

## **Influence of synoptic scale in the generation of extremely cold days in Europe**

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### RESUMEN

Una base de datos homogéneos de temperaturas mínimas de 135 observatorios distribuidos en Europa ha sido analizada con el objetivo de estimar las variaciones de tendencias e identificar las principales situaciones sinópticas que contribuyen en un día de frío extremo (DFE). Se ha considerado un Día de Frío Extremo (DFE) definido por el percentil 5% de la serie de temperatura mínima diaria de cada observatorio; valores que tiene efectos sobre la salud. Para este análisis se utiliza el periodo de 1 de enero de 1955 hasta el 31 de diciembre de 1998; período que presenta el mayor número de estaciones de medidas con series completas. La conexión entre los DFE con la circulación general de la atmósfera, está basada en un análisis detallado obteniendo un coeficiente de eficacia para cada patrón sinóptico. Para simplificar la información obtenida, se aplica un análisis de componentes principales rotadas (RPC) y se obtienen los patrones sinópticos con mayor contribución a los DFE. Al mismo tiempo se ha hecho un análisis de tendencia en cada uno de los patrones sinópticos y también un estudio comparativo entre los diferentes DFE de las situaciones sinópticas.

### ABSTRACT

A homogenized database of minimum temperatures from 135 observatories distributed around Europe was analyzed in order to estimate trends and to determine the main synoptic weather patterns that contribute to an extremely cold day (ECD). An ECD is defined as a day whose minimum temperature is within the lowest 5th centile of the daily temperature series for each observatory; these values represent temperatures below which public health concerns may be expected. The period from 1 January 1955 to 31 December 1998 was chosen for this analysis because it represents the period for which the greatest number of measuring stations with complete time series was available. The relationship between the occurrence of an ECD and the general circulation of the atmosphere was based on a statistical analysis in which a coefficient of effectiveness for each synoptic pattern was obtained. In order to simplify the manipulation of the data, a rotated principal components (RPC) analysis was applied and the synoptic patterns with the greatest contribution to the ECD were obtained. Trends for each synoptic pattern were studied in order to examine the relationship among the ECD.

**Keywords:** Extremely cold days, GWL patterns, ECD over Europe.

## 1. Introduction

The increase in the global mean temperature during the twentieth century, in particular over the last 30 years, has provided a strong incentive for investigations of climate change. The average global temperature has increased by approximately 0.6° C between the end of the nineteenth century and the present day (IPCC, 2001). For this time interval, two periods of strong global warming have been identified, firstly between 1910 and the early 1940s, and secondly between the mid 1970s and the present day (Jones *et al.*, 1999; Karl *et al.*, 2000). It has been confirmed that in Europe the majority of the increases of temperature coincide with periods when global temperatures also increased (Klein Tank *et al.*, 2002). Analyses of temperature records show that warming does not happen homogeneously but is instead concentrated around certain specific regions (Easterling *et al.*, 1997), thus requiring research that is focused on the study of temperatures within these regions.

Heat or cold waves are characterized by the occurrence of a sequence of days with high or low values of temperature. These waves have significant impacts in terms of their socioeconomic effects on health, agriculture, forest fires, and the production and consumption of energy (SIAM, 2002; García-Herrera *et al.*, 2005; Pereira *et al.*, 2005; Trigo *et al.*, 2005). Observations from some European capitals show a direct and proportional relationship between extreme temperatures and their impacts on public health (Díaz *et al.*, 2002). Both maximum and minimum extremes in temperature are associated with impacts on public health, although the relation between minimum temperatures in winter and mortality is not as noticeable as the equivalent high-temperature relationship during summer months. It is clear that the effect of the cold on mortality depends on the time of exposure to these temperatures and, in addition, minimum extreme temperatures occur in general in the hours before dawn, when people are usually indoors and are thus protected from their effects. However, it is possible to find a relationship between low temperatures and the occurrence and intensification of breathing problems (Hajat and Haines, 2002). Díaz *et al.* (2004) verified that the effects of cold waves do not generally cause sudden death, but may instead lead to a fatality several days later, unlike the effects of the summer temperature maxima.

The aim of the present study is to determine the influence of synoptic patterns that cause extreme daily minimum temperatures. To do so, we will select the series of daily minimum temperatures in 34 European countries and the main synoptic patterns that occur in Europe, in the near-surface region and at different altitudes, associated with particular sequences of extremely cold days.

The present study is structured as follows: Section 2 contains a discussion of the trends analysis used in this study. In Section 3, the data used and the methodology applied to the synoptic weather patterns are described, as well as the method of identification of those synoptic patterns that have the greatest impact on the occurrence of extremely cold days (ECD). This section also contains an analysis of the trends of the synoptic patterns for the period of study. Section 4 concludes.

## 2. Temporal analysis

In this section, the temporal analysis technique, based on the investigation of trends leading to the occurrence of ECD is explained. Firstly, the characterization and methodology applied to the series of daily minimum temperatures is described. Next, an ECD is defined. Finally, the processes and

results of trends based on the annual frequency of ECD are discussed, as well as the factors that contribute to the increase or decrease in extreme minimum temperatures.

### 2.1 Minimum temperature series

The series of minimum daily temperatures used here were obtained from the ECA Dataset (Klein Tank *et al.*, 2002), which is available on-line for the 44 years from 1 January 1955 to 31 December 1998. This data set was chosen because it possesses the greatest number of complete time series of temperatures. Station selection was based on the need to cover as much European territory as possible. In total, 135 time series of distributed minimum temperatures in 34 countries were selected (Fig 1).

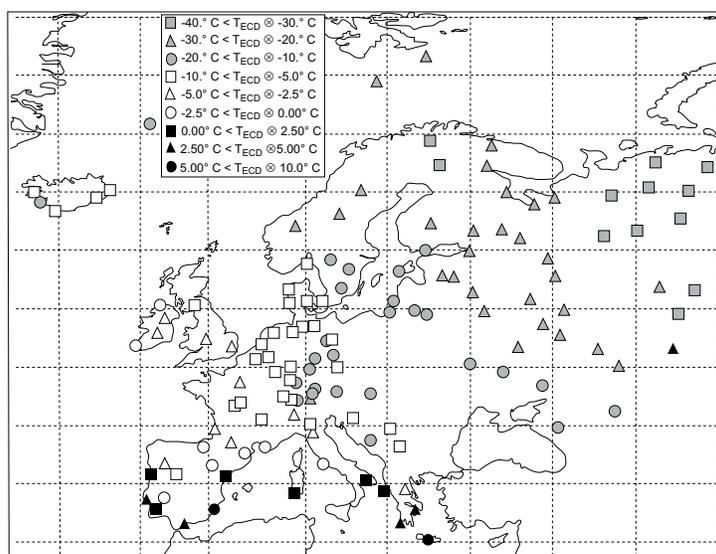


Fig.1. The 135 minimum temperature series. The intervals threshold temperature are according to the caption for each station.

The time series of minimum temperature ( $T_{min}$ ) were selected and subjected to a homogenization process in order to eliminate discontinuities (Easterling *et al.*, 1992; Della-Marta *et al.*, 2005). In this case, the techniques of homogenization applied in this study are similar to those developed by Peterson and Easterling (1994), and used by Prieto *et al.* (2002). The technique consists, firstly, on the construction of an homogenous reference series from nearby stations that show a similar variability in the observed parameters. In the same way as Peterson and Easterling (1994) it has been decided to take the five nearest stations that showed the greatest correlation with the original series. We evaluated the use of five different methods of spatial interpolation: multiple discrimination analysis (Miller, 1962), multiple linear regression, standardized anomaly, weighted average, and an average of the four previous methods. Of these, the weighted average method produced the best results. Using this method, series of annual average temperatures for the 135 stations were created and were used as a reference for the rest of the analyses. In all the time series, a method of 'search and detection' for discontinuities was applied, the technique used being similar to that of Easterling and Peterson (1995).

### 2.2 *Extremely cold days*

In a previous work on extreme temperatures, threshold temperatures have been used to identify days of extreme cold or heat. Some studies define an extreme in temperature on the basis of the impacts that they have on the environment, but there are other purely statistical definitions. In this case, the 1st, 5th or 10th percentile of the minimum temperature series, and the 99th, 95th or 90th centile in the case of maximum temperatures series, are used (DeGaetano, 1996).

In our analysis, we used the 5th centile of the series of minimum temperatures. This was computed for each of the 135 time series of temperatures selected from November to March. Therefore, an ECD is defined as a day on which the minimum temperature lies within the 5 percentile of the distribution of daily minimum temperature series. This threshold in the series of minimum temperatures agrees with studies in Spain that demonstrate it as having the most significant impact on public health (Díaz *et al.*, 2003).

Figure 1 shows the different thresholds in temperature for each station from measurements distributed within the 34 European countries. The distribution of thresholds in minimum temperatures varies between 6.1° C at Heraklion (Greece, Lat. 35.33°/ Lon. 25.18°) to -39.1° C at Hoseda Hard (Russia, Lat. 67.08°/Lon. 59.38°). It is evident that the temperature thresholds are lower at higher latitudes and altitudes, for instance, at Zugspitze (Germany, Lat. 47.25°/Lon. 10.59°, altitude 2960 m) the threshold is -21.4° C.

However, the selection of temperature thresholds is not critical to the determination of the frequency of ECD, when the interannual variability in temperature is taken into account. The series of annual frequencies of ECD does depend on the temperature threshold selected, but it is much more sensitive to the interannual variability in temperature. In order to verify this, the series of annual frequencies of ECD, was calculated by considering a difference of 1° C in selected threshold values. For most stations, this yields a variation in threshold of from 2 to 8 percent of the original value. Comparison of the series with the new thresholds and the series obtained using the original thresholds shows an average correlation coefficient of around 0.93 (at the level of 99.9%), with a maximum of a 0.98 and minimum of 0.82. It therefore follows that most of the variability of the ECD frequency series does not depend on the threshold selected and thus, the threshold used here will provide information relating to the interannual variability of ECD.

### 2.3 *ECD trend over Europe*

In this analysis, the objective was to verify the trends in the annual frequency of ECD that occurred throughout the whole period of study in the 135 series of minimum temperatures in Europe.

The technique that is used most commonly for calculating meteorological variable trends is linear regression. However, this method cannot be used to calculate extreme temperature trends because the deviations in the observed data do not generally follow normal distributions. Moreover, linear regression is affected by values at the extremes of the series, especially for shorter time series, and this can lead to significant errors. Consequently, it is necessary to use another technique that provides estimations of the trends but avoids this type of error. An alternative method for analyzing

trends was developed by Karl and Williams (1987) and later applied in the calculation of extreme frequency trends by DeGaetano (1996). Using this technique, we can obtain reasonable estimates of the trends of annual frequencies that would not be possible with traditional techniques. In order to calculate the significant trends ( $p$ ), it has been applied a Monte Carlo test. By carrying out this test, 5000 random series disordering the original ones were obtained and the statistical  $t$  was calculated for each of them. The trends' significance value was then obtained as the percentage of simulations whose statistical  $t$  exceeded the original one.

This method of tendencies was applied to the 135 annual series of ECD frequency. The results are shown in Figure 2, where statistically significant trends at the levels of 99%, 95% and 90% are shown. In all stations, the trends were negative, but in 64.4% of the stations, the measurements showed significantly high trends ( $p < 0.10$ ). The highest decreases were detected in Mediterranean and Central European observatories.

The temperature follows a Gaussian distribution, the variations in the extremes being due mainly to changes in the mean or standard deviation. For this reason, it is important to know the temporal evolution, the average, and the variance of the series of temperature in order to know which of these two factors, minimum average temperature and standard deviation, has a greater influence in the increase or decrease of ECD.

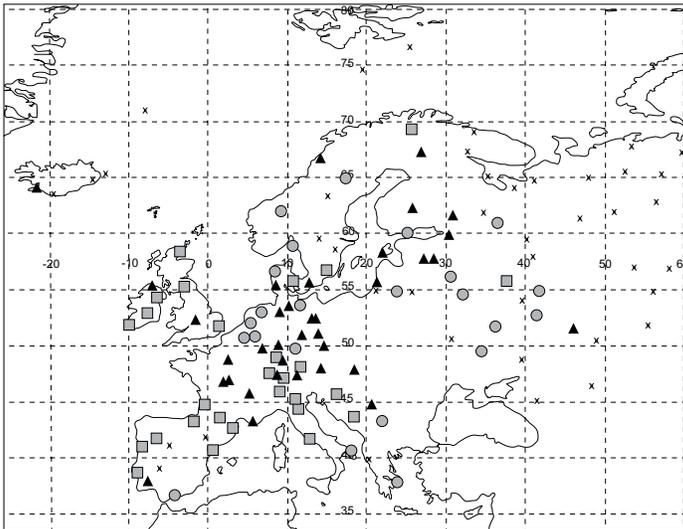


Fig. 2. frequency trends for ECD over Europe from 1955 to 1998 using squares for 99%, circles for 95% and triangles for 90%.

Figure 3a shows the analysis of trends in the minimum average temperature from November to March for those trends that are positive. An increase may be observed in the majority of the stations. Seventy-three percent of the stations present significant highest positive trends ( $p < 0.10$ ). It may be observed that stations that show trends in the minimum average temperature do not correspond with stations that present significant trends in the annual frequency of ECD. Therefore, this is an important factor in the decrease of annual occurrence of ECD, because the trends analysis estimates

increases between 0.5 and 2.0° C in the minimum temperature. In terms of the standard deviation, the analysis of trends shows that 53.3% of stations with significant measures show negative trends. These results are shown in Figure 3b. In this case, it may be seen that standard deviation is not an important factor for the decrease of the annual frequency of ECD.

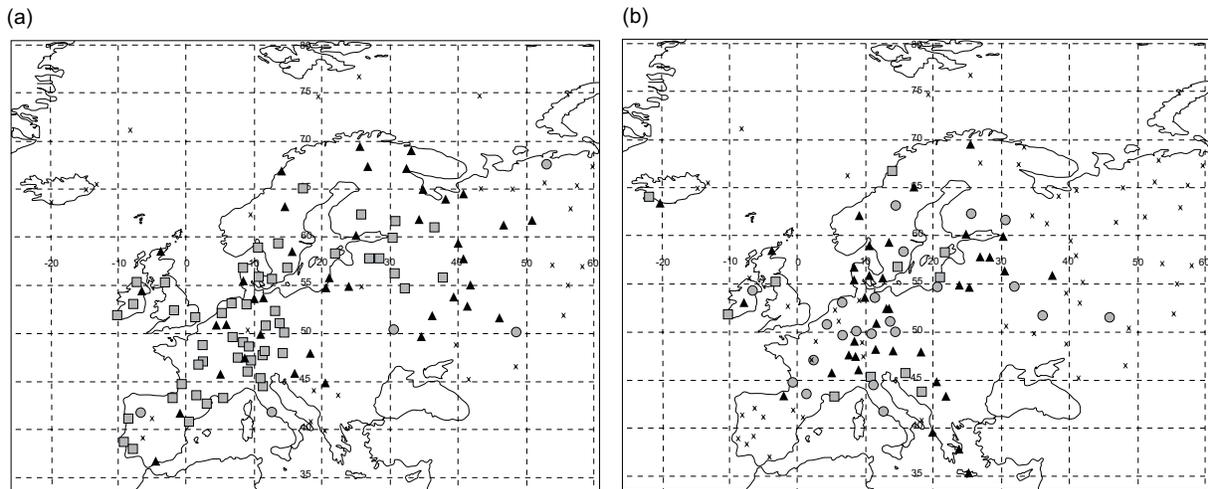


Fig. 3. a) Significant trends of the minimum temperature average from November to March. b) Significant trend of standard deviation for the same period but for daily minimum temperature. The figure uses the same captions as Fig. 2.

### 3. Synoptic scale

This section describes the synoptic patterns that have the greatest influence on the generation of extremes of temperature. In Section 3.1, the data obtained from synoptic patterns is described and the reasons for using these weather data are explained. In Section 3.2, the processes used to connect the synoptic patterns and the ECD are described. Finally, in Section 3.3, a method is applied that considers the effect of the synoptic patterns that have the greatest influence on ECD generation, as well as the characterization of each pattern. An analysis of the trends in the synoptic patterns is also described and discussed.

#### 3.1 The Grosswetterlagen catalogue-GWL

The Grosswetterlagen catalogue (Hess and Brezowsky, 1977; Gerstengarbe and Werner, 1993; Gerstengarbe *et al.*, 1999) from 1901 to 1998, inclusive, was used to analyze the statistical relationships between the ECD and the atmospheric synoptic patterns. The classification recognises three groups of circulations types (zonal, half-meridional and meridional), which are divided into ten major types (Grosswettertypen, GWT) and 29 subtypes (Grosswetterlagen, GWL; Table I).

Table I. List of Hess-Brezowsky major types (GWT) and types (GWL) (Hess and Brezowsky, 1977; Gers-tengarbe *et al.*, 1999).

Major type (GWT)	Abbrev.	Type (GWL)	Abbrev.	No. GWL
A. Zonal circulation				
West	W	West cyclonic	WZ	02
		West anticyclone	WA	01
		West angular	WW	04
		Southern West	WS	03
B. Mixed circulation				
Central European high	HM	Central European high	HM	09
		Central European ridge	BM	10
Central European low	TM	Central European low	TM	11
		Southwest	SW	05
Northwest	NW	Southwest anticyclone	SWA	06
		Southwest cyclonic	SWZ	06
		Northwest anticyclone	NWA	07
		Northwest cyclonic	NWZ	08
C. Meridional circulation				
East	E	Fennoscadian high anticyclone	HFA	20
		Norwegian Sea/Fennoscadian high anticyclone	HNFA	22
		Fennoscadian high cyclonic	HFZ	21
		Norwegian Sea/Fennoscadian high cyclonic	HNFZ	23
South	S	South anticyclone	SA	26
		South cyclonic	SZ	27
		British Isles low	TB	28
		Western Europe trough	TRW	29
		Southeast	SE	24
Southeast	SE	Southeast anticyclone	SEA	24
		Southeast cyclonic	SEZ	25
North	N	North anticyclone	NA	12
		North cyclonic	NZ	13
		North, Iceland high, anticyclone	HNA	14
		North, Iceland high, cyclonic	HNZ	15
		British Isles high	HB	16
		Central European trough	TRM	17
		Northeast	NE	18
Northeast	NE	Northeast anticyclone	NEA	18
		Northeast cyclonic	NEZ	19

One of the advantages in using this classification is that it considers the main synoptic patterns that occur in European climates. Fink *et al.* (2004) used the classification of Hess and Brezowsky for a study of heat waves in 2003 and Domonkos *et al.* (2003) used it in an analysis of extremes of temperature at eleven stations in central Europe.

### 3.2 Connections between ECD and GWL

The relationship between an ECD and a synoptic pattern GWL was investigated using statistical tests relating the frequencies of synoptic patterns for those days when an ECD occurred. Once the ECD from each observatory had been identified, a daily classification of the synoptic patterns during these extreme days was obtained.

Using the relationship between the partial relative frequencies ( $F_{\%ECD}$ ) and total relative frequency ( $F_{\%}$ ) of the synoptic patterns and the ECD that occurred during the period of study (November-March), a statistical coefficient was obtained to show the occurrence of a certain synoptic pattern GWL at a certain station. An effectiveness coefficient (EC) may be defined as:

$$EC = \frac{\frac{F_{A_{ECD}}}{N_{ECD}}}{\frac{F_A}{N_T}} = \frac{F_{\%ECD}}{F_{\%}} \quad (1)$$

where  $F_{A_{ECD}}$  is the frequency of the synoptic patterns during an ECD,  $N_{ECD}$  is the number of ECD occurring during the period of study for each observatory,  $F_A$  is the total frequency of synoptic patterns occurring in the months November-March for the whole period, and  $N_T$  is the total number of days (Nov-Mar) throughout all 44 years.

The EC obtained from Eq. (1) may be used to investigate the connection between a GWL pattern and the occurrence of an ECD. A matrix of data is obtained that demonstrates the presence of synoptic patterns. An EC greater than 1 indicates that a certain synoptic pattern has occurred more frequently in a station during an ECD than another one, while an EC less than 1 indicates that the synoptic pattern has occurred less frequently.

### 3.3 Synoptic patterns GWL analysis

In order to relate synoptic patterns (GWL) to the occurrence of ECD, a rotated principal components analysis (RPC) was used (White *et al.*, 1991), which took into account the EC obtained for every GWL pattern and every observatory under consideration. An RPC analysis considers that all the information of the different series is contained in its variance, and it is for this reason that its matrix-covariance is calculated. In this study, we used the Varimax method, which is commonly used in climatology (Richman, 1986; Stone, 1989; White *et al.*, 1991), and to select the number of components to rotate, we used Kaiser's (1958) criterion, which only uses those components with an eigenvalue greater than 1.

To determine the influence of the synoptic patterns in an ECD, in the RPC analysis, we took the first three orthogonal functions (EOF), which explain 68.8% of the accumulated variance. These EOF are represented by a series that comprises a number of coefficients, or weights, that assign to each original series the relative value of this component. By reconstructing the series of these

coefficients of EOF it was possible to select the synoptic patterns that have the greatest influence on the generation of an ECD.

Table II shows the synoptic patterns through the reconstruction of the series of the coefficients for the first three EOF. It may be observed that patterns of GWL are equal in the three EOF, differing only in the value of the coefficient (in brackets). These five synoptic patterns are therefore the ones that contribute most to the occurrence of an ECD.

Table II. The synoptic patterns selected through the reconstruction of the series of the coefficients (in brackets, the greatest values) for the first three EOF.

1st EOF	2nd EOF	3rd EOF
GWL15 (3.54)	GWL15 (3.19)	GWL14 (2.83)
GWL23 (3.09)	GWL14 (2.95)	GWL15 (2.74)
GWL22 (2.96)	GWL22 (2.84)	GWL23 (2.67)
GWL14 (2.66)	GWL23 (2.82)	GWL22 (2.45)
GWL12 (2.44)	GWL12 (2.32)	GWL12 (2.02)

Figure 4 shows maps of anomalies in sea level pressure (SLP) for the emphasized synoptic patterns and similar characteristics are observed among them (Fig. 4a to e). These characteristics are some types of weak anticyclone in the Atlantic Ocean and European north, successive losses in central and Western Europe, northerly winds, barometric marsh situations in the Mediterranean area (GWL14), and lows in Lithuania and Estonia which introduces cold air towards the center of Europe.

After the greater synoptic patterns that contribute to the occurrence of ECD had been identified, a trends analysis was carried out to verify the behavior of these situations, by taking into account the results obtained in the analysis of the annual frequency of ECD. The methodology used to calculate the trends analysis was the same as that applied in the analysis of trends of ECD. Table III shows the results of the trends analysis of the synoptic patterns with negative and significant values in all cases ( $p < 0.10$ ). In our study, an average decrease in the absolute frequency of the synoptic situations that influence an ECD of  $-0.10/\text{year}$  was determined.

Table III. The significant positive (negative) trend at the  $p > 0.10$  level from the five synoptic patterns classified for the first three EOF.

GWL Pat. Trend (significant p)	
GWL12	N (-0.10)
GWL14	N (-0.06)
GWL15	N (-0.01)
GWL22	N (-0.01)
GWL23	N (-0.09)

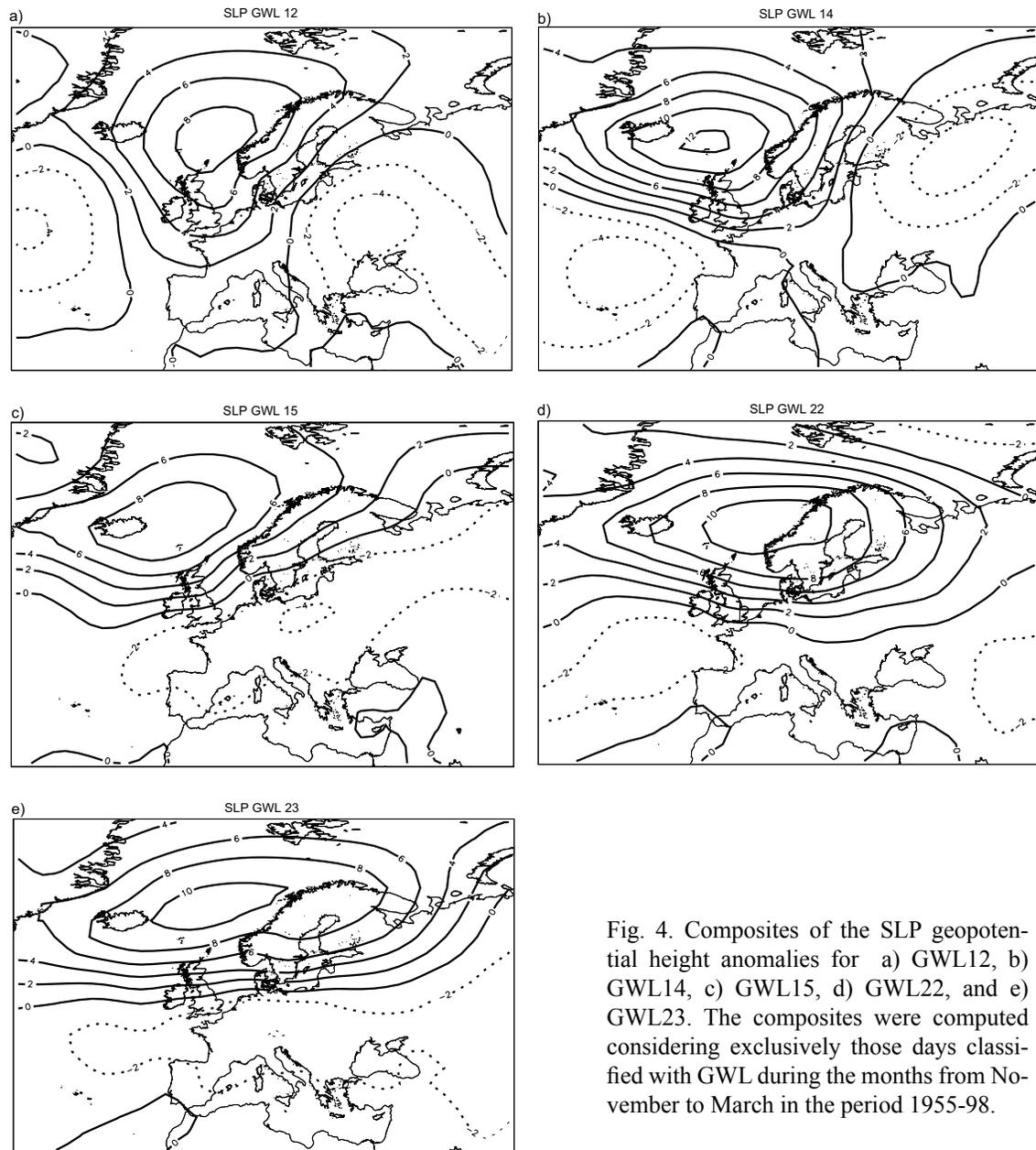


Fig. 4. Composites of the SLP geopotential height anomalies for a) GWL12, b) GWL14, c) GWL15, d) GWL22, and e) GWL23. The composites were computed considering exclusively those days classified with GWL during the months from November to March in the period 1955-98.

#### 4. Discussion and conclusions

In this section, the main results obtained in our study are summarized. One hundred and thirty-five complete and homogenous series of distributed daily minimum temperatures in 34 European countries were considered from 1 January 1955 to 31 December 1998.

A methodology is developed in order to analyze trends in the annual frequency of extremely cold days over Europe. The results obtained showed significant negative trends ( $p < 0.10$ ) at 64.4% of the observatories located in the central and Mediterranean region. In this analysis, temporal evolution of the average minimum temperature and standard deviation were calculated. The results showed significant positive trends ( $p < 0.10$ ) in the average minimum temperature (73.3% of the measuring stations) and significant negative trends in the standard deviation (53.3% of the measuring stations). It is verified that one of the factors in the decrease of ECD in Europe is the change in the minimum temperature average, which in fact, has increased significantly. The trend analysis estimate an increase of 0.5 to 2.0° C in the average minimum temperature of Europe mainly in the western regions.

Regarding the synoptic patterns of greater influence in the generation of an ECD, five GWL situations of greater influence has been identified. In this case, a statistical coefficient has been used to associate synoptic patterns GWL to the ECD; rotated principal components analysis was applied (effectiveness coefficient index) to obtain this five synoptic patterns where the first tree EOF explain 68.8% of the accumulated variance. The classified synoptic patterns from this analysis (RPC) were: GWL15 (3.54), GWL23 (3.09), GWL22 (2.96), GWL14 (2.66) and GWL12 (2.44); in parentheses are the values of the significant coefficient of eigenvalue.

These major situations are characterized by types of weak anticyclone in the Atlantic Ocean and European north, successive lows in central and Western Europe, northerly winds, barometric marsh situations in the Mediterranean area (GWL14), and lows in Lithuania and Estonia which introduces cold air towards the center of Europe; these synoptic patterns lead to extreme cold phenomena.

The results obtained from the trends analysis of the synoptic patterns GWL occurrence, have shown significant negative trends ( $p < 0.10$ ) in the five patterns previously mentioned; these results come in agreement with the decreasing of ECD: the increase of the minimum temperature average and the decreasing of the frequency of those synoptic patterns which generate cold waves, produce the decreasing of ECD over Europe.

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