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THERMAL SEASONALITY OF THE HIGH MOUNTAIN BELTS OF THE PYRENEES

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ABSTRACT The seasonality of Pyrenean temperature fluctuations, varying with both altitude and longitude, is established and three critical isotherms are delineated. Each season is defined by the relationship between mean temperature and a previously established threshold temperature, either 0°C or 7°C. The vegetative period is defined as the period during which the mean temperature is equal to, or higher than, 7°C. Six seasonal periods are defined using similar criteria.

Altitudinal gradients of thermal variables (e.g., mean temperature from December to March, warmest month, annual) and seasonal means (duration, dates, intensities) are presented as regression equations. This allows the extrapolation of such variables to a range of altitudes. No variable showed a significant longitudinal change.

The 0°C isotherm for the period December–March inclusive was calculated to lie at 1,694 m a.s.l. This represents the lower limit of the stable winter snow cover. The 10°C mean isotherm for the warmest month (July) was located at 2,438 m. This represents the potential upper forest limit. Finally, the 0°C mean annual isotherm is at 2,726 m and indicates the lower limit of permafrost and related processes.

RÉSUMÉ *Saisonnalité termique des zones de hautes montagnes dans les Pyrénées.* La saisonnalité des fluctuations de température dans les Pyrénées, variant en fonction de l'altitude et de la longitude, est établie et trois isothermes critiques sont mises en évidence. Chaque saison est définie par la relation entre la température moyenne et un seuil de température déjà établi ou 0°C ou 7°C. La période végétative est donc définie comme la période pendant laquelle la température moyenne est égale ou supérieure à 7°C. Six périodes saisonnières sont définies à l'aide d'un critère similaire.

Les gradients altitudinaux des variables termiques (par exemple, la température moyenne de décembre à mars, pour le mois le plus chaud, pour l'année) et les moyennes saisonnières (durée, dates, intensités) sont présentées sous forme d'équations de régression. Cela permet d'extrapoler ces variables sur une zone altitudinale. Aucune variable n'a exhibé de variation significative en fonction de la longitude.

Les calculs ont déterminé que l'isotherme 0°C pour la péroide décembre–mars inclusivement se trouvait à 1.694 mètres au-dessus du niveau de la mer. Cela représente la limite inférieure de la couverture neigeuse stable en hiver. L'isotherme moyenne 10°C pour le mois le plus chaud (juillet) se situe à 2.438 m, et représente la limite supérieure potentielle de la forêt. Finalement, l'isotherme moyenne annuelle 0°C se situe à 2.726 m et indique la limite inférieure du pergélisol et des processue connexes.

ZUSAMMENFASSUNG *Jahreszeitliche Temperaturgänge in den Hochgebirgsgürteln der Pyrenäen.* Saisonbedingte Temperaturschwankungen in den Pyrenäen werden als Funktion von Höhenlage und geographischer Länge erfaßt und drei kritische Isothermen werden erläutert. Jede Jahreszeit wird durch das Verhältnis von Durchschnittstemperatur zu einer festgelegten Vegetations-Grenztemperatur, entweder 0°C oder 7°C, bestimmt. Dementsprechend wird die Vegetationsdauer als Zeitraum angegeben, in dem die Durchschnittstemperatur 7°C erreicht oder übersteigt. Sechs Jahreszeiten können unter Anwendung ähnlicher Kriterien definiert werden.

Die Höhengradienten von Temperaturvariablen (z.B. Durchschnittstemperatur von Dezember bis März, wärmster Monat, jährlich) und jahreszeitlich bedingte Mittelwerte (Dauer, Datum, Intersität) werden in Näherungsgleichungen erfaßt. Diese lassen eine Extrapolation der Variablen auf unterschiedliche Höhenlagen zu. Keine Variable zeigte eindeutige, der geographischen Länge zuzuschreibende Veränderungen. Es wurde berechnet, daß die 0°C Isotherme unter Einbeziehung des Zeitraumes von Dezember bis März bei einer Höhe von 1.694m ü.M. liegt. Diese Höhenlinie setzt eine untere Grenze für eine dauerhafte Winterschneedecke. Die 10°C Isotherme für den wärmsten Monat (Juli) liegt bei 2.438m. Diese Höhenlinie bestimmt die mögliche obere Waldgrenze. Die 0°C Isotherme des Jahresdurchschnitts liegt bei 2.726m und bildet eine untere Grenze für Permafrost und der damit zusammenhängenden Vorgänge.

RESUMEN *Regimen térmico estacional en la Alta Montaña Pirenaica.* Se establecen las fluctuaciones estacionales de la temperatura, variando con la longitud y la altitud, trazando tres isotermas críticas. Cada estación se define por la relación entre el valor de la temperatura media y la temperatura umbral 0° ó 7°C., previamente establecidos. De esa manera, el periodo vegetativo se define como aquel, durante el cual, la temperatura media es igual o superior a 7°C. Utilizando criterios similares, se distinguen seis periodos estacionales.

Se presentan datos en forma de ecuaciones de regresión, de las variaciones con la altitud de variables térmicas, tales: temperatura media de diciembre a marzo, idem del mes más cálido, media anual, lo mismo que de medias estacionales (duración, fechas e intensidades). Todo ello admite la extrapolación de tales variables según franjas de distinta altitud. Por el contrario, los cambios longitudinales no parecen como significativos.

Le isoterma de 0° del periodo diciembre-marzo incluido, se calculó como stuada a 1.694 m. S/M. Tal cota representaría el límite

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inferior y estable de innivación invernal. La isoterma de 10°C, correspondiente al mes más cálido (julio) se localizó a 2.438 m. S/M., representando al límite superior del bosque potencial. Finalmente, la media anual de 0°, establecida a 2.726 m. S/M., indicaría el límite inferior del "permafrost", —es decir, el suelo permanentemente congelado de año en año—y procesos relacionados.

INTRODUCTION

The macroclimate of the Pyrenees is strongly influenced by its east-west orientation between the Mediterranean Sea and the Atlantic Ocean. The extreme western section falls under the influence of the Atlantic, characterized by cyclonic precipitation and relatively small differences in temperature between summer and winter. Penetration of Atlantic moist air masses is accentuated by the Aquitanian topographic depression along the northwestern section of the range. This Atlantic influence decreases progressively eastward until a typical Mediterranean summer (warm and dry) prevails. The Central Pyrenees, distant from both water bodies, only weakly experience the effects of either. This continentality is enhanced by the local mountain mass (*massenerhebung*) effect (Figure 1).

Several authors (Kerbe, 1974; Creus and Puigdefabregas, 1978; Creus, 1983; Izard *et al.*, 1985; Devau, 1987) have studied these physical factors with particular reference to the low and mid-altitudinal belts. Little work, however, has been carried out on the high mountain belt. This is due, in part, to the scarcity of meteorological stations and the associated difficulty of obtaining conventional statistical information. Consequently, there is no climatic reference framework for the high Pyrenees.

The purpose of this paper is twofold: first, to establish the altitudinal limits of the basic geoecological belts; second, to produce a set of equations for calculation of the seasonal periods for a given altitude and longitude. Temperature criteria have been adopted because the regularity of this type of variable makes them suitable for regression analysis. It is hoped that this study will contribute to the climatology of the Pyrenees at large and also facilitate comparisons with other mountain ranges.

DEFINITIONS OF CLIMATIC VARIABLES

ALTITUDINAL LIMITS

Critical isotherms for biological and geomorphic processes have been used in this work to delimit three main belts in the Pyrenean high mountains. Mean winter air temperature (MWAT), for the months December–March inclusive, was calculated in order to establish the altitude of the 0°C isotherm for that period. Above this elevation it is assumed that most of the winter precipitation is in the form of snow (Rijckborst, 1967; Garcia-Ruiz *et al.*, 1985). The 0°C isotherm is regarded as the approximate lower limit of the high mountain belts, particularly in areas where the timberline has been lowered as a result of human impact. Another critical altitude is delineated by the 10°C mean July air temperature isotherm (MJAT). This was calculated by using the altitudinal gradient of the mean air temperature of the warmest month, usually July. This temperature, or close approximations to it, has been cited by several authors as approximate to the upper forest limit (Williams, 1961; Tranquillini, 1979). The relationship is closest for mid-latitude mountains (Hollermann, 1985). Finally, the variation in altitude of the mean annual air temperature (MAAT) was used to calculate the position of the 0°C MAAT isotherm.

In such way three basic altitude belts have been defined. The 10°C MJAT isotherm coincides with the lower limit of active solifluction (LLAS) in mid-latitude mountains (Hollermann, 1985). Hollermann, however, draws attention to the need for the allowance where the elevation of the timberline has been depressed by human interference. In such a situation, the LLAS may be lower because of the disappearance of a stabilizing forest cover. Thus the 0°C MWAT isotherm in this paper is regarded as the theoretical lower boundary of the LLAS extension. The vertical spacing between the 10°C MJAT and the 0°C MAAT isotherms demarcates a well-defined melt season with a period of strong vegetation growth during the warm months; in-

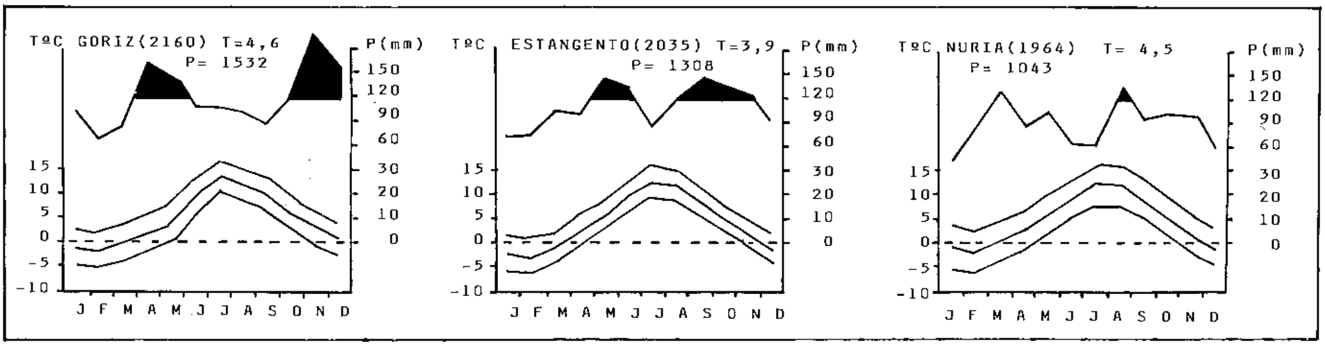

FIGURE 1. Climatic diagrams of representative meteorological stations in the Pyrenees (for locations, see Figure 3).

active solifluction forms predominate in this belt. Above the 0°C MAAT isotherm mean air temperature values fall progressively. Frequent freeze–thaw cycles combine with a short vegetative period so that active solifluction forms and patterned ground are widespread wherever topography and thickness of regolith are suitable. These conclusions are supported by field observations; the paper by Garcia-Ruiz *et al.* (this issue, pp. 201–214) provides more detailed information.

Seasonal Periods

In order to investigate the altitudinal variation in the geomorphically and biologically active seasons along these belts, a functional seasonality was defined (Figure 2). The Vegetative Period (VGP) is considered as the time during which mean air temperature is equal to or above 7°C, which is considered the threshold temperature for most biological processes. In the same way, the Freeze-Thaw Winter (FTW) period is defined as the period during which mean air temperature is equal to or below 0°C. No melting takes place on average during the FTW, but a "freezing" daily freeze–thaw cycle is occurring.

Of course, intermediate seasons occur between the FTW and the VGP. There is a period following the FTW when the mean air temperature rises above 0°C but mean minimum temperature is still below this value. Hence there is a "thawing" daily freeze–thaw cycle on average, and that season is named Freeze-Thaw Spring (FTS) in this work. Afterwards, when the mean minimum temperature of the air is above 0°C and the mean has not yet reached 7°C there are no freeze–thaw cycles on average yet the environment is still not warm enough for full activation of biological processes. This is the Non-Freezing Spring (NFS). In the same manner, but in an inverse order, after the VGP is completed, the Non-Freezing Autumn (NFA) and the Freeze-Thaw Autumn (FTA) periods are defined.

Two remarks are relevant to the definition of these variables. Air temperature does not necessarily correspond with that of the soil. Thus, there cannot be an exact correspondence between the actual seasonal periods and those defined using the available temperature data. Also, a colder period within the FTW could be distinguished with its mean maximum temperature below 0°C. During such a period, designated the Below Freezing Winter (BFW), hypothetically, no melting would occur. Such periods, however, are not detectable from the monthly climatological data.

According to this approach it will be seen that the main climatic variables used are thermal (MAAT, MWAT, MJAT) and seasonal. The latter include the previously defined periods (FTW, FTS, NFS, VGP, NFA, FTA) in days (from 1 to 365), together with their intensity. The intensity is represented by two variables: the thermal summation of daily means and the mean for the entire period. Seasonal variables were calculated by linear interpolation from the mean air temperatures and the mean monthly minima. An attempt has been made to ensure coincidence between some of these variables and those used by other authors (cf., Hollermann, 1985); this was done in order to obtain a common standard for subsequent comparisons.

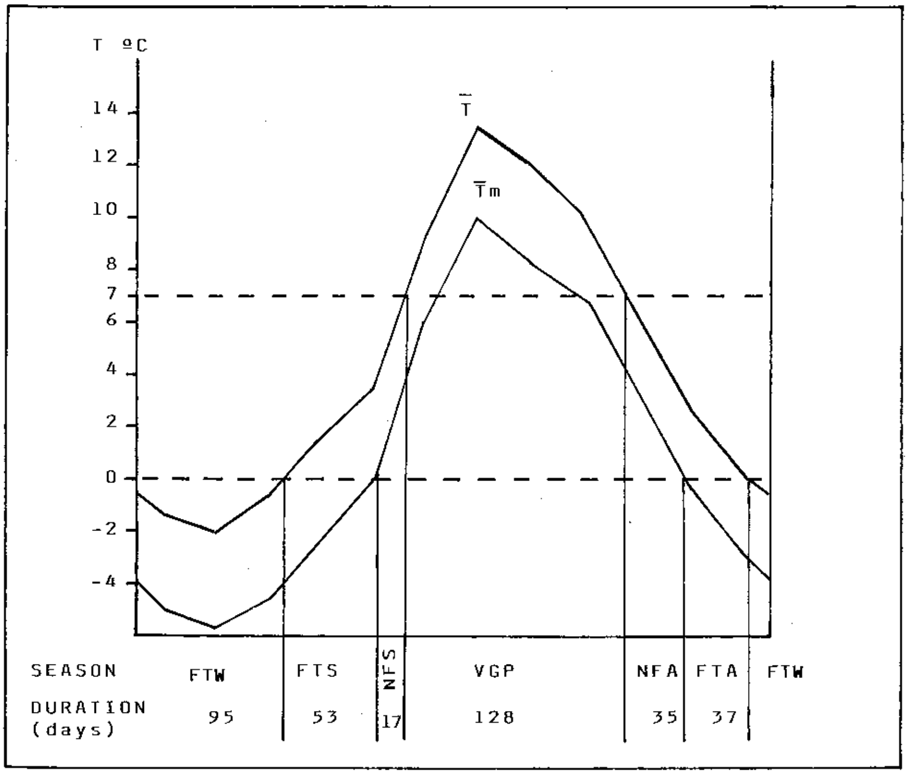

Figure 2. Periods of seasonality at the meteorological station at Goritz.

SPATIAL VARIATION OF CLIMATIC VARIABLES

The dependence of climatic variables on altitude and longitude was established by using a stepwise regression. Sixteen meteorological stations with a 1,545 m range in altitude and 161 minutes (about 250 km) in longitude were chosen; valley bottom stations were eliminated to avoid their depressing effect on thermal gradients (Figure 3). Table 1 shows that not all the stations have data for both thermal and seasonal variables so that two levels of analysis were undertaken.

Altitude was the first variable in the stepwise regression. Table 2 shows that most of the variables have a significant altitudinal relationship; FTA and NFS are the only exceptions. However, residuals from this first step did not show any relationship to longitude. Thus, it was necessary to conclude that there is no linear relationship among these variables with longitude, and residuals from each variable were examined to determine whether or not a pattern other than linear exists. No clear result was obtained, and only the case of the VGP intensity variables (deg-VGP and mat-VGP) will be discussed below. As a result, when periods are defined using temperature criteria, the thermal pattern shows a strong relationship with altitude, but none with longitude.

The altitudinal gradients of the thermal variables were then used to calculate the boundaries of the previously defined belts. Thus, the 0°C MWAT isotherm occurs at 1,694 m, the 10°C MJAT isotherm occurs at 2,438 m, and the 0°C MAAT isotherm at 2,726 m. The highest and lowest boundaries as calculated coincide quite well with the underlying processes (cf., Garcia-Ruiz *et al.*, this issue, pp. 201–214). The 2,438 m altitude for the 10°C MJAT isotherm provides only a rough approximation for upper timberline in the Central Pyrenees. Further east and, especially, westward the timberline appears to fall below 2,438 m, to between 2,000 and 2,200 m. The discordance is related to the available growing degree days for the vegetative period of the forest trees. However, precipitation and snow dynamics are also important factors, but they are not considered further in this paper. In any case, an examination of the residuals of deg-VGP and mat-VGP indicates a more intense vegetative period than statistically expected for those stations located in the central part of the Pyrenean Range; this intensity decreased toward the extremes. The same conclusion is supported by Balcells (1976) in a study on the phenology of Pyrenean amphibians. He established the number of accumulated degree days necessary for completion of the life cycle of *Rana temporaria,* and proved that the cycle was completed earlier at comparable altitudes toward the Central Pyrenees.

Analysis of levels of significance in the starting and ending date of the seasons (Table 2) shows that the precision of prediction decreases through the course of the year. A possible explanation is that part of the heat supply is consumed in evaporation. However, since moisture distribution after winter and spring is rather uniform, the effect of evapotranspiration also should be homogeneous. Yet, by the end of summer the soil is almost dry although there are local differences in soil water distribution. The heat energy consumed by evapotranspiration, therefore, will not be homogeneous so that not all the mountain sites will have the similar responses to seasonal change, even when they are at the same altitude.

Figure 4 shows the variation in seasonal periods according to altitude by plotting the regression equations of limit dates (variables with prefix Beg- or End- in Table 2). The duration of each season should be calculated by using the

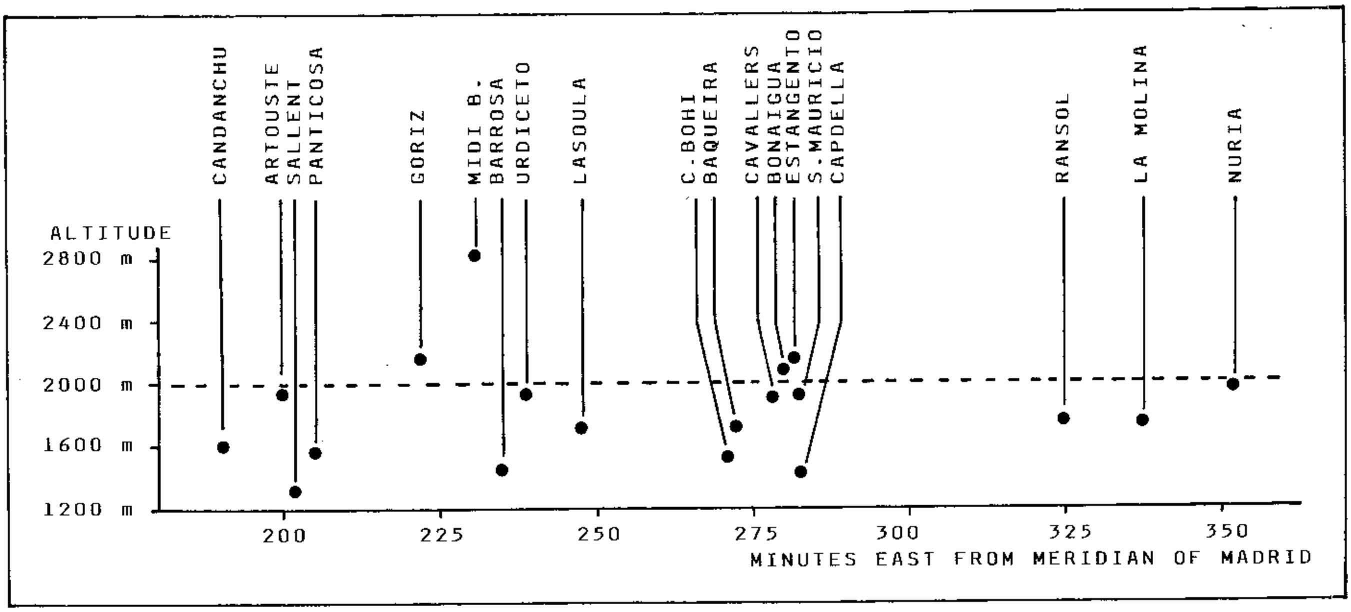

FIGURE 3. The distribution of meteorological stations in the Pyrenees used in this study.

TABLE 1

Values of the climatic variables at meteorological stations in the Pyrenees

VARIABLE STATION	Candanchu	Artouste	Sallent	Panticosa	Goriz	Midi de Bigorre	Urdiceto	Lassoula	Baqueira	Bonaigua	Estangento	San Mauricio	Cavallers	Ransol	La Molina	Nuria
Altitude	1613	1990	1305	1555	2160	2850	1920	1700	1880	2072	2174	1890	1737	1725	1714	1964
Longitude	190	200	201	204	221	230	237	247	278	280	281	281	291	324	337	351
MAAT	5.2	3.7	8.0	7.2	4.5	-1.2	3.6	6.0	5.0	3.2	3.9	4.4	6.6	5.5	5.2	4.5
MWAT	-0.7	-2.0	1.8	1.3	-0.9	-6.9	-2.6	0.1	-0.3	-2.4	-2.8	-2.0	1.9	-0.6	-1.0	-0.8
MJAT	13.9	11.4	16.6	15.6	13.8	7.2	12.8	13.4	13.3	10.4	12.6	13.7	14.6	13.3	13.6	12.4
FTW	86	128			95	203	139	68	77		121		61		97	95
VGP	149	125			128	8	120	167	135		120		147		150	133
FTS	50	35			53	30	38	74	45		31		49		50	49
FTA	33	21			37	23	22	27	54		19		42		36	39
NFS	24	27			17	17	20	11	24		32		28		17	26
NFA	23	29			35	84	26	18	30		42		38		15	23
End-FTW	62	89			83	135	91	37	76		87		75		68	70
End-FTS	112	124			136	165	129	111	121		118		110		118	119
Beg-VGP	137	152			154	195	150	123	146		151		139		136	146
End-VGP	285	276			281	202	269	289	280		270		285		285	278
Beg-FTA	309	306			317	275	296	308	311		313		324		301	302
Beg-FTW	342	327			354	298	318	335	365		332		15		337	341
Deg-VGP	1631	1241			1385	57	1265	1857	1488		1249		1728		167	1360
Mat-VGP	10.9	9.9			10.8	7.1	10.5	11.1	11.0		10.4		11.7		11.2	10.2
Deg-FTW	-109	-229			-111	-1085	-303	-72	-42		-234		-25		-112	-94
Mat-FTW	-1.3	-1.8			-1.2	-5.3	-2.2	-1.0	-0.5		-1.9		-0.4		-1.2	-1.0

ABBREVIATIONS

MAAT: mean annual air temperature (°C)
MWAT: mean winter (December–March) air temperature (°C)
MJAT: mean air temperature of the warmest month (July) (°C)
FTW: freeze–thaw winter
VGP: vegetative period
FTS: freeze–thaw spring
FTA: freeze–thaw autumn
NFS: non-freezing spring
NFA: non-freezing autumn
End: indicates the ending date of season
Beg: indicates the date beginning a season
Deg: indicates the summation of mean daily temperatures along VGP or FTW
Mat: indicates the mean air temperature during VGP or FTW
Altitude is in m a.s.l.
Longitude is in minutes east from meridian of Madrid

specific regression equation when it is significant rather than substracting limit dates from each other.

When different levels of altitude are compared, there is the expected reduction in the length of the VGP with increasing altitude. It is also important to emphasize the role played by the intermediate seasons in relation to this period. Thus, at the 0°C MWAT isotherm the VGP is an extensive season (about 158 days) but the adjacent NFS and NFA periods are short. In such a situation there is a high probability of low, or even freezing, temperatures occurring within the VGP. In contrast, at the 0°C MAAT isotherm there are only 39 days of VGP; the NFS and NFA periods, however, are rather long. It follows, therefore, that in the High Pyrenees the VGP is a short season, but one of greater consistency than its lower altitude equivalents. Balcells (1976) also indicates the occurrence of this phenomenon. Frogs begin to lay eggs with a delay of 5–10 days for every 100 m increase in altitude, with some variation depending on the particular valley, and the regularity of this feature increases with altitude.

CONCLUSIONS

The Pyrenean high mountains can be divided into three basic altitudinal belts according to thermal criteria. These belts have their own geoecological character, being delimited by critical isotherms. The lowest is the 0°C mean

TABLE 2

Regression equations of climatic variables according to altitude (see abbreviations in Table 1)

Dependent variable	Regression equation y = bx + a		Correlation coefficient	Significance level
y	b × 10²	a	r	2α
MAAT	−0.5639	15.3708	−0.9436	0.001
MWAT	−0.5497	9.3119	−0.8781	0.001
MJAT	−0.5550	23.5318	−0.8946	0.001
FTW	9.9704	−90.3438	0.8511	0.001
VGP	−11.4569	351.6200	−0.9460	0.001
FTS	−2.2196	89.6091	−0.6133	0.050
FTA	−1.1602	54.9807	−0.3688	—
NFS	−0.0996	24.0566	−0.0552	—
NFA	4.9660	−64.9741	0.9087	0.001
End-FTW	6.1477	−41.9245	0.8828	0.001
End-FTS	4.2072	40.9050	0.9218	0.001
Beg-VGP	4.9971	49.5031	0.9530	0.001
End-VGP	−6.4599	400.1750	−0.9148	0.001
Beg-FTA	−2.3834	352.6590	−0.6417	0.050
Beg-FTW	−3.8228	414.4190	−0.5922	0.100
Deg-VGP	−132.7880	3977.7000	−0.9512	0.001
Mat-VGP	−0.3188	16.7260	−0.9025	0.001
Deg-FTW	−76.8094	1295.7400	−0.8813	0.001
Mat-FTW	−0.3354	4.9986	−0.8609	0.001

winter air temperature isotherm, calculated to occur at 1,694 m a.s.l. It represents the proposed lower limit for the high mountain belt because there is a stable snow cover above it from December to March. The next isotherm is that of 10°C mean air temperature for the warmest month. This occurs at 2,438 m and is an approximation both for the potential upper timberline and the lower limit of active solifluction. Finally, the 0°C mean annual air temperature isotherm lies at 2,726 m and represents the theoretical lower limit of permanently frozen soil (permafrost).

A pronounced seasonal variation occurs according to altitude, across these belts. At the altitude of the 0°C MWAT isotherm warm periods clearly prevail over cold ones. Therefore, the mean air temperature is above 7°C for about 158 days, while it is below 0°C only for 79 days (accumulating a negative thermal summation of only 5 degree days). This situation reverses at higher elevations. For example, at the altitude of the 0°C MAAT isotherm there are 39 and 181 days of vegetative period and freeze-thaw winter respectively, and the winter period accumulates a negative thermal summation of 798 degree days.

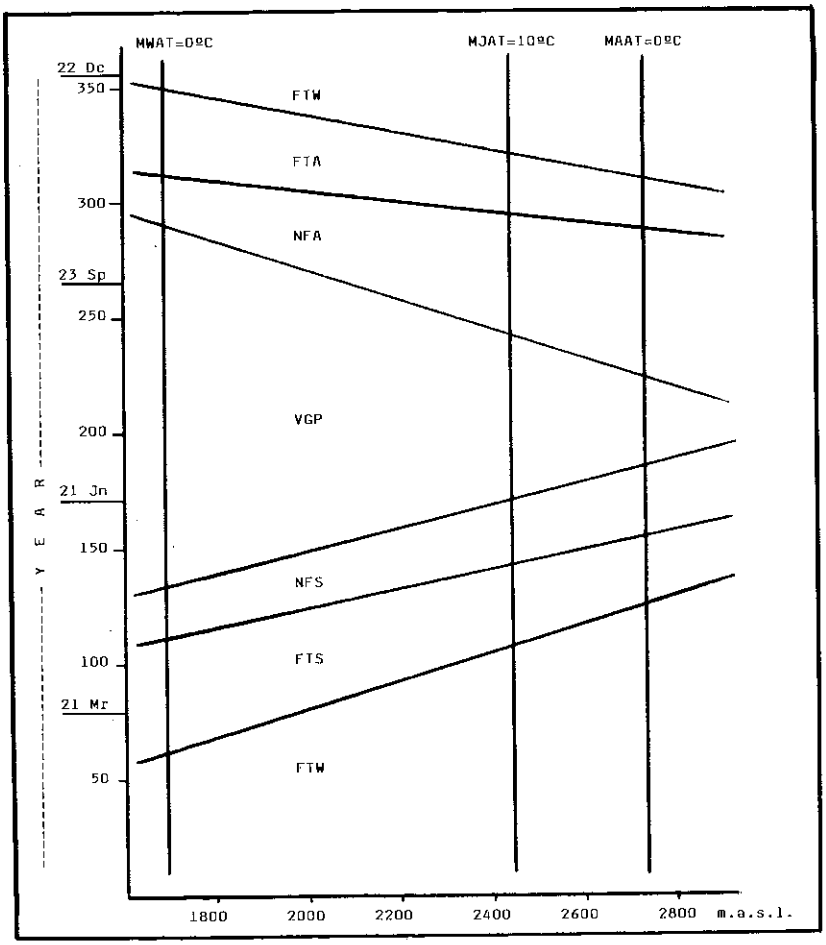

FIGURE 4. Variations of seasonal periods according to altitude.

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