meteorological stations across Europe.

The paper includes an analysis of the sensitivity of the Meteodiversity Index to changes in the inputs. Then, the evolution of the Meteodiversity Index is studied, both by climate type, according to Köppen climate classification system, and by geographical location.

Finally, in the light of the results, another analysis is performed to determine the relationship between the Meteodiversity Index and the climatic tendencies of Europe.

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

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Dedication

First, I would like to express my gratitude to the co-directors of the thesis, professors David Pino and Jordi Mazon for their contributions, guidance, knowledge and patience along the elaboration of the thesis, as well for the initial proposal for the main concept. Without their invaluable help, this study would not have been possible.

Besides, I would also like to thank the European Climate Assessment & Dataset for the data collected and provided through their work and the European Meteorological Society (EMS), for their constant contribution to science and the motivation provided.

Last, I would also like to mention the contribution of my family and friends for their constant source of moral support, encouragement and strength along the journey.

Introduction

The concept of biodiversity is defined in the United Nations Environment Program and [11] as the diversity of animal and vegetal species living in a given space. Similarly, the proposed concept of Meteodiversity (see [1]) is defined as the amount of different meteorological phenomena occurring in a given space over a period of time.

In order to quantify the Meteodiversity, a Meteodiversity index is proposed in [1]. It is based on an adaptation of the Shannon index, used for quantifying the biodiversity (see [10]) and usually symbolized by H. However, for the scope of the project, Meteodiversity Index will be symbolized by MI.

The main purpose of this project is to use daily data from several weather stations across Europe dating from 1950 until 2000, according to the available dataset, to calculate the MI values and behavior, and analyze the different patterns in Europe and their tendency.

The project consists in the following three sections:

I. In Chapter 1, a definition of the Meteodiversity Index will be given, and the aeronautical application of this concept will be proposed.
II. In Chapter 2, all data used for the analysis will be presented, including descriptions on the climate classification system used, the main climate types found and the indices of extremes employed.
III. In Chapter 3, a deeper analysis will be performed upon the behaviour of the Meteodiversity Index. Also, the obtained values of the study will be related both to climate types and geographical locations. Finally, Meteodiversity Index will be related to the climate patterns in Europe.

Chapter 1. Theoretical study

1.1. Meteodiversity index

Mazon and Pino (2017)- proposed the concept of Meteodiversity (see [1]). Similar to the concept of biodiversity, Meteodiversity considers the amount of each meteorological phenomenon that occurs over a defined area.

In order to quantify this amount, a Meteodiversity index is proposed in [1]. It considers a number of atmospheric variables obtained from instrumental and observational records, such as cloud cover, pressure, extremes of temperature, types of precipitation and wind. The restrictions on the variables used are limited only by the meteorological relevance of the variables in each area, defined by the user, and the amount of data available. The index is calculated using (1.1):

$$MI = -\sum_{i=1}^{s} p_i \, log_2(p_i) \tag{1.1}$$

where s is the total number of different recorded or observed weather phenomena occurring in a location, and p_i is the proportion of the number of cases of the meteorological phenomena (n_i) with respect to the total amount of cases of the whole phenomena and events (N). In other words, $p_i = (n_i/N)$.

The typical values studied for MI in [1] indicate that values lower than 1 are associated with poor meteodiversity, like deserts, while values higher than 3 correspond to great meteodiversity, like rainforests.

1.2. Aeronautical application

The present studio is useful for defining the variation of the climate over a specific area at ground height, up to FL100, or an approximate height of 3000m. Above this height, Low Significant Weather charts (SWL) are replaced for Medium Significant Weather charts (SWM), indicating big differences in most of the phenomena. From this height upwards, the meteorological index calculated at ground level stops being reliable, as the variables studied at ground level, specially temperature, can vary significantly (see [12] for more information).

As there is no way to obtain a significant amount of data source for the last 50 years spread enough across Europe above 3000 m, the meteorological index cannot be used to establish the stability of the climate on a flight plan, especially in the cruise phase, becoming a little more useful for this purpose on the departure and arrival phases, when the airplane is at a height low enough to expect a similar meteorology that the one present at ground level at that area on that moment.

Most of the stations are selected near cities with aerodromes/airports. The variables used in the calculation of the MI account are mostly temperature and precipitation. Being this the case, the main application of the MI when is related to aviation is to quantify the variability of the meteorological conditions found in an airport. Hence, in already built airports, the tendencies extracted from the MI variation patterns can be used to predict how the ground operations management is going to be affected with the time. Good examples can be the air conditioning and heating consumption before take-off and in the installations, the icing countermeasures, the needed drainage systems efficiency or even the expected variations in the runway length and width margins. The MI could also be used to help choosing a possible location for the runway and the installations, complementing the studies performed about the climate of the region with a predicted variation of this climate.

A higher MI value over an area would indicate that more variability in the climate phenomena is expected, whereas a lower MI value means a steadier climate, with generally a predominant type of phenomena that has to be dealt with (if it causes an unfavorable situation).

The evolution of the MI indicates how the climate of the region is varying through the years. In consequence, for two distant decades in the same region, a higher mean value of the MI indicates that the area has changed its meteorology significantly, and it is advisable to take some measures to prevent issues related to the change on phenomena distribution.

Theoretically, it might be better to have a low, constant mean value of the MI over an area to ensure the quality and continuity of the measures used to counter the predominant phenomena adverse effects (for example usefulness of the drainage or irrigation systems).

However, the problem is more complex, as Meteodiversity could be also related to the climate type. Therefore, MI becomes the most powerful when it is used for comparing regions with similar climates.

Chapter 2. Methodology

2.1. Selected data

In this studio, the data used is obtained from the *European Climate Assessment and Dataset project* available at *ECA&D* website (see [14]). Here it can be obtained meteorological data on weather and climate extremes from 10584 meteorological stations distributed over the most part of Europe, north of Africa and Middle East, from the year every station was built until June of 2017. The available meteorological data is used to calculate a total of 72 meteorological variables.

2.2. Variables used

The data was downloaded from the available at *ECA&D* website ([14]). From the available variables, only few of them can be used, because a reliable amount of data is needed for each station (we consider the period 1950-2000), and some of these variables are based on calculations using predefined formulas and meteorological data, such as cloud cover, minimum and maximum temperature and amount of precipitation. Unfortunately, most of the instruments that measure the variables to calculate the indices were not available at all the stations at 1950.

Therefore, the variables selected for the study are temperature, precipitation and snow depth, the most spread ones. From those, only temperature and precipitation have a significant amount of data in a widespread group of stations and years (minimum 90% of the years from 1950 to 2000 and a minimum of 20 stations well distributed across Europe) to be suitable as base variables for the main study.

By using temperature and precipitation, the main variables used when calculating MI are already presented in *ECA&D* [14]:

- Frosty days are those days with minimum temperature lower than 0^oC, regardless of the maximum temperature. In those days, there is a probability of formation of frost, but icing is not ensured because the temperatures can be only below 0^oC for an instant (the calculation is based on the minimum temperature), giving no time for the water to freeze.
- Icy days are those days with maximum temperature below 0^oC. As all the temperatures will be below 0^oC for a whole day, small sources of water at rest will probably freeze during those days. Typically, these days will be the coldest, as the minimum temperature can far below 0^oC in this index.
- Summer days present maximum temperature above 20^oC. As an inversion of temperature high enough to lower the temperatures below water

freezing point is extremely unprovable, those days are classified as summer days, even if not necessarily have to be the warmest days or belong to the northern hemisphere summer season.

- Tropical nights present minimum temperature above 20ºC. As this means that in any point of the day, including the coldest one, typically at the end of the night, the temperatures will be above this point, this type of days can be classified as days with tropical nights (and will be typically hotter than the normal summer days).
- Wet days are the days with a minimum of 1mm of any type of precipitation during all the day, including snow, hail, sleet and even acid rain. As this grouping is made, there is no immediate way to add a general index defining specific types of precipitation. In addition, the presence of snow or other types of precipitation cannot be obtained objectively groping wet days and icy days, because the temperatures are measured at the surface and can increase or decrease when reaching the height of the clouds.
- Heavy precipitation days are those days within a year with a minimum amount of 10mm of precipitation of any type during the day. Very heavy precipitation days are the same, but with a minimum of 20mm of precipitation during the day, without a maximum amount of precipitation defined. It is remarkable that very heavy precipitation days can and will be overlapped with heavy precipitation days and wet days, in the same way that icy days are overlapped with frosty days and tropical nights with summer days.

All these variables are also the most suitable when defining a meteorological situation, as they can be calculated in amount of days per year with non-negligible amounts (as an example the day with maximum temperature or the number of consecutive days with a given index happening would be very small when compared to this indices).

2.3. Köppen classification

In order to determine how MI varies across Europe, we organize the meteorological stations according to their climate. The final objective is to be able to determine if there is any resemblance in the evolution and values of MI between two distant stations if their climates are similar or if MI evolution presents a dependence on climate.

The grouping of the stations has been made using the Köppen climate classification system (see [4] and [13]), widely spread since 1918. This system is used nowadays as a reliable and upgraded climate classification criteria, and generally preferred over other climate classification systems, like Strahler climate classification system, which is based mainly on latitude, or traditional climate classification system, based mainly on temperature (see [19]).

The main strengths of Köppen classification system are that it is able to classify the climates in a worldwide scale and it generally relates well the air masses circulation in the atmosphere with the climate. The main weakness of this type of classification is the precision when defining the climate types in the regions with transitions of climates, sometimes leading to arbitrary or dissenting local classifications, as the system is designed to work on a planetary scale.

Köppen classification system is based in a combination of 3 letters, according to the general and more specific characteristics of every climate, based upon latitude (the globe is divided in warm, temperate and cold latitudes for a first division), precipitation, temperature and vegetation found in an area. The first letter indicates the climatic group, while the second letter marks the amount of seasonal precipitation and the third one describes the amount of heat. In Table 2.1, a general description of the system can be found.

Table 2.1: General explanation of Köppen climate classification scheme and meaning of the symbols

1st letter	Climatic type	2nd letter	Precipitation distribution	3rd letter	Heat
A	Tropical	f	Well distributed precipitation each month	h	Hot (coldest month mean temperature above 0ºC)
B	Arid	m	Driest month with between 4% of the total precipitation and 60mm	k	Cold (at least one month mean temperature below 0ºC)
C	Temperate	w	Driest month with precipitation less than 4% of the total precipitation (and below 60mm)	n	Mild

D	Cold	W	Desert (precipitation below 30% of given threshold, and extremely low)	a	Hot summer (warmest month averaging above 22^{o}C, 4 or more months above 10^{o}C)
E	Polar	S	Semi-arid (precipitation between 30-70% of given threshold)	b	Warm summer (warmest month averaging below 22^{o}C, 4 or more months above 10^{o}C)
		T	Similar to desert but with minimal evaporation and wetter summers	c	Cold summer (warmest month averaging below 22^{o}C, 1-3 months above 10^{o}C)
		F	Nearly non-existing precipitation or snow due to extreme cold temperatures	D	Very cold winter (coldest month averaging below -38^{o}C, 1-3 months above 10^{o}C)

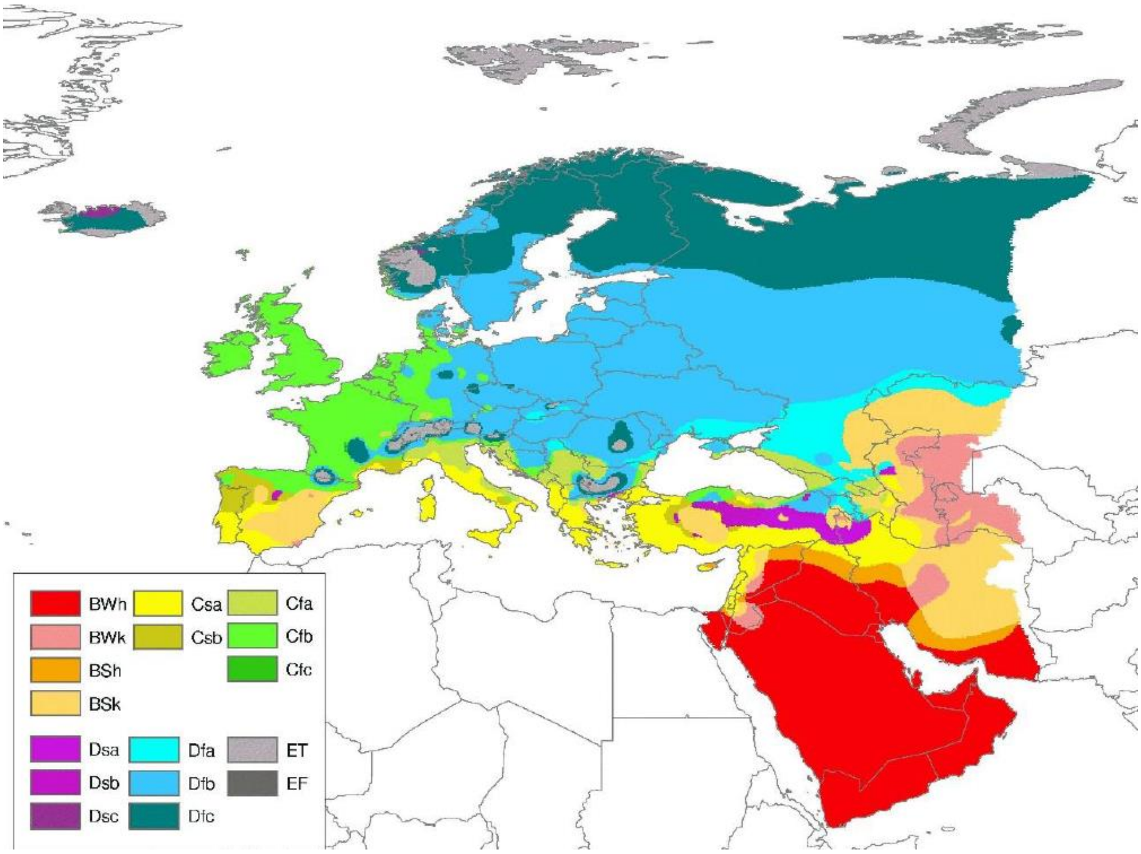

Fig. 2.1: Köppen climate classification distribution system over Europe and the Middle East areas [13]

As seen in Fig. 2.1, in Europe some of the possible combination of letters that create a climate do not appear. In consequence, Europe has a predominance of some climates for the most part. As a result, only some climates, described in section 2.4, are spread enough to be described in the study.

Regarding the special distribution of the data used, in Table 2.2 and Fig. 2.2, a list of the stations employed in the study and their location is shown. This list describes the location and climate type of each of the stations used, explained in Section 2.4. It is important to note that some cities, like Barcelona (that has a Mediterranean climate), count with some microclimates that cannot be perfectly perceived within Fig. 2.1.

Table 2.2: Meteorological stations across Europe chosen for the MI analysis, including the location, elevation and climate type according to Köppen classification

Stations	**Latitude (g:m:s)**	**Longitude (g:m:s)**	**Elevation (m)**	**Climate type**
A Coruña, Spain	+43:22:01	-008:25:09	58	Cfb
Madrid, Spain	+40:22:40	-003:47:21	687	Bsk
Barcelona, Spain	+41:17:34	+002:04:11	4	Csa
Marseille, France	+43:26:30	+005:13:36	5	Csa
Nantes, France	+47:09:36	-001:36:00	27	Cfb
Maastricht, Netherlands	+50:54:19	+005:45:42	114	Cfb
Jena, Germany	+50:55:36	+011:35:03	155	Dfb
Dublin, Ireland	+53:25:41	-006:14:27	71	Cfb
Stornoway, United Kingdom	+58:19:48	-006:19:12	9	Cfb
Geneva, Switzerland	+46:12:00	+006:09:00	405	ET/Cfb
Hellinikon, Greece	+37:54:00	+023:45:00	10	Csa
Brindisi, Italy	+40:37:59	+017:55:59	10	Csa
Verona, Italy	+45:22:59	+01:52:00	68	Csa/Cfa
Ljubljana, Slovenia	+46:03:56	+014:31:01	299	Cfb
Debrecen, Hungary	+47:29:25	+021:36:38	107	Dfb
Buzau, Romania	+45:07:59	+026:51:00	97	Dfb
Kiev, Ukraine	+50:24:00	+030:31:59	166	Dfb

Odesa, Ukraine	+46:28:48	+030:37:48	42	Dfb
Kaunas, Lithuania	+54:52:59	+023:49:59	77	Dfb
Vilsandi, Estonia	+58:22:59	+021:48:55	6	Dfb
Helsinki, Finland	+60:10:00	+024:57:00	4	Dfb
Sodankyla, Finland	+67:22:00	+026:39:00	179	Dfc
Karlstad, Sweden	+59:26:40	+013:20:15	107	Dfb

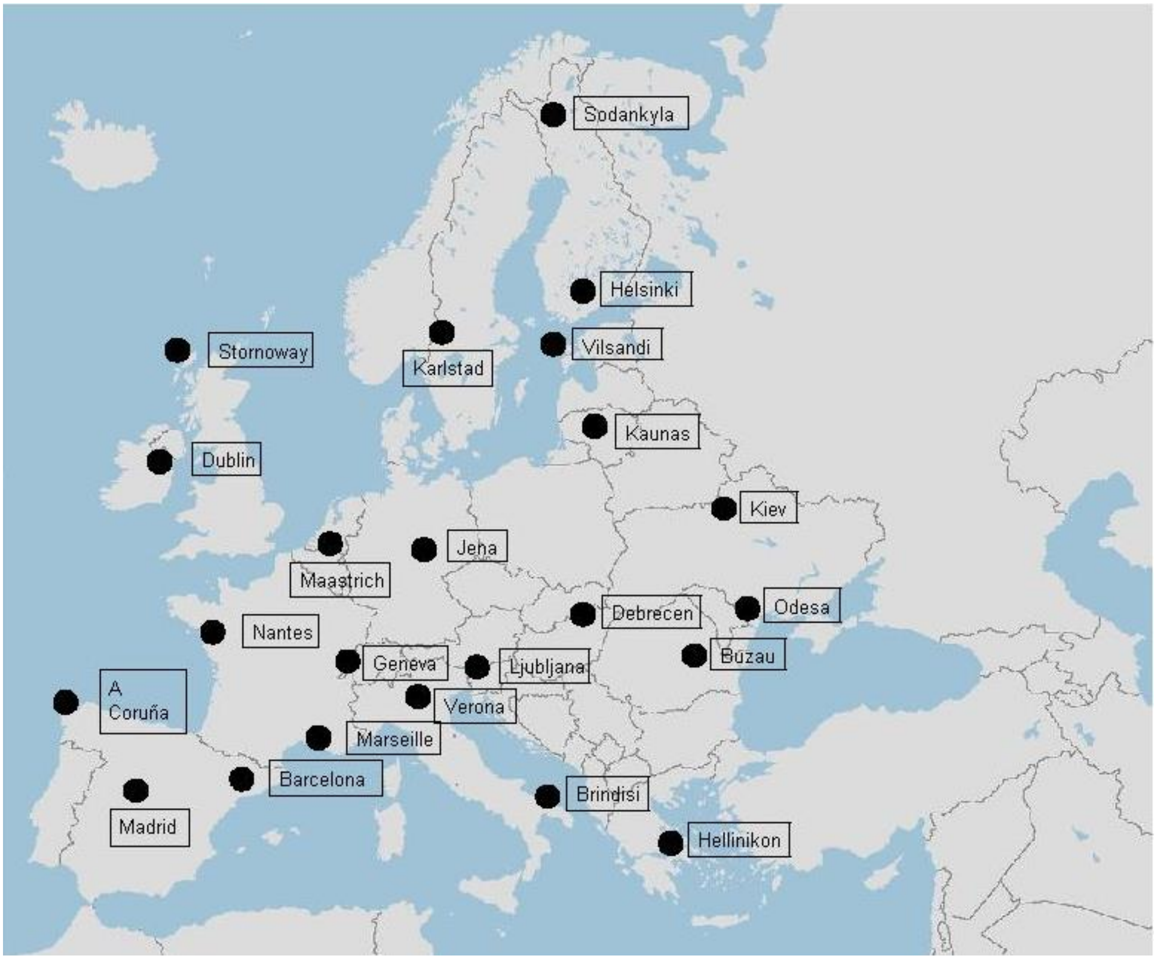

Fig. *2*.2: Meteorological stations across Europe chosen for the MI analysis with their geographical location

2.4. Main European climates description

According to Fig. 2.1, the most extended climates found in Europe are Temperate Oceanic climate (Cfb), Continental climate (Dfb) and Mediterranean climate (Csa). Subartic Continental climate (Dfc) is also found in the north part of the Scandinavian peninsula with also Dry Steppe climate (Dfc) in the center of Spain. Tundra climate (ET) and Subtropical Humid climate (Cfa) are found near some cities of the study, heavily influencing their MI values. Europe also includes other climates in small regions but we didn't select any station in these regions. Below we describe the main climatic regions where used meteorological stations are located. Fig. 2.1, used for the classification, is obtained from [3], while the climates characteristics can be obtained from the links in [13].

2.4.1. Mediterranean climate (Csa)

Csa climates are often found near the Mediterranean coastline, a large body of water, that helps to have moderate temperatures. This climate counts with dry and warm to hot summer periods, with mean temperatures above 22ºC. Winters are usually not very cold, almost always above 0ºC, and more humid (around 50mm per month). Often, precipitation amount is inversely proportional to the temperature in this type of climate. A possible explanation is the fact that, due to the usually large temperatures, the land is generally hotter than the sea. However, when the temperature falls, the process reverts, creating a low pressure (due to the temperature difference) system over the land that favours the creation of clouds thanks to the high humidity of the coastal air, and increases the chance of precipitation on land. This process is called land breeze (see [7]), and is very common in coastal areas.

In some areas, like at the Spanish or Italian coasts the mountain ranges may alter the precipitation creating thunderstorms due to the contrast of temperatures of the mountain and coast air masses, displacing the maximal amounts of precipitation to the autumn and spring stations.

2.4.2. Subtropical Humid climate (Cfa)

Found in some areas between Mediterranean and Continental Climates, this climate does not have summers cold enough to be included in the Oceanic Climates and their winter temperature is above that found in Continental climates. The main difference of this climate compared to Mediterranean climate, which also have this temperature patterns is the precipitation amount values, generally much steadier through the year, but slightly favoring precipitation in the colder stations.

2.4.3. Temperate Oceanic climate (Cfb)

Found in the largest part of Europe, this climate is characterized by a temperature range between 0 and 22ºC for the most part of the year and with soft transitions. As a result, summers are cool and winters are not very cold. Precipitation is very common and spread through the year (usually 60mm every month), without humid or dry stations. As temperatures can go below 0ºC for some months in northern areas, it is expected to have snow falling annually.

Even inland, this climate is usually influenced directly or indirectly by the ocean airmasses: in Europe, the areas with this type of climate are placed below some important air flows that bring the marine humid air inland, causing fronts that, depending on the temperatures and orography can create storms, fogs and increase the overall cloudiness.

Also, as this climate is very spread through Europe, some areas present an evolution of this climate to Mediterranean, continental or subarctic climates. As a result, the general tendency is altered depending on the location and orography even for areas with the same Köppen classification.

2.4.4. Continental climate (Dfb)

Dfb climate can be found across the eastern part of Europe. This climate is typically found in areas isolated from the sea, having as a consequence temperatures not smoothed by its influence. As a result, winters are very cold (usually below 0ºC even at equatorial latitudes) and summers are warm, with a minimum of four months with temperatures above 10ºC, and no upper limit. The precipitation on this type of climate in Europe is moderate and concentrated in the warmest months, in the form of thunderstorms.

However, for Europe, this climate can also be found near the Baltic and Black seas. This means that not at all times this climate type is found inland. In consequence, some climate evolution to other types is expected depending on the geography and the tendency of the patterns can be altered depending on the location.

2.4.5. Dry steppe climate (Bsk)

Cold, semi-arid climate can be found in some areas of the centre of the Iberian Peninsula. This climate is usually found at some distance of the coast, separated from its influence either by distance or by altitude, that can be caused by mountain ranges or plateaus. These areas usually have warm to hot summers, with similar characteristics to Mediterranean summers, but with a bigger gradient of temperatures between day and night (20ºC of difference are not uncommon), and cold winters. The precipitation amount in the cold semi-arid climate found in Europe is very similar to the precipitation found in the Mediterranean coast, with dry summers, wet winters and wetter springs and autumns.

Winds also play a bigger role than they do in the Mediterranean climate, as in Europe the orography gradient is bigger in these areas, with the associated mountain and valley breezes (see [21]), and they are not very far away from the Atlantic Ocean influence. This fact also enhances the occurrence of some types of fog, in some regions (see [6]).

2.4.6. Tundra climate (ET)

Mostly found near the poles and in the highest mountains around the world, some locations in Europe are influenced by this type of climate. It characterizes by having temperatures low enough to have the subsoil permanently frozen through the year, but with at least a month with temperatures above 0ºC.

When this climate is found near the poles, only two stations of the year can be found: summers, in which the frozen soil can melt, and winters, very dark and cold. It is also an extremely dry climate, similar to the Desert climate, but with no evaporation due to cold temperatures.

When found in mountains layers (Alpine Tundra climate), this climate is caused by low air temperatures, so it is harder to find permafrost and stations are not as dark.

2.4.7. Subarctic Continental climate (Dfc)

Characterized by long, harsh winters, with minimal annual temperatures below -40ºC the weather is typically cold and dry. However, in summer, the temperatures can exceed 30ºC, but not for a long time, typically between 1 and 3 months. The air masses are usually artic in winter and maritime polar in summer. As the cold humid air encounters a warm land beneath, precipitation is found more commonly around the middle and end of the summer periods, when the temperatures are high. However, extremely rarely does this precipitation exceed 100mm per month, as the hot temperatures do not last for long.

Chapter 3. Analysis

3.1. Meteodiversity index sensitivity analysis

Before studying the values obtained from the suggested formula (1.1), it is basic to understand what is the sensitivity of the MI to changes in the different variables that affect it.

In the current study, the expected minimum values of the variables influencing MI is 0, as the minimum number of days with a given phenomenon in a year are 0 days, and the maximum is 1, as the input variable ρ_i is a proportion of one phenomenon respect the total phenomena happening over a year.

First, in order to deal with the 0 value, that generates a negative infinite on the formula (1.1), it is assumed that, if in a given year the number of days with a given phenomenon is 0, the contribution of the phenomenon to the global MI of the year is null; there is no diversity contribution from this phenomenon in the current year because the phenomenon does not happen-. According to this, a value of 0 is assigned in the contribution to the global MI of the given phenomenon.

Consequently, if for a given year all variables considered for the study never happen (an extremely unlikely situation) the MI for this year is 0.

Another improbable scenario that has to be considered is the one when, in a given year, all the phenomenon that occurs is of one type, regardless of the number of days with the phenomenon occurring. In this case, as the formula for calculating the MI uses the proportion ρ_i of individuals, and the proportion is 1 for a given variable and 0 for the rest, when the formula calculates the variability only this variable has weight in the addition. And, as the calculation involves a logarithm of the proportion ρ_i, the value ρ_i =1 gives always a MI of 0. Hence, if only a given phenomenon happens over a year, there is no variability and the MI for the year is also 0.

And finally, the unlikely scenario where the variability is maximum must be the one where all the individual phenomena occurs the same amount of days than the others and as a consequence the weather of the year would be the most diverse. For the study, all the variables should occur the same amount of days (as multiple phenomena can happen on a day) in order to reach the maximum index. With this condition, $\rho_i = 1/7$ for all phenomena and the MI value (regardless of the number of any phenomena, as long as all numbers are equal) for the year is 2.8. This value is the maximum value the index can have in the scenario of this study.

Therefore, all the values obtained will be in the range of values between 0 and 2.8. The lower and upper limits are theoretical, as both states involve steady situations happening for over a year that cannot happen naturally in the European area.

The data used for the study, approximately ranges between 0.9 and 2.5. According to this information, the real range of values found for the MI in Europe in the last 50 years is an 60% of the possible theoretical range of values that the index can compute between the unusual, theoretical situations previously explained. So, to have a reference value for the range, this real range of values will be used to settle which changes are significant and which are negligible.

In order to compute how the index changes when some of the phenomena is artificially decreased, three stations are used, each in one of the following cities: Barcelona, Dublin and Ljubljana.

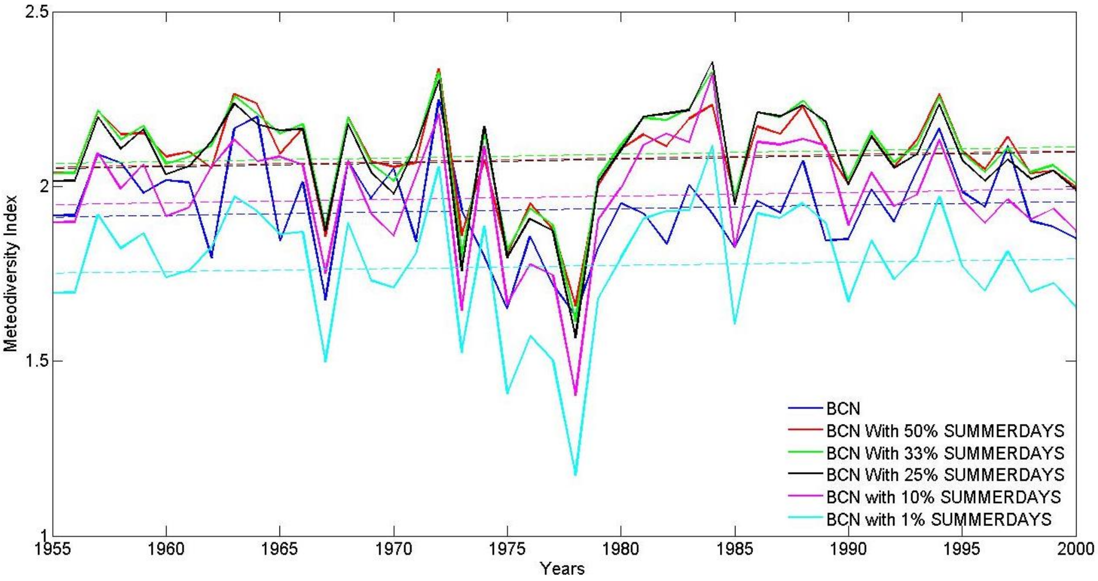

Fig. 3.1: Temporal evolution of Barcelona MI (blue line) and sensitivity to reductions in the number of summer days: 50% (red), 33% (green), 25% (black), 10% (magenta) and 1% (cyan). Dashed, thin lines represent the trend line for each case

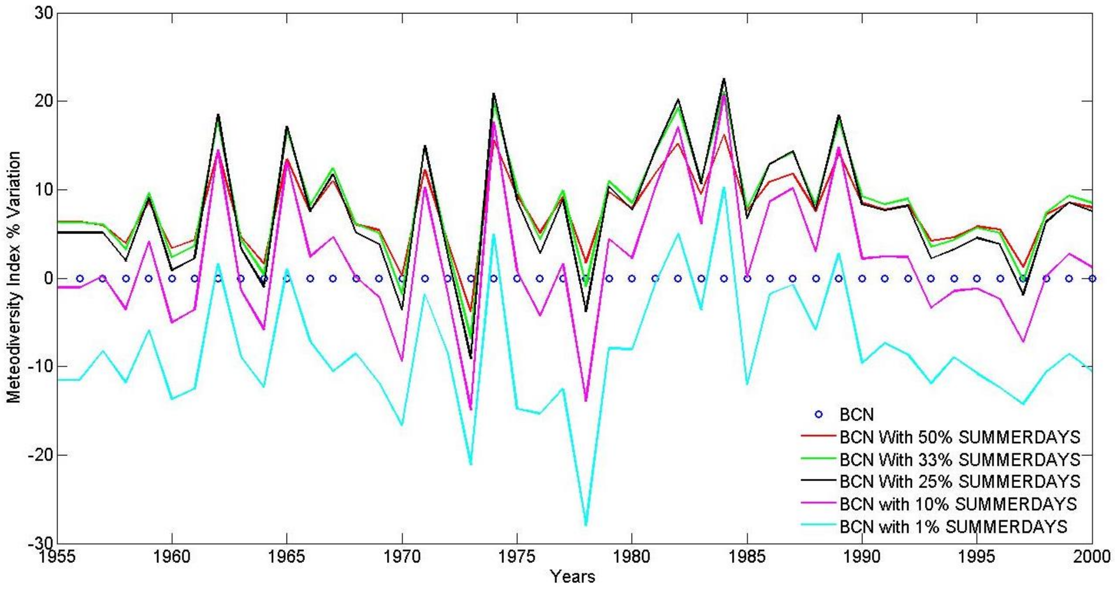

Fig. 1.2: Percentage of Barcelona MI variation respect to the actual values (circled, blue line) when reducing the number of summer days to: 50% (red), 33% (green), 25% (black), 10% (magenta) and 1% (cyan)

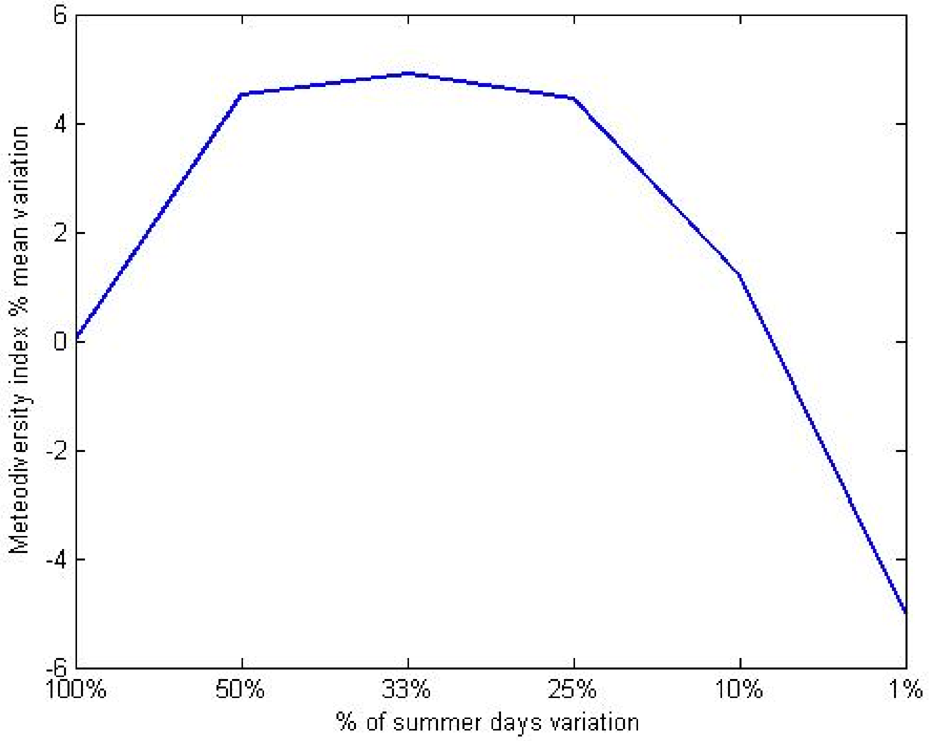

Fig. 3.3: Mean variation (%) of Barcelona MI values respect to the real values when reducing the summer days per year

Fig. 3.1 shows how the Barcelona MI values change when a reduction of a given phenomenon per year is applied to all the years of the study. In this case, the number of summer days presents the largest values in the last 50 years, and it is chosen as the variable to modify, so in Fig. 3.1 it can be seen the evolution of the MI when the number of summer days is multiplied by 0.5; 0.33; 0.25; 0.1 and 0.01. From Fig. 3.1 it can be observed that the reduction in summer days is not directly related to a decrease in MI values, as for most of the reductions the MI increases.

To better visualize the changes, Fig. 3.2 shows the percentage of change for every modified value of Barcelona MI respect to the initial ones according to the reduction applied. With Fig. 3.2 it is easier to notify that, generally, the values of the MI are higher when the amount of summer days is artificially reduced, up to a point when the summer days are reduced below 10%. Fig. 3.2 is also useful to notify that, when the summer days of Barcelona are reduced, the values of the MI can increase to an approximate maximum of 20% of their initial value and decrease to an approximate minimum of -30% of their initial value.

Fig. 3.3 shows the mean variation of the MI respect to the initial values for the 50 years of the study, to better comprehend in which grade the reductions affect the MI. As expected, decreasing this significant phenomenon results in an increase of the diversity of the meteorology. This tendency is maintained until the until the number of summer days is reduced to around 10% of its original value. When the number of summer days is decreased even more, the MI decreases below its initial value.

This happens because the proportion of summer days respect the total number of phenomena in a year in Barcelona is usually much bigger (can be 10 times higher) than the proportion of any other phenomena. According to this, when the summer days are reduced, the diversity of the meteorology is increased, because the proportion of the rest of phenomenon become more important, up to a certain point when the days of summer start to be less significant than the rest of the phenomenon.

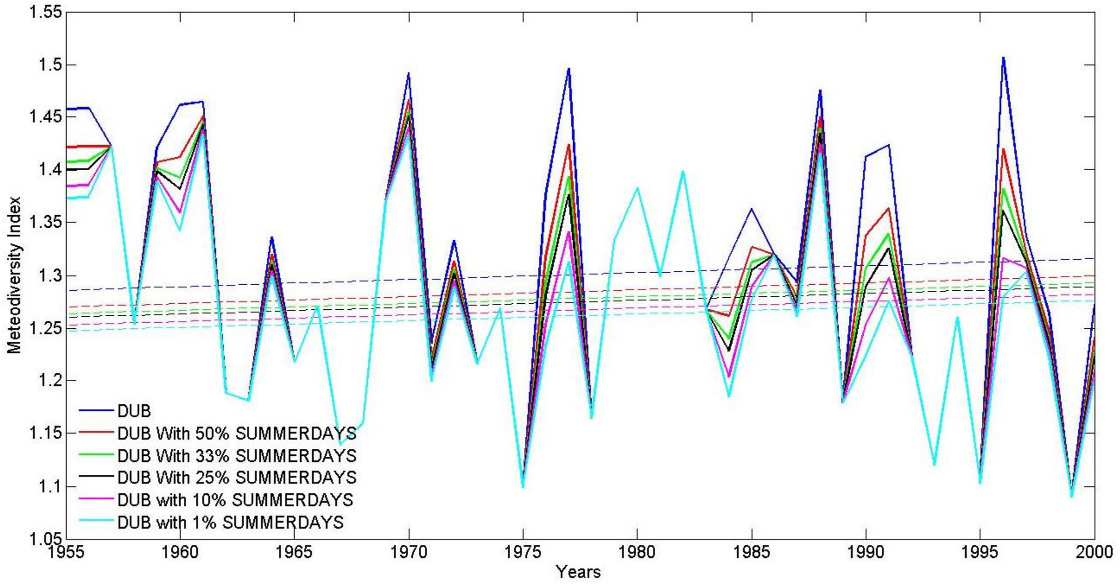

Fig. 3.4: Temporal evolution of Dublin MI (blue line) and sensitivity to reductions in the number of summer days: 50% (red), 33% (green), 25% (black), 10% (magenta) and 1% (cyan). Dashed, thin lines represent the trend line for each case

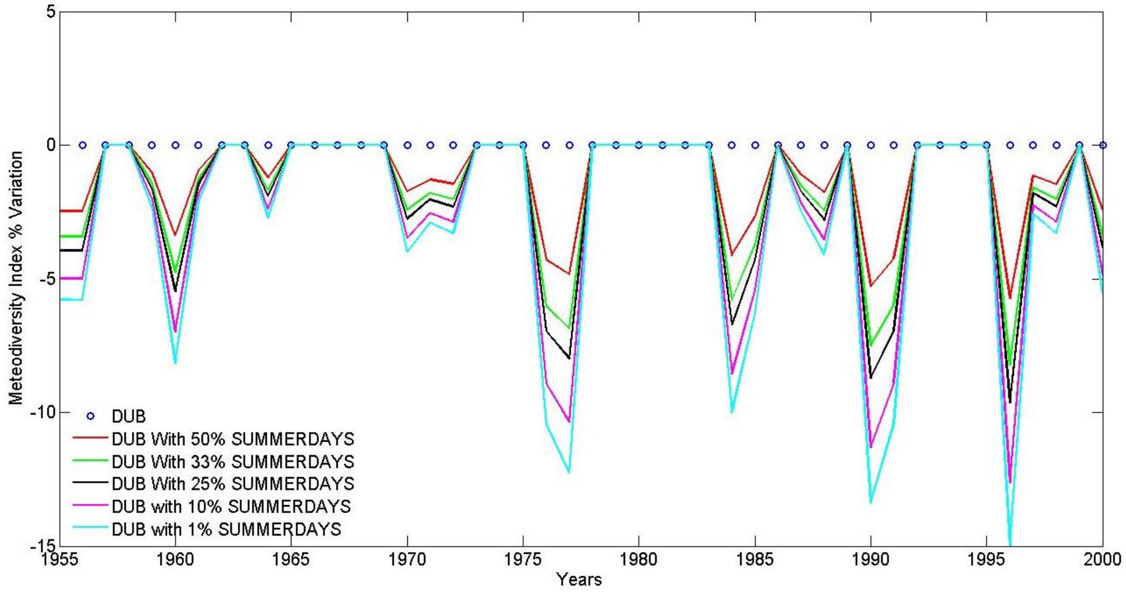

Fig. 3.5: Percentage of Dublin MI variation respect to the actual values (circled, blue line) when reducing the number of summer days to: 50% (red), 33% (green), 25% (black), 10% (magenta) and 1% (cyan)

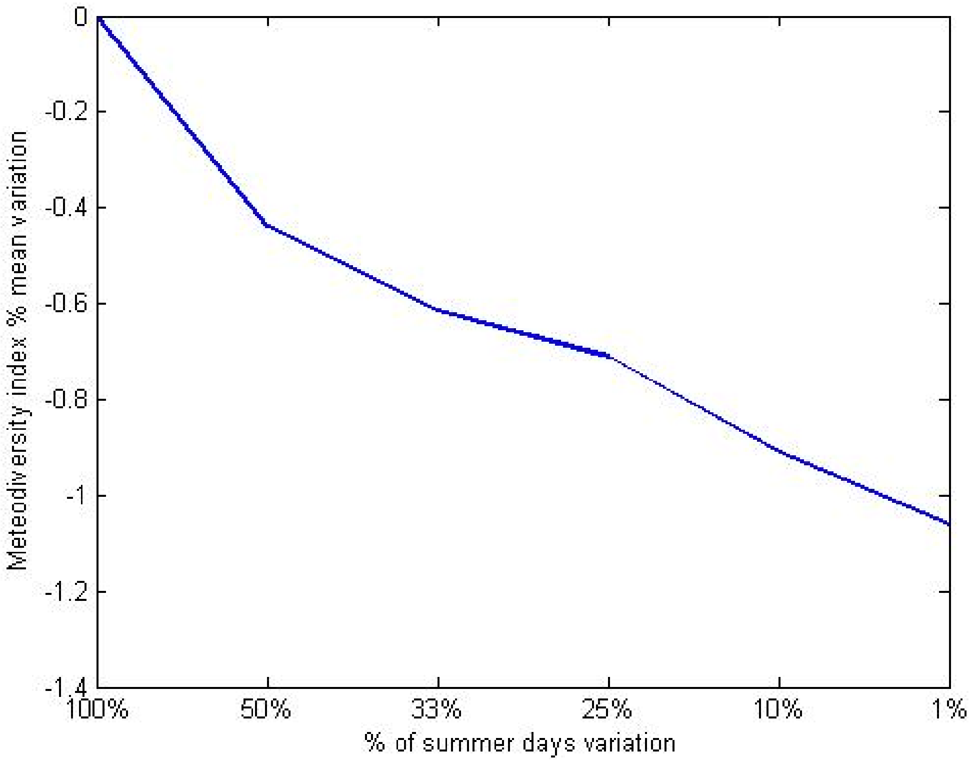

Fig. 3.6: Mean variation (%) of Dublin MI values respect to the real values when reducing the summer days per year

Fig. 3.4 shows how the Dublin MI values change when a reduction of the less significant phenomenon (the number of summer days per year) is applied to all the years of the study. In Fig. 3.4 it can be seen the evolution of the MI when the number of summer days is multiplied by 0.5; 0.33; 0.25; 0.1 and 0.01. It can also be observed that the reduction in summer days is related to a decrease in MI values for all the cases.

To better visualize the changes, as some variations are very small, Fig. 3.5 shows the percentage of change for every modified value of Dublin MI respect to the initial ones according to the reduction applied. Fig. 3.5 is adequate to notify that, when the summer days of Dublin are reduced, the values of the MI can decrease down to an approximate minimum of -15% of their initial value. This range from 0% to -15% is smaller than previous Barcelona range from +20% to -30%, and makes perfect sense as Dublin summer days are uncommon, while in Barcelona the are very common, and they do not contribute as much to the MI final values.

Fig. 3.6 shows the mean variation of the Dublin MI respect to the initial values for the 50 years of the study, to better comprehend in which grade the reductions in summer days affect Dublin MI. From the information available in Fig. 3.6, in can be seen that the decrease results in a more uniform decrease of the MI, as reducing them only lowers the diversity of phenomena. In fact, reducing the summer days per year to 1% of the initial value on Dublin only decreases the index in a 1.4% average, as their initial values are already very small and make little contribution.

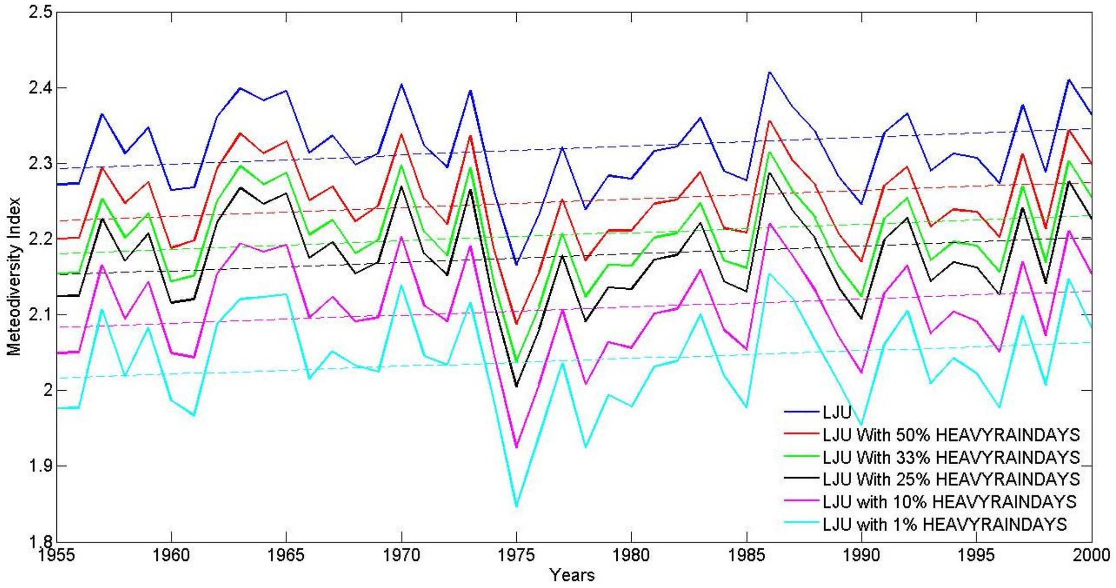

Fig. 3.7: Temporal evolution of Ljubljana MI (blue line) and sensitivity to reductions in the number of heavy rain days: 50% (red), 33% (green), 25% (black), 10% (magenta) and 1% (cyan). Dashed, thin lines represent the trend line for each case.

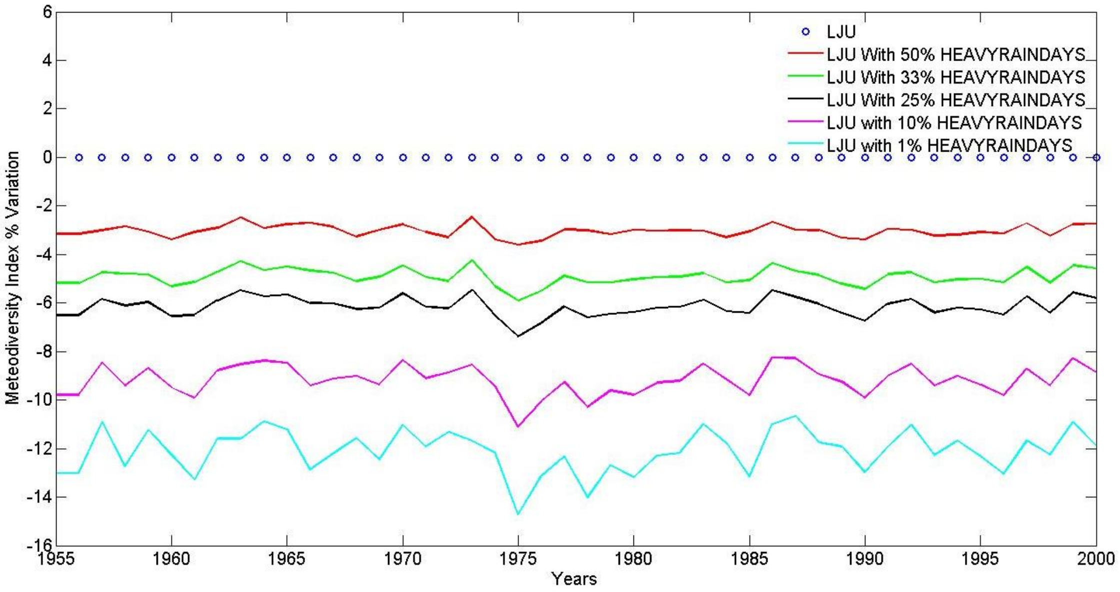

Fig. 3.8: Percentage of Ljubljana MI variation respect to the actual values (circled, blue line) when reducing the number of heavy rain days to: 50% (red), 33% (green), 25% (black), 10% (magenta) and 1% (cyan)

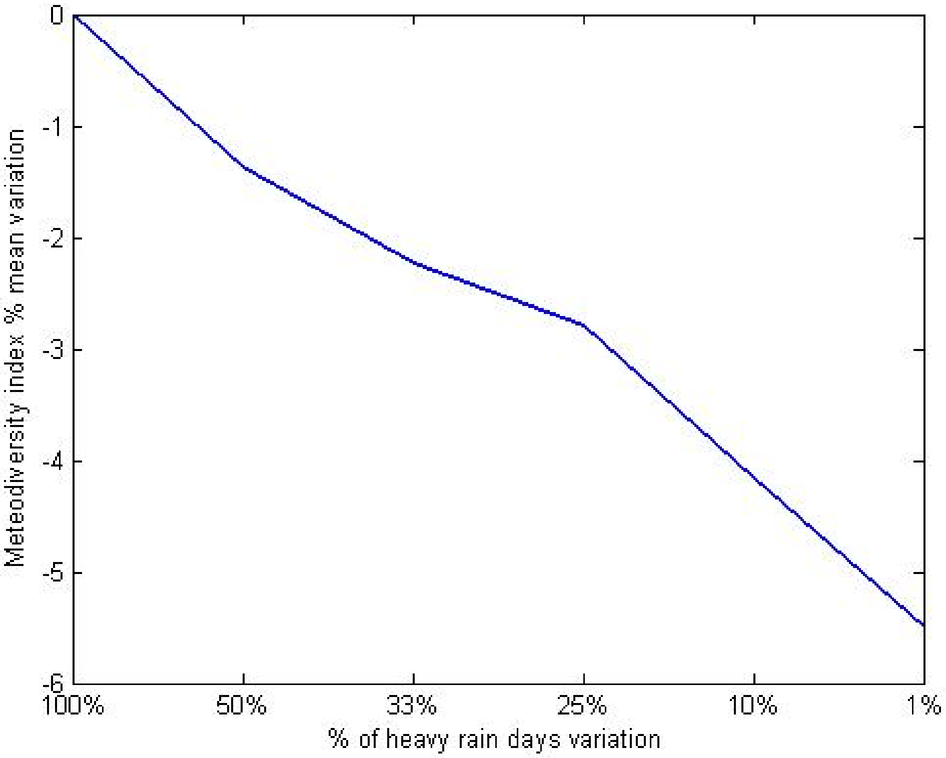

Fig. 3.9: Mean variation (%) of Ljubljana MI values respect to the real values when reducing the heavy rain days per year

Figure 3.7 shows how the Ljubljana MI values change when a reduction of a phenomena with moderate significance (the number of days with heavy rain) is applied to all the years of the study. In Fig.3.7 it can be seen the evolution of the Ljubljana MI when the number of heavy rain days is multiplied by 0.5; 0.33; 0.25; 0.1 and 0.01. The decrease results in a decrease of the MI for all cases. This is expected because the number of days with heavy rain is similar of the amount of frosty and summer days, and these are less than the number of rainy days (any type of rain). If, instead of the heavy rain days, the rainy days were decreased, a partial increase in MI should be expected, with similar patters than those seen in Barcelona (Fig. 3.1). It can also be notified that the same reductions decrease the MI values more for this study than in the Dublin study (Fig. 3.4). This is due to the fact that the number of real heavy rain days in Ljubljana represents a more significant variable than the number of summer days in Dublin.

Figure 3.8 is given in order to better quantify the variations. It plots the percentage of change for every modified value of Ljubljana MI respect to the initial values according to the reduction applied. Figure 3.8 is adequate to notify that, surprisingly, when the values of heavy rain days are reduced for Ljubljana, the values can decrease (with the values computed) down to a minimum of -15%. Being the maximum value 0% (no reduction applied), and the minimum -15%, the range of modified values is very similar to the range of Dublin. This contradiction can be explained looking at the values when the minimum is obtained. While in Ljubljana for a decrease to 0.01 of the initial heavy rain days value all MI values obtained are below -10% of the initial value, applying the same reduction to Dublin summer days only gives 5 years with MI modified values below -10%. Hence, it is necessary to obtain the mean variation of the MI to fully compare both cases.

Figure 3.9 shows the mean variation of the Ljubljana MI respect to the initial values for the 50 years of the study is plotted. The form is comparable to the form of the mean variation of Dublin MI (Fig. 3.6), only that the values are reduced down to a -6% average when the heavy rain days are multiplied to 0.01, way lower than the -1.5% previous average. This justifies the explanation to the contradiction observed comparing the ranges from Figs. 3.5 and 3.8, because in average it is more impactful to lower the heavy rain days in Ljubljana than the summer days in Dublin, as the first phenomenon happens more often than the second one.

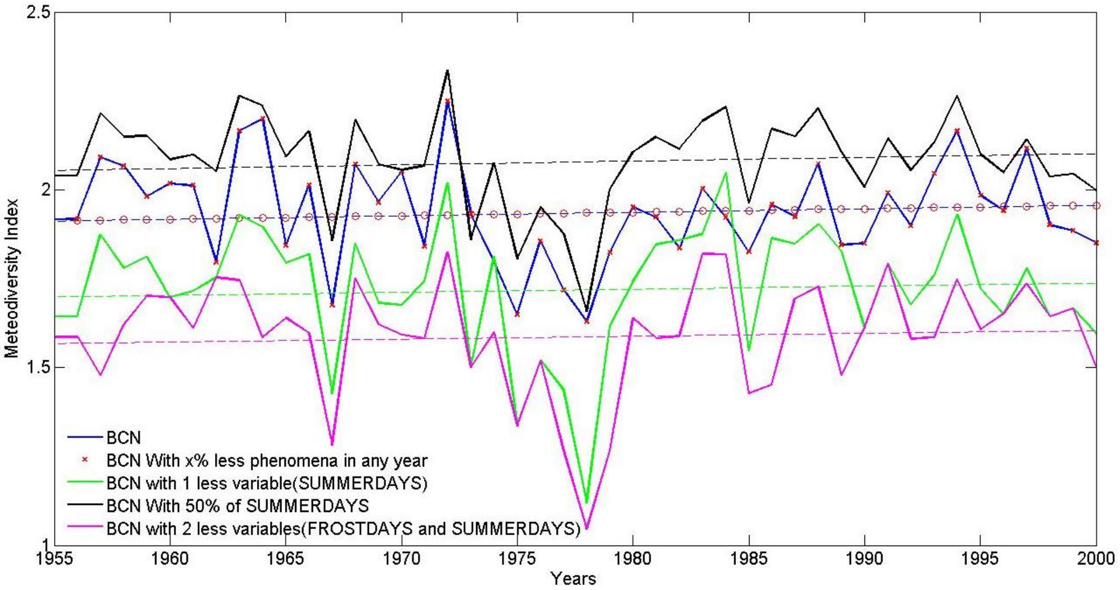

Figure 3.10: Temporal evolution of MI (blue line) in Barcelona and sensitivity to variations in the number of summer days: -50% (black), -100% (green). Purple line shows MI without considering any summer or frosty days. Red, crossed dots shows -x% in every phenomenon. All dashed and circle lines show the trend line for each case.

Figure 3.10 shows the sensitivity of MI to a reduction of the number of summer days in Barcelona. First, in the red dotted line, all the existing data of phenomena -the given days per year with a particular phenomenon occurring- for Barcelona is lowered in a given percentage (50%, but any percentage of reduction or increase produces the same result). As expected, the global MI (in blue, both of them overlapped) does not change, because the proportion of the individual phenomenon does not change, giving the same result at all times.

Then, the days of summer in Barcelona are halved for all the years of the study. As a result, the MI increases 0.2 for most of the years, or a 12.5% increase with respect to the original MI calculation. This increase happens because the number of summer days is the most significant variable (the phenomena that occurs more frequently) in Barcelona, and when they are lowered, all the values of the variables come closer, resulting in an increase in the diversity of the meteorology of the area.

Continuing with Fig.3.10, in green, the same phenomenon (the days of summer per year) is assumed 0 on all the 50 years. Again, as expected, the pattern of the MI along the years maintains a similar trend line (see [20]), and lowers all values in 0.23; representing a 14.6% decrease with respect to the original MI calculation.

Figure -.3.10 also shows the MI evolution when two variables (the days of summer per year and the days of frost per year) are not considered (magenta lines). As a result, the pattern of the MI changes, maintaining similar tendency and decreasing the MI by a mean value of 0.18 with respect to the previous nullification of summer days (26.1%). The change is less important compared with the previous one, due to the fact that in Barcelona frosty days tend to be lower than summer days, and there is less impact on the overall data.

Summarizing, it can be stated that the MI can increase or decrease when one of its variables is modified, according to the significance of the variable on the area for the given years. The magnitude of the changes is also related with the significance of the modified variables.

To anticipate the impact of a given variable change on the index, it is best to think how the diversity will be affected by the change, and it is unlikely that changes on the MI bigger than 10% take place when only one variable is modified.

3.2. MI according to Köppen climate classification

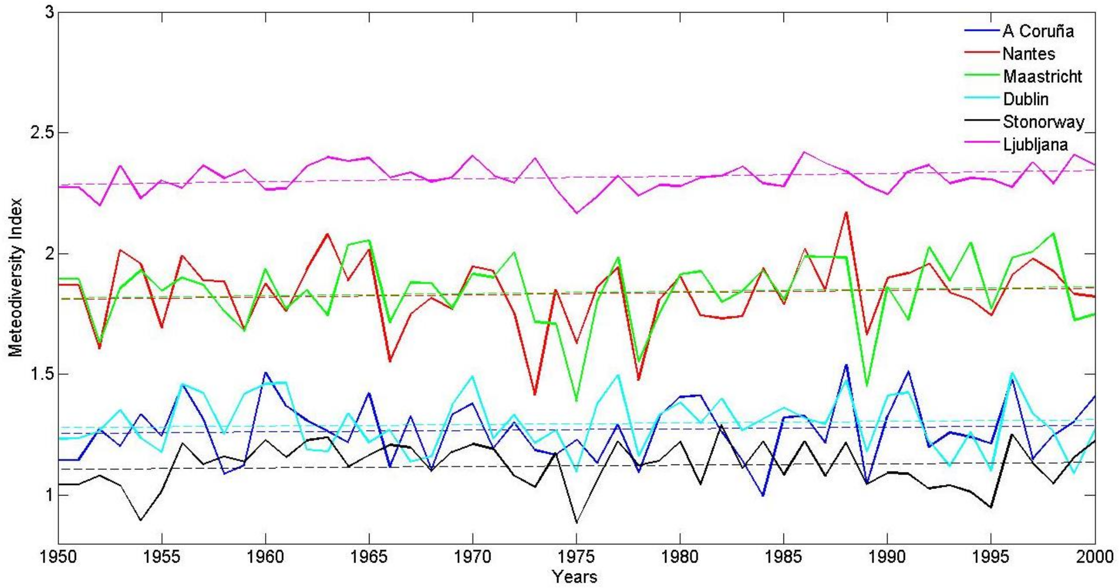

Fig. 3.11: Temporal evolution of MI values for meteorological stations with Temperate Oceanic climate (Cfb): A Coruña (blue), Nantes (red), Maastricht (green), Dublin (light blue), Stornoway (black) and Ljubljana (pink). Thin, dashed lines show the trend line of each station.

Figure -.3.11 shows the temporal evolution of the MI at 6 stations with Temperate Oceanic climate (Cfb). The values of MI are distributed between 1 and 2.5, so Temperate Oceanic climate presents the largest range of possible MI values possible for a European climate.

The results show that the city with a higher MI is Ljubljana, with an almost constant value of 2.3; while Stornoway presents the lowest MI, around 1.1. From Fig.3.11, it is possible to group the European cities studied with this climate in 3 groups according to their MI values, the first one having the cities with MI values usually between 1 and 1.5, the second with MI normally between 1.5 and 2 and the third with MI values above 2.

The first group is formed by the stations of Stornoway, Dublin and A Coruña, but the MI mean is closest between Dublin and A Coruña. The three cities are far away of each other, but all of them share a vicinity with a mild-cold sea, and the largest variable in all of them is the number of rainy days, with not very significant number of summer days or frosty days (more frequent for the northern cities). The hypothesis is that the vicinity of the sea smooths the temperatures and bring precipitation, reducing the variability as a result.

The stations in Nantes and Maastricht form the second group. Their evolution is very similar. Both cities share low values of the number of tropical nights and icy days, between 5 and 50 summer and frosty days in any year and a predominance of rainy days (but never more than 150), with a small percentage of them being heavy rain days. Both cities are near two rivers (Loire and Meuse, respectively), not very far away from a cold sea and in similar latitudes. The fact that the contact with the cold sea is not direct can explain the MI higher than the first group, because the climate is not smoothed by the influence of the sea.

The third group only includes the city of Ljubljana. This city is also between two rivers (smaller compared with the previous ones) and relatively near the Adriatic Sea, which is not a cold sea. However, this particular region is situated in an area where the Temperate Continental climate (typically a humid climate) turns into the Continental climate (see Fig. 2.1), that has typically a larger variation of temperatures through the year, explaining the higher MI due to the existence of more summer, icy and frosty days.

Consequently, it is stated that in Ljubljana, the only city in the third group, there are more types of phenomena happening every year than in the other stations, where a more stable meteorology occurs. This can be justified by looking at Table 3.1, provided as a tool to better comprehend the MI values, containing the values of the variables for a given year (1970) in a city of each group.

Table 3.3: Values of each variable considered for the MI calculation during 1970, including representative stations with Continental Temperate climate

	Summer days	**Tropical nights**	**Icy days**	**Frosty days**	**Rainy days**	**Heavy rain days**	**Very heavy rain days**
Stornoway	0	0	0	63	248	33	4
Nantes	35	1	4	43	122	18	7
Ljubljana	59	0	22	100	127	48	25

As expected, the number of rainy days with any type of rain is the highest variable for this type of climate. In Stornoway, where the MI is lower, rainy days represent 71% of the proportion when computing the MI, and three of the variables do not appear. Because of the low diversity, the MI is low for the year. On the other hand, in Ljubljana, where the highest MI is found for this climate, the number of frosty days for this year are high enough to have a similar impact on the MI value than the rainy days (the number of rainy days has a proportion of 33% and of frosty days of 26%). Additionally, all the other variables (except the number of tropical nights) make a significant contribution (their proportion is greater than 5%). Nantes has more rainy days than any other variable and 3 of the variables have a proportion lower than 3%, explaining why Ljubljana has a higher MI, but the number of rainy days of Nantes do only make for 53% of the proportion, giving an overall MI higher than Stornoway.

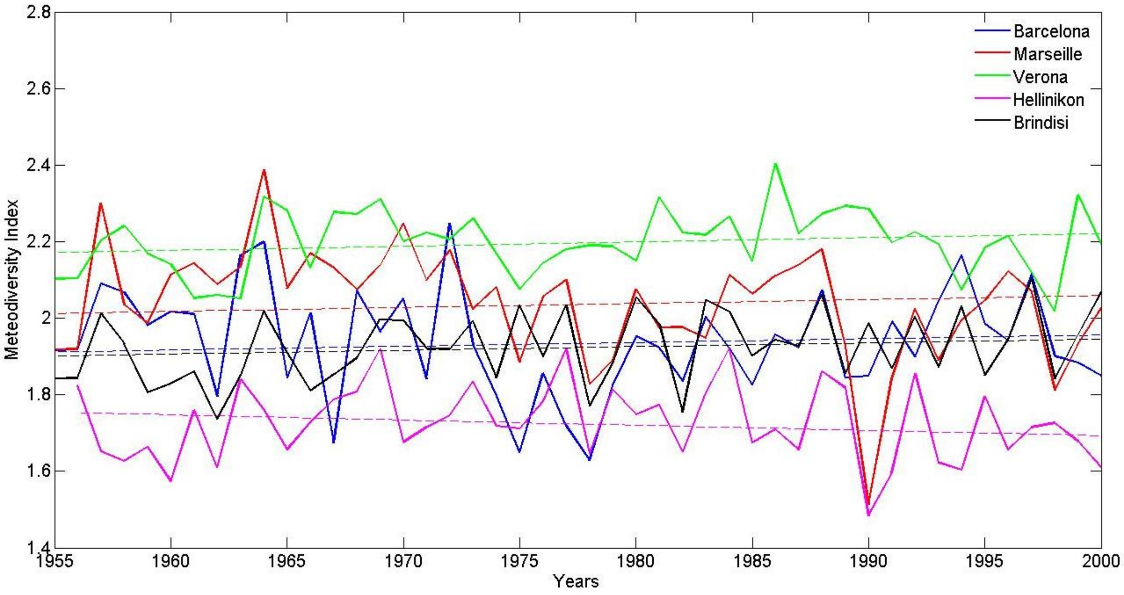

Fig. 3.12: Temporal evolution of MI values for meteorological stations with Mediterranean climate (Csa): Barcelona (blue), Marseille (red), Verona (green), Brindisi (black) and Helinikon (pink). Thin, dashed lines show the trend line of each station.

Figure 3.12 shows the temporal evolution of the MI at 5 stations having Mediterranean climate (Csa). All the stations have MI values between 2.4 and 1.5, having a smaller range compared with MI at the stations with Temperate Oceanic climate; Csa is the climate with smallest range of MI among the studied stations. Additionally, as the MI values from this climate have no similar values between them, like the ones found in Temperate Oceanic climate, no groups can be made.

For the most part, the number of icy days are always near 0 and it is not mentioned. This is explained with the fact that the Mediterranean climate is not usually a very cold one.

The station with the highest MI within this climate is Verona, while the city with the lowest MI is Hellinikon. However, Hellinikon, the only station with enough available data in Greece, presents two particularities that are worth to mention. The first one is that is the only station with Mediterranean climate that has a perceivable decrease in MI values during analyzed years (see Fig. 3.12). The second is that in Hellinikon meteorological data starts in 1956 while the other stations have data since 1955.

Verona has a particularly high MI value for this type of climate. As seen in Table 2.2, the climate of Verona is not purely Mediterranean, but is mixed between Mediterranean and Subtropical Humid climates. Both climates are similar, with only a difference in the precipitation amount and distribution. However, for Verona, the climate is cooler than the typical Mediterranean climate, with less contrast between the amount of summer days (around 90) and frosty days (around 70). Additionally, the number of rainy days are higher, between 60 and 100. Those two factors increase the variability of the station, giving an overall higher MI than the others found in pure Mediterranean climates.

Marseille presents a variable number of rainy days, between 40 and 70 days with 20 days of heavy precipitation and 10 days of very heavy precipitation, similar to other Mediterranean stations, like the ones in Barcelona and Brindisi. But, curiously, the number of frosty and icy days of Marseille are normally higher (up to 30) before 1975, and lower (up to 20) after 1975. In contrast, the summer days and tropical nights are normally lower (up to 75 and 20, respectively) before 1975 and higher after this year (up to 125 and 45, respectively). This increase in the most significant variables and decrease in the less significant ones explain well why the MI has lower values after 1975 for this station. For the downfall of the MI in 1990, it happened because the year had very low precipitation (30 days) in addition to previous phenomena.

Barcelona and Brindisi stations both have a low number of frosty days, no icy days and predominance of summer days (usually more than 100 for Barcelona and more than 110 for Brindisi) and a moderate amount (half of the summer days) of tropical nights. While Barcelona has always less than 70 days of precipitation (below 20 days of that 70 have heavy and very heavy precipitation), Brindisi can have up to 100 days of precipitation of any type, with a smaller proportion of this number being heavy and very heavy rainy days (also below 20 for the most years). This increased amount of rainy days and summer days of Brindisi, which are two of the most significant variables tend to make its MI slightly lower than the one of Barcelona, as seen in Fig.3.12.

Hellinikon shows indices values similar to Barcelona. The main differences are that summer days can go up to 165 days, tropical nights can go up to 100 days and rainy days can go up only to 50 days, with less than 10 heavy and very heavy precipitation days. This explains why the MI is significantly lower than the rest of cities, because the number of summer days and tropical nights is much larger than all the rest. As for the decrease in the MI during the analyzed years, it can be explained by looking at the variables separately: while the number of summer days remains more or less constant, the number of rainy days uses to decrease, while the number of tropical nights increases, decreasing the overall MI.

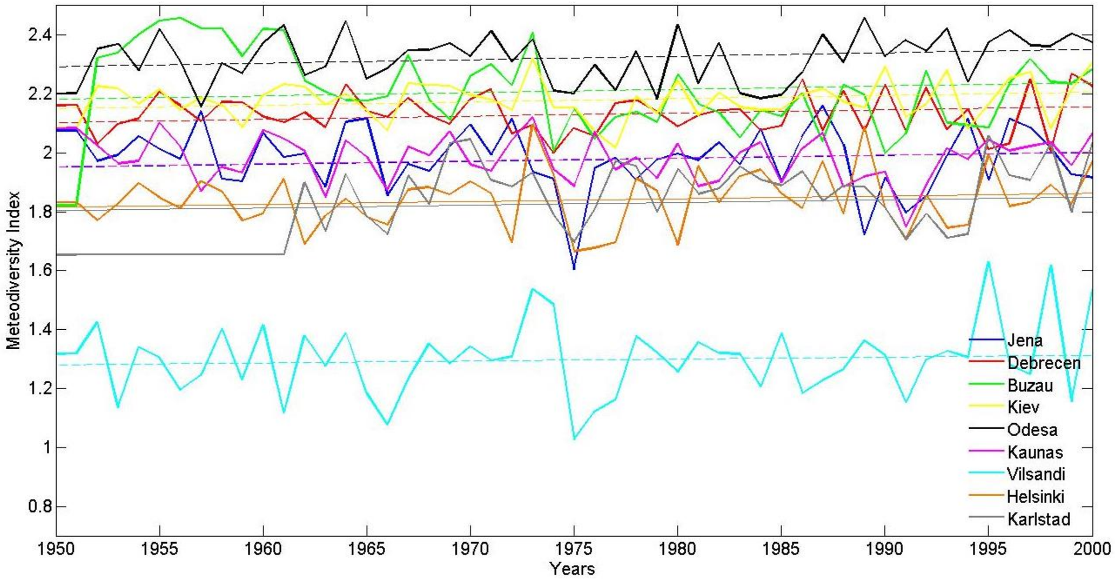

Fig. 2.13: Temporal evolution of MI values for meteorological stations with Continental climate (Dfb): Jena (blue), 1Debrecen (red), Buzau (green), Kiev (yellow), Odesa (black), Kaunas (pink), Vilsandi (light blue), Helsinki (orange) and Karlstad (grey). Thin and thin, dashed lines show the trend line of each station.

Figure .-3.13 shows the temporal evolution of MI for the stations having Continental climate (Dfb). This type of climate presents a distribution of MI usually between 1.5 and 2.5, with the exception of the station in Vilsandi. According to this, for the variables used in the study, the MIs obtained from this climate are more uniform than MI for the stations having Temperate Oceanic climate and less uniform than the ones with Mediterranean climates. Continental climate is a colder and drier climate, consequently all the stations present a very low number of tropical nights and very heavy rainy days.

Odesa presents the largest value of MI (from 1960 onwards), while Vilsandi, the lowest one, has a remarkable difference of 0.5 in MI value with the previous one, Helsinki. Because of this, Vilsandi is studied separately. For the rest of the stations, it is adequate to make a group with MI values typically between 1.7 and 2 and another group with MI values above 2. The first group includes Helsinki, Karlstad and Jena and Kaunas, whose MI evolution is very similar. The second group includes Debrecen, Kiev, Buzau and Odesa stations, with MI values more separated.

Vilsandi station has a large number of frosty days per year (values of 90 are common), and approximately half of these days are also icy days. The summer days are seldom, with a maximum amount of 20 per year, and a maximum of 8 tropical nights. The precipitation is extremely low (maximum of 20 days of precipitation of any type, with no heavy precipitation at all). These values are quite strange taking into account that Vilsandi station is located near the Baltic Sea. This is an indicator of a possible malfunction in rain gauge of the Vilsandi meteorological station, according to the difference in MI values with the nearest stations.

For the first group, Helsinki and Karlstad stations are both near a big water body (the Baltic Sea and the Vänner Lake, respectively) and are placed at similar latitudes. Both stations have a moderate number (commonly more than 100) of rainy days, with some days with heavy rain (20 days) and a high number of frosty days (more than 120, with half of them being also icy days). Karlstad also has a slightly warmer climate, counting with some summer days (more than 15), which makes its MI be higher than Helsinki’s. It has to be remarked that Karlstad had a loss of meteorological information from 1950 to 1960, but for the rest of the years the values follow this tendency. The rest of the values are similar to those of Vilsandi, which is also near the Baltic Sea, but the moderate amount of precipitation makes the difference.

Jena and Kaunas are located inland, with at least 200km to the Baltic Sea. The phenomenon occurring more often are frosty days and rainy days, with values above 100, while their summer days are above 20, which makes the difference in MI with the previously analyzed stations. This can be due to the lower latitude of these stations, producing a warmer climate.

For the second group, Debrecen and Kiev, both inland stations (however Kiev is by the river Dnieper) share the coldest climate of the group, with more than 110 frosty days per year and more than 30 icy days at least (double for Kiev). Their precipitation is moderate, always above 60 days, with 20 of them being days with heavy precipitation. However, both present a high number of summer days (more than 35), which makes a contrast with their usually very cold temperatures. This value of summer days is responsible of their MI being usually higher than the previous group. Also, the station in Kiev has a bigger number of frosty days and doubles the number of icy days (a variable with less significance) of Debrecen, explaining why the MI of Kiev is higher.

Finally, Odesa and Buzau are the stations with the highest MI observed in all climates. They are both near the Black Sea, with a good balance between frosty and summer days. Their typical number of rainy days is above 60, with 15 days of heavy rain. Also, the tropical nights values for both are not null, and are typically above 10, a similar value than the number of icy days. This balance between hot and cold days and nights and this moderate amount of rain explain why both cities have the highest MI values of the study. Also, Buzau has a lot of tropical nights during the fifties (more than 70), but this value descends to 10 for the rest of the years of the study, and the summer days value increases in 20. Despite data for

Buzau presents some gaps during 1960, (probably due to a possible previous malfunction with the stations thermometers). These decrease in the number of tropical nights explains why the MI values are higher for Buzau from 1950 to 1960 than for the rest of the years of the study, and why is Odesa presents the largest value of MI.

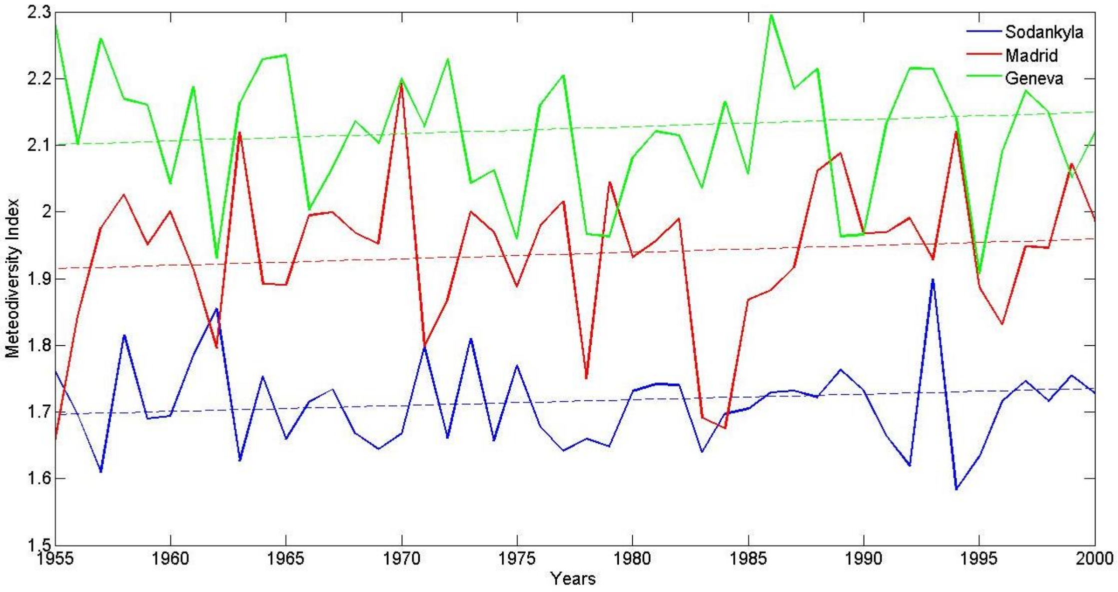

Fig. 3.14: Temporal evolution of MI values for meteorological stations with Dry Steppe climate (Madrid, red), Oceanic climate influenced by Alpine Tundra climate (Geneva, green) and Subarctic Continental climate (Sodankyla, blue). Thin, dashed lines show the trend line of each station.

Figure 3.14 shows the temporal evolution of the MI on stations located on stations located in the southern, northern and more elevated parts of Europe. Those cities are Madrid, a city that has Dry steppe climate, Geneva, with a Temperate Oceanic climate influenced by Tundra climate, and Sodankyla, a city with Subarctic continental climate.

For the station in Geneva, with a climate classified as Temperate Oceanic, but found in the Alpine Tundra zone, the MI is high. For a Tundra climate a low MI should be expected, as the frosty and icy days are the most impactful phenomena and the climate is very dry. However, this is not the case. Geneva has in fact significant frosty days (up to 100 days), but the summer days (usually up to 80) and tropical nights are not zero and the main variable is the number of rainy days. So, even if the city station is placed in the Tundra climate (ET) zone of the Köppen climate classification map, in this particular case Alpine Tundra climate does only influence the main climate of the city, which is Temperate Oceanic. Because of this, a zone expected to be mostly cold presents a good balance between hot and cold days and for the most years and more than 120 days of rain, which is too much for a true Tundra climate, and makes the station have a hybrid climate.

For the station in Madrid, with dry steppe climate, it is shown that the MI typical values are similar to those found in Mediterranean climates, with values between 1.7 and 2.2. Madrid has a large amount of rainy days for this type of climate (at least 40 days per year, with half of them being heavy rain days). The summer days are the most predominant phenomena, with more than 100 summer days per year, and the frosty days are up to 40. These significant values are very similar to those of Barcelona and Hellinikon, and explain the similitude with the Mediterranean climate MI values. Furthermore, as Madrid is located between the Atlantic Ocean and the Mediterranean Sea, even if its climate is classified as dry steppe climate, it shows particularities of a more humid one. Otherwise, it should have a lower MI, as only summer days and frosty days would play an important role when calculating it.

For the station in Sodankyla, a lower MI is found. The most significant variable are the frosty days, above 200. They are followed by the number of icy days, with more than 130 and then the number of rainy days, over 100. All the other variables occur less than 20 times per year and have almost no impact on the MI. The fact that there are 3 significant variables is what explains that the city MI has typical values above 1.5. Other stations with this type of climate in Europe should expect similar or lower MI values, depending on the amount of precipitation they receive, because the number of frosty days will be the most significant variable in any case. Therefore, the hypothesis is that, for the stations with Subartic Continental climate in Europe, MI should increase with the amount of precipitation and heavy precipitation experienced.

Generally speaking, for all the climates studied, it can be appreciated a small increase in MI values from 1950 to 2000 (between 0.05 and 0.1 during 50 years). This small increase could be justified by the fact that the global temperature is higher, consequently increasing the summer days in all climates, adding diversity, especially in the climates with higher MI values. For this same reason, the climates with a predominance of summer days (and significant value in tropical nights) should see a lower increase of the MI value or an overall decrease. As seen in Figs. 3.11 to 3.14, this argument is not always valid because there is not a larger increase for the cities with colder climates (like Sodankyla) than for the cities with warmer climates (like Hellinikon). In order to comprehend why is this happening, a deeper analysis is made in Section 3.4.

Also, from Figs. 3.11 to 3.14, it is possible to conclude which MI values are common for every type of climate. It is found that Temperate Oceanic climate presents the largest variation. Both Mediterranean and Temperate Oceanic climate have values of MI having a smaller range. For the other studied climates, Sodankyla MI values are expected to be more representative than those of Madrid, as Madrid climate is mixed.

Relating the MI values and the Köppen first letter, which is the most general classification value, it can be stated that, for this study, Temperate climates (all climates starting with C), and the stations with mixed climates influenced by Temperate climates (Geneva and Madrid) have values of MI between 1 and 2.4. If the cities placed near very cold seas are excluded (Dublin, Stornoway, A Coruña), the range shortens, finding only values between 1.6 and 2.4. For cold climates, (all climates starting with the letter D) the range of MI values goes between 1.5 and 2.5 (excluding Vilsandi). A possible explanation to this fact is that the temperature difference is bigger in continental climates, classified as cold ones, having more diversity of phenomena related to temperature and an overall higher MI values ceiling. Also, as it is possible to achieve colder, drier climates in the northern regions, also classified as cold climates, the MI values floor is also lower.

Taking into account this lack of uniformity, with some MI values more representative than others because of their geographical location and a lot of possible values and groups for each climate type, it can be stated that the Köppen climate classification has low direct relation with the MI values of the cities, and those values are more related with the geographical location and orography of the stations. A good example of this is the finding of similar values in Dublin, A Coruña and Stornoway while those values differ a lot with the ones from Ljubljana, that also has a Temperate Oceanic climate.

3.3. MI distribution across Europe

In this section, the distribution of the MI value over the studied period is analyzed. Figures 3.15 to 3.19 show the decadal mean value of MI in Europe at the studied stations.

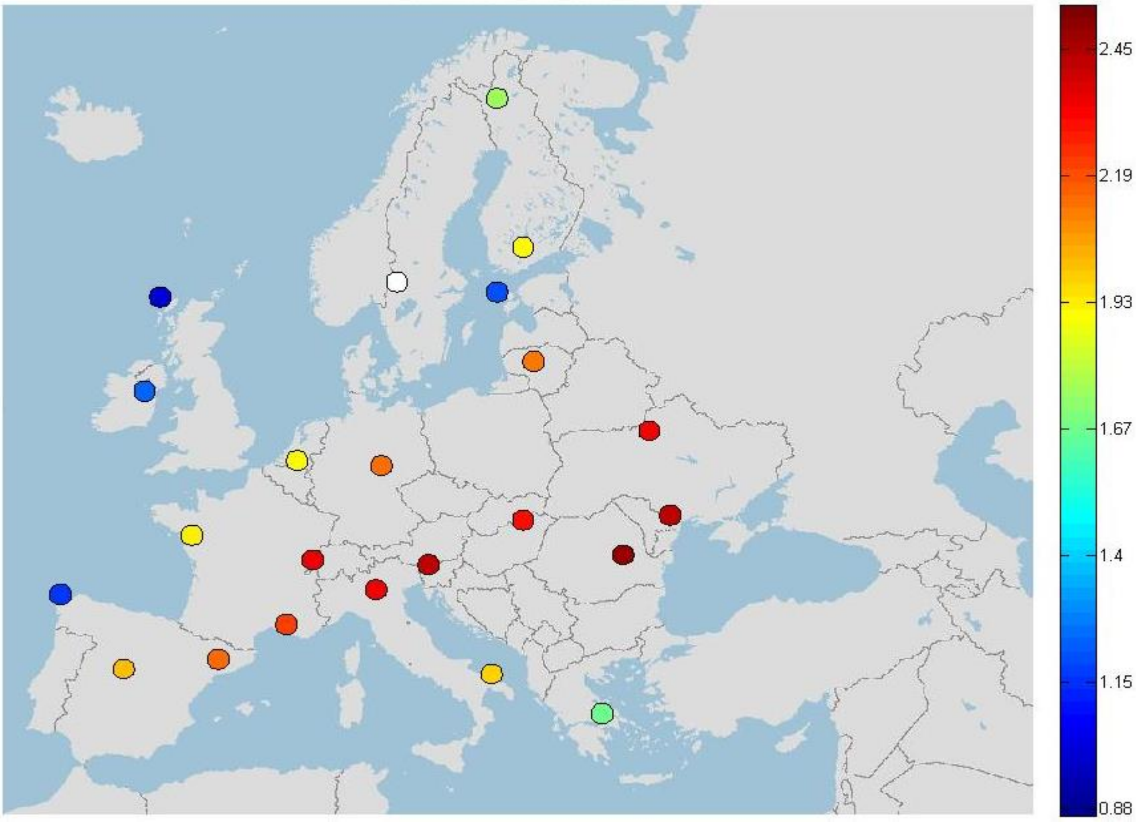

Fig. 3.15: MI mean value distribution across Europe for the decade from 1950 to 1959 at the meteorological stations listed in Table 1. White dot means lack of data.

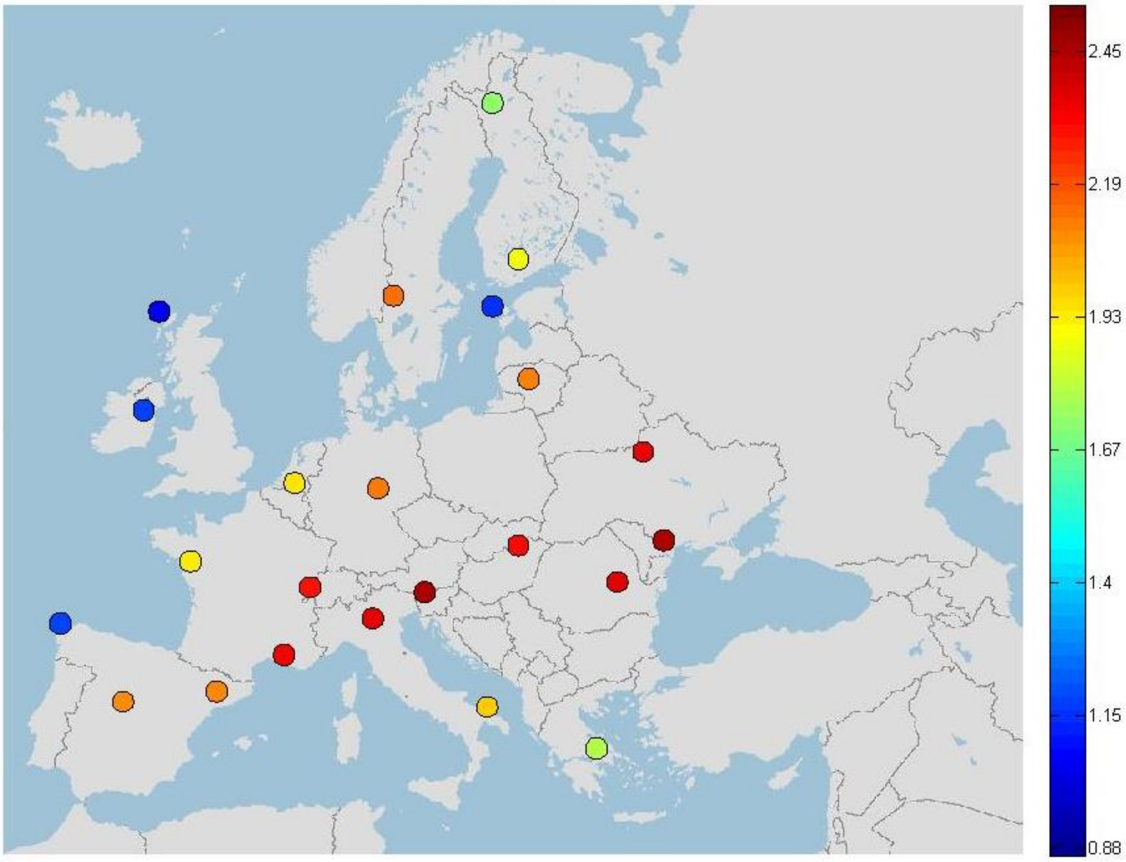

Fig. 3.16: MI mean value distribution across Europe for the decade from 1960 to 1969 at the meteorological stations listed in Table 1

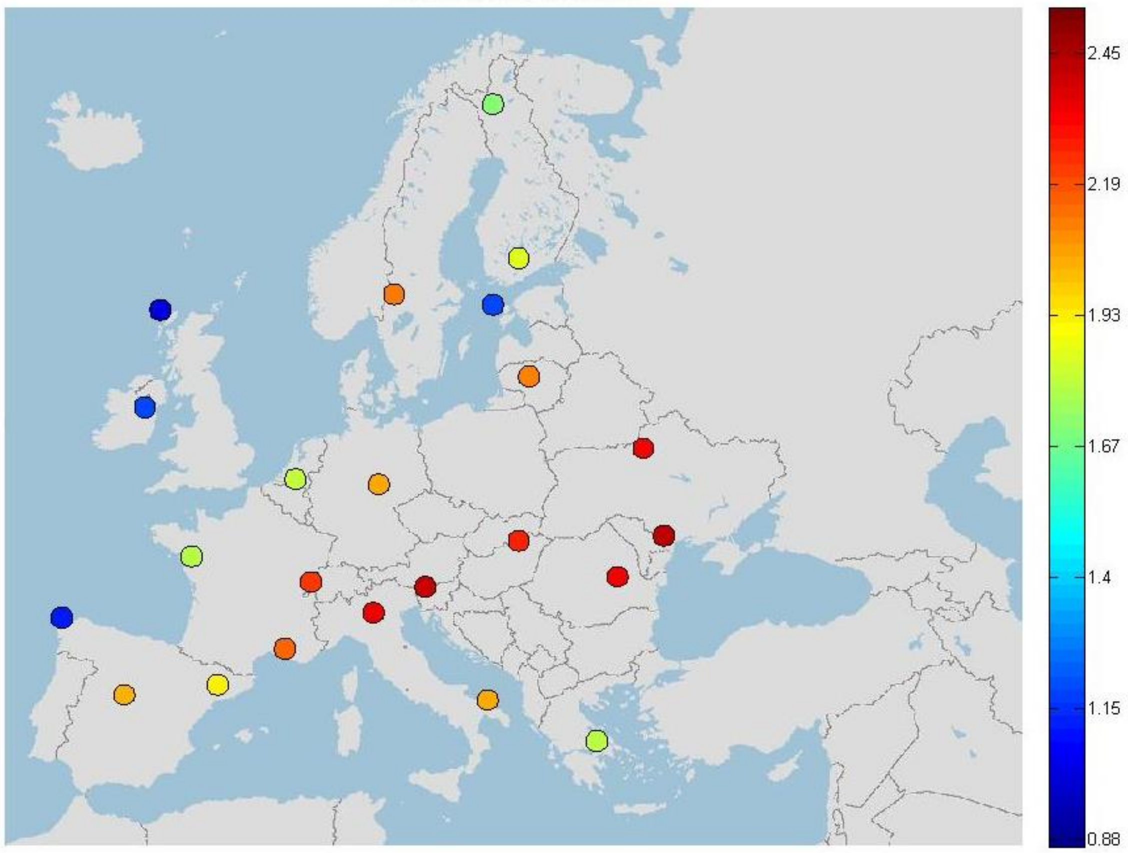

Fig. 3.17: MI mean value distribution across Europe for the decade from 1970 to 1979 at the meteorological stations listed in Table 1

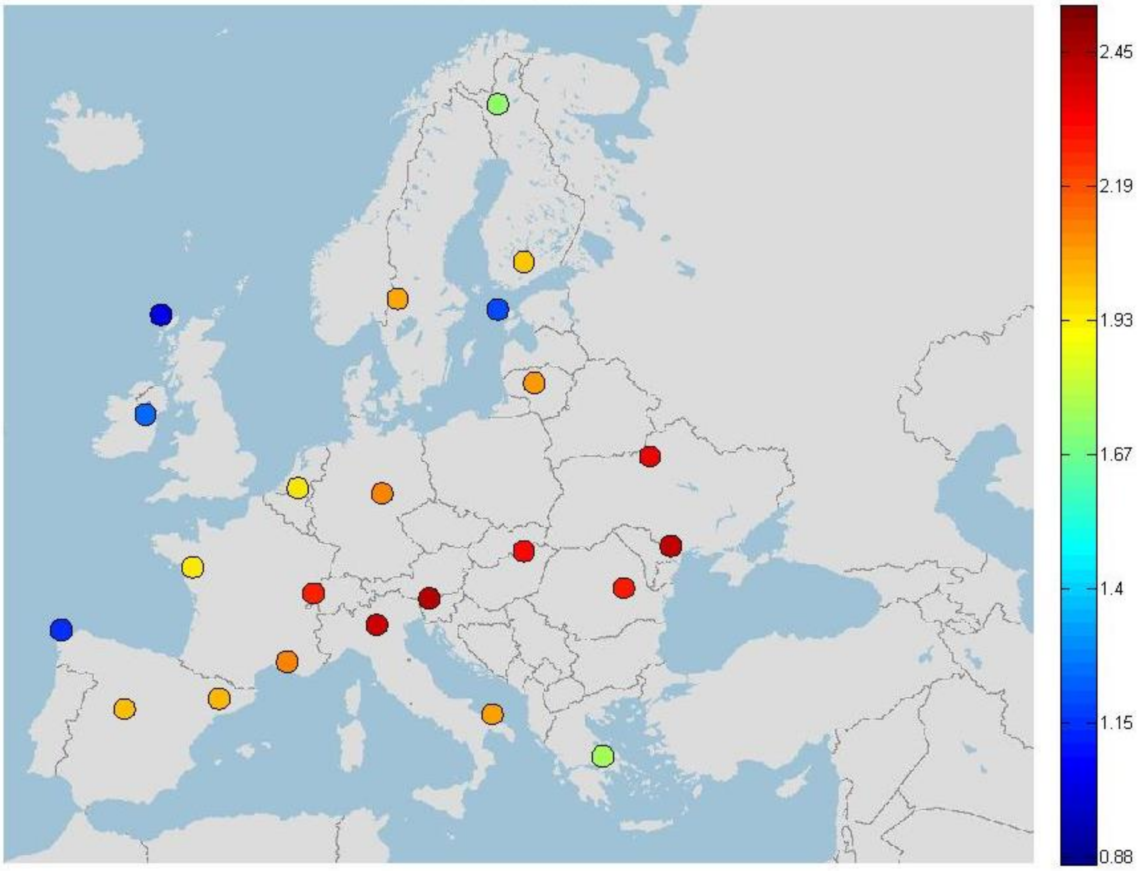

Fig. 3.18: MI mean value distribution across Europe for the decade from 1980 to 1989 at the meteorological stations listed in Table 1

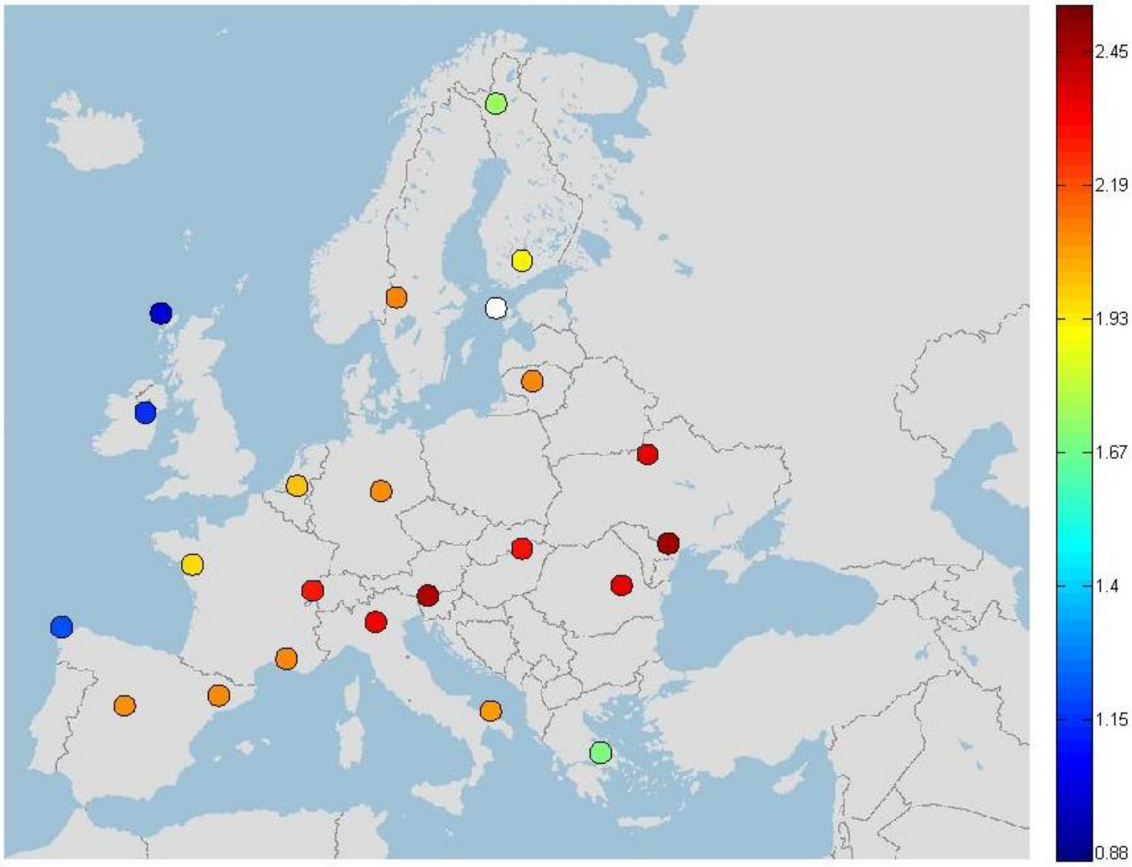

Fig. 3.19: MI mean value distribution across Europe for the decade from 1990 to 1999 at the meteorological stations listed in Table 1. White dot means lack of data.

The higher MIs are found near the west of the Black Sea and north of Italy, above the coast of the Adriatic and Tyrrhenian seas. Those are not particularly hot seas (lowest temperatures in the Black Sea can reach values of 4ºC, while in the Mediterranean they use to be around 15ºC), so there is no direct relation between temperature and MI for Europe considering these variables. The values are also pretty stable, with only one slight decrease in the MI values at Buzau from the fifties to the sixties. This decrease is justified by the decrease of its tropical nights in that decade, and explained in Section 3.2.

Very high MI values are also found at Kiev and Debrecen, with constant mean values. As explained in section 3.2, those areas are continental and have high variation of temperatures during the year, with moderate precipitation.

The stations located north of the Mediterranean Sea (east of Spain, south of France, and around Italy) tend to have high MI values, but a little more variability for the different decades. This variability is larger for Barcelona station during the seventies, lowering the MI mean value in more than 0.15, or -6.5% with respect the previous and posterior decades.

Moderate to high MI decadal values can be found in the area of Europe that is directly below the Baltic Sea (with the exception of Vilsandi). These values are also quite stable along the years of the study when comparing to the rest of the stations.

Moderate values of the MI can be found in the area of Greece, the northern part of France and in the areas of Sweden and Finland near the Baltic Sea. In this group, the variability in MI is the highest, with all the stations experiencing increases or decreases of the MI values during the analyzed years:

- For Sweden and Finland, with medium (north of Finland) to high values (rest), it can be expected that cities that are in the vicinity of the Baltic Sea behave similarly than those on the south of this sea, only with lower temperatures because the latitude is higher and overall lower temperatures are expected. The cities placed in the zone closest to the Baltic Sea have also a mean MI peak in the decade of 1980 (the south of Finland experiences a rise of 0.35, or +13.5% in the MI mean value compared to previous and posterior decades).

- For the stations located on north of France and the Netherlands, both stations behave similarly to each other, as both of them share the same ocean, with a moderately high value of MI for all decades, but lesser than the MI values found for the strip below the Baltic Sea. Additionally, both of the stations experiment a similar decrease of 0.1 (or -5%) in MI mean value during the seventies.

- For Greece, the MI is moderately low, a rare thing for a city in the south of Europe, but the proximity of the Aegean Sea can explain the different behaviour. The variability is also high, with a rise on the MI mean value for the decades of 1960 and 1970.

The stations where minimum MIs can be found are A Coruña, Dublin, Stornoway and Vilsandi. Except for the latter, which had probably a problem with the rain gauge, as explained in Section 3.2, all of the zones have very constant values, with variations in MI hardly perceived, inferior to 0.1 (10% on the worst cases). Also, all of the stations mentioned share a vicinity with a mild-cold sea (Cantabrian and North Sea) or a northern part of the Atlantic Ocean. The stations share a massive predominance of rainy days and some heavy rain, with low number of summer or frosty days (depending on the latitude). Due to proximity to the ocean for these three stations, MI is more or less constant.

Generally speaking, it can be stated that, for Europe:

- Mediterranean climate (Csa) tends to have values of MI of around 2, with variations of around 0.1 (5%). All the zones, share similar precipitation amounts and temperatures, explaining the similarities. The exception is Verona, with a higher mean MI, explained by the influence of Humid Subtropical climate. It is also noticeable how the values typical for a Mediterranean climate can be found on higher latitudes on the two last decades. This can be explained by the change of patterns of the climate from 1975 to 2000, explained in Section 3.4.

- Temperate Oceanic climate (Cfb) has the lowest mean values of MI in the regions that contact directly with the Atlantic Ocean, with constant values around 1. However, the regions of the north of France and Germany are further away from the smothering influence of the ocean and tend to have moderate values of MI, from 1.6 to 2 with much more variation. Geneva has higher MI values because its climate is colder, as it is influenced by Alpine Tundra climate.

- Continental climate (Dfb) has the highest MI values, up to 2.5, especially in middle latitudes and on the regions to the east of Europe. The higher range of temperatures that can be found in these areas explains the higher than average MI values and is reduced when moving to norther latitudes. That, and the increase of precipitation due to the vicinity of the sea is the reason behind the lower values (around 2) in the Dfb regions located south of the Baltic Sea.

- Dry steppe climate (Bsk) is only found in the Iberian Peninsula and, the stations, being not very far away from a water body, has similar values to those of the Mediterranean climate.

- Subartic continental climate (Dfc) is mainly found in the northern parts of the Scandinavian peninsula, with some influence of Continental climate and has generally moderate values of MI (around 1.6) and low variation. As the temperature is typically low but can be high during some months, with moderate precipitation, the MI is not as low as in the Cfb areas near the Atlantic Ocean, where only rain is a significant variable.

Overall, the MI value is related to the climate of the stations, with some typical values according to the type of climate of the region and the proximity of water bodies.

In Section 3.1 it was shown that the MI value could, theoretically, vary from 0 to 2.8. Some regions have values of 0.9, meaning that for those regions there is always a predominant group of phenomena, as lower values of the MI can only be achieved when one phenomena has a proportion much larger than the rest. On the contrary, the regions with values above 2 are locations with a good meteorological balance.

When the mean values are considered, it is easily seen that the regions have consistent values, showing no evolution of more than 0.1 (less than 10%) from the decade of 1950 to the decade of 1990. This is a good indicator of how the climates in Europe can, regardless of the change in the number of phenomenon during the years maintain a similar proportion within 50 years. However, this evolution is better shown and explained in Section 3.4, where the behavior of the variables along the years is considered.

To be able to fully determine if there is an evolution in the Meteodiversity in Europe, the study should be repeated for a longer period of time. As nowadays the meteorological data is well recorded and stored in all regions, it should be possible to perform a 100-year study considering more stations in the future.

3.4. General MI evolution

Generally speaking, all climates share a MI trend line with little to no slope for 50 years, with increases of MI between 0.05 and 0.1 for some of the stations. This value represents an increase of between 3% (in the stations with higher MI trend line and less increase) and 5% (in the stations with lower MI trend line and more increase) of the MI typical values.

However, if the analysis is divided in two periods: 1950-1975 and 1975-2000, some of the stations present significant increases or decreases in the second period. Figure 3.20, shows the stations having largest slope in the trend lines (one for every type of climate). It can be seen that, even when the trend line is split, the MI trend never decreases or increases more than 0.2; for a maximal variation of 14%.

It has to be stated that, as the trend lines show the prevailing direction of the MI values for a time interval, the smallest the time interval, the greatest the slope is going to be. For this reason, furtherly splitting the trend lines would not be useful, as local maximums or minimums would affect them.

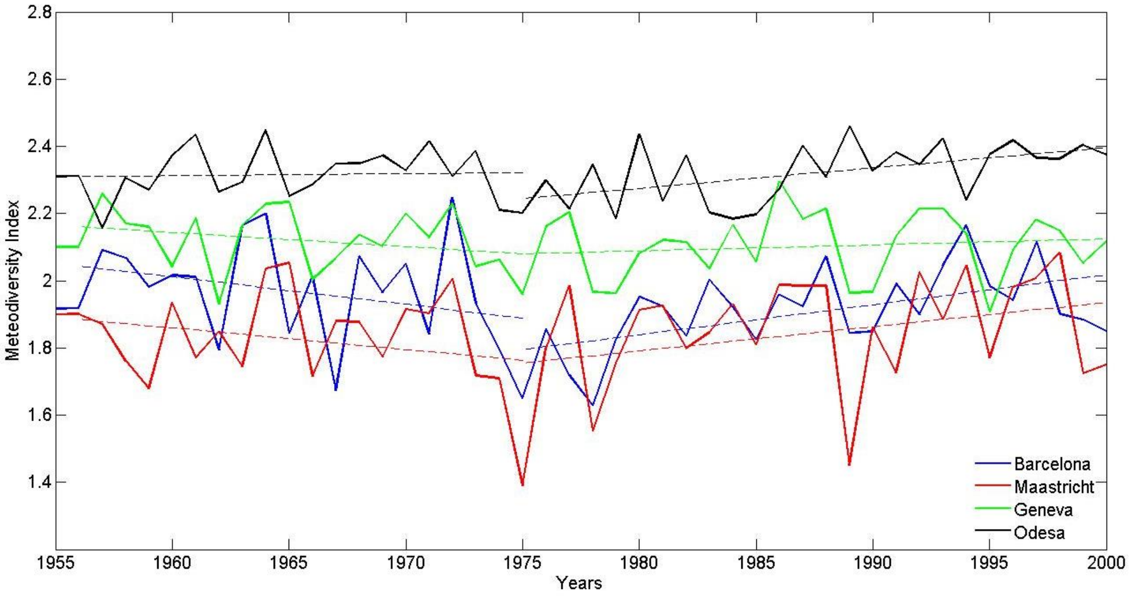

Fig. 3.20: MI evolution from 1950 to 2000 for Barcelona (blue), Maastricht (Red), Geneva (green) and Odesa (black). Thin, dotted lines show the trend lines from 1950 to 1975 and 1975 to 2000.

This happens because, generally speaking, two climate patterns can be found in the last 50 years in Europe:

- Between 1950 and 1975 no significant variations in the MI tendencies are found, except for a few stations with a negative trend line, decreasing always less than 0.15 (or 10% of the MI average values). For this time period, some of the less significant variables tend to decrease or remain constant, while some of the most significant increase. The generalized patterns show a constant or slightly decreasing heavy and very heavy rain days (up to 15% of decrease, compared to 1950), constant or slightly increased tropical nights and a generalized descent in icy days (also 15% less than the initial values). At the same time, the rainy days, that are significant in almost any climate tend to increase in an amount not greater than 10%, except in the Mediterranean climate. The summer and frosty days would also decrease for this time period (but also always less than 20% of 1950 value). As a result, in this time period, except for most Mediterranean climates and some other exceptions, the general tendency of the MI values is to decrease, as a result of increasing the weight of the rainy days while decreasing most of other variables impact.
- Between 1975 and 2000 MI trend lines present an increase of 0.2 (around 14%) during the 25 years. This occurs because the general climate is becoming warmer and drier. A proof of this is that the amount of rainy days

(decreasing down to 66% of the values in 1975), frosty days and icy days (both with decreases to 85% of 1975 value) is generally decreasing, while the amount of summer days and tropical nights increases greatly (more than 50% of increase for some regions in summer days and 75% in tropical nights) in a lot of cases. If to this is added the fact that the heavy and very heavy rain days do generally increase (but only in 15%), the result is a hotter climate with rarer but heavier precipitation. In the colder climate the increase in Meteodiversity is self-explained with the temperature inversion, but for the hotter ones, a good explanation is the up rise of a normally insignificant phenomena as tropical nights, while maintaining or slightly increasing the amount of heavy and very heavy rain days.

In order to better comprehend how these variations are measured, Fig. 3.21 shows the evolution of the number of tropical nights in some stations with Mediterranean climate. It can be seen that some stations, like Barcelona, have a small number of tropical nights around 1975, but this value increased largely from that moment. This study has been done for every station and variable, allowing to obtain the generalized behaviors that explain the common slopes in MI trend lines.

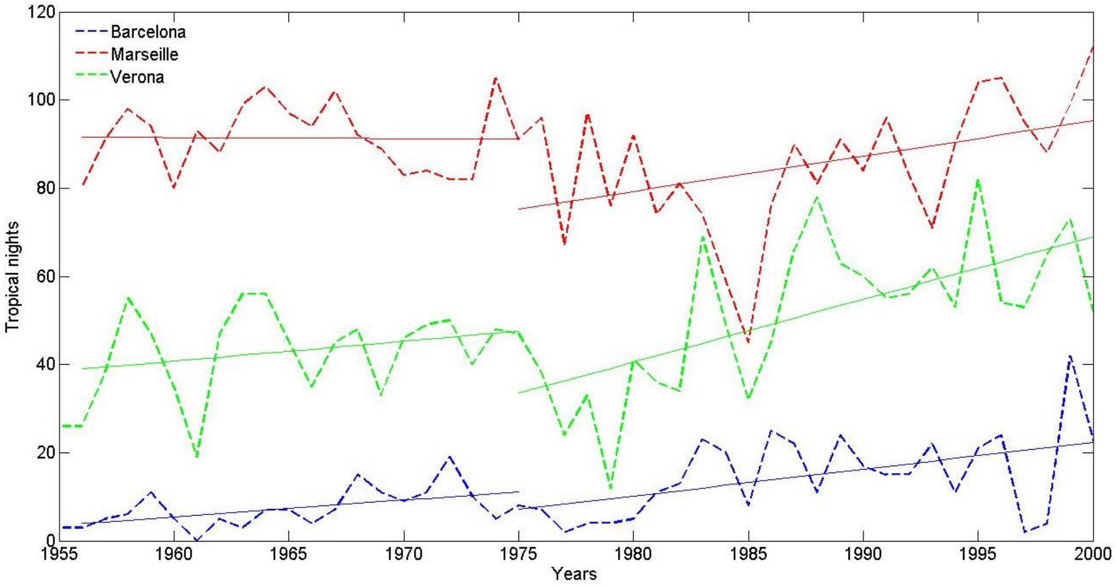

Fig. 3.31: Amount of tropical nights for Barcelona (blue, dashed), Marseille (red, dashed) and Verona (green, dashed). Thin, solid lines show the trend lines of the tropical nights from 1950 to 1975 and from 1975 to 2000.

Conclusions

Meteodiversity is a new concept proposed to consider the evolution of the diversity of meteorological phenomena that happens in a defined area over a period of time. With the purpose of quantifying this concept, the distribution of a Meteodiversity index across Europe is studied.

The data analyzed to carry out this project consists in 7 indices of precipitation and temperature extremes obtained from 23 different stations distributed across Europe in the 50 years period between 1950-2000. The indices of extremes are used to calculate the Meteodiversity index annually and the values are grouped by decades and seasons using Matlab scripts.

First, to establish how the Meteodiversity index behaves a theoretical and sensitivity analysis is performed. The results show that the MI can have values from 0 to 2.8 when 7 indices of extremes are used, but the real values will rarely range below 0.5 or above 2.5. The MI variations are not directly related to a diminution or an increase of one or more of the variables, as reducing a significant enough variable can lead to a significant increase or decrease of the MI values, depending on the magnitude of the reduction. However, generally speaking, reducing moderate or not significant variables will lead to light, steady reductions in MI values.

Secondly, to determine if there is any common trend in the evolution of the Meteodiversity index across Europe, the meteorological stations have been organized into different climatic regions with similar climatic characteristics using the Köppen climate classification system. Every station has been related to each other that shares the same climate type using the typical values of the MI for the time period.

According to the results obtained, no clear relationship other than the range of values is found regarding the climate type of the stations and the MI value. It is found that the stations with a Temperate climate have a higher range of possible MI values, from 1 to 2.4; while Cold climates have a range typically smaller, from 1.5 to 2.5. However, in the coldest and drier climates of the northern regions, the MI value tends to be lower, due to the lack of contrast of phenomena while, as expected, the higher MI values are found in the Continental climates, where a high annual temperature gradient and moderate precipitation occur.

It is also found that most of the stations share a slight increase in MI typical values when moving from 1950 to 2000. The time period is then analyzed in two halves, from 1950 to 1975 and from 1975 to 2000. The first half has typically stable or decreasing MI values, explained by generalized increase in steady precipitation values, while extreme temperature values are smoothed. The second half has a noticeable generalized increase in MI values explained by the increase in heavy precipitation values and days with very high minimum temperature.

Finally, the distribution of the MI decadal values across Europe is plotted, in order to stablish if there is any relation between MI typical values and geographical locations. It is observed that the MI mean values are high (above 2.2) in the center and east of Europe, coinciding with most Continental climate zones; near the coasts of the Mediterranean and Baltic seas (with Mediterranean and Temperate Oceanic climates) MI has moderate values, between 1.5 and 2, and near cold and mild-cold seas the MI has low values, typically below 1.5, regardless of the climate type. Therefore, with the indices considered, the MI values are related mainly to the geography, as orography and presence of water bodies is more influential than climate type.

From the point of view of the variation of the MI decadal values, few stations show variations (mostly increases) bigger than 5%. Those stations are located in the northwest of the continent, Greece and the Scandinavian peninsula, and their evolution is caused by the increase in temperature extremes.

Future work

As this project consists on a first approach to the analysis of Meteodiversity in Europe during the second half of the last century, several additional research studies can be performed to extend the scope of this work.

The first line of research includes increasing the time and space ranges used for this study. Providing a large and reliable enough dataset, the scope of the study should be placed worldwide and for a century at least. This way, plenty of climates that are not significant enough in Europe to be considered in this study could be included, expanding the investigation to show if there is any more relation between the general climate type, the geographical location and the values of the MI. In this same line, climatologic effects that were not considered in this study could be included in the analysis, like the oceanic influence, the air masses circulation and the Foehn effect (see [8] and [9]).

In a related line of research, a common set of variables could be defined, in order to include more stations spread through Europe. With this additional information, it should be possible to generate an interpolation map, though meshing techniques, with the MI values in every location of the continent.

Additionally, it would be interesting to study how the MI behaves when more climate indicators are added to the calculation. Indices like snow days, sleet days, days with variable or intense wind, days with fog, low or high-pressure days, cloudy days and days with thunderstorms could and should be added to the calculation, as they are impactful enough to affect aviation. This would, however, modify the sensitivity analysis and it should be repeated.

Another possible approach could be to modify the MI formula by applying a given weight to the indices according to the impact that each index causes to a given scenario. This way, a zone with an increase in a variable that is desirable to be avoided, like the icy days when deciding where to build an airport, would show up clearly.

Finally, the human influence could also be analyzed: by deeply studying each station MI values it could be visualized the impact of the industrialization on the different climates and regions.

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Attachment A: MAIN CSA

```
%% Main program to obtain the MI values for each year and variable
clear all
close all
clc

%The function calculates the MI from the equation, with the data
adquired in the reads
addpath(genpath('C:\Users\Arturo\Desktop\TFG')); %To add the folders
and subfolders to the reading (user must input files location)

FilenamesCSA={'indexFD002969.txt','indexID002969.txt','indexRR1002969.
txt','indexR10mm002969.txt','indexR20mm002969.txt','indexSU002969.txt'
,'indexTR002969.txt';

'indexFD000031.txt','indexID000031.txt','indexRR1000031.txt','indexR10
mm000031.txt','indexR20mm000031.txt','indexSU000031.txt','indexTR00003
1.txt';

'indexFD000177.txt','indexID000177.txt','indexRR1000177.txt','indexR10
mm000177.txt','indexR20mm000241.txt','indexSU000177.txt','indexTR00017
7.txt';

'indexFD000060.txt','indexID000060.txt','indexRR1000060.txt','indexR10
mm000060.txt','indexR20mm000060.txt','indexSU000060.txt','indexTR00006
0.txt';

'indexFD000174.txt','indexID000174.txt','indexRR1000174.txt','indexR10
mm000174.txt','indexR20mm000174.txt','indexSU000174.txt','indexTR00017
4.txt'};

            %% Set the color of the plots

Colors={'b','r','g','m','k'};
Colorstendence={'--b','--r','--g','--m','--k'};
j=1;

            %% Read values and adjust format
while (j<=5)
[Yearsfrost, Daysfrost]=ReadDays(char(FilenamesCSA(j,1)));
Frostdays=Daysfrost/100;
[Yearsice, Daysice]=ReadDays(char(FilenamesCSA(j,2)));
Icedays=Daysice/100;
[Yearsrain, Daysrain]=ReadDays(char(FilenamesCSA(j,3)));
Raindays=Daysrain/100;
[Yearsheavyrain, Daysheavyrain]=ReadDays(char(FilenamesCSA(j,4)));
Heavyraindays=Daysheavyrain/100;
[Yearsveryheavyrain,
Daysveryheavyrain]=ReadDays(char(FilenamesCSA(j,5)));
Veryheavyraindays=Daysveryheavyrain/100;
[Yearssummer, Dayssummer]=ReadDays(char(FilenamesCSA(j,6)));
Summerdays=Dayssummer/100;
[Yearstropical, Daystropical]=ReadDays(char(FilenamesCSA(j,7)));
Tropicaldays=Daystropical/100;

            %% Anual calculation
```

```
%This climate has few data before 1955, so the reading starts this
year
i=find(Yearstropical==1955);
Years=zeros;
N=zeros;
MI1=zeros;
MI2=zeros;
MI3=zeros;
MI4=zeros;
MI5=zeros;
MI6=zeros;
MI7=zeros;
MI=zeros;
while (i<=(find(Yearstropical==1955)+45))% 45 years study as all
countries use to start collecting data at max 1955
   %Null and wrong values set to NaN
    if (Frostdays(i)==(-9999.99))||(Icedays(i)==(-
9999.99))||(Raindays(i)==(-9999.99))||(Heavyraindays(i)==(-
9999.99))||(Veryheavyraindays(i)==(-9999.99))||(Summerdays(i)==(-
9999.99))||(Tropicaldays(i)==(-9999.99))
       MI(i)=NaN;
       Years(i)=Yearsfrost(1)+i;
          i=i+1;
    else

       %Total amount of phenomena

N(i)=Frostdays(i)+Icedays(i)+Raindays(i)+Heavyraindays(i)+Veryheavyrai
ndays(i)+Summerdays(i)+Tropicaldays(i);
    %To get rid of inf caused by 0 values
     if Frostdays(i)==0
        MI1(i)=0;
     else
        %Contribution to the MI of this phenomena
        MI1(i)=(Frostdays(i)/N(i))*log(Frostdays(i)/N(i));
    end
    if Icedays(i)==0
        MI2(i)=0;
    else
        MI2(i)=(Icedays(i)/N(i))*log(Icedays(i)/N(i));
    end
    if Raindays(i)==0
        MI3(i)=0;
    else
        MI3(i)=(Raindays(i)/N(i))*log(Raindays(i)/N(i));
    end
    if Heavyraindays(i)==0
        MI4(i)=0;
    else
        MI4(i)=(Heavyraindays(i)/N(i))*log(Heavyraindays(i)/N(i));
    end
    if Veryheavyraindays(i)==0
        MI5(i)=0;
    else

MI5(i)=(Veryheavyraindays(i)/N(i))*log(Veryheavyraindays(i)/N(i));
    end
    if Summerdays(i)==0
        MI6(i)=0;
    else
        MI6(i)=(Summerdays(i)/N(i))*log(Summerdays(i)/N(i));
```

```
    end
    if Tropicaldays (i)==0
        MI7(i)=0;
    else
        MI7(i)=(Tropicaldays(i)/N(i))*log(Tropicaldays(i)/N(i));
    end
    %Add all MI contributions and multiply them by the conversion
factor
   k=1/(log(2));
   MI(i)=-k*(MI1(i)+MI2(i)+MI3(i)+MI4(i)+MI5(i)+MI6(i)+MI7(i));
   Years(i)=Yearsfrost(1)+i;
   i=i+1;
   end
end

            %% Decade value (all data stat at 1955 after removing NaN
and 0)
MIx=MI(~isnan(MI));
MIok=MIx(MIx~=0);
l=1;
t=1;
%First decade only has 5 years
while (l<=40)
    if(l==1)

MIdecCSA(j,t)=0.2*(MIok(l)+MIok(l+1)+MIok(l+2)+MIok(l+3)+MIok(l+4));
      l=l+5;
      t=t+1;
      %Then 10 years per decade, as intended
    else

MIdecCSA(j,t)=0.1*(MIok(l)+MIok(l+1)+MIok(l+2)+MIok(l+3)+MIok(l+4)+MIo
k(l+5)+MIok(l+6)+MIok(l+7)+MIok(l+8)+MIok(l+9));
      l=l+10;
      t=t+1;
    end
end

            %% Plotting part

Years(find(isnan(MI)==1))=NaN;
%Commented part is used to split the tendence line
%Years75=Years(find(Years==1975):find(Years==2000));
%MI75=MI(find(Years==1975):find(Years==2000));
%Years50=Years(find(Years==1956):find(Years==1975));
%MI50=MI(find(Years==1956):find(Years==1975));
line(j)=plot(Years(~isnan(Years)), MI(~isnan(MI)),
char(Colors(j)),'linewidth',1.5);
xlim([1955 2000])
p1=polyfit(Years(~isnan(Years)),MI(~isnan(MI)),1);
f1=polyval(p1,Years);
%p2=polyfit(Years75(~isnan(Years75)),MI75(~isnan(MI75)),1);
%f2=polyval(p2,Years75);
%p3=polyfit(Years50(~isnan(Years50)),MI50(~isnan(MI50)),1);
%f3=polyval(p3,Years50);
hold on
plot(Years(~isnan(Years)), f1(~isnan(f1)), char(Colorstendence(j)))
%plot(Years75(~isnan(Years75)), f2(~isnan(f2)),
char(Colorstendence(j)))
%plot(Years50(~isnan(Years50)), f3(~isnan(f3)),
char(Colorstendence(j)))
```

```
j=j+1;
end

            %% Adjusts plot characteristics
set(gca, 'fontsize', 15)
xlabel({'Years'});
ylabel({'Meteodiversity Index'});
legend =
legend(line,'Barcelona','Marseille','Verona','Hellinikon','Brindisi','
Location','NorthEast');
set(legend,'color','none','Box','off')
hold off
```

Attachment B: MIvsEUROPE

```
%% Main program to plot the decadal MI value in a map of Europe

% This function gets all decade values from the climate MAINS and plot
them
%in a blank map of Europe, according to every station position, in
every
%decade.

            %% Open MAINs and get decade mean values
MainCSA
MAINCFB
MAINDFB
Mainextra
clearvars -except MIdecCSA MIdecCFB MIdecDFB MIdecextra
close all
%Put them in a vector
MIdec=[MIdecCSA
    MIdecCFB
    MIdecDFB
    MIdecextra];
i=1;
j=1;
sizeMI=size(MIdec);
Titles={'MI distribution over 1950 decade','MI distribution over 1960
decade','MI distribution over 1970 decade','MI distribution over 1980
decade','MI distribution over 1990 decade'};

            %% Adjust every value to a fitting color value in gbr
%using manually calculated fitting functions
while(j<=sizeMI(2))
colorMI=zeros;
while(i<=sizeMI(1))
    if(MIdec(i,j)==0)
        colorMI(i,1)=1;
        colorMI(i,2)=1;
        colorMI(i,3)=1;
    end
    if(MIdec(i,j)>0)&&(MIdec(i,j)<=1.2)
        colorMI(i,1)=0;
        colorMI(i,2)=0;
        colorMI(i,3)=(MIdec(i,j)-0.48)*1.38;
    end
    if(1.2<MIdec(i,j))&&(MIdec(i,j)<=1.53)
        colorMI(i,1)=0;
        colorMI(i,2)=(MIdec(i,j)-1.2)*3.12;
        colorMI(i,3)=1;
    end
    if(1.53<MIdec(i,j))&&(MIdec(i,j)<=1.83)
        colorMI(i,1)=(MIdec(i,j)-1.53)*3.175;
        colorMI(i,2)=1;
        colorMI(i,3)=1-((MIdec(i,j)-1.53)*3.175);
    end
    if(1.83<MIdec(i,j))&&(MIdec(i,j)<=2.15)
        colorMI(i,1)=1;
        colorMI(i,2)=(MIdec(i,j)-2.15)*(-3.12);
```

```
        colorMI(i,3)=0;
    end
    if(2.15<MIdec(i,j))&&(MIdec(i,j)<=2.46)
        colorMI(i,1)=(MIdec(i,j)-2.77)*(-1.61);
        colorMI(i,2)=0;
        colorMI(i,3)=0;
    end
    i=i+1;
end
figure(j);

            %% Open blank map and hold it
EU=imread('Europe_blank_map.jpg');
imshow(EU)
hold on
%Get a visual aid on color scaling
colormap
%For setting every point location use:
cur=[1 1]; %Circle
a=20;
positions=[215-a 670-a 20 20
           280-a 635-a 20 20
           365-a 600-a 20 20
           580-a 725-a 20 20
           475-a 685-a 20 20
           65-a 605-a 20 20
           190-a 545-a 20 20
           290-a 470-a 20 20
           145-a 400-a 20 20
           160-a 305-a 20 20
           415-a 575-a 20 20
           370-a 475-a 20 20
           505-a 530-a 20 20
           600-a 565-a 20 20
           625-a 440-a 20 20
           645-a 525-a 20 20
           515-a 370-a 20 20
           480-a 300-a 20 20
           505-a 255-a 20 20
           385-a 290-a 20 20
           480-a 105-a 20 20
           125-a 680-a 20 20
           305-a 570-a 20 20];%matrix of 23x4 with cord x-20, cord y-
%20, 20 20
pos=[(475-20) (685-20) 20 20]; %Exaple of position
t=1;

            %% Place every circle in the corresponding place and with
%the corresponding color
while(t<=sizeMI(1))
rectangle('Position',positions(t,:),'Curvature',cur,'FaceColor',colorM
I(t,:))
t=t+1;
end
%To show the colormap used in the fitting in the plot, with some
%values to scale
colormap jet
colorbar('YTicklabels',[0.88, 1.15, 1.40, 1.67, 1.93, 2.19, 2.45])
            %% Adjusts plot characteristics
set(gca, 'fontsize', 15)
hold off
```

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

Attachment C: ReadDays

```
%% Main program used to read values from the database

%The aim of the code is to read any file of the format amount of x
days, and return the x days value per year
%Header of file must be eliminated and user must provide name of the
file
function [Years, Days]=ReadDays(FileName)
    Data=importdata(FileName);
    Days=zeros;
    Years=zeros;
    i=1;
    while (i<=length(Data))
        Days(i)=Data(i,3);
        Years(i)=Data(i,2);
        i=i+1;
    end
end
```