12. IMPACTS ON NATURAL HAZARDS OF CLIMATIC ORIGIN

Gerardo Benito, Jordi Corominas and José Manuel Moreno

Natural disasters are defined as natural phenomena occurring within a limited space and period of time, causing disruption to peoples' lives (Olcina and Ayala-Carcedo 2002). In Spain, from 1971 to 2002, natural disasters caused material damages of over 3,400 million Euros (>110 million Euros per annum, according to the Consortium of Insurance Compensation 2003, figures expressed according to December 31st 2001 values), causing over 1,680 deaths (according to Olcina *et. al.* 2002; including the 794 casualties in the 1962 floods in Catalonia). During the last decade, coinciding with the International Decade for Natural Disaster Reduction (1990-2000), these damages have increased considerably, almost in an exponential manner (see damage statistics in Piserra *et al*., this volume), with material damages of over 515 million Euros and 480 fatalities (according to the Consortium of Insurance Compensation 2003 and Olcina *et al*. 2002, respectively). This upward tendency of damages caused by natural disasters supports the idea that extreme events associated with the effects of climate change are occurring with greater frequency. In this respect, we must disassociate the frequency and magnitude of natural disasters from the socio-economic impact and perception by the media, which, frequently, responds more to the intensive occupation of the territory (exposure to risk of property and people) and the reduced thresholds of social tolerance to natural hazards.

The climate-related natural hazards with the greatest impact in Spain, affecting terrestrial areas, include floods, droughts, landslides, avalanches, lightening, forest fires, gales, blizzards, hail, storms, cold spells, heat waves and subsidence affecting buildings and civil engineering works. The greatest losses of human life in the last five decades have resulted from flooding (1,525 fatalities), cold spells (>40 fatalities), heat waves (>300 fatalities), landslides (>39 fatalities), avalanches (>17 fatalities), wind storms (>15 fatalities), and lightening (>2,100 fatalities). This chapter will deal with the possible impacts of climate change in relation to certain natural disasters, in particular floods, landslides and avalanches, lightening and forest fires.

12. IMPACTS ON NATURAL HAZARDS OF CLIMATIC ORIGIN

A. FLOOD RISK

Gerardo Benito

Contributing authors

M. Barriendos, C. Llasat, M. Machado, V. Thorndycraft

Reviewers

A. Jiménez Álvarez, T. Estrela, A. Díez Herrero

Y. Enzel

ABSTRACT

The characteristics of climate and relief on the Iberian peninsula favour the generation of floods. In Spain, these floods have historically had serious socio-economic impacts, with over 1,525 fatalities in the last five decades. Floods are the consequence of abnormal weather at a limited spatial-temporal scale and, so far, cannot be simulated with the physical models that predict the different scenarios of future climate change. Possible scenarios of the impact of climate change on flood regimes can be diagnosed through the use of millennial scale relationships of flood response to changes in climate, these obtained from geological and documentary data.

In Atlantic basins, the generation, duration and magnitude of floods are very much associated with changes in winter rainfall. Palaeoflood and documentary flood records show greater frequency of ordinary and extraordinary events during the initial and final phases of cold periods such as the Little Ice Age (1550-1850). In the instrumental period (1910 to the present), Atlantic rivers underwent a decline in the frequency of extraordinary floods, although the magnitude of the most catastrophic floods has remained the same, despite the flood control effect of reservoirs. This upward trend of hydrological variability is expected to continue in the forthcoming decades (medium level uncertainty) if we take into account the intensification of the positive phase of the North Atlantic Oscillation (NAO). In the case of rivers Duero and Ebro, peak discharges might be affected by the sudden snowmelt resulting from sudden variations in winter and spring temperatures.

In Mediterranean basins, past flood series indicate that extreme floods occur during periods of high irregularity of both seasonal and annual rainfall. In recent periods (the seventies and eighties) an increase has been observed in intense rainfall episodes, some of which have caused extraordinary floods. These recent floods reached maximum discharges above those recorded in gauging stations in the first half of the 20th Century (prior to the construction of reservoirs). In this sense, existing data indicate (high uncertainty level) that the temperature rise could increase the irregularity of the flood and drought regime and cause the generation of flash floods in Mediterranean basins.

The areas vulnerable to floods are located close to town centres and tourist resorts (particularly in the Mediterranean). There has been a considerable increase in these vulnerable areas as a consequence of increased exposure resulting from the spread of urban areas, new construction works (e.g. roads, railways, canals) and from human activity close to water courses. The socio-economic sectors that could be affected by increased flood hazards are tourism, transport and distribution, and, to a lesser degree, the insurance sector.

The main adaptation options are based on better understanding of the preventive measures, aimed at improving land planning, and on prediction systems currently operating in some basins.

Among the main research needs, we can highlight the reconstruction of past flood series, analysis of instrumental gauging series, and the development of coupled regional climate-hydrology models that can provide reliable scenarios of hydrological extremes, considering the particularities of the Atlantic and Mediterranean basins.

12.A.1. INTRODUCTION

Given the climatic, topographic and geologic conditions of the Iberian Peninsula, flooding episodes and prolonged periods of drought constitute normal hydrological phenomena with which society has to live. Floods are the natural risk with the greatest economic and social impact that can be generated in a short space of time (hours or days), although, if we are dealing solely with economic losses, drought impact in crops and losses in hydroelectric power generation can lead to higher economic costs (Pujadas 2002). Since the floods in Valencia in 1957, there has been, on average, one serious flood every 5 years (CTEI 1983). The 10 most important events with regard to compensation paid out by the Consortium of Insurance Compensation (CCS) have occurred recently, six in the 1980s and four in the 1990s (see see Chapter 15).

The impact of climate change resulting from the greenhouse effect in relation to flooding constitutes one of the main uncertainties of all the reports drafted to date by international bodies. The latest report written by the IPCC (IPCC 2001) indicates that the increases in greenhouse gasses and aerosols in the atmosphere will cause an increase in climatic variability and extreme events in many parts of the world. In Europe, the frequency and severity of floods could increase, especially in the largest river basins in central and Western Europe, due to the concentration of rainfall in winter and spring months (IPCC 1996). Likewise, increased temperatures at the end of spring and during summer could lead to an increase in torrential rainfall of a convective nature in small basins and, therefore, to increased risk of flash flooding, especially in mountain areas and in Mediterranean regions.

The Acacia Report (Parry 2000) indicates that the main risk in southern European countries derives from flash floods caused by torrential rains. This report informs that for the year 2020, abnormally hot summers, like the one that occurred in 2003, will be between four and five times more frequent than at present. In spite of all these conjectures, in reality none of the global or regional atmospheric circulation models are capable of generating reliable scenarios of the changes to be expected in relation to extreme events, and these statements are based on the idea that climate change will alter the whole volume of monthly rainfall in the same proportion, without considering rainfall concentration over short time periods (for example at hourly or daily timescales).

12.A.2. CLIMATIC SENSITIVITY

12.A.2.1. Present climatic sensitivity of floods

The magnitude and frequency of floods vary in different drainage basins, depending on their morphometric variability, network scale and, in particular, the type of circulation patterns generating the floods (Benito *et al.* 1996; 1997; Fig. 12.A.1). During winter, flows from the west and northwest dominate, and are closely related to a high frequency of zonal circulation at high altitude. This situation conditions to a greater degree the areas affected by Atlantic air masses, mainly the rivers Duero and Tagus and basins in Galicia and Cantabria. The latter areas, however, are more influenced by intense rainfall caused by northern advection, which also affects the headwaters of the Ebro and the Duero. The Guadiana and Guadalquivir basins, although affected by these disturbances, register the most noteworthy episodes when circulation acquires an intense southern component, which is usually associated with the presence of low pressure in the Gulf of Cadiz bringing very wet flows from the southwest.

At the end of winter, when the circumpolar vortex becomes weaker and the setting of an undulating circulation pattern occurs (a change on main flow towards south and southwesterly directions takes place, presenting their higher frequency at the end of spring. This type of circulation is responsible for large volumes of rainfall in the East and Southeast of Spain, mainly in the Mediterranean basins of the Júcar, Segura, Ebro and the Eastern Pyrenees and southern rivers. In Mediterranean basins, the advance of air masses from the Atlantic that are relatively colder than the sea can increase instability and facilitate the formation of convective systems. The highest number of cold pools is generated during this season (Llasat and Puigcerver 1990), occurring mainly in the western part of Spain (Llasat 1991) and which can be associated in some cases with moderate rainfall. Some rivers in Spain also present a second flow peak during spring, due to sudden snowmelt that occurs mainly at the riverheads in mountain areas (Fig. 12.A.1).

Summer is characterised by scarce rainfall throughout much of Spain, especially to the south of the Cantabrian Range. In northern Spain (Galicia, Cantabria and the Basque Country), however, on exceptional occasions there can be flooding associated with northern flows and with the presence or lack of cold pools. Intense, short-lived rainfall episodes affect usually the Pyrenees and the Catalonian coast at this time of year, responsible for flash floods in *arroyos* and ephemeral streams. The contribution of these rainfall events to the hydrological budget of these mountain catchments is nevertheless small, due to the short time duration of these rainfall events and small catchment areas. The total rainfall contribution of these summer events to the basins is low, due to their short duration and small area.

Finally, during autumn, there is an increase of the west and northwest circulation, as well as of the southwest type. Situations from the southeast at low atmospheric levels and the southwest at high altitude (associated with the presence of a high altitude trough or cold pool), with advection of very hot and humid air at low levels, are very favourable for the development of organised convective systems, which generate floods (Jansà *et al* 1996). These systems affect mainly the Mediterranean coast, leading to events that generate floods in rivers of the Eastern Pyrenees, the Júcar and Segura basins and also in the Ebro basin and southern rivers. In the case of the Mediterranean rivers that drain the Iberian Range (Júcar, Segura and Turia), the highest peak discharges are recorded during this period. Indeed, the average discharge of these rivers can be multiplied by up to 11,000 times during the largest floods (Masach 1950).

Analysis of the series of annual maximum discharges recorded at gauging stations indicates a decrease in the peaks of ordinary floods over the last 40 years (Fig. 12.A.2). This decrease in peak discharge is partly due to the construction of dams, built mostly between the 1950s and 1960s, currently exceeding one thousand dams (1,133 including weirs), with a storage capacity of over 56,000 hm^3. This flood control effect of reservoirs, however, is insufficient in the case of the largest floods, such as those recorded in Mediterranean basins in 1982 and 1987, or in the Atlantic basins in the year 1979. As can be seen in Figure 12.A.2, these floods presented the highest peak discharges in the systematic gauging records (last 50 years). It is evident that hydraulic infrastructures have modified the natural trends of maximum discharges, which hinders hydroclimatic analysis of instrumental series. In some cases, the series of maximum discharges have been restored to their natural regime to eliminate the noise artificially caused by the inclusion of the reservoirs, although there are very few studies of this type in Spain. We should, therefore, be somewhat cautious when interpreting the tendency of flood discharges recorded in the last 30 years in regulated rivers, in relation to the effects of climate change.

In the Atlantic basins, flood generation, duration and magnitude, are closely related to changes in winter rainfall. Although the relationships between mean discharge, rainfall and peak discharge are not straightforward in these basins, the extremely wet years (Fig. 12.A.3), correspond to years with high peak discharges. The heaviest rainfall in the Atlantic basins occurs when the zonal circulation is displaced towards lower latitudes (35-45º N) and the Occidental Iberian Peninsular Coast is affected by the entry of successive frontal systems, thus generating heavy and persistent rainfall in the basins of the Duero, Tagus, Guadiana and Guadalquivir rivers. A southerly wet air flow associated with an undulating flow circulation pattern is often responsible for intense rainfall over the Guadiana and Guadalquivir basins. In the Mediterranean basins, the relationships between rainfall and floods do not respond to any specific pattern, and climate–flood relationships are, therefore, difficult to establish.

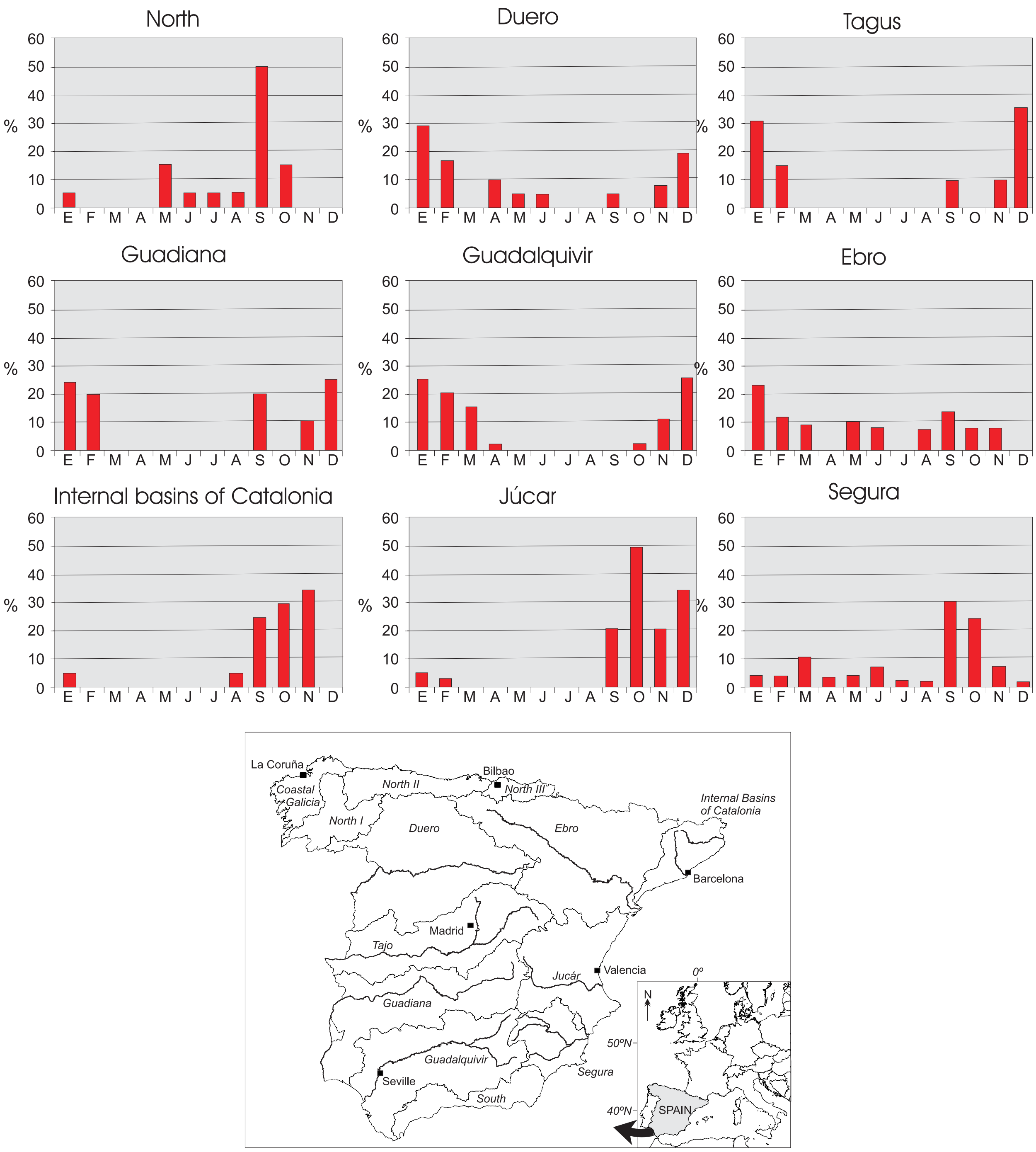

Fig. 12.A.1. *Upper figure: Monthly distribution of historic floods in different river basins (after Benito et al. 1996). Lower figure: Spanish administrative watershed distribution.*

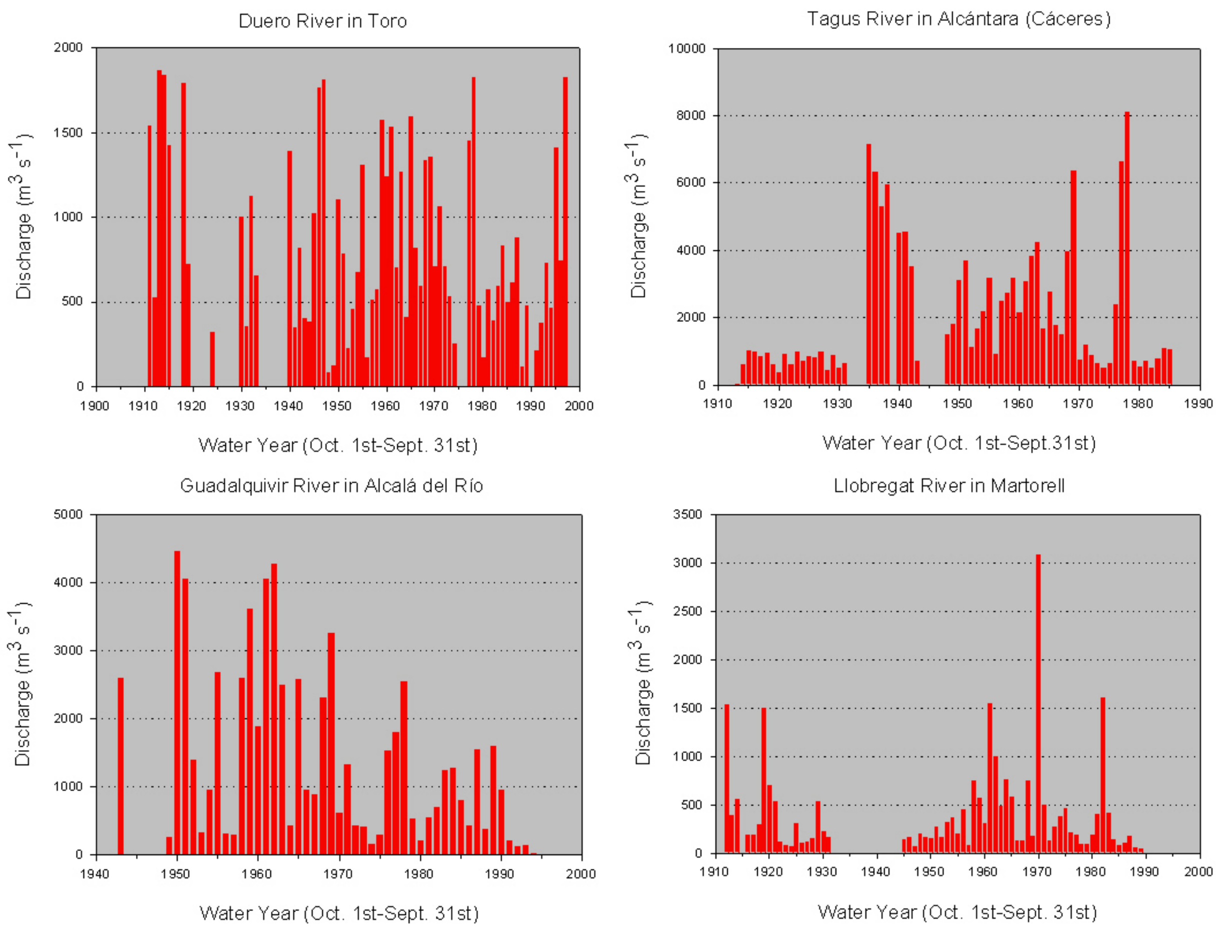

Fig. 12.A.2. *Annual series of flood discharge in the rivers Duero (Toro), Tagus (Alcántara), Guadalquivir (Alcalá del Río) and Llobregat (Martorell).*

12.A.2.2. Effects of climatic variability on hydrological risks based on past series

Alternating warm and cold periods has been described for the last thousand years (e.g. the Medieval Warm Period, around AD 900-1200 and the Little Ice Age, around AD 1550-1850, Flohn 1993). In the same way floods and droughts have also varied, in response to these climate changes. Geologic and documentary records make possible the reconstruction of the frequency and even the magnitude of these extreme events. Geologic records are based on studies of the sediments deposited by rivers during floods (Benito *et al*. 2003a) and they enable us to go back in time up to 10,000 years ago (the Holocene). With regard to documentary records, archives of public and ecclesiastical administrations, at country, regional or local level are used. Three types of registers are obtained from these documentary sources: i) complete and continuous series from the 16th Century till present time; ii) discontinuous series between the 14th and the 15th Century, and iii) occasional events since classical times through the use of Greco-Roman and scattered Christian medieval and Arab documents (Benito *et al*. 2004; Barriendos and Coeur 2004). In all cases, it can be seen that floods are not evenly distributed in time, rather there are periods in which an abnormal concentration of atmospheric circulation patterns generate extreme events and respond to changing climatic situations.

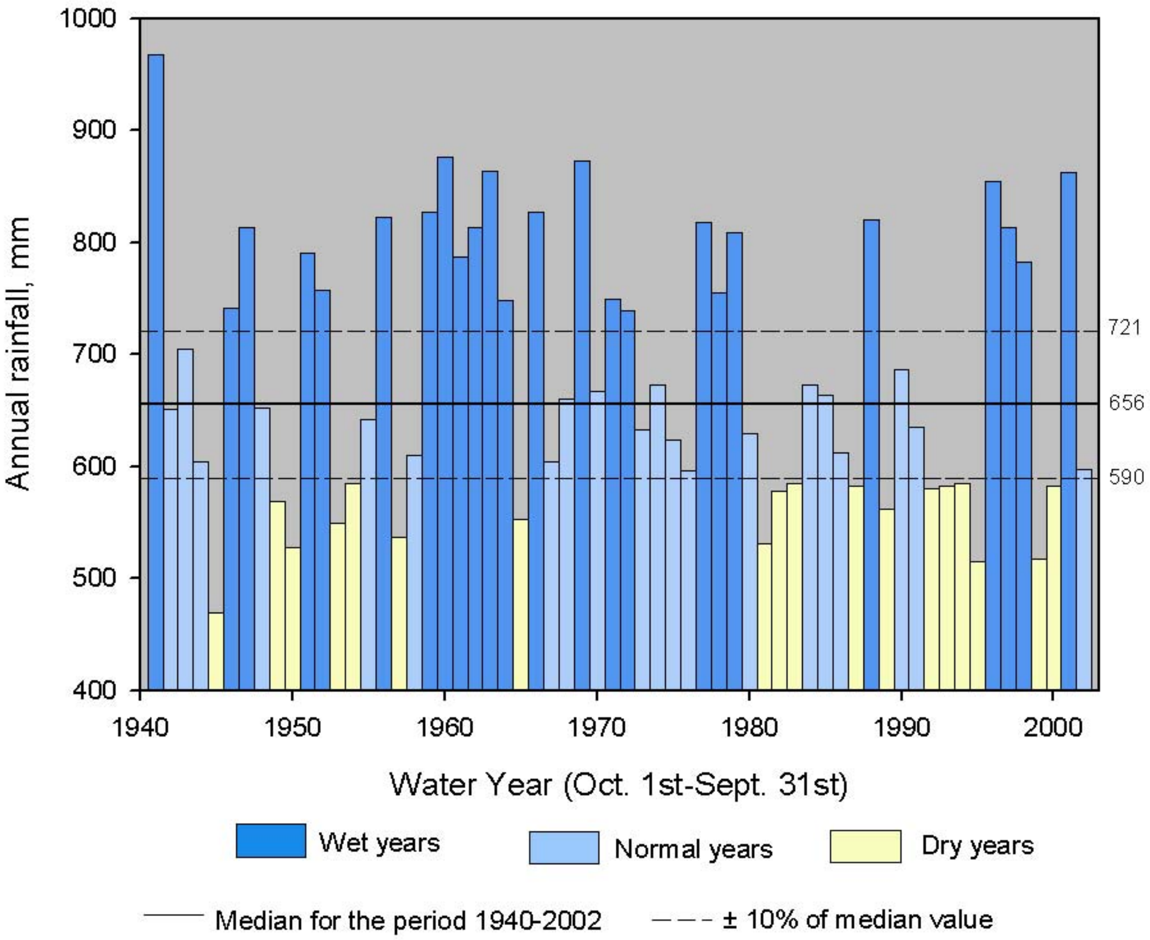

Fig.12.A.3. *Temporal variation in annual rainfall (mm) in mainland Spain and classification of years according to their deviation from the mean (656 mm) for the period 1940/41 - 2002/03 (hydrological year – October to September).*

It is generally assumed that for the past 3,000 years the general circulation of the atmosphere has presented similar characteristics to those at present and it is, therefore, in this period that analysis of climate–flood relationships is of greatest interest. During this period, hydrological response was affected both by climatic variability and human activities, especially during the last 1,700-2,000 years with the establishment of agricultural societies that set in motion intense deforestation processes. It is evident, however, that the generation of floods in medium-sized to large-size basins responds to excessive rainfall in these basins, with a moderate or less important role played by human activity in terms of the infiltration capacity of soils.

Palaeoflood records show an abnormal concentration of extreme events in different basins in the Mediterranean environment from 2860 to 2690 years B.P. ("before present"), that is, between 850 and 550 B.C. (Thorndycraft *et al*. 2004¸ Fig. 12.A.4). This period precedes or is close in time, to a cold and wet phase around 2,650 years ago (van Geel *et al*. 1999), which is associated with variations in the emission of solar radiation. In the River Llobregat, the magnitude of the floods generated in this period practically doubles those recorded in the 20th Century and can only be compared to some observed in the 17th Century (Thorndycraft *et al*. 2004; Fig. 12.A.4).

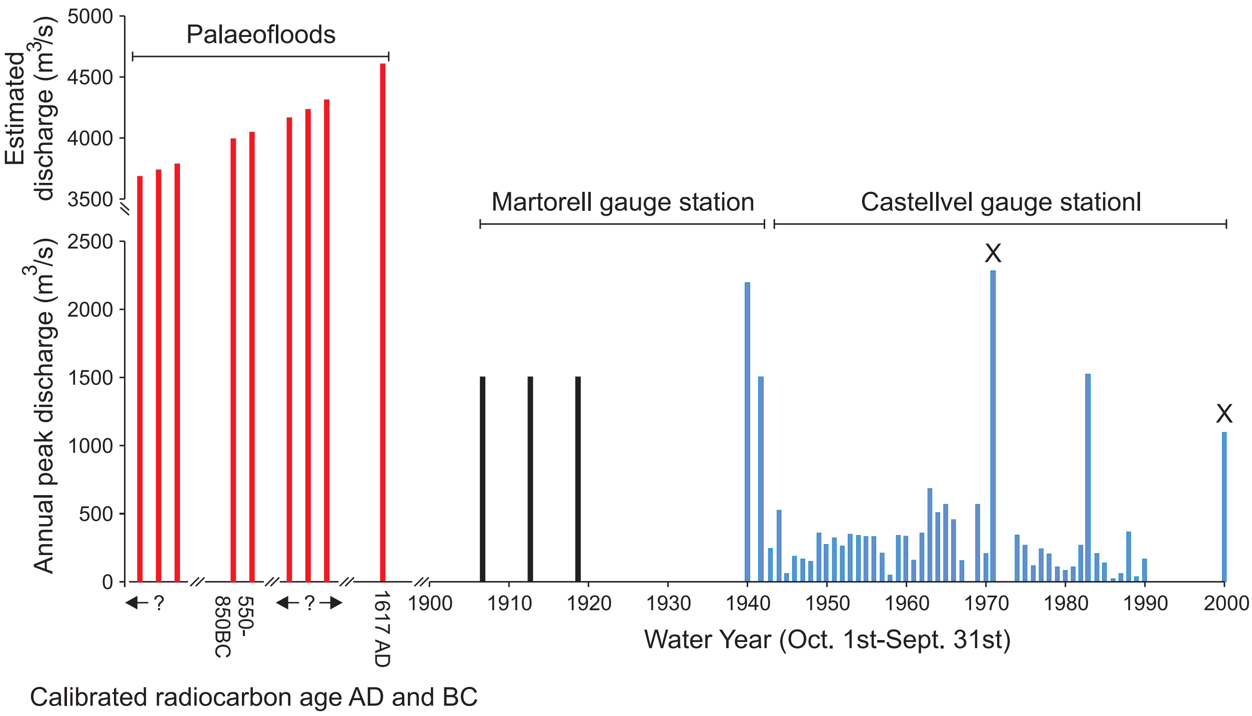

Fig. 12.A.4. *Estimated discharges of the largest floods that occurred in the last 3,000 years in the medium-lower reaches of the river Llobregat using geologic records (red), together with those recorded in gauging stations in Martorell (black) and Castellvell (blue) (modified from Thorndycraft et al. 2004).*

Sediment records of palaeofloods covering the last 2,000 years indicate an abnormally high frequency of large floods during AD 1000-1200, AD 1430-1685 and AD 1730-1810 periods. The resolution of the radiocarbon dating technique for the last 300 years is poor, and this last period could, therefore, reflect dating errors. These periods correlate in time with those obtained from documentary records, which show an increase in the frequency of floods of large magnitude in the Atlantic basins of the Iberian Peninsula during the periods 1150-1290 1590-1610 1730-1760 1780-1810 1870-1900 1930-1950 and 1960-1980 (Benito *et al*. 1996; 2003b; Fig. 12.A.5). The climatic conditions prevailing in these periods with a high frequency of floods are difficult to estimate. In historic climatology, the terms Medieval Warm Period and Little Ice Age have been used to define two secular climatic episodes involving warming and cooling, respectively, which have occurred in the last 1,000 years. However, a number of recent studies show that the start and duration of these periods vary regionally.

The study of floods and climate during the Little Ice Age (LIA) in the Iberian Peninsula has been studied also using historical documentary sources. These studies indicate an intense climatic variability, characterised by periods of increased frequency of torrential rains, reflected in catastrophic flooding, as well as by an increased frequency of prolonged droughts. This abnormal behaviour usually lasted for 30 or 40 years (Fig. 12.A.6), being the periods of 1580-1620 and 1840-1870 the ones where the highest flooding severity was registered (Barriendos and Martín Vide 1998). Regarding droughts, it is more difficult to define distinct periods due to their complex spatial distribution, but they were clearly more frequent in the middle 16^{th} (1540-1570) and 17^{th} centuries (1625-1640), less severs in 1750-1760, as well as between 1810-1830 and 1880-1910 (Barriendos 2002). The existence of periods with flood frequency together with droughts should also be mentioned. To date only one such period is known, between 1760 and 1800, but its effects spread throughout much of Western and Central Europe, with a clear impact on agricultural production and even social crises in different countries (Barriendos and Llasat 2003).

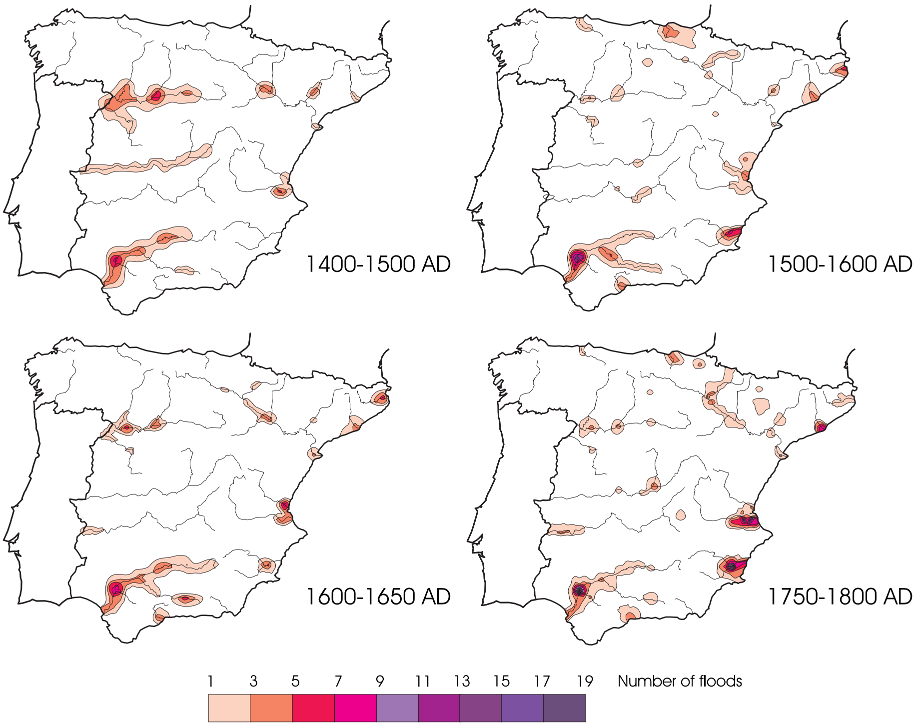

Fig. 12.A.5. *Distribution of historic floods in Spain during different periods (according to Benito et al. 1996).*

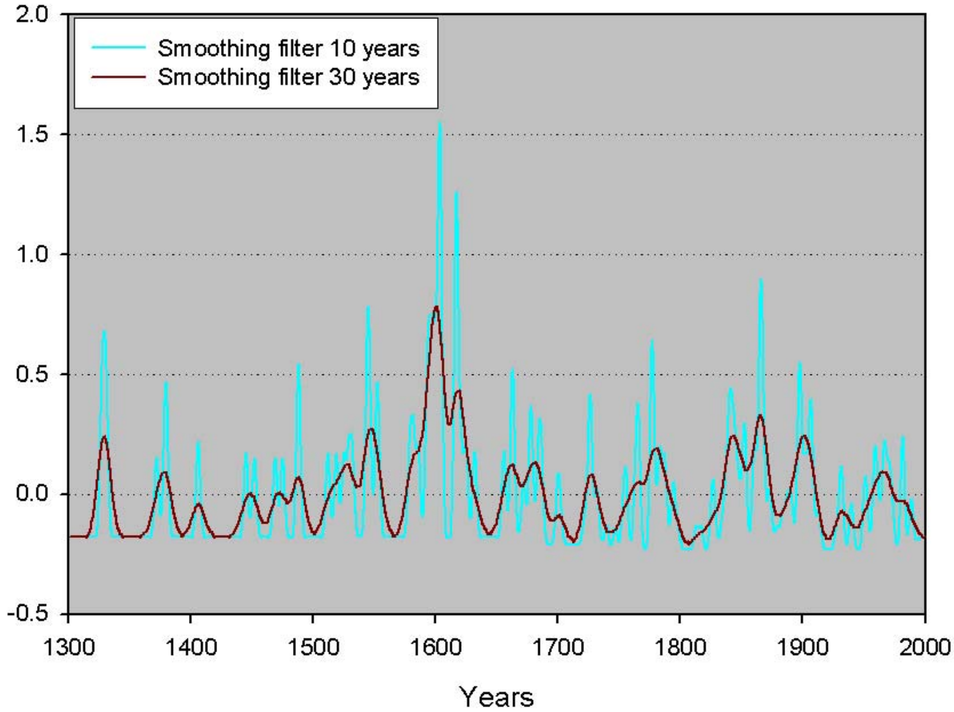

Fig. 12.A.6. *Frequency of extraordinary and catastrophic floods at Catalonia rivers (NE Spain). Values obtained from the application of a smoothed Gaussian weighted filter to times series (10 and 30 years) to the standardised mean (data from M. Barriendos).*

One aspect worth mentioning with regard to the LIA is the identification of extreme hydrological events that have not been recorded during the modern instrumental period (Fig. 12.A.7), but that can be repeated in future, under future climate scenarios and likely to cause unforeseen impacts. This appears to be the case of continuous torrential rains, causing catastrophic flooding in January-February of 1626 1708 1739 1856 1860 1876 1881 1895 and 1897 in the Atlantic basins (Guadalquivir, Guadiana, Tagus, Duero; Benito *et al.* 1996; 2003b) or the event of November 1617 in Mediterranean basins (Barriendos 1995; Fig. 12.A.6). Also identified are exceptional episodes of other phenomena that are more difficult to appreciate with regard to duration and magnitude, such as the continental cold spell from December 1788 to January 1789 (Barriendos *et al*. 2000).

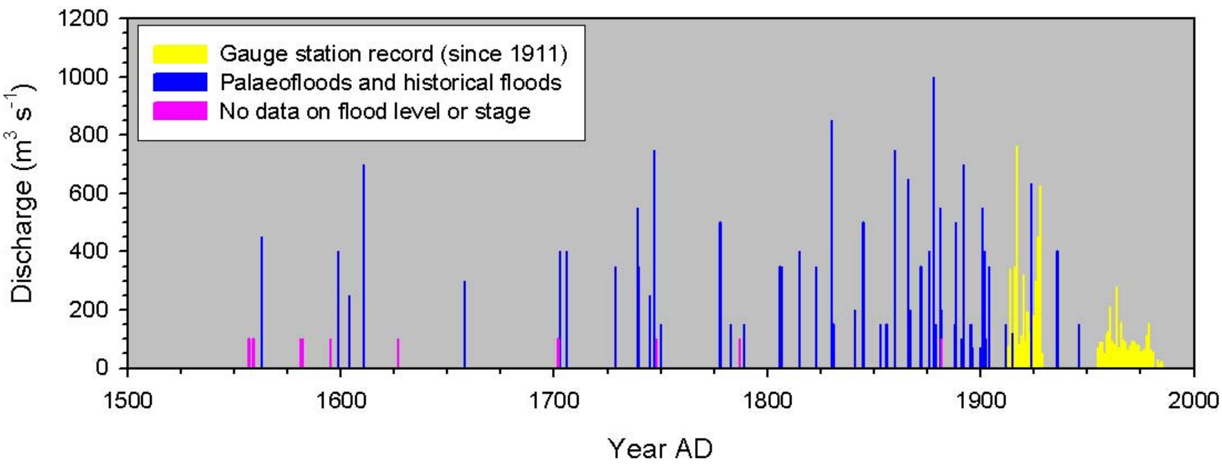

Fig. 12.A.7. *Peak discharges estimated for palaeofloods and documentary floods of the River Tagus at Aranjuez (after Benito et al. 2003), and data recorded at the gauging station (since 1911 in yellow).*

12.A.3. MAIN IMPACTS OF CLIMATE CHANGE

Even minor changes in climate can affect the number of hydrological extremes recorded in a year, their interannual frequency, as well as the duration, volume and peaks of recorded floods. Atmospheric patterns generating floods are complex and it is difficult to establish a direct and clear relationship between climate and floods.

Different indices have been established to define the position of zonal circulation in Europe in general and in Western Europe in particular. Among these indices the North Atlantic Oscillation index (NAO) is one of the most used and is defined as the standardised difference in pressure at sea level between two regional pressure centres: (1) a low pressure centre in Iceland and (2) a high pressure centre in the Azores (Walker and Bliss 1932; van Loon and Rogers 1978). Associations have been observed between these pressure differences and the distribution of winter rainfall and discharge in the Atlantic basins of the Iberian Peninsula (Trigo *et al*. 2003), particularly in the river Guadalquivir (Fig. 12.A.8). Periods with the NAO in a negative phase are associated with humid/wet conditions in the western Mediterranean and northern Africa (Wanner *et al*. 1994) and cold air in northern Europe. A study of the wintertime correlation between the NAO index and total winter precipitation in the different regions of Spain for the period October 1897 to September 1998 shows (Table 12.A.1) that the most sensitive areas to NAO are the basins on the Centre-North (Duero-Tagus) and Centre-South (Guadiana-Guadalquivir) of the Iberian Peninsula. Recent studies have shown that the NAO index decreases during secular maximums of solar activity and increases during periods of decreased solar activity (Kirov and Georgieva 2002).

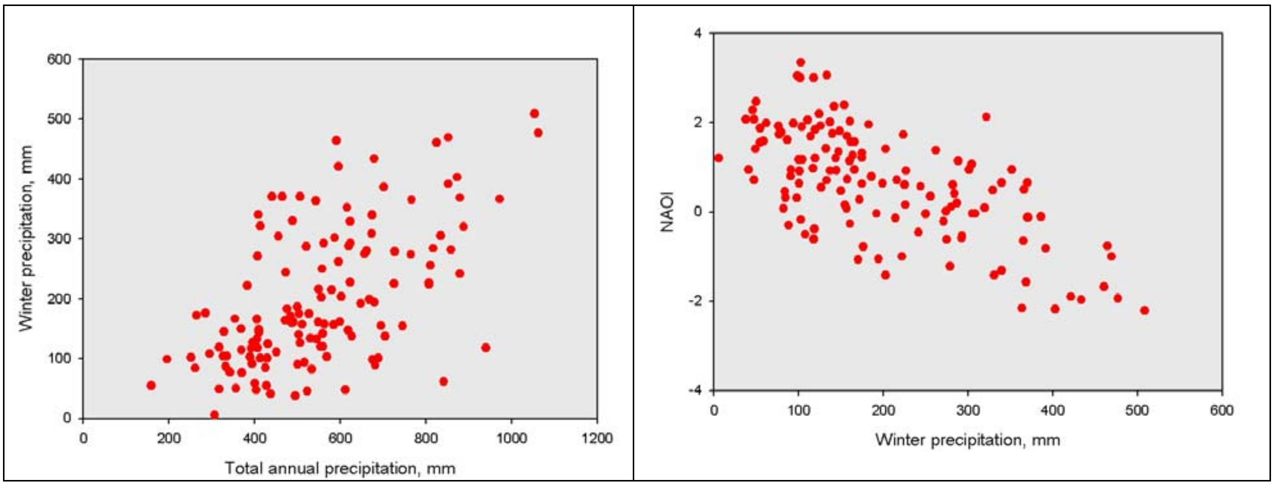

Fig. 12.A.8. *Left: Relationships between total annual rainfall and rainfall during the months of December-February (winter) in Seville (Gaudalquivir basin). Right: Winter precipitation versus North Atlantic Oscillation Index (NAO).*

Table 12.A.1. *Pearson's correlation coefficients between the NAO index (from December to March) and winter total precipitation in different pluviometric regions (after Barrera 2004)*

Region	NAO index (DJFM)
Northwest	-0,43
North	-0,51
Northeast	-0,59
Centre-North	-0,62
Centre-South	-0,72
Levante/East coast	-0,45
Canary Isles	-0,42

Given the complexity involved in the modelling of hydrological extremes through the use of atmospheric general circulation models, the response of floods and droughts can be estimated in scenarios of global change through the establishment of relationships between the NAO, solar activity and the magnitude and frequency of floods. Figure 12.A.9 shows the temporal variation in the NAO index, reconstructed by Luterbacher *et al*. (2002), and floods with discharges of over 3,500 m^3s^{-1} for the historic series of the Guadalquivir in Seville. A strong correlation is generally observed between periods with a higher number of extreme floods and periods of a negative NAO, as expected, given the correlation between rainy years and years with large floods in the Guadalquivir basin. However, negative NAO index values are not always related to the existence of extraordinary floods. The link between the NAO index and extreme floods, can also be detected in certain episodes, obtained through historic documents for the basins of the Tagus (Benito *et al*. 2003b and 2004) and Guadiana (Ortega and Garzón 2004), as well as a correlation between some flood periods and moments of maximum solar activity (Vaquero 2004).

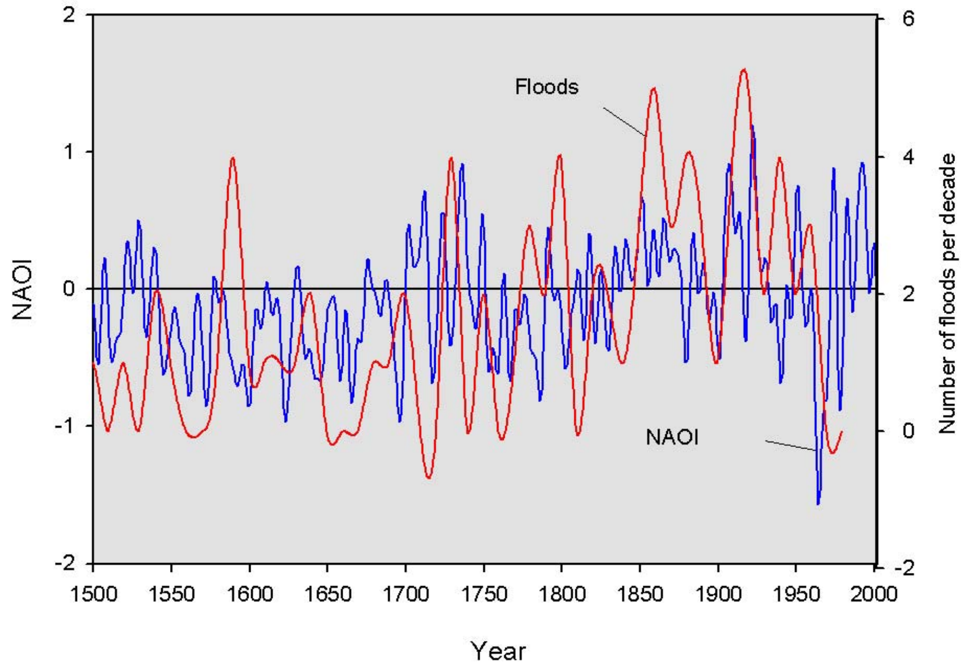

Fig. 12.A.9. *Number of floods with peak discharges over 3,500 m^3s^{-1} and variation in the mean of the NAO index for winter months (Dec-Jan-Feb) since AD 1500, with a smoothing filter for 3-year intervals. NAO index values after Luterbacher et al. (2002).*

Scenarios and predictions of future variations in this index are currently being generated with the use of climate simulation models (GCMs), which can be used to establish the patterns of future flood behaviour in Atlantic rivers. The projection of this index in relation to climate change resulting from the greenhouse effect is unclear and it is not agreed whether the tendency during the positive NAO phase in the 1980s and 1990s, when compared with the one from the 1900-1930 period, will be maintained or will intensify during the first half of the 21st Century. Presently half of the models predict a positive intensification of the index associated with global change, whereas the other half predict that the NAO index will remain at levels comparable to those of the last few decades. In both cases, if the NAO index increases or if it remains at the levels of past decades, we can expect a clear downward tendency of extraordinary floods in the Atlantic basins of the Iberian Peninsula in relation to the frequency patterns existing during the second half of the last century. This projection appears to tally with the GCM, which predict a 10% decrease in rainfall, which could lead to a decrease in the frequency of extreme floods in the basins of the large Atlantic rivers (Table 12.A.2). In the rivers Duero and Ebro, peak discharges could be affected by phenomena of rapid snowmelt as a consequence of sharp temperature rises during winter months and at the start of spring (Table 12.A.2). On the other hand, taking into account the last 400 years (Fig. 12.A.9), a high variability of the NAO is observed, even during episodes of global warming (e.g. the decades following the LIA). This NAO variability may produce an increase in hydrological variability within a scenario of climate change.

Regarding the Mediterranean basins, where the mechanisms established between climate and floods are more complex, no valid indices have been established or models developed to enable predictions to be made within a scenario of climate change. It is assumed that an increase in summer temperatures will likely favour the generation of storms (Table 12.A.2). These local storms may cause flash floods in small basins. In these cases, the temperature differences between the Mediterranean and the continent will favour convective rainfall over mountainous areas, especially in autumn.

In the Mediterranean rivers, palaeoflood and historical flood series indicate that extreme floods have occurred during episodes of irregular rainfall, both at seasonal and annual scales (droughts followed by flooding events; e.g. 2700 years B.P., and the start of the LIA). In recent times, an increase has been observed in the generation of intense rainfall, as occurred in the 1980s in the Mediterranean area of the Iberian Peninsula, which was interpreted as a response to climate change. However, this tendency was reversed in the 1990s, which reveals the complexity involved in the generation of extreme events.

Table 12.A.2. *Qualitative analysis of the response by different basins in Spain to possible impacts of climate change.*

Possible impact of climate change	**Guadalquivir Guadiana Tagus**	**Duero**	**North**	**Ebro**	**Internal basins of Catalonia**	**Levante/South**
Change in zonal circulation (positive NAO)	-Extremes (higher discharges) +Ordinary	-Extremes +Ordinary				
Increased cold pools			+Irregularity of extremes		+ Irregularity of extremes	+ Irregularity of extremes floods/droughts
Generation of convective rainfall	+Flash floods	+Flash floods	+Flash floods	+Flash floods	+Flash floods	+Flash floods
Sharp temperature changes		+Floods caused by the snowmelt		+Floods caused by the snowmelt	+Floods caused by the snowmelt	

12.A.4. MOST VULNERABLE AREAS

Apart from the likely increase in extreme events resulting from climate change, the areas more vulnerable to hydrological risks are those where there is also greater sensitivity or exposure of property. In this sense, vulnerability to floods in Spain should not be seen exclusively in terms of natural hazards related to a change on climate, but also in terms of the uncontrolled housing development of the last few decades. *A priori,* the type of area that is highly sensitive to hydrological extremes involves highly populated areas with recent housing development and with sensitive socio-economic sectors such as tourism and industry. Climate models predictions indicate an intensification of dry periods in summer and whereas the winter total precipitation should remain similar to the present, although concentrated in a shorter number of months. Studies conducted during the last decades indicate that the events with the biggest socio-economic impact are flash floods, which affect medium or small-sized basins. The areas with the highest statistically probability of being affected by flash floods, are located in the Mediterranean coastal belt, inland areas of the Ebro valley and other small catchments in the Iberian Peninsula present these characteristics. Moreover, in the case of the highest climatological and hydrological sensitive area of the Mediterranean coastal belt, with a high population density and high economical dynamics, the vulnerability is higher. (Fig. 12.A.10). In certain cases, with a moderate or low threat of extreme events, there can be a high degree of vulnerability due to greater exposure related to a lower social awareness of the problem. Likewise, torrential areas with frequent extreme events could present a lower degree of vulnerability if the necessary measures have been taken to lessen the risk. In general terms it can be said that, although the number and magnitude of hydrological extremes have decreased in recent decades, when compared to the first half of 20th Century, the estimated global damages were substantially greater (see see Chapter 15) due to the increased vulnerability and exposure of human activities along to the fluvial systems, as a consequence of the spread of urban areas.

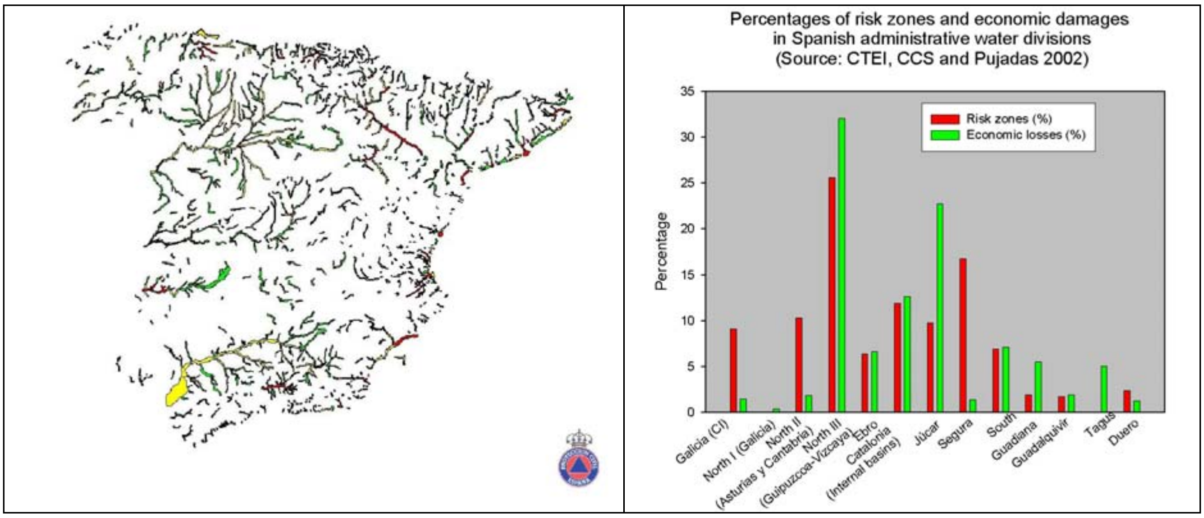

Fig. 12.A.10. *A: Map of conflictive areas due to flooding in Spain (source: Civil Protection). Legend: Red: High risk; GreIn: intermediate risk; Yellow: Low risk. B: Percentage of risk areas and economic losses in different basins (Pujadas 2002). In some basins a high percentage of losses is observed in comparison to the proportion of risk areas, which reflect their high vulnerability to floods.*

12.A.5. MAIN ADAPTATIONAL OPTIONS

The climatic, hydrological, physiographic and socio-economic variability of Spain prevent a generalised application of adaptational options throughout all the regions of the country. The best adaptational option lies in advances in the systems and methodologies of prevention and prediction (warning systems for medium and large-sized basins), and in the planning and management of risk situations. These best practices can be applied at three levels:

At the *technical level*, improvements are needed in the systems of protection of exposed property, based on structural and non-structural measures. Structural measures are generally applied to protect areas with a certain level of human activity, such as housing development, from the effects of floods. Non-structural and preventative measures should be promoted and based on regulations aimed at controlling construction in flood prone areas once the necessary protection measures have been developed. It should be pointed out that structural interventions to water courses (dams, weirs, channels and warning systems in real time) can never guarantee absolute protection.

At the *political and management level*, there should be more legislative control in the improvement of risk planning within town and industrial plans. In this respect, current legislation and sectorial regulation dealing with the hydrologic context and the Spanish Land and Valuation Law (*Ley del Suelo y Valoraciones*) are very ambiguous and ineffective. These laws should contemplate the compulsory application of the directives indicated by risk maps within the different scopes of town and land-use planning. The Water Law should clarify the definition of the river channel and flooded zone according to criteria based on geomorphological, hydrological, historical and ecological elements. The characteristics of the natural drainage network should be maintained, especially with regard to drainage capacity and sediment delivery, thus avoiding interventions that can block flows and promoting the environmental recovery of river areas.

At an *educational level*, there is a need to inform the population of the risk of natural disasters, encouraging prevention and reduced exposure. Subjects related to risk and prevention should be taught at school and information should be given on how to act in the event of a catastrophe. In this respect, previously flooded areas and the associated socio-economic consequences should be considered in the design of any policy or strategy aimed at dealing with floods.

12.A.6. REPERCUSSIONS FOR OTHER SOCIOECONOMIC SECTORS OR AREAS

Insurance sector. In Spain, the insurance cover for catastrophes, in particular for flood damage, is based on the application of a non-differentiated premium for all risks covered and for the whole country, this being handled by the Consortium of Insurance Compensation (CCS). Consequently, increased flood damage would not affect the private insurance sector to any great degree, because all insured parties pay a fixed amount, regardless of their degree of exposure to the risk (Table 12.A.3). In the case of drought damages, the private insurance and reinsurance companies could be affected economically due, fundamentally, to agricultural insurance.

Energy sector. This sector would be affected mainly in situations of prolonged drought, especially in the context of electricity generation (Table 12.A.3). Floods, when they occur, can negatively affect the transport and distribution of energy, whereas they can have a positive effect on the generation of hydroelectric energy, because floods can seasonally increase water resources.

Tourism sector. Flooding and news thereof in national and international media negatively affects the tourism sector (Table 12.A.3). For instance, tourism in the Tena valley (central Pyrenees) after the flood in the Arás stream, in which 87 people were killed, showed a decrease in the years following the catastrophe. Drought conditions have less impact on tourism, which may occasionally, though, be favoured by prolonged hot periods.

Industry and Transport sector. The transport and distribution sector is very sensitive to increases in floods, as these can cause the temporary closure of communication routes (Table 12.A.3). Periods of drought favour the transport and distribution sector but can negatively affect companies that require large amounts of water in their production processes.

Table 12.A.3. *Degree of positive (+) and negative (-) impact in different socio-economic sectors. 0: No impact; 1: low; 2: medium; 3: high*

Sector affected	**Floods**		**Droughts**	
	Increase	Decrease	Increase	Decrease
Insurance	-1	+1	-3	+2
Energy (hydroelectric and biomass)	+2	0	-3	+2
Tourism	-2	+3	-1	0
Industry	-3	0	-1	0
Transport and distribution	-3	+2	+3	+2

12.A.7. MAIN UNCERTAINTIES AND GAPS IN KNOWLEDGE

In Spain, advances are being made in the characterisation of scenarios of average rainfall and/or temperature extremes, which could be valid for the basins in which floods are related to the frequency of zonal circulation in winter months, as is the case of the Atlantic basins. In the case of the Mediterranean basins, however, there is a high degree of uncertainty, due to the fact that it is difficult to model the complex interactions in the Mediterranean environment related to extreme events.

These models require long time series of extreme phenomena in order to explain the response of floods to climate variability. Palaeofloods and documentary data can provide evidence of extreme hydrological events in Spain in relation to climatic variability in the last few millennia. Likewise, the study of rainfall series for the pre-industrial period (prior to the 20th Century) allows the natural component of climatic variability to be separated from the greenhouse effect, since the start of intensive CO_2 emissions.

12.A.8. DETECTING THE CHANGE

Around the world different authors have emphasized the high level of sensitivity of floods to slight climate variations. The detection of minor climate change can be observed in large modifications in the magnitude and frequency of extreme events. If we analyse available time series of floods over the last 2,500 years, the frequency and magnitude of floods occurred mainly at times of climate transition. Noteworthy among these, due to the increase and severity of the flooding, are the periods 1580-1620 and 1840-1870 in the Mediterranean (Barriendos and Martín Vide 1998) and in 1590-1610 1730-1760 1780-1810 1870-1900, in Atlantic basins. In the 20th Century, two periods were observed with increased magnitude and frequency of floods in Atlantic basins, namely 1930-1950 and 1960-1980, with a decrease in the peak discharges of extraordinary floods in the last 25 years. In the Mediterranean, great irregularity was observed in the patterns, with increased cold pools in the 1980s, which generated historic maximum discharges in 1982 and 1987, and a reduction thereof in the 1990s. From 1990 to 2000, there has been an increase in convective rainfall, which causes flash floods in small basins, such as those in Yebra and Almoguera (Guadalajara), Biescas (Huesca), Alicante, and Badajoz, and which had dramatic social consequences (207 fatalities). This change in the pattern of flood magnitude and frequency in Atlantic and Mediterranean basins may be interpreted as a sign of changes in the present climate.

12.A.9. POLICY IMPLICATIONS

Regardless of the severity of future climate change, hydrological extremes (floods and droughts) constitute the most obvious manifestation of climate and hydrology in Spain. Legislation must therefore deal with regard to dealing with land-use planning problems, including taking climate change into account in relation to hydrological risks. However, certain modifications are needed in the legal aspects of natural hazards. The political implications of climate change in natural hazards should involve improved management and legislation in risk-related aspects (Basic Directive of Civil Protection Planning), improved legislation in laws related to land planning (Water Law and Land Law), improvement and application of Watershed Management Plans, and the development of Technical Regulations for Dam and Reservoir Safety. Technical studies developed for the application of legislation should, wherever necessary, analyse the effects of climate change on floods and establish response strategies contemplating new scenarios of extreme events in relation to resources and land management.

In relation to floods, regulations should be revised in order to determine potential flooding zones and risk analysis within the land planning process, taking the floods that have occurred in the past into account. At present, the Land Law (Legislative Royal Decree1/1992) and the Water Law (Law 29/1985, dated August 2nd) and the Regulations on the Hydraulic Public Domain (Royal Decree 849/1986), dated April 11th) are too ambiguous in relation to extraordinary floods.

In the legislative aspect, it should be pointed out that land planning and population protection are currently the responsibility of the Regional Autonomies and therefore, they should take the initiative. So far, the Regional Autonomies have hardly developed any legislation in relation to flood risk, with the exceptions of the Basque Country, Catalonia and Valencia regions. These autonomies have developed their own emergency flood plans, which should subsequently be approved by the Civil Protection Department. In addition, these regions have introduced legislation on land-use planning in flooding zones and drawn up risk maps for their whole territory.

Within the European scope, The European Framework Directive on Water Policy (DIRECTIVE 2000/60/CE, dated October 23rd 2000) attempts to establish a framework for the protection of continental surface waters, transitional waters, coastal waters and groundwater. Recently, various documents on best current practices related to flood risks have been published, which in no case are binding in national regulations. This document makes specific mention of the increased flood risk resulting from climate change and constitutes the first steps towards the development of legislative measures aimed at legally binding Member States. Likewise, financial instruments have been established within the European framework, such as the so-called European Union Solidarity Fund (EUSF) aimed at mitigating economic damages deriving from natural disasters, and which are the result of the devastating floods that took place in August 2002 in Central Europe. These funds are based on the idea of dealing with the foreseeable repetition of catastrophes related to the negative environmental effects of human activities, and in particular, to reduce the impacts of climate change.

12.A.10. MAIN RESEARCH NEEDS

This report highlights the scant knowledge currently available on the effects of climate change on the magnitude and frequency of floods. In this respect, the main research themes to be developed in the future are the following:

- Reconstruction of flood series from the past based on geologic (palaeofloods) and documentary indicators.
- Analysis of the response of floods to climatic variability in the past in different regions of Spain.
- Improved reconstruction of the atmospheric situations associated with extreme events for long time series.
- Development of regional and local atmospheric circulation models for obtaining reliable scenarios of hydrological extremes, taking into consideration the distinct characteristics of the Atlantic and Mediterranean basins.
- Development of coupled climate-hydrology models for simulating extreme events at the basin scale.
- Downscaling methods of AGCM to drainage basin scale.
- Incorporation results of these studies into the analysis of flood frequency for use in land planning and the design of high-risk structures. Introduction of non-stationary data into risk planning, taking into consideration different scenarios of climate change.

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12. IMPACTS ON NATURAL RISKS OF CLIMATIC ORIGIN

B. SLOPES INSTABILITY RISK

Jordi Corominas

Contributing authors

F. J. Ayala, A. Cendrero, J. Chacón, J. R. Díaz de Terán, A. González, J. Moya, J. M. Vilaplana

Reviewers

C. Bonnard

ABSTRACT

Slope instability causes economic losses of hundreds of millions of Euros every year, which fundamentally affect communication infrastructures and, to a lesser degree, population settlements. Whereas the number of deaths caused by landslides has decreased in the last few decades, there has been an increase in those caused by snow avalanches due to the fact that more people frequent the mountains.

Landslides and avalanches are concentrated in the main mountain ranges, especially in the Pyrenees, and the Cantabrian and Betic ranges. However, the banks of the rivers draining the large Tertiary basins are also unstable. Relief, together with the lithological component, account for the geographic distribution of the slope failures, whereas the origin of snow avalanches is due to both the accumulation of snow in the supraforestal and the steep relief. In coastal areas, failures are concentrated on rocky cliffs exposed to marine erosion.

The main triggering mechanisms of landslides are rainfall, melted snow, earthquakes, volcanic eruptions, and undermining by both waves and river erosion. Landslides can also occur spontaneously, for no apparent reason. Climate-related landslides are the most frequent. The relationship between climate and slope instability, however, is a complex one, due to the great variety of failure mechanisms. High-intensity, short-lasting rainfall episodes (over 100 mm in the Cantabrian range and over 180 mm in the Pyrenees) generally cause shallow landslides, debris flow and rockfalls. Prolonged low or moderate-intensity rainfall lasting for several days or weeks reactivate landslides and mudslides. The behaviour of large landslides is very dependent on the geological-geomorphological context thereof, but their reactivation is frequently associated with abnormally rainy seasonal periods. It must be kept in mind, in any case, that anthropic modifications (logging, leaks, overloading) are a frequent cause of new, apparently spontaneous slope faiures.

Two more rainy periods with associated landsliding activity were detected in the last century, in 1905-1930 and 1958-1987, and a relatively calm period from the 30s to the 50s. This apparent cyclicity has also been observed in other European regions, although not simultaneously. With regard to snow avalanches, no change in tendency, frequency or typology has been observed in the last few decades.

Uncertainty related to the increased frequency of torrential rainfall and abnormally rainy episodes prevent from any conclusive statement. Increased torrentiality will cause a greater number of shallow landslides and debris flows, the effects of which could be exacerbated by changes in land use and reduced plant cover. We can consequently expect increased erosion of slopes which will be seen in the degradation of the quality of surface waters, due to increased turbidity and a higher clogging rate in reservoirs.

The decrease in snowfall does not necessarily imply lesser avalanches, because of the increase in melting snow avalanches, although their geographic area can be expected to diminish.

The best adaptational tool involves regional and urban planning that avoids the development in the most susceptible areas. Winter tourism, however, could be negatively affected by the decrease in snowfall.

There is a need for a complete inventory of landslides and better damage assessment, as this is much greater than available figures reflect. There is a need for more in-depth study of the relationships between rainfall events and the different types of landslides.

12.B.1. INTRODUCTION

Slope instability involves the failure and displacement of a mass of rocks or earth down a slope, caused by the action of gravity. It is also generically known as landslide. Unlike other natural hazards, landslides are scattered throughout the territory, especially in mountainous or unpopulated areas. For this reason, there are less economical losses and casualties than in river floods or earthquakes. In any case, in the last 1,000 years, they have caused the death of at least 280,000 people throughout the world (Ayala-Carcedo 1994). The prediction of losses in Spain for the 1986-2016 period was estimated for a hypothesis of medium risk, at over 4,500 million Euros (Ayala-Carcedo *et al*. 1987).

The failure of slopes clearly affects local economy. Villages like Alcoi (Alicante); Castellbisbal, El Papiol qand Sant Sadurní d'Anoia (Barcelona); Arcos de la Frontera and Medina Sidonia (Cadiz); Benamejí (Cordoba); Blanes, Castellfollit de la Roca and L'Estartit (Girona); Albuñuelas, Almuñécar, Izbor, Monachil, and Olivares (Granada); Rosiana (Gran Canaria); Brallans and Tamarite de Litera (Huesca); Abella de la Conca, Cabdella, El Pont de Bar, La Coma, La Guingueta, Puigcercós, Sort-Bressui (Lleida); Argueda, Azagra, Falces, Funes, Lodosa, Peralta, Valtierra, (Navarre), to give a few examples, have suffered varying degrees of damage. Certain movements have also compromised the construction of dams such as Zahara (Cadiz), Arenós (Castellón), Beninar (Granada), Lanuza (Huesca), Giribaile (Jaén), La Viñuela (Malaga), Las Picadas and el Atazar (Madrid), Urdalur (Navarre), Contreras and Cortes de Pallás (Valencia). This required a lot of countermeasures and detailed programmes for monitoring of the movements (Sánchez and Soriano 2001)

The biggest damage, however, has been due to anthropic causes. In particular, as a result of changes in land use (logging, alterations of drainage on slopes) and due to excavations and cutslopes. Thus, on roads, there are frequent both slope and embankment failures, which occasionally isolated valleys and the populations therein, like what occurred in La Massana (Principality of Andorra) in October 1987 which cut the valley off from the Valira del Nord for a month. Although no official figures are available, the costs of slope instability surpass by far hundreds of millions of Euros a year. The winter rains alone in 1995-96 and 1996-97 in Andalucia caused hundreds of cutslopes and embankment failures on the principal roads. In the province of Malaga, for example, at a section of only 10 km between Ardales and Campillo, there were over 100 failures (González *et al*. 1997). The costs and inconvenience caused in the huge traffic jam by the collapse of embankments in March and May 2004, on the A-3 motorway in Perales de Tajuña (Madrid) or on the AP-7 in Viladesens (Girona), respectively, are difficult to estimate.

The increasing use of mountainous areas for tourism and sports activities, has led to an unusual frequentation in clearly unstable areas. New roads and human settlements are spreading towards places in which slides, rockfalls and other type of movements occur relatively frequently, thus increasing the risk for people and facilities. This is why the number of isolated incidents increases year after year (table 12.B.1).

In slope instability, snow avalanches are having an increasing impact. The more frequent practice of winter sports in the last 15 years has led people to frequent the mountains more in Spain's different ranges. To the habitual practice of alpine skiing within the demarcated skiable domains, we must add off-track skiing, mountain and cross-country skiing and winter mountaineering. The intense development of ski resorts leads to the development of high-mountain valleys, changes in land uses and the need to keep roads open throughout the winter. As a consequence, high-mountain areas in Spain traditionally exposed to the risk of avalanches are currently frequented by a large number of skiers, mountaineers, buildings, roads and other infrastructures.

Table 12.B.1. *Landslides in the last 150 years with victims and relevant damages (own compilation based on different sources)*

Site	Date	Type	Consequences
Felanitx (Majorca)	31 March 1844	failure of embankment	414 dead and 200 injured
Azagra (Navarre)	1856	rockfall	11 dead
Azagra (Navarre)	21 July 1874	rockfall	92 dead and 72 houses destroyed
Puigcercós (Lleida)	13 January 1881	slide	Houses destroyed. Village abandoned
Albuñuelas (Granada)	25 December 1884	slide	102 dead and over 500 injured. 463 houses destroyed
Azagra (Navarre)	20 January 1903	rockfall	2 dead
Bono (Lleida)	26 October 1937	Debris avalanche	River dammed
Rocabruna (Girona)	18 October 1940	Debris flow	6 dead
Alcalá de Júcar (Albacete)	1946	rockfall	12 dead and several houses destroyed
Azagra (Navarre)	13 May 1946	rockfall	2 dead
Rosiana (Gran Canaria)	17 February 1956	slide	Bridge and houses destroyed. 250 evacuated
Benamejí (Cordoba)	February 1963	slide	55 houses destroyed and 50 damaged
Senet, Benasque (Huesca),	3 August 1963	debris flow	River dammed. Road affected
Villanueva de San Juan (Seville)	May 1964	Earthflow	Partial obstruction of river. Road closed
Alcoi (Alicante)	December 1964	Rotational slide	Cracking in houses
Pont de Bar (Lleida)	7 November 1982	Slide	Houses destroyed. Village abandoned
Capdella (Lleida)	7 November 1982	Debris flow	3 dead
Cabra del Camp (Tarragona)	September 1987	rockfall	1 dead. Bus hit
Guixers (Lleida)	October 1987	rockfall	2 dead. Vehicle hit
La Massana (Andorra)	October 1987	Slide	2 dead. Vehicle hit
Benamejí (Córdoba)	27 December 1989	Slide	Dozens of houses affected
Camprodón (Girona)	May 1992	Debris flow	2 dead
Collado Escobal (Asturias)	December 1993	Slide – debris flow	3 dead. House destroyed
Sant Corneli (Barcelona)	17 December 1997	Slide	1 seriously injured. Road closed
Ampuero (Cantabria)	10 January 1999	Slide – Earthflow	Several houses destroyed
Montserrat (Barcelona)	10 June 2000	Debris flow and rockfall	Different roads and cable car damaged
Tenerife	31 March 2002	rockfalls	TF-1, TF-2 and TF-5 roads closed
Mogán – Gran Canaria	12 December 2002	rockfall	1 dead –vehicle hit
Cala Sr. Ramon de Palafrugell - Girona	25 August 2003	rockfall	2 dead and 2 injured
Barruera – Vall de Boí-Lleida	20 September 2003	rockfall	2 injured. Road closed.
Buscabrero de Salas (Asturias)	16 November 2003	slide – debris flow	2 dead - house

From 1990 to 1999, 47 people lost their lives in Spain in snow avalanches. The Massifs or ranges with the highest death rates were the Pyrenees, with 41 victims, but there were also victims in Sierra Nevada (1) and in the Cantabrian Range (5). The number of casualties in avalanches has been rising: 25 in the seventies, 38 in the eighties and 47 deaths and 37 injured in the nineties (ICC database; López *et al*. 2000; Rodés 1999). The annual average of fatal victims caused by avalanches since 1970 is between 3 and 4 (an average of 3.5 deaths in the last 30 years). In the decade 1990 – 1999, the annual average increased to 4.7 deaths. This increase is accounted for by the high accident rate in the 1990 – 1991 season which, with 22 deaths, practically represents 50% of all deaths in the decade. One of the most serious accidents occurred in this season, with a very high number of deaths. A group of soldiers doing military ski exercises in El Pico de Paderna (Benasque valley) caused a slab avalanche which killed nine people.

In view of the activity in the mountains in the winter season, in 1990 in the Pyrenees of Catalonia a programme was initiated for the systematic collection of information on all avalanches involving people. The data obtained showed that the lives of a high number of people were endangered by the threat of avalanches, a total of 187 people in 38 accidents during the nineties. Unfortunately 20% of these correspond to deaths or serious injuries (6% deaths and 14% injuries).

12.B.2. SENSITIVITY TO CLIMATE

12.B.2.1. Sensitivity to the present climate

12.B.2.1.1. Triggering factors of slides and avalanches

A trigger is an external stimulus that causes the almost immediate failure by means of the rapid increase in stresses or the reduction of the resistance of the material the slope is composed of. The main mechanisms causing landslides are rain, melting snow, earthquakes, volcanic eruptions, undermining by waves and river erosion. Landslides can also occur spontaneously for no apparent reason.

Rainfall is the most frequent and widespread landslide trigger in Spain. It causes instability due to the infiltration of water into the slope, with the consequent increase of pore water pressures and joints of the terrain, thus reducing its strength. The ratio between the amount of water that has infiltrated and what drains out of the slope controls the changes in groundwater pressure. With rainwater infiltration, water pressure rises to the critical level at which the failure occurs. The rate of infiltration is controlled by the topography, plant cover and the permeability of the materials. Furthermore, slope stability is conditioned by the resistance of the terrain and by the geometry thereof. The critical rainfall needed to cause a failure will vary from one slope to another and establishing regional rainfall thresholds in relation to the failure of slopes therefore involves a noteworthy level of uncertainty. Nevertheless, the thresholds obtained are of inestimable usefulness in risk management.

It must be kept in mind that human action conditions to a great extent the occurrence slope instability events, giving rise to landslides that are apparently spontaneous. Thus, leaks in water supply or drainage systems, alteration in vegetation cover or land use changes (forest logging, new pastures, excavations, mining etc.) lead to modifications in the stress field on slopes. These actions often favour the slope failure under relatively moderate conditions with regard to the triggering factors.

Human influence is also evident in provoking snow avalanches. If we analyse the number of casualties according to types of avalanches, slab ones are those that present the highest risk level for mountaineers. A figure of 44% of the total number of victims corresponds to recent snow avalanches, 38% to slab avalanches, and melted or wet snow avalanches 18%. Recent snow avalanches generally involve large amounts of powder snow unleashed by natural factors which has a heavy impact upon victims. Slab avalanches, on the other hand, involving skiers and mountaineers are usually accidentally caused by the victims themselves, when they are on the slab. In accidents related to melted or wet snow avalanches (flows of dense snow caused by temperature rises) the casualties are usually hit by the flow on the slopes or in the hollows.

12.B.2.1.2. Meteorological conditions and slope stability

In spite of the possible multiple causes of slides, the vast majority of landslides are caused by the rainfall regime on the Iberian Peninsula. All the main movements in Catalonia in the XX century have been the result of rainfall episodes. In the Asturian Coal Basin, an analysis of 213 landslides from 1980 to 1995 (Domínguez 2003) showed that 80% of these were the direct result of rainfall, whereas the rest were due to anthropic causes (works, filtration, mining...). Two very intense rainfall events (over 100 mm in 24 h) have been recorded in Cantabria in 1983 and 1994, that caused numerous landslides throughout the whole region (González-Díez 1995). In a review of 20 landslides throughout Spain, Ferrer and Ayala (1997) observed that failures and reactivation in slides, earthflows and debris flow occurred during abnormally intense rainfall episodes, with values ranging from 15 to 120% of mean annual rainfall. Lamas *et al*. (1997) found that the rainfall that caused landsliding episodes in Andalucia from 1996 to 1997 exceeded the historic maxima of the last 100 years in 30% of the weather stations. The rainfall accumulated from November 1996 to January 1997 was over double the value corresponding to the same seasonal period in all the observatories in the Southeast of Andalucia.

The duration and intensity of rainfall episodes, the materials comprising the slope and the morphology thereof are the main factors conditioning the type of landslide. In the Pyrenees, three situations have been distinguished that cause slope failure or the reactivation of slides (Moya and Corominas 1997; Corominas *et al*. 2002): (a) short duration high-intensity rainfall cause widespread shallow slides, debris flow and rockfalls; (b) rainfall episodes of moderate to low intensity that last for several days or weeks reactivate rotational and translational slides, and mudslides; (c) abnormally rainy seasonal and interannual episodes cause the reactivation of large-scale slides. In particular geological contexts, short duration rainfall can also cause reactivation.

In the Cantabrian Range, a relationship has been established, for the last 100,000 years, between periods of increased rainfall and greater frequency of landslides (González-Díez *et al*. 1996 1999). At a scale of the last few decades, the relationship is well known between intense rainfall episodes (e.g., in August 1983) and slides, in particular shallow ones (Remondo 2001, Remondo *et al*. 2004; Cendrero 2003; Cendrero *et al*. 2004; Remondo *et al*. 2004).

Rockfalls are frequent during rainy periods. These are caused, however, by the effect of freeze-thaw cycles, root penetration or in a spontaneous manner, due to the action of weathering mechanisms. For this reason, the relationship with rainfall is a weak one. Both the steep slopes in valleys shaped by glacial processes, and all other rock cliffs present stress release joints, which are a source of rockfalls. The rate of occurrence of rockfalls appears to have been conditioned more by temperature fluctuations, around º0, than by rainfall regime during the Little Ice Age (Grove 1972).

Shallow slides and rockfalls

On slopes covered with surficial deposits (colluvium) and weathered rocks, intense rainfall of short duration are capable of triggering slides, debris flow and rockfalls. In the Eastern Pyrenees, analysis of the isoyets and their relationship with the distribution of landslides in different recent episodes has allowed the establishment of a rainfall intensity threshold of 180-190 mm in 24-36 h (Gallart and Clotet 1988; Corominas and Moya 1999). In these cases, antecedent rainfall was not necessary. To the contrary, persistent low-intensity or moderate rainfall hardly causes shallow slides at all. This is due to the presence of large interparticular voids in the colluvium and of macropores (root casts, piping, animal burrowing) in weathered claystone formations, which facilitates rapid drainage of infiltrated water from low-intensity and moderate rainfall. Only high-intensity rainfall can generate significant increases in pore water pressure leading to the failure. This threshold is not far off 171 mm in 19 hours, which in June 2000 caused numerous events of debris flow, slides and rockfalls in Montserrat (Marquès *et al*. 2001).

Determined local contexts can modify these relationships. In Cantabria the occurrence of shallow slides has been noted on steep slopes, sculpted in Keuper materials, with rainfall intensities of between 50 and 65 mm/h, well below what was to be expected. The current hypothesis is that during months with greater accumulated rainfall, a strong groundwater flow is generated through existing piping in Keuper clays, rich in gypsum. When rainfall intensity increases, water rapidly concentrates in the pipes and is capable of triggering “argayos” (shallow slides) at the groundwater outlet point.

In road and railway cutslopes, these thresholds can show a substantial downward trend. This is due to the fact that the stability of the cutslopes is also conditioned by geometry (angle and height of the cuslope) and to the excavation procedure which, depending on whether this was done mechanically or with explosives, can affect the quality of the rock. Thus, the rainfall instability threshold for slope and cutslope failures in Asturias has been established at 60 mm in 24 hours (Domínguez *et al*. 1999; Domínguez 2003) and in the Eastern Pyrenees at 110 mm in 24 hours (Moya and Corominas 1997; Moya 2002), well below what has been observed on natural slopes. This lower threshold may also be explained by the inability of the soil to store water in the cut-slopes.

Slides and earthflow

Earthflow and rotational and translational slides, with volumes from a few tens to hundreds of thousands of cubic metres, are usually reactivated during moderately intense episodes, between 40 and 100 mm of rainfall in 24 h, provided that 90 mm or more of rainfall has accumulated in the preceding days (Corominas and Moya 1999). This type of slides occurs in low-permeability clayey and silty-clayey geologic formations. In these formations, the infiltration of rainwater is controlled by the size of the particles and, to a lesser degree, through fissures and by recharge through the more permeable layers, such as interbedded sandstone. The authors quoted have established the following threshold for the Pyrenees:

$$I = 66.1\ D^{-0.59}$$

Where I, is average rainfall intensity in millimetres per day and D is the duration of the storm in days. The expression is valid for rainfall episodes of a duration of more than one week, and which have accumulated at least 90 mm of rain.

Large landslides

Historical records show that most first-time failures in large landslides were caused by non-climatic factors (Corominas 2000). To the contrary, rainfall is the most frequent cause of reactivation of dormant slides and of the acceleration of those that are already active. It is not easy to establish the relationship between rainfall and slide activity; this is due to the fact that we do not yet avail of sufficient knowledge of the hydrological behaviour of large slides. Advances in this field require complex mechanical-hydrological modelling, which needs a great deal of data on the terrain and instrumental ones, which are rarely available. In general, long rainy periods (at seasonal, annual or ten-year scale) appear to have a certain influence in the reactivation of large landslides (figure 12.B.1) although the relationship can often only be established in a qualitative manner.

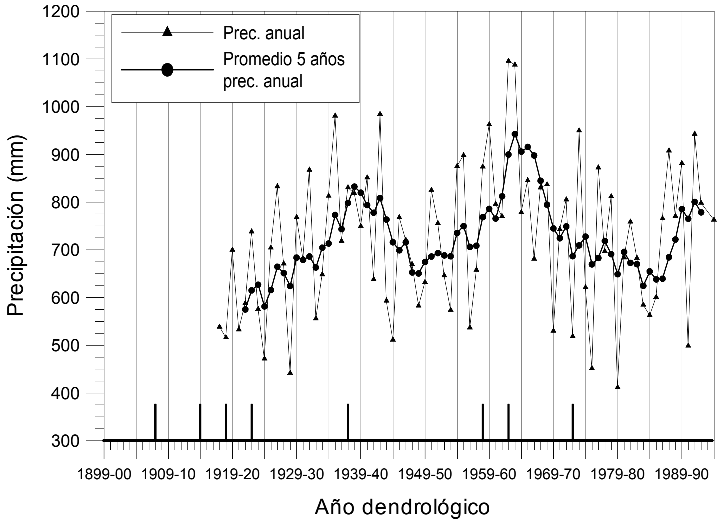

Fig. 12.B.1 *. Reactivation episodes (vertical bars) of the landslide of the Barranco de Boés in Llavorsí (Central Pyrenees) and the relationship between this and mean annual rainfall and that recorded over five years in the Capdella weather station. Reactivation episodes have been identified with the use dendrogeomorphological analysis. (Corominas et al. 2004).*

However, in very particular geomorphological contexts that favour instability, either through extraordinary amounts of groundwater (e.g. contact with karstic massifs) or due to brusque topographic changes (e.g. toe erosion), landslides can be reactivated by very intense, short-lived rainfall episodes. Some cases were observed during the intense rainfall on November 6^{th}-7^{th} 1982 in the Eastern Pyrenees (Corominas and Alonso 1990). Some slides are also in permanent movement, like in Vallcebre (Eastern Pyrenees), with a volume estimated at over $20x10^6$ m^3 (Corominas *et al*. 1999). The presence of cracks, which facilitate rainfall infiltration into the slide, together with toe erosion by a torrent can facilitate the acceleration of the movement in a question of a few hours (figure 12.B.2).

Omission of these aspects could give rise to an erroneous perception of the role of climate in causing slides.

12.B.2.1.3. Instability of slopes in Spain. Spatial distribution

The distribution of slides in Spain is governed by two fundamental elements: relief and the presence of susceptible materials (table 12.B.2). Vegetation and land use also have an effect, but to a lesser degree. Climate, erosion and earthquakes are, in that order, the most frequent triggering mechanisms. The western and central sectors of the Peninsula, which constitute the Hercinian basement of the Plateau, are the least problematic ones. This is due to the resistant characteristics of the materials (plutonic rocks, gneiss, quartzite and schist) and to the gentle morphology (Araña *et al*. 1992). To the contrary, mountain ranges present the highest number of phenomena, favoured by their relatively young relief, high rainfall and the presence of susceptible lithologies. The eminently carbonated nature of outer Ranges of the Plateau makes these areas relatively stable; the clayey and sandy formations, abundant in certain parts of the Cantabrian Range, are highly unstable. In Tertiary basins, it is common to find tabular reliefs resulting from the sub-horizontal arrangement of the strata. The rivers draining these basins excavate big valleys the sides of which are composed of highly unstable silty or clayey materials.

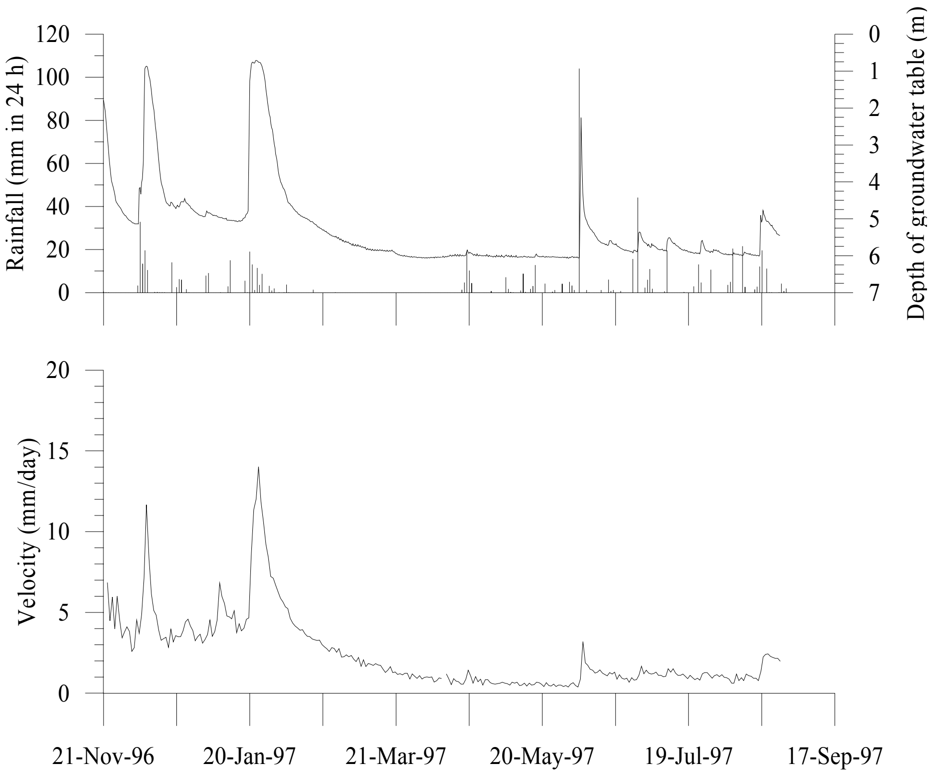

Fig. 12.B.2. *Rainfall episodes and slide response in Vallcebre (Barcelona). Above: rainfall record (vertical bars) and changes in groundwater levels in the borehole S-2. Below: rate of horizontal displacement of the ground surface at the borehole end (Corominas et al. 1999).*

Taking into account the morpholithological context, three main domains of slides can be distinguished: (a) the main mountain ranges, (b) Neogene depressions and (c) coasts with cliffs.

<u>(a) Slope failures in the main mountain ranges</u>. The Pyrenees, the Cantabrian Range, Iberian Range, the Baetic Ranges and the Coastal Ranges of Catalonia concentrate a great deal of these failures, due to the coincidence of a sharp relief, sculpted to a great extent by glacial and/or periglacial (active or relict) morphogenetic systems, the presence of susceptible terrain and a favourable rainfall regime, especially in the Mediterranean area. Two factors of relief that favour instability can be highlighted: the steepness of slopes due to the erosive action of the Pleistocene glaciers and the valley cutting by the present fluvial network, favoured in some cases by mechanisms of orogenic uplift (e.g. valley of the river Guadalfeo, Baetic Ranges). Materials susceptible to sliding are fundamental in slope failures. There are different sensitive lithostratigraphic formations that are often affected by phenomena of instability. A synthesis of the most susceptible lithologies of the Pyrenees can be found in Corominas and Alonso (1984). In this range, the Silurian shales have given rise to large landslides in Pardines and Nevà (Girona), Pont de Bar and Arduix (Lleida), mainly earthflow but also translational slides (Bru *et al*. 1984a; Fleta 1988). Likewise, the marls and gypsum of the Keuper cause rotational slides and eathflows in Pont de Suert. The Mesozoic flysch facies cause complex rotational failures and flows, or slides from the Nogueras area to the Jaca basin. In glacial deposits (tills), there are abundant debris flow and avalanches, as well as rotational slides (Brocal 1984; Bru *et al* 1984b). The instability of these materials have left deep scars in La Guingueta, Artíes, Taüll, Capdella and Bono (Lleida), Senet and Benasque (Huesca). Colluvia cover a wide area of the slopes and give rise to slides and debris flow. Of particular significance were the events in

October 1937 in the upper Segre basin, October 1940 in the Ter basin, November 1982 in the basins of the rivers Llobregat, Segre and Nogueras.

Tabla 12.B.2. *Unstable lithologies in Spain. associated types of failure and geographical distribution (synthesis based on data from Corominas 1985; Corominas 1989; Araña et al. 1992; Corominas 1993).*

Lithology	Age	Type of failure	Area
Black shales	Silurian	Slides, earthflows	Pyrenees
Claystones and gypsum	Keuper	Rotational and translational slides, earthflows	Pyrenees, Coastal Ranges of Catalonia, Cantabrian Range, Iberian Range, Tramuntana Range, Subbaetic System
Red-lilaceous clays, marls and siltstones (Weald Facies)	Lower Cretaceous	Rotational and traslational slides	Cantabrian and Iberian Ranges
Alternancias of blue marls with limestones	Aptian	Rotational and translational slides and earthflow	Iberian Range
Alternances of lutites, red sandstones, lignites (Facies Garum)	Upper Cretaceous	Rotational and translational slides and earthflow	Pyrenees
Marly clays	Lower Eocene – Lutecian	Rotational slides and earthflow	Pre-Pyrenees, Prebaetic Ranges
Marls and alternances of sandstones, marls and limestones (Flysch)	Eocene inferior	Earthflow, slides	Pyrenees, coast of Cantabria
Massive gypsum	Oligocene	Rockfalls and topples	Ebro Basin
Clays, sandy silt	Miocene	Rotational slides and mudslides	Duero, Tajo Basins. Mountain depressions in Vallès-Penedès, Cerdanya, Granada, Hoya de Alcoy
Boulders and gravels with sandy-silty or clayey matrix (glacial till)	Pleistocene	Debris flows and avalanches. Rotational slides	Pyrenees, Cantabrian Range,
Gravels, sand, silt and clays (coluvium)	Pleistocene-Holocene	Slides and debris flow	All the mountain ranges
Basalts	Miocene, Pliocene, Pleistocene	Large slides Rockfalls	Canary Isles, Olot Region

In the Cantabrian Range there is a great abundance of sediment formations with clays with interbedded marls and siltstones from the Weald Facies and the Keuper Facies. These formations produce rotational and translational slides, like in the Pas valley (Fernández-Montero and García Yagüe 1984) and in the Miera, Saja Besaya valleys (García-Yagüe and García-Álvarez 1988; González-Diez *et al*. 1996). The lignite layers present in the Carboniferous formations in the Sil valley also favour large translational slides. Like in the Pyrenees, colluvium cover constitutes the source of shallow slides and debris flow; this became clear in August 1983 in the Basque Country and Cantabria. In the Baetic Ranges, the unstable materials are relatively young. The clays and marls from the Lower-Mid Cretaceous cause mudslides like the in Olivares (Rodríguez-Ortiz and Durán 1988; Chacón and López 1988). In the Baetic domain there are abundant translational and rotational slides and debris flow, especially in phyllites (El Hamdouni 2001; Chacón *et al*. 2003) whereas in the Subbaetic, the predominance of outcrops of Jurassic and Cretaceous marls can be seen in the abundance earthflows (Irigaray and Chacón 1991; Irigaray 1995). In the Iberian range, interbedded marls among the calcareous formations have allowed for the development of large slides and earthflows, like in Puebla de Arenoso (Castellón).

Apart from the presence of a susceptible lithological formation, the structural arrangement thereof also conditions the appearance of slope failures. Even in resistant rocky formations, phenomena of instability occur with certain frequency, these making use of structural weaknesses (bedding planes, joints, faults, schistosity planes). When the latter dip unfavourably in relation to the orientation of the slope, large slides can occur, both in calcareous formations and in granites or sandstone. This is particularly evident in the sedimentary formations in the pre-Pyrenees, Cantabrian Range and Baetic Ranges. This accounts for the large translational slides like the ones in Vallcebre (Corominas *et al*. 1999), those in the Magdalena-Pas valley and Miera in Cantabria (González-Diez 1995; González-Diez *et al*. 1999), those in the Asturian Coal Basin (Menéndez 1994; Domínguez 2003). In the Beatic Ranges, translational slides are associated with metapelites and rotational ones with phyllites and schists (Chacón and Soria 1992; Fernández *et al*. 1997a).

Thus, the steep relief along with the harsh climatic conditions (ice) facilitate the development and opening of cracks which, in turn, facilitate the appearance of rockfalls and topples in these rocky formations. In limestone and Cantabrian quartzite reliefs, the unfavourable orientation of the strata and joint sets has favoured the development of rock avalanches (Jiménez 1997; Menéndez and Marquínez 2002).

Snow avalanches occur in the main mountain ranges. If we treat the number of victims according to mountain ranges, it can be seen that 61% of these have occurred in the Aragón Pyrenees and in Navarre, and 26% in the Pyreness of Catalonia. The accident rate has been doubled in the Pyreness of Catalonia than in Aragón, but in the latter region the accidents have been more serious and have caused more victims. The number of deaths in the Cantabrian Range was 5 (4 in Asturias and 1 in Palencia) and in Sierra Nevada (Granada) there was one death for the same period considered.

(b) Neogene basins. The Duero, Tajo and Guadalquivir valleys, and the intramontaneous basins such as those in Cerdanya, Vallès-Penedès , el Bierzo, Hoya de Alcoy or the Granada basin, are filled with thick detritic formations among which can be found big layers of continental and marine clays and gypsum formations interbedded with marls. The migration of the meanders of the main courses, which causes the erosion of slope foot, is the main cause of translational and rotational slides on the banks of the Duero (Berganza and Modrano 1978; Martínez and García Yagüe 1988; Monterrubio *et al*. 2001), of rockfalls and topples on the banks of the Ebro (Gutiérrez *et al*. 1994) and of the Guadalquivir. The valley cutting by the tributary network destabilises the slopes in the lower basin of the river Llobregat (Bordonau and Vilaplana 1987), in the basin of the river Anoia (Barcelona), in the the Bierzo Depression (Alonso and Lloret 1988) and in the Granada basin (Chacón *et al*. 2001 and 2003). Although these landslides are not usually very large some of them can reach several million cubic metres, like the one in Benamejí (Cordoba) or Hontoria and Tariego de Cerrato (Valladolid).

(c) Coastal Cliffs and Volcanic Islands. The whole Cantabrian coast from the Basque Country to Asturias presents numerous slide phenomena resulting from erosion and undermining of the cliffs. In particular, the outcrops of Eocene flysch in the Basque Country (Salazar and Ortega 1990) and the Bay of Cadiz (Andreu and Martínez-Alegria 1984), the facies Keuper in Asturias (González-Villarías 2001) and the northern coast of Majorca (Ferrer *et al*. 1997; Mateos 2001). The granite and fractured limestone massifs on the Costa Brava produce frequent falls of blocks and rock wedges. In the Canary Isles, erosion and retreat of the stacked lava flows generates imposing cliffs with frequent rockfalls.

The Canary Isles constitute a very particular context. The piling of successive lava flows and pyroclastic materials has built volcanic structures that have produced the largest landslides known in Spain, of around several cubic kilometres, like in the Oratava valley and in Teguise on Tenerife (Bravo 1962; Ancochea *et al*. 1990; Watts and Masson 1995) the one of Golfo on Hierro (Soler 1997), la Palma (Carracedo *et al* 1999) etc. These landslides are prehistoric, and although the most accepted hypotheses for failure indicate an origin associated with the accumulation of volcanic material, dyke intrusions and the associated seismicity, and marine erosion, we cannot rule out the influence of climate as an additional factor (Hürlimann *et al*. 1999) and, indirectly, the drop in sea level associated with glacial episodes (Carracedo *et al* 1999; Ablay and Hürlimann 2000). In Gran Canaria, the surface of failure of the large slides in the Tirajana Depression have made use of the presence of weak layers (tuff, ashes and ash flows) interbedded in the lava flows (Lomoschitz *et al*. 2002).

12.B.2.1.4. Seasonal distribution of the landslides

There is notable heterogeneity in the temporal distribution of slope failures between the Mediterranean environment and the rest of the Peninsula. In the last century, the biggest episodes of slope instability in the Coastal Mountain Ranges of Catalonia, the Eastern Pyrenees and the Iberian Range, were fundamentally concentrated in Autumn –October and November – although there have been sporadic episodes distributed throughout the other seasons. In the Cantabrian Range, in the Betic Ranges and in the Neogene Basins, there is a predominance of failures in winter. An analysis of the instability events in the Asturian Coal Basin over a 15-year period (1980-1995) shows that most of the 213 failures occurred in November, December and April (Domínguez 2003). Rainfall episodes, however, are not unusual in spring-summer, and these cause numerous slides. For instance, the aforementioned one in August 1983 was probably the one that caused most slides in the last few decades in Cantabria and the Basque Country (Remondo *et al*. 2004). On the Canary Isles, slides and rockfalls are mostly concentrated in the winter months.

12.B.2.1.5. Changes in slope failure frequency and recent reactivation

The last few decades of the last century were particularly active with regard to the occurrence of new breakages and reactivation episodes. In the central and eastern Pyrenees, the reactivation of medium and large-sized slides and earthflows (figure 12.B.3) has increased. Observing the reactivation records obtained with the use of dendrogeomorphological techniques, covering the whole of last century, one can see a certain cyclicity with the presence of two wet periods of greater activity: 1905-1930 and 1958-1987. There was a relatively quite period from the 30s to the 50s, and in the last third of the last century, an increase in activity was also observed in regions of Europe, although this did not occur simultaneously (Eisbacher and Clague 1984; Brunsden and Ibsen 1994; Janbu *et al*. 1995; Noverraz *et al* 1998).

In any case, it should be remembered that anthropic disturbances can produce significant changes in the frequency of the slope failures. Analyses carried out in the Cantabria area (Remondo 2001; Remondo *et al*. 2004; Cendrero 2003; Cendrero *et al*. 2004) have shown that the frequency of slides and the volume moved by these was multiplied practically by ten from 1954 to 1997, but it has not been possible to correlate this notable increase with comparable increases in total rainfall, number of storms or annual number of rainy days above certain thresholds, which show no significant changes. On the other hand, there does appear to be a relationship between the degree of human intervention in the territory, through very different actions which, in turn, are related to economic activity as a whole. What this seems to indicate is that human intervention modifies the sensitivity of the surface layer to the action of the main activating agent, rainfall, thus greatly reducing resistance to failure and, therefore, the rainfall threshold needed to provoke slides.

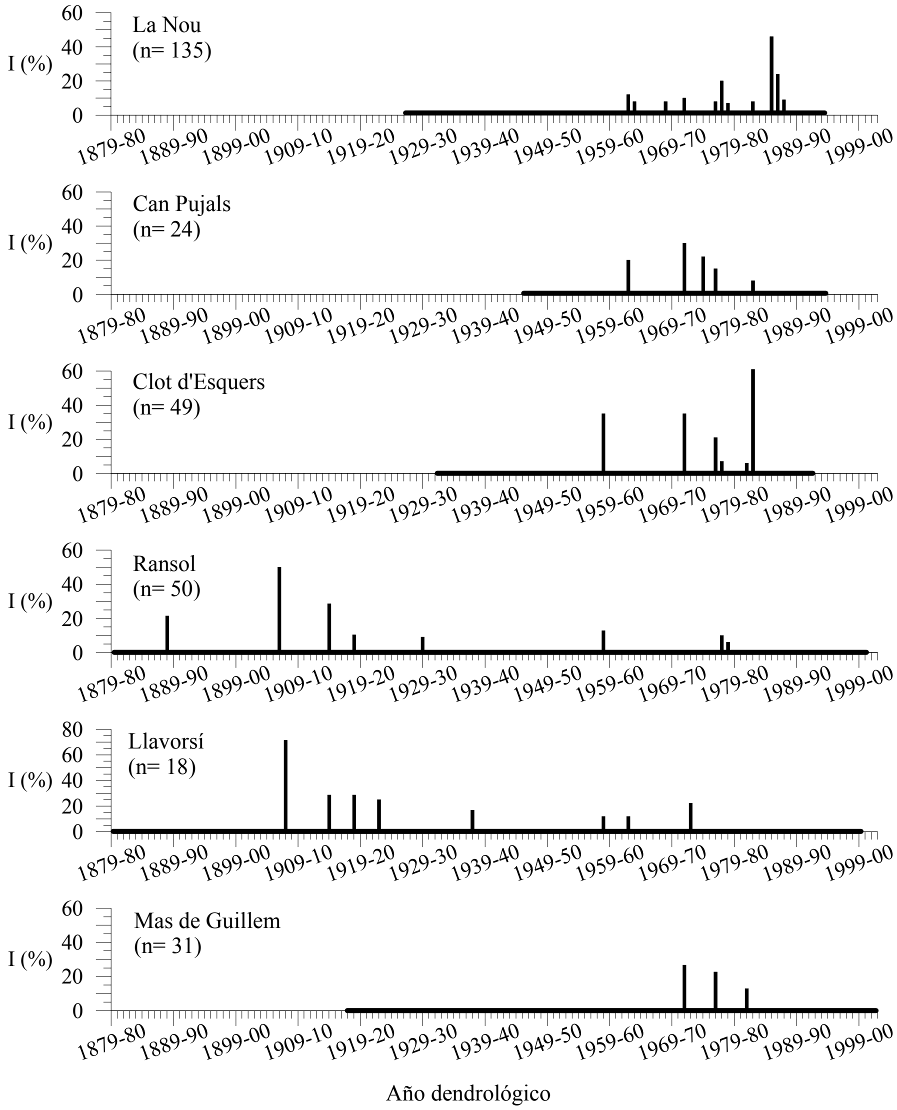

Fig. 12.B.3. *Reactivation events, shown by the vertical bars, deduced from the dendrogeomorphological analysis of six movements distributed throughout the Eastern Pyrenees. I: activity index (percentage of trees sampled presenting response); n: number of trees sampled: the lower thick line indicates the period covered with the sampled trees (Corominas et al. 2004).*

Few data are available in Spain referring to time series that directly inform us of the activity of snow avalanches. In Catalonia, the region where first started the systematic collection on snow avalanches and their hazard (Vilaplana and Martínez 1996), the data collected by ICC (Catalonian Cartographic Institute) provide some idea of the trend. If we consider the climatic factors conditioning the snow layer (temperature and rainfall during the winter season), the thermopluviometric interpretation indicates that between the 1977-78 (starting date of the snow meteorological series in the Catalan Pyrenees) and the 1986-87 seasons, a balance can be seen in the annual mean temperature and rainfall values in relation to the mean values of the series with some deviation towards colder values. To the contrary, more unbalanced values can be appreciated between the 1987-88 and 2001-2002 seasons, with a tendency to deviate towards warmer values (between 0.5 and 2.5ºC in relation to the average), drier winters alternating with warmer ones.

The ICC database contains a snow meteorological series for the last 25 years. The currently available information on avalanches is very fragmented, and it is therefore difficult to reach conclusions. For the last few years of the information series, this is more accurate, but it covers a non-representative period. In spite of the fact that in recent years there has been more snowfall in spring, no relationship can be established with the activity of avalanches or with the typology of these. In the events of greater magnitude, it cannot be appreciated that snow avalanches show any decrease in favour of melting snow avalanches. No appearance of slush flow episodes has been noted, either, and only one of these has been indicated in the Pyrenees of Lleida (Furdada *et al*. 1999).

12.B.2.2. Slope instability in the past. Relationship with climate

12.B.2.2.1. Criteria for establishing the climatic origin of slope instability compared with other causes

The evidence that rainfall is mainly responsible for the failure of many slopes leads us to question whether the different types of slides are associated with specific climatic signature. We can transfer the question to the present: Does the activity of slides at the present time enable us to establish a clear climatic pattern? What other factors could question climatic interpretations in relation to the activity of slides?

The first studies on the theme (Starkel 1985) suggested a synchronicity in glacial advance phases, of solifluction and of a decrease in the upper tree line, coinciding with intense storms, persistent rainfall, rainy years and greater landslide activity. More complete recent studies, however, show that non-climatic factors often blurry climatic signal (Berrisford and Matthews 1997) and that series of landslides often contain movements of non-climatic origin. For this reason, before establishing cause-effect relationships, a careful selection must be made of the group of slides in order to ensure that only climate is responsible for its activity.

There is no specific type of failure or morphological characteristic in an isolated landslide that irrefutably indicates that it was caused by rainfall or climatic phenomena. Both rainfall and earthquakes cause rockfalls, slides, debris and earthflows and large landslides. In the case of recent slides that have occurred in the last few decades or in the last hundred years, it is initially possible to infer the triggering mechanism, by contrasting their age with rainfall, flooding and earthquake records. This is not feasible in the case of old landslides (several hundreds of years). The triggering mechanism, however, can be deduced on occasions from the analysis of landslide populations. The methods used are based on the presence of different concurring features. To this end, a population of contemporary slides of an established age is needed. The main hypothesis consists of grouping the slides in one same time lapse, which indicates that they share the same triggering mechanism. The type of the landslide population can provide some clues for the identification of the causal factor (table 12.B.3). There is a direct relationship between the spatial distribution of landslides and the triggering mechanism: climate, earthquake, fluvial incision (Palmquist and Bible 1980; Crozier 1991). The first two cause failures that are distributed over large areas. Slides caused by an earthquake, however, tend to adjust to an ellipse which main axis is centred on the fault that has caused them, whereas rainfall causes slides distributed more homogeneously throughout the region. Furthermore, the modal size of slides caused by earthquakes is greater than that of those caused by rainfall. Rainfall episodes can cause isolated failures of large landslides but apparently only earthquakes can cause numerous deep slope failures in a simultaneous manner. Landslides caused by fluvial incision are only found at the foot of the slopes, at the valley bottom.

Other types of slope movements, such as rock avalanches are believed to have been caused by earthquakes (Schuster *et al*. 1992). Seismic inference was also obtained from the widespread occurrence of rockfalls (Bull *et al*. 1994). Rockfalls dated with the use of lichenometry were considered to be the result of earthquake events after calibrating the frequency distributions of the size of the lichens with historic seismic activity.

Tabla 12.B.3. *Characteristics of landslides in relation to climate and earthquakes*.

Type of slide	Seismic cause	Climatic cause
Widespread slope failures	Failures appear distributed around the active fault, constructing an ellipse with its main axis parallel to the layout of this. Large modal size	Failures distributed throughout distant regions Modal size less than those caused by earthquakes
Rockfalls	Simultaneous rockfalls	Associated with freeze-thaw cycles Often caused by rainfall Thresholds not logical
Rock avalanches	Clustering of rock avalanches	Rarely due to climatic causes
Debris flow and shallow slides	Possible if there is a high water content on the slope	Very intense short-lived storms
Earthflow	Frequent during earthquakes	Moderate intensity and long duration to reactivate dormant movements Little rainfall for active movements
Rotational and translational slides	Triggered by earthquakes, usually some days after the event	Moderate intensity and long duration to reactivate latent movements
Large landslides	Clustering of first-time failures	Rarely first-time failures Seasonal or annual rainfall reactivates dormant landslides or accelerates active ones. Complex relationship.

The most characteristic movements caused by climatic factors are debris flow and shallow slides, although seismic causes cannot be ruled out in tectonically active regions. Rotational slides and earthflows are caused both by rainfall and by earthquakes. Attention should be paid to flows (earthflow) as these can remain active for centuries. In this case, the concurrence of these with causal mechanisms is simply a coincidence, although transient acceleration can occur. In such a case it is not possible to establish a relation with the triggering mechanisms.

It should be kept in mind that certain periods with a higher frequency of slides are associated with the erosion of coasts or rivers. Climate has a direct control over river flooding and sea storms, but the continued erosion of the base of cliffs and of the deposits accumulated at the foot of these are what control long-term stability.

Multicriteria analysis techniques (analysis of geomorphological features, stratigraphic relationships, absolute and relative dating) were used in the Canary Isles (Lomoschitz and Corominas 1992; Lomoschitz *et al*. 2002) and in the Cantabrian range (González-Díez 1995; González-Díez *et al*. 1996; González-Díez *et al*. 1999; Jiménez 1997) to group landslides into populations of similar ages.

In spite of the fact that climate is not the only cause of slides, it plays an important role in the resistance of the terrain, through control of the water pressures therein, and it therefore has an important influence, albeit indirect, with regard to landslides triggered by other mechanisms.

12.B.2.2.2. Effects of climatic variability on slope instability based on dated slide series

As has already been pointed out, not all prehistoric slides can be attributed to climatic conditioning factors. The huge lateral apertures of volcanic buildings in Gran Canaria (Barranco de Tirajana gorge) or in Tenerife (Oratava and Güimar valleys) are the result of the sliding of gigantic lava stacks and pyroclasts, during the Pliocene and the Pleistocene and their origin is generally attributed to the seismicity associated with volcanic eruptions, to gas pressure and intruded dykes in the volcanic buildings, to marine erosion, etc

In areas of moderate or low seismicity, the activity of big slides is believed to be associated with rainy periods. In the Pas valley, the spatial distribution and typology of slides, classified according to age, has enabled reasonable hypotheses to be established with regard to their climatic or seismic origin or to fluvial or anthropic intervention (González-Díez 1995; González-Díez *et al*. 1996; González-Diez *et al*. 1999). This allowed for the use of dated slides as indicators of past climate (figure 12.B.4).

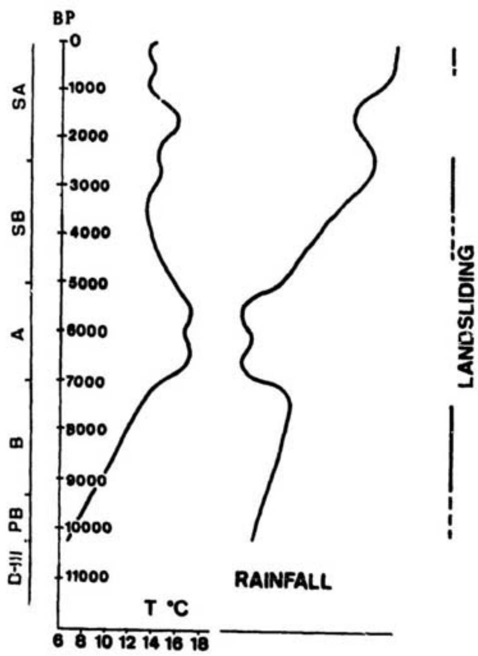

Fig. 12.B.4. *Relationship between rainfall, temperature, and the occurrence of landslides in the Magdalena-Pas Valley, Cantabrian Range (González-Diez et al. 1996)*

Data from the Cantabrian Range (González-Diez *et al*. 1999) indicate that the periods of greater slide activity correspond to the beginning of the last interglacial period (125,000 BP), to the beginning of the glacial thaw, coinciding with a temperature increase (50,000-45,000 BP), in a short interglacial episode (25,000-20,000 BP), coinciding with deglaciation and increased rainfall at the end of the Dryas III (15,000-5,000 BP), coinciding with the Neolithic colonisation and subsequent deforestation and increased rainfall (5,000-3,000 BP), in the second half of the 3,000-200 BP period, especially the XVI-XVIII centuries, a phase in which shipbuilding involved cutting down forests in the region and, lastly, in the XIX century, coinciding with the end of the Little Ice Age and with increased rainfall and human intervention. In the Pyrenees, several phases of this type have also been observed (Moya *et al*. 1997).

12.B.3. FORESEEABLE IMPACTS OF CLIMATE CHANGE

Based on scenarios for the Iberian Peninsula (see Chapter 1), four aspects were considered in relation to the effects of climate change on slope stability: (a) an increase in winter rainfall on the Cantabrian coast and the northern basin of the Duero river (b) a decrease in rainfall in absolute terms and a possible increase in the irregularity of rainfall in the Mediterranean Arch; (c) a moderate rise in sea level; and (d) higher temperatures with the consequent altitudinal displacement of vegetation.

With regard to snow avalanches, the study by Glazovskaya (1998) predicts that snowfall and the activity of avalanches on the Iberian Peninsula will not be subjected to changes in the future, but highlights the need for more accurate studies, in a regional context that is better delimited with regard to this theme.

12.B.3.1. Foreseeable changes in the appearance of new failures according to the typology of the movements

New first-time large failures are not expected, due to the absence of big rainfall episodes and to the fact that a rise in sea level will be a factor that reduces the possibilities of an incision of the fluvial network. Only in the Baetic ranges, torrential flooding could favour new failures, due to slope undermining in slopes made of shales. There is much uncertainty with regard to an increase in torrential rainfall. Christensen and Christensen (2003) predict an increase in the frequency of torrential rains during summer months in Europe, although the results for the Iberian Peninsula are very uncertain. Other autors (see Chapter 1), on the other hand, believe that there will be no significant alteration in the degree of torrentiality of rainfall. In any case, an increase in shallow slides, debris flow and rockfalls due to alterations of anthropic origin and to less protection of slopes by vegetation, which will have more adverse climatic conditions with regard to development and which will be affected increased forest fires. Substitution of plant species favours slope failures, especially in those areas in which the autochthonous vegetation is substituted by plants with shallower roots, which provide poorer retention of the surficial formation. In the Los Serranos (Valencia) region, it has been observed that the rainfall threshold capable of causing failures decreased after several fires (Izquierdo and Abad 1997).

Increased temperature in mountain ranges will favour the increase in rockfalls at higher elevations which, at present, are protected from temperature changes by the layer of snow, practically from December to May. The melting of the permafrost could cause an increase in debris flow. Although no data are available on the distribution of permafrost, the area of this, in the very best of cases, is very limited and restricted to the higher parts of the Pyrenees-Cantabrian Range and of the Baetic ranges. Finally, on rocky coasts, the rise in sea level will favour erosion and failure of cliffs consisting of weak rock formations (flysch, clays and sandstone, lava and pyroclasts, etc.). In the XXI century, however, the latest forecasts reduce this rise to barely a few decimetres (Sánchez-Arcilla *et al*. 2004), which will limit the occurrence of new failures.

For snow avalanches, the report on climate change in Catalonia, drawn up by the *Consell Assessor per al Desenvolupament Sostenible* (advisory council for sustainable development) *of the Generalitat de Catalunya* (Catalonia regional govt.), predicts that a temperature increase will cause the altitudinal displacement of the snow layer in the Pyrenees, which will rise to above 2,000 m and which will show a decrease with regard to total area. We can consequently expect the area exposed to avalanches to decline. The same report warns that, based on certain global studies dealing with rainfall prediction, we can expect a decrease in the number of rainy days at our latitudes, and an increase in global rainfall, which implies increasingly intense events. With regard to the typology of the avalanches, greater frequency of snow melting avalanches is to be expected, and eventually, of slush flow avalanches. In any case, we require many more data on the activity and types of avalanches in all Spanish mountain ranges, in order to make any type of predictions.

12.B.3.2. Changes to be expected in the magnitude and frequency of reactivation episodes, according to the different types of movements

The immediate consequence of greater frequency of intense rainfall will be an increase in shallow slides, debris flow and rockfalls. In the medium-long term, however, the rate of appearance of failures is also limited by the availability of movable material on the slope (Marqués *et al*. 2001). Two high-intensity rainy events very close to each other can have very different results. The first event can transport large amounts colluvium and weathered soils from the more susceptible slopes. The slopes that have been purged will not suffer new failures because of the lack of material. Infill of the hollows with new material and weathering could require several decades.

Increased winter rainfall in the Cantabrian Range and the northern Duero basin would favour the reactivation of some big rotational slides and earthflows, especially if the increased rainfall is accompanied by river floods capable of sustaining the erosive action of the meanders on the river banks. In the rest of the Peninsula, the loss of seasonal and interannual rainfall will mean that some large movements will become dormant landslides. The exceptions will involve large landslides associated with particular geological context such as landslides fed with large amounts of groundwater in the event of intense downpours (Pont de Bar, La Coma and Gòsol in Lleida or Intza in Navarre) or those situated on riverbanks subjected to extraordinary floods.

Relict slides, in particular dismantled ones and ones disconnected from the current drainage network, as occurs with the oldest ones (Upper Pliocene- Mid Pleistocene) in the Tirajana basin (Lomoschitz *et al*. 2002) have very little chance of reactivation.

12.B.4. MOST VULNERABLE AREAS

As a consequence of what has been indicated in the previous sections, the big slides in the Cantabrian Range are the most susceptible to reactivation, especially in the Pas, Besaya, Magdalena-Pas and Miera valleys, which contain clusters of large landslides and earthflows. In the remaining mountain ranges, the reactivation of large movements will only occur in particular contexts (areas with an extraordinary supply of groundwater, areas of river erosion).

If torrential rainfall becomes more frequent, the increase in shallow slides, debris flows and rockfalls will occur in practically all the mountain ranges, even in the Cantabrian environment. However, in the Central Range and in the Mediterranean sector of the Iberian and the Baetic ranges, there will be less increase due to the calcareous nature of the rock formations and the scant current cover of the soils susceptible to failure. On the other hand, in the Pyrenees and the Coastal Ranges of Catalonia, a significant increase is to be expected due to changes in vegetation.

A rise in sea level, along with the frequency of sea storms, will cause undermining, fall and sliding of the terrain, especially in rock cliffs made up of soft rocks, such as the Triassic and Miocene formations of the northern coast of Majorca (Banyalbúfar, Valldemossa), the Cantabrian coast (flysch in Zumaya, Triassic in Asturias), lava flows stacks on the Canary Isles and, to a lesser degree, the fractured rocky massifs on the Costa Brava and the Costa del Sol.

12.B.5. MAIN ADAPTATIONAL OPTIONS

The impact of increased surface slides and debris flow can be mitigated, partly through policies aimed at the reforestation of slopes and the maintenance of species better adapted to the conditions of the environment. The growth of forests also constitutes a clearly sustainable element for protection against rockfalls (protection forest). Priority should therefore be given to reforestation and fire-fighting policies in the future.

The best adaptational tool involves town planning and land planning that takes into consideration and avoids, as far as possible, development in the areas most susceptible to slope instability.

Public works, especially related to roads and railways should consider construction procedures aimed at avoiding the reactivation of large landslides. To this end, there is a wide range of measures, ranging from minimising the cutslopes to be excavated, reducing overload on slopes (light embankments), contention works (walls and anchoring systems) and drainage systems.

It will be very difficult to establish protection measures against erosion and undermining of coastal cliffs, except in very justifiable specific cases for which measures are economically feasible. Likewise, only those large slides threatening property and infrastructures of value could be corrected and contained.

12.B.6. REPERCUSSIONS FOR OTHER SECTORS OR AREAS

From the socio-economic point of view, both the increase in snowfall elevations and the displacement of snowfall to springtime, will cause losses in winter tourism during the start of the winter (Christmas and new year).

The hydrological regimes of rivers flowing from high-mountain basins could be affected by the delay in the snow melting period, whereas the possible increase in the sediment load in suspension could accelerate the clogging process in reservoirs, reducing the capacity of these, with the consequent implications for hydroelectricity production and in water supply.

12.B.7. MAIN UNCERTAINTIES AND KNOWLEDGE GAPS

Predictions of the future behaviour of slopes are based on the different scenarios considered in the use of available climate change models. At present, these scenarios present great uncertainty with regard both to the area distribution and the frequency of irregular rainfall on the Iberian Peninsula. In this respect, in spite of the fact that increased sea temperature should favour storms in the Mediterranean environment, it cannot be ascertained that torrential downpours will be more frequent although some studies in the Alps claim that this will happen (Bader and Kunz 1998). Furthermore, the predicted increases in temperature and rainfall in the Cantabrian range do not correspond with the responses by landslides in the past. Indeed, figure 12.B.4 shows that the phases with the highest temperatures and rainfall during the Holocene were accompanied by a decrease in rainfall and in the activity of large landslides. As climate models allow for better definition of the rainfall regime on the Iberian Peninsula, the conclusions of this chapter will require confirmation.

There is still great uncertainty with regard to the response to rainfall episodes of both large and small landslides. In spite of the fact that, in scientific literature, different rainfall thresholds have been proposed in relation to the triggering of shallow landslides, these vary greatly depending on the geologic, morphological and climatic conditions of each region. Critical rainfall thresholds have been proposed in Spain for the Eastern Pyrenees, but they still need to be established for the rest of the territory. Furthermore, there is no available knowledge of the hydrological response of most active or dormant large landslides distributed throughout the main mountain ranges.

12.B.8. DETECTING THE CHANGE

Detection of change is related to increased frequency, depending on the type of movement, of the first time slope failures and reactivation episodes.

In the Mediterranean area, the change will be evidenced by the increased frequency of high-intensity rainfall and, consequently, a higher number of debris flows and shallow slides. The increased activity of these events in the last twenty years might be due to this, but we must remember that greater knowledge and interest now exist in relation to these phenomena, which could previously have gone unnoticed.

The increase of the frequency of wintertime reactivation of earthflows and large slides along the increase of both sea storms and the instability of sensitive coastal cliff, would be indicators as well.

12.B.9. IMPLICATIONS FOR POLICIES

12.B.9.1. Environmental policies

The increase in surface slides and debris flow as a consequence of the greater irregularity of rainfall involves the direct supply to the water course of the material mobilised and the erosion of the landslide scarps made up of colluvium and clay formations. As a consequence there will be a significant increase in solid load in suspension in the water course, with the resulting decrease in quality and possible reservoir clogging downstream. For example, in the Vallcebre area, large badlands provide 13% of the sediment load in suspension in the upper basin of the river Llobregat, whereas the area of this only occupies 4%. In this basin, 50% of the solid load is supplied by the badlands, which take up 3.7% of the area, and 32% of the load results from the erosion of spoil tips which take up 4% of the area. Mean annual erosion is 1,000 Tn/km^2/year (Balasch 1986; Clotet and Gallart 1983). In this basin, landslide volume is 20 times the volume of sediment exported annually from the basin, whereas the large Vallcebre slide involves 500 times more.

Large snow avalanches destroy forest throughout large areas of the Pyrenees. As an example, between February 5th and 8th 1996, in the Aigüestortes and Estany de Sant Maurici National Park, 30 big avalanches were counted, that damaged the forest and destroyed an estimated total of 97 hectares of forest. A decrease in the number and magnitude of avalanches would influence the spread of forests.

12.B.9.2. Policies related to risk management

At a general level, there is serious need of a complete and updated inventory of unstable areas. It is also vital to draw up maps of susceptibility, hazard and risks in the most sensitive areas, especially the inhabited ones or those subjected to greater development.

We must avoid situating sensitive facilities (schools, hospitals, etc.) and dangerous industries in areas susceptible to slope failure or reactivation.

In some large slides in inhabited areas, risk prevention and mitigation strategies should be developed. On one hand, if feasible, protection and contention works should be implemented. If this were not possible, there would be a need for early warning devices and evacuation procedures for emergencies.

12.B.9.3. Infrastructures and construction works policies

Construction works for big infrastructures (motorways, railways,...) should be designed with great caution to prevent them from cutting through potentially unstable areas. Infrastructures the breakage of which could cause serious environmental damage (e.g. oil pipelines) should also avoid dangerous areas or design them carefully.

Form the socio-economic point of view, both the rise in snowfall elevations and the displacement of snowfall to springtime could cause losses in winter tourism at the start of winter (Christmas and New Year) as can be already observed in the Swiss Alps. The hydrologic regimes of rivers flowing from high-mountain basins could also be affected by the delay in the snow melt period.

12.B.10. MAIN RESEARCH NEEDS

12.B.10.1. Response of the different types of slope movements to present climatic variability in the different regions of Spain. Behaviour models

There is a crucial needs for an inventory of currently active, latent, sleeping, relict, stabilised, etc. slides. This inventory should also consider large landslides in particular geologic contexts.
The relationship between rainfall and slides is very dependent upon local geologic conditions and regional climatic conditions. Rainfall thresholds at which slides are started should be defined for the different regions and typologies of failures.
With regard to snow avalanches, there is a pressing need to consolidate preventive strategies aimed at mitigating the risk (Vilaplana 2001). In this respect there is a fundamental need to establish a general inventory of avalanches in Spain (Martí *et al*. 1995; Ferrer *et al*. 2000) that deals with two aspects: cartography and the characterisation of avalanche areas throughout the territory exposed, and the establishment of a snow meteorological and avalanche database linked to a network of mountain stations.

12.B.10.2. Response of slope movements to past climatic variability in different regions of Spain

The future behaviour slides can partly be predicted, thanks to the observation of responses by slopes in the past. There is a need to complete historic and prehistoric series on slope failures and reactivation episodes. This task also requires improved techniques for reconstructing series of old slides, as well as improved analysis of the relationship with climatic situations (extreme rainfall events, persistent rainfall events).

12.B.10.3. "Downscaling" of the situations projected by Climate Change models

Although slope instability can, on occasions, occur in a generalised manner throughout a region, it is a local phenomenon that depends on the amount of rainfall collected in the closest surroundings. For this reason, predictions by global circulation models must specify rainfall at detailed scale. Analysis of downpours in the last few decades indicates significant variations in rainfall in mountain areas, where most slope failures occur.

12.B.10.4. Improvement of hydrological models and mechanisms of slope movements for reproducing the effects of Climate Change

In large slides it has been seen that no simple relationship can be established between rainfall and slide activity. Different hydrological and mechanical models have recently been developed which enable the behaviour of complex landslides, with different materials and hydrological-mechanical properties, to be studied when both climatic and geomechanical conditions are well known (Laloui *et al*. 2004). It is precisely the large landslides that pose the biggest threat in the event of reactivation. It is therefore necessary to improve existing models with the help of monitoring data of the landslides. The hypotheses and predictive capacity of the tools used could thus be validated.

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12. IMPACTS ON NATURAL HAZARDS OF CLIMATIC ORIGIN

C. FOREST FIRES RISK

José M. Moreno

Contributing Authors

E. Chuvieco; A. Cruz Treviño, E. García Díez, E de Luis Calabuig, B. Pérez Ramos, F. Rodríguez Silva, J. San Miguel, R. Vallejo, J.A. Vega, R. Vélez Muñoz, G. Zavala

Reviewers

M. Casal, C. García-Vega, C. Hernando, J.C. Mérida, J. Pausas, J. Piñol, J. Raventós, A. Vázquez

D. X. Viegas, P. H. Zedler

ABSTRACT

In Spain, there are more than 20,000 forest fires every year, affecting over 150,000 ha throughout the whole country. These fires occur mainly in summer and are caused by people, accidentally in most cases. Fires are favoured by the presence of inflammable vegetation and dessicating climate conditions (high temperatures, low relative air humidity, drought). In Spain, fires have been more numerous in conditions of high temperatures or fire danger rating indices and low rainfall, with relatively rare extreme situations beeing more important than the average ones.

The fire danger rating indices, based on small number of meterorological variables are good predictors of fire occurrence. Fire danger increases from West and North to East and South, the probability of large fires also increasing in this direction. The greater the danger, the higher the variability in the size of the fires, and this becomes less predictable depending on climate.

With climate change there will be an increase in temperatures and in soil dryness, and especially in the frequency of water scarcity, which will cause greater desiccation of live and dead fuels and, therefore, increased flammability. On the other hand, in areas the become arid fuel accumulation will be reduced.

During the XX century, the fire danger rating index has constantly risen, and will continue to do so in the XXI century. There will be greater incidence in time of high danger zones, the duration of this during the year, and of extreme danger situations. There will probably be a greater frequency of fires with these increases. There will be an increase in ignitions caused by lightning.

The abandonment of marginal lands will continue. The more mesophytic vegetation will be replaced by a more xerophytic one. More burnt surface area will lead to more shrubland vegetation. In short, there will be an increase in flamability potential of the territory. The most vulnerable areas will be in the North of Spain, in high mountain or plateau areas, as these will be exposed to a more adverse fire regime than the present one.

The reevaluation of the fire-fighting policy, the inclusion of the fire danger associated with a determined use, an improvement in the surveillance and early-warning systems, and better training and information for the public are some of the adaptive options for mitigating adverse impacts. Management schemes based on the total exclusion of fire must be modifed. Fire must be incorporated as a management tool in order to reduce fire hazard in a given area.

The production potential of the forestry sector will diminish, as will the risk of soil and biodiversity loss. The residential use of forest and wildlands will be affected.

Major unknowns are how the number of fires will change, the role of landscape in determining the area burnt, the risk associated with the recreational use of the territory and the importance of processes that increase vegetation necromass, such as pests or droughts.

The detection of change in fire occurrence requires the maintenance of the EGIF database on forest fires in Spain. The change in the fire regime will affect fire-fighting and prevention policies, and policies dealing with soil conservation and desertification, biodiversity conservation and land use. The most relevant research needs involve establishing the interaction between drought, fire danger and the response of the vegetation to fire, and availing of climate and vegetation scenarios with appropriate spatial and temporal resolution.

12.C.1. INTRODUCTION

12.C.1.1. Background on climate and fires

Forest fires are one of the most important factors influencing the structure and functioning of many terrestrial ecosystems. They also are responsible for the release of large quantities of CO2 and other gasses to the atmosphere (Prentice *et al*. 2000). At present, over 1000 Mha are burnt every year, mostly in tropical savannahs, and in tropical and boreal forests (Levine 1991). Mediterranean areas and those in southern Europe also have a high occurrence of fires (Vélez 2000a).

In the past, there has been a close relationship between climatic variation and forest fires (Clark 1988; Carcaillet *et al*. 2002), so that these have been more frequent in hot periods than in cold ones. There is increasing knowledge in Spain of the relationship between past climate change, vegetation and fires, in particular after the Holocene (Peñalba 1994; Goñi and Hannon 1999; Carrión and van Geel 1999; Santos *et al*. 2000). During this period, Spain's vegetation was extremely dynamic, with changes associated with climate. There is an intermittent presence of charcoal in sediment records. The relationship between climate and fires can be clearly seen in the reconstruction in the Sierra de Gádor mountains: increasing aridification following the mid-Holocene led to an increase in the frequency of extreme fire events (ranging from peaks of 300-400 years to others of 100-200 years), and to a change in the vegetation (Carrión *et al*. 2003). The appearance of man caused an increase in fire frequency in most of the sites studied, and a change in the predominant vegetation.

Although historic references to forest fires are commonly found (Lloret and Mari 2001; Pausas 2004), or to regulations associated with them (Vélez 2000a), a reconstruction of the fire regime in Spain based on historic data has not been possible, and even less so if we refer to climate-related changes. Furthermore, the lack of old forest has hindered the establishment of the degree of recurrence of fires. Scar dating on *Pinus pinaster* in the Sierra Bermeja mountains shows a high frequency of surface fires during the end of the XIX century and the start of the XX century (recurrence of 11-35 years), which was probably associated with grazing (Vega 2000).

12.C.1.2. Temporal trends in the number and area burned by fires in Spain

The number of forest fires recorded in Spain has increased during the past decades, just levelling off lately. The tendency of annual surface area burnt is different. Form the 60s to the 80s, the area burnt was multiplied until it reached the current situation, which is characterised by a large annual variability (Fig. 12.C.1). Although part of this change is due to the fact that the old statistics dealt with publicly managed land, the fires have spread in time from a limited number of points to practically the whole of Spain (Moreno *et al*. 1998). There are, however, a few areas, in the Northwest, Centre, Levant, South and Southwest where they are particularly abundant (Fig. 12.C.2).

The origin of these fires is mainly human (>95%), Galicia being one of the regions with the highest number of deliberate fires. There are few fires caused by lightning, but they do occur in some areas: in the province of Teruel more than half of all fires are caused by lightning; one third of the area burnt in the regional autonomies of Valencia, Castilla-La Mancha or Aragón from 1989 to 1995 was caused by lightning; a major part of fires larger than 10 000 ha were caused by lightning (Vélez 2000b). The fires occur mostly in summer, although there is a certain variability throughout the country and in relation to the cause of the fire. Thus, whereas fires caused by lightening are clearly limited to this season, they can be caused by man at any time of year (Fig. 12.C.3).

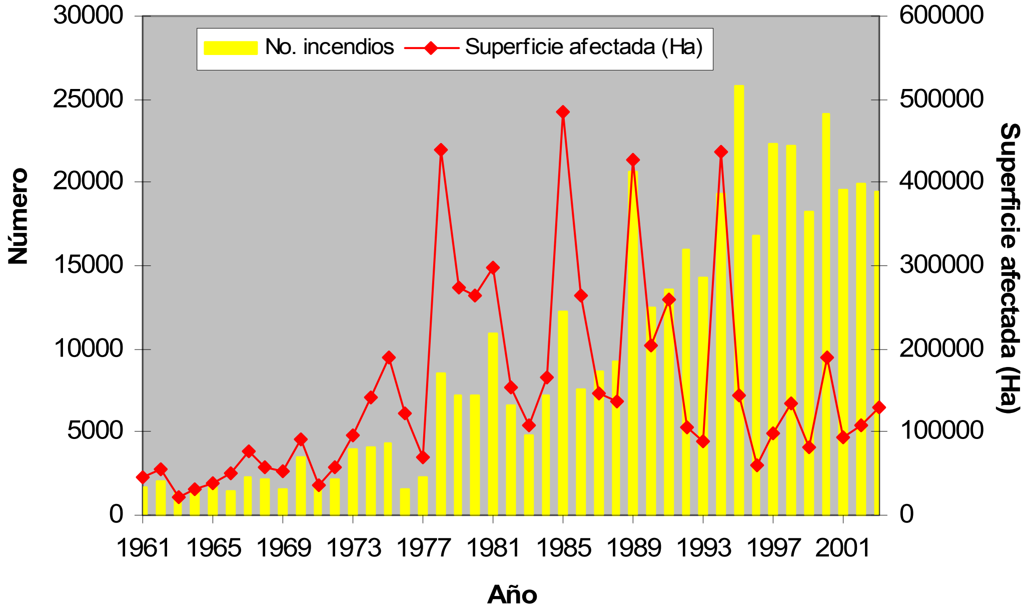

Fig. 12.C.1. *Annual number of fires (bars, yellow) (number) and area affected by these (line, red) (ha) in the last few decades. Source: EGIF (DGB, MIMAM) and own ellaboration.*

Furthermore, the type of landscape burnt has been changing over time: in the last few years, there has been a dominance of unwooded areas over forests (Fig. 12.C.4). In the forests burnt, conifers dominate, in particular *Pinus halepensis* and *Pinus pinaster*. The average age of the trees burnt barely reaches 25 years (Moreno *et al*. 1998).

12.C.1.3. Scope of fires in Spain

On average from 1991 to 2002, the area burnt annually was 0.55% of total forest area. This means that if the whole forest area were to be equally affected, it would take 180 years for it to be burnt once. This overall figure conceals the fact that there are large differneces in the recurrence time. In 100 years some areas will be expected to burn many times and others will not burn at all (Vázquez and Moreno 1998). Great losses are caused by fires, either of primary products or of environmental values, and in particularly bad years these can exceed 400 M€ in direct profits and 1000 M€ in total profits (EGIF, DGB, MIMAM). Furthermore, the costs related to combating and preventing fires and restoring the damage are very high. If, for example, we take the Generalitat de Valencia (regional autonomy), in the 90s, 9.34 M€ was invested, most of this (77%) in extinction, and this figure rose to 60.77 M€ in 2000 (65% in extinction). This increase by almost 7 times for extinction and by 10 times for prevention had not an equivalent effect in reducing the area burnt (Vega García 2003). Parallel to the regional administrations, the central government invests large sums, an annual average in the last decade of 50 M€, 35% in prevention and 65 % in firefighting (DGB, MIMAM). This indicates that the capacity to control the areas affected by fire is limited, and that bigger investments do not necessarily mean greater effectiveness. In this sense, policies emphasising prevention aspects, with specific plans for prevention through ownership, as is implemented in certain Regional Autonomies, might be more effective.

12.C.2 SENSITIVITY TO THE PRESENT CLIMATE

12.C.2.1. Factors controlling forest fires

Climate, vegetation and fuel

Climate determines the dominant vegetation in a region (Rivas Martínez 1987) and therefore the amount and kinds of fuels available to carry fires. Consequently, the climate-vegetation relationships tend to be good ones (Moreno *et al*. 1990, Fernández Palacios 1992; Gavilán and Fernández-González 1997; Ojeda *et al*. 1998). In general, in Spain, the mature vegetation made up of deciduous trees dominates in the rainier areas, whereas that made up of evergreens does so in the dry areas. There is a scarcity of mature natural vegetation in our country, due to the intense use thereof, and the natural vegetation more frequently comes from secondary succession or reforestation. The flammability of this secondary vegetation is, in many cases, greater than that of the mature natural vegetation. This is particularly so when pioneer vegetation is dominated by species that accumulate fine fuel and necromass. Because of this, the relationship between the flammability of the vegetation and climate is not simsple. During the final part of the XX century, the dominant vegetation has increased its potential flamability as a result of less exploitation and reduced grazing, and to the abandonment of marginal croplands and lack of use of wood as fuel (Vélez 2000a). Furthermore, the vegetation that grows after plantations of conifers or broadleaf species like eucalyptus have been burnt, is often highly inflammable.

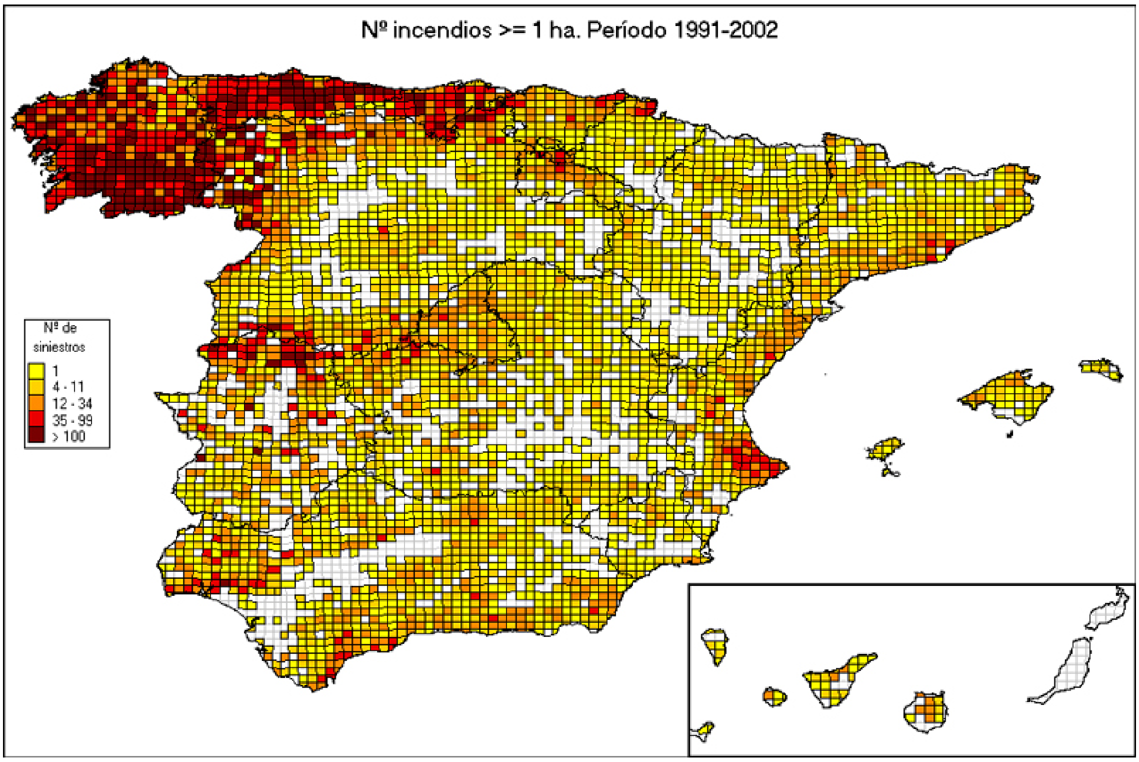

Fig. 12.C.2*. Distribution of forest fires equal to or bigger than 1 ha in Spain during the 1991-2002 period. Source: DGB, MIMAM.*

Meteorology

The meteorological variables most influencing the development of fires are temperature, wind speed, air relative humidity and stability of the atmosphere. In the stable and dry summer environments the energy received from the sun increases temperature and reduces the relative air humidity. Both variables (temperature and relative humidity of the air) control the hydration state of dead fuels. Wind is another critical element: the speed of the spread of the fire front is directly proportional to wind speed. The most dangerous situations are those involving strong, dry winds. *Föhn*-type winds are particularly critical; these are winds blowing on the leeward side of mountains as a result of the adiabatic compression of the air on blowing down the slopes (Millán *et al*. 1998), and these are the cause of some of the large fires in Spain (Gómez-Tejedor *et al*. 2000).

Fire heats the air, which rises, drawing in cool air towards the base of the fire which provides oxygen to sustain combustion. When there is wind, this effect is augmented on the downwind side by the wind-driven air flow.. The stability of the lower levels of the atmosphere determines the degree of intensity of the local wind caused by the fire. Situations of atmospheric instability favour the vertical movement of the hot air, facilitating the lateral movement of the air towards the fire front. To the contrary, in stable conditions, fires are relatively less dangerous. Thus, with two parameters of atmospheric stability, Díez *et al*. (2000) calculated, to a high degree of accuracy, the daily occurrence of fires in Galicia. The synoptic situations determining the state of the atmosphere are therefore critical for the occurrence of forest fires (Díez *et al*. 1994). These determine atmospheric flow, and, through this, wind, precipitation or lightening discharges, among other phenomena (Gómez-Tejedor *et al*. 2000; González-Hidalgo *et al*. 2001; Goodess and Jones 2002; García-Herrera *et al*. 2003; Muñoz-Díaz and Rodrigo 2003; Tomás *et al*. 2004). Consequently, many fires occur in determined synoptic conditions (Bardají *et al*. 1998). This is similar for the rest of the world (Da Camara *et al*. 1998; Johnson and Wowchuk 1993).

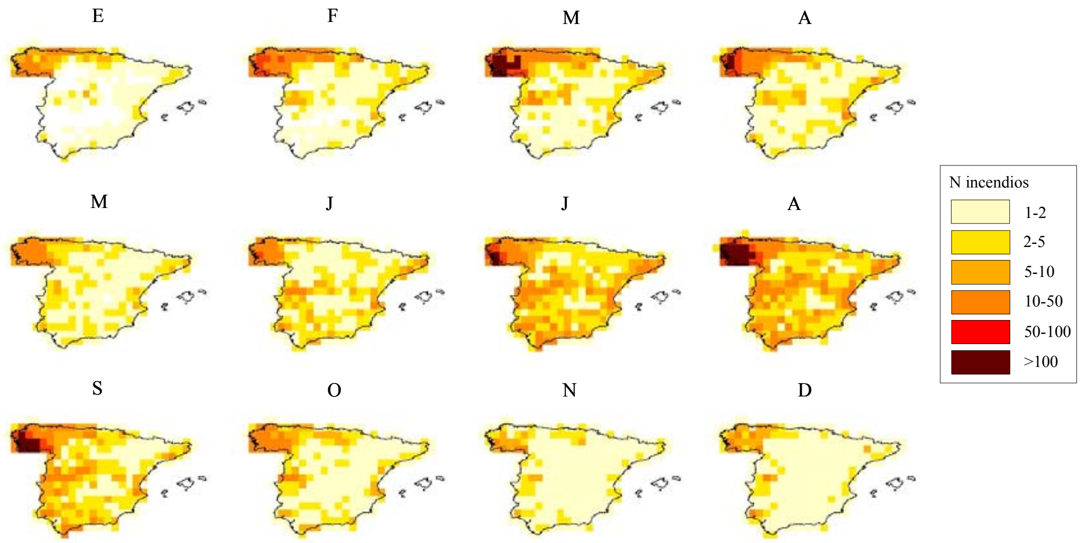

Fig. 12.C.3. *Occurrence of fires on the Spanish Peninsula in the different months of the year during the decade 1990-1999. (The average number of fires per month is shown). (Moreno et al. 2005).*

Fuels

Moisture of fine fuels: The moisture content of live fine fuels varies throughout the year, being maxium in spring and minimum at the end of summer. The moisture content is related to phenology and to the availability of water in the soil, and is therefore well related to drought indices (Viegas *et al*. 2001; Castro *et al*. 2003) (Fig. 12.C.5). This relationship is such that the most important effects take place in the initial phases of soil water deficit. The relationship varies according to species. Thus, pioneer species tend to vary more and to be more closely related to rainfall than the other, late successional ones, which have access to water at greater depths (Moreno and Cruz 2000; Peñuelas *et al*. 2001; Viegas *et al*. 2001; Filella and Peñuelas 2003). The state of the live fuels therefore depends on how much it rains and on when this occurs. Moisture content can also vary with the age of the plant (Baeza *et al*. 2002).

Chemical composition. Apart from water, the chemical composition of plants determines their energy content and flammability. Ether extractives (essential oils, resins, etc.) favour flammability (Trabaud 1976). Forest species experience sharp seasonal variations in chemical content (Elvira and Hernando 1989; Núñez-Regueira *et al*. 1999), which in turn cause variations in their flammability throughout the year (Núñez-Regueira *et al*. 2000).

Moisture of dead fine fuel: The moisture content of living fuels is maintained by the transport of water from the soil, and thus live leaves and branches have relatively high moisture contents even in times of drought. But the moisture content of dead fuels fluctuates widely in response to variation in relative humidty, rainfall, and solar radiation, to name the three most important factors. The spread of fire is very sensitive to the presence of dead fine fuel ($\phi \leq 6$ mm), because it is the most flammable when exposed to heat. In addition, is the one that adjusts most rapidly to meteorological conditions. The moisture content of standing dead fuel varies throughout the year, and is lower in summer. In stable atmospheres, relative humidity decreases with an increase in temperature, and the moisture content of these fuels is therefore maximum at the start of the day, and minimum at the start of the evening. Likewise, the moisture content of the litter depends on meteorological conditions, its exposure to the sun, and also on soil moisture content. The more dessicant the atmosphere, and the lower the soil moisture, the drier the litter will be, which will increase the flammability and combustibility of this, and of the standing dead fuels (Valette 1988; Viegas 1998).

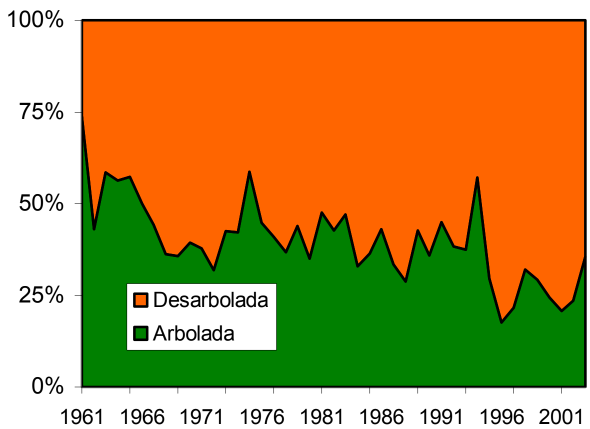

Fig. 12.C.4. *Variation over the last few decades in the type of surface affected by fir (wooded: greeen; unwooded: orange) Source: Anonymous and EGIF(DGB, MIMAM)(own compilation).*

Topography

The spread of fire increases with the angle that the terrain offers to the fire front. An upslope spread is therefore rapid and dangerous. Fires do not occur by chance, but rather are more frequent in certain topographies (Vázquez and Moreno 2001; Lloret *et al*. 2002). Although topography may not change, vegetation can do so, particularly after a fire. This makes the risk in a given area vary in time as the vegetation changes, and according to the topographic conditions of the area in question.

Lightning as a source of ignition

In Spain, the frequency of lightening discharges is related to sea temperature (de Pablo and Soriano 2002; Soriano and de Pablo 2002), and are more abundant when this is higher. Lightening is more frequent in mountain areas (Pyrenees, Iberian System and Central System), with a gradient of abundance from lower (Southwest) to higher (Northeast) (Soriano *et al*. 2001a, b). There is a higher frequency of discharges in summer (Ju, Jl, Ag), followed by autumn (Se, Oc) and spring (My). The number of discharges is related to certain circulatory synoptic types (Tomás *et al*. 2004), and the highest number of discharges is caused by cyclonic situations and by easterly flows. The geographic distribution of fires caused by lightening generally tallies with the distribution of these, but is different in the case of fires caused by man (Vázquez and Moreno 1998).

12.C.2.2. Fire danger

Fire danger is a measure of the likelihood of a fores fire, and is based on temperature, relative humidiy, wind force and direction and the dryness of the fuels (Vélez 2000c; Viegas *et al*. 2000). Thus, fire danger indices are useful in representing the probability of fire in time and space. Plotting one of this (the Canadian Weather Index) for Spain for the 6 critical warm season months shows how fire danger ingrease first in West Central Spain and then spreads eastward and inland along the eastern coast through the summer. The North and Nortwhest, because of thwie cool and moist clime, remain at low fire danger throughout the season of maxium danger. (Fig. 12.C.6). The days with fires, multiple fires or large fires are often more frequent when the fire danger indices are higher (Andrews *et al*. 2003). Consequently, a higher frequency of high indices implies greater probability of the occurrence of this type of fires. The chances of a large forest fire occurring are related to the presence of masses of unstable air and a low moisture content (Haines 1988). As has been stated, the occurrence of fires in Spain has been related to climatology, and has varied according to areas and ignition sources (Vázquez and Moreno 1993) (Fig. 12.C.7). What appears to be more critical than the mean values of a determined variable or index, however, are the extreme situations, that is to say, the number of particularly hot days, or the time elapsed since the last rains (Vázquez and Moreno 1993; Piñol *et al*. 1998; Pausas 2004).

Fire danger indices are based on climate, but because humans can start fires at any time of the year it is possible to have fires even when fire dange index is not high. Vázquez and Moreno (1995) found that the fire season, considered as the period in which 50% of the fires of a given year occurs, or in which a similar area is burnt, is longer in the Levant than in the Central region, but not than in the Northwest. This is contrary to what might be expected based on the duration of high fire danger situation. Furthermore, in the Northwest, the years with a greater number of days with higher temperatures the area burnt was bigger. However, the fire season was shorter, not longer. These relationships were in part related to the source of ignition, being deliberate fires the ones that most closely reflected this pattern. Consequently, the fire-alert season may not necessarily determine the fire season. In those areas dominated by deliberate fires, it is the cause of the fire that can determine temporality.

12.C.2.3. The size of the fires

The meteorological variability of Spain's climates (see Chapter 1) affects the annual distribution of the size of the fires, so that these are more unequal when annual meteorological variability is greater. Thus, in the Levant, a small number of fires often burns a high percentage of the area burned during the year. This percentage is lower in the Northwest. The annual variability of the distribution of fire sizes is also greater in the Levant than in the Northwest. Besides, the degree of prediction of the parameters describing the shape of the fire-size frequency distribution is lower then annual climatological variability is higher (Vázquez and Moreno 1995) (Fig. 12.C.8). In other words, in these trhee areas of Spain studied, those having a more variable climate produced fire-size frequency distributions that were more unequal, with greater importance of a small number of big fires over the total area affected by fire in one year. In addition, these fire-size frequency distributions were less predictable as a function of climatic variables.

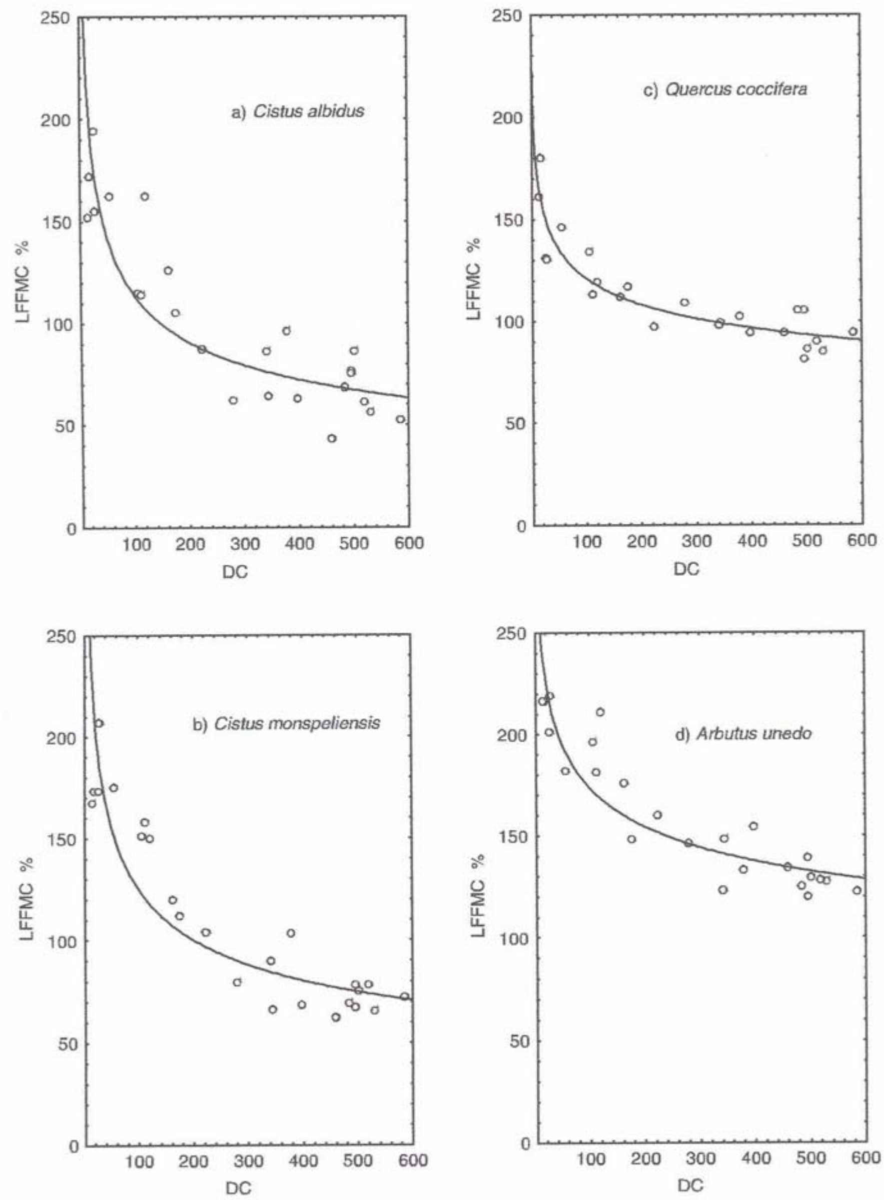

Fig. 12.C.5. *Live fine fuel moisture content (LFFMC%) according to the Drought Code of Canadian Fire Danger Rating System in Collserola (Barcelona). Please note the difference between more or less pioneer species. De Viegas et al. (2001).*

The size of a fire depends on the ignition source. Deliberate human ignitions tend to produce fires that are less variable in area burned than ignitions caused by lightning. But the degree of difference in fire size for fires caused by different ignition sources depends on the climatic zone.

Paradoxically, ignition source was more determinant on the fire-size frequency distribution as climate-related danger in the area was lowest. In other words, an area with a high climate-related danger (Levant) produced similar fire-size frequency distribution among those fires caused by different sources, whereas other areas with a lower danger (the Northwest) have produced more variable distributions. This is, the ignition source produced higher fire-size variability in a less-fire prone area than in a more fire-prone area. Furthermore, the relationship between the parameters describing these fire-size frequency distributions with climatic variables was low, although in the Northwest (lower danger), the relationship was higher than in the Levant (higher danger) (Vázquez and Moreno 1995).

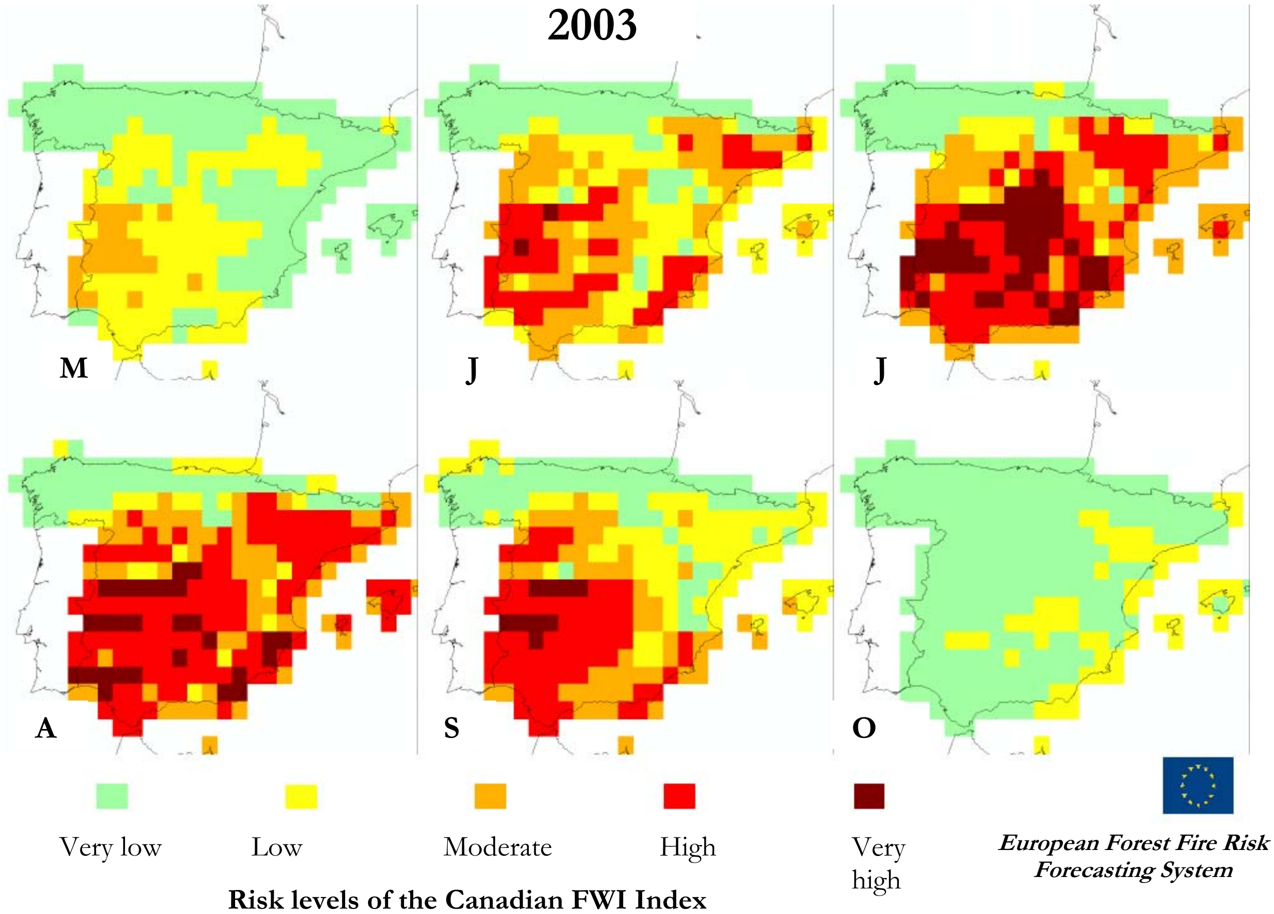

Fig. 12.C.6. *Fire danger in Spain according to the Canadian FWI Index from May to October 2003. Map taken from the European Forest Fire Risk Forecasting System, European Institute of the Environment and Sustainable Development , CEC, JRC, Ispra, IT. (http://natural-hazards.jrc.it/effis/effrfs/).*

12.C.3. FORESEEABLE IMPACTS OF CLIMATE CHANGE

12.C.3.1. Impacts associated with climatology

Temperatures

The tendencies for the future climate of Spain point to an increment in mean temperature of 0.4ºC/decade in the winter and 0.6-0.7º/decade in the summer. Thus, mean temperature increase is higher in summer than in winter. The frequency of extreme termperatures will increase everywhere. The number of days with maximum extreme temperatures will increase in the summer. There are evidences for such tendencies in some areas of Spain (see Chapter 1). The spread of fire is favoured during the day by the temperature increase and the decrease in relative air humidity, which can reduce the moisture content of dead fuels, lowering the threshold for ingnition, making an ignition event more likely to lead to fire. Likewise, night-time temperature increases will be proportionally greater than the daytime ones (Easterling *et al*. 1997). In other words, temperatures during the night will tend to become comparatively higher, with the consequent negative effect on fuel moistening. Assuming that the number of ignition sources and the vegetation do not vary, flammability can therefore be expected to be greater and the fires more frequent, and that once they have broken out, they will spread better and get bigger.

Precipitation

The tendencies for precipitation during this century are not consistent among models, although, they all agree the total annual precipitation will decrease, in particular in spring and summer. (Chap. 1). Precipitation patterns determine the level of soil moisture reserves, and recharge periods are critical with regard to providing the soil with greater stability in water content (Martínez-Fernández and Ceballos 2003). Assuming that total precipitation does not vary, the concentration of this in winter and the consequent lack of rainy days in spring and summer will affect live and dead fuels. This, together with the temperature increase, will cause and increment in potential evapotranspiration (Pausas 2004). Rainfall during the growth period has a great influence on the abundance of herbaceous species (Figueroa and Davy 1991). Rainy springs maintain more surface moisture in the soil, leading to greater development of fine herbaceous fuels, which will subsequently dry out. Temperature increases may cause the development period of herbaceous species to be advanced to early spring or winter, so that, even in a scenario of reduced springtime rainfall, this vegetation may develop well, thus contributing an element of hazard relatively early in the year. This is more relevant in the humid areas which, in time, may become more susceptible to greater summer dryness, which may also appear earlier in the year. Furthermore, less moisture availability in the surface layers of the soil will make the dead fuels in the soil dry out sooner. The lower number of rainy days will keep them dry for a longer time. In pine forests and ecosystems with well developed litter, there will be an increase in flammability and in the period of susceptibility to fire.

The standing vegetation will undergo physiological and phenological changes in response to changes in rainfall patterns. In the first place, the concentration of precipitation in winter, along with the decrease in the number of rainy days during the year, will lead to an increase in the number of days during which plants are subjected to water stress (Martínez-Fernández and Ceballos 2003), with the consequent increase in the duration of the fire season (Rambal and Hoff 1998). The rooting pattern, that is to say, the soil depth that each plant is capable of exploiting, together with its physiological characteristics, determines its level of water stress (Filella and Peñuelas 2003; Martínez-Vilalta *et al*. 2003). The species with shallower rooting systems, which are more susceptible to the availability of surface water, such as certain shrubs as rockrose (*Cistus*), rosemary (*Rosmarinus*), some heather (*Erica*) and other nanophanerophytes, may present higher stress indices (Gratani and Varone 2004) and during extended periods, being more sensitive to changes in the patterns of rainfall than to total precipitation. This will lead to a higher and longer level of hazard in the communities dominated by them (Mouillot et 2002) than in those with deeper rooting systems, like may species of trees (Mediavilla and Escudero 2003a). A lower moisture content in the fine materials will increase their potential flammability thoughout the year, even more so when rainfall is lower and more concentrated early in the year.

In contrast, deep-rooting species may be affected more by decreases in total rainfall. In dry periods, water scarcity may force species to adjust their leaf area (Mouillot *et al*. 2002; Sabaté *et al*. 2002), decreasing the size and number of leaf cohorts that they bear, tending towards a higher proportion of current year leaves than in previous years. In extreme situations, some species may not develop current year leaves (Peñuelas *et al*. 2001). This may affect their flammability, given that old leaves have less water and more energy content (Mediavilla and Escudero 2003b). Furthermore, prolonged drought can cause total or partial death of individuals, with the consequent addition of dead matter. Such situations have been observed in the recent past, like the drought half way through the 90s. During this period, a high death rate of plants was observed, which was widely distributed among the different species, first among those presenting surface rooting (*Cistus* or similar), and afterwards to other deep-rooting ones, although with differences among species that depended on their capacity to tolerate water stress (Peñuelas *et al*. 2001). This effect was more notable on the S slopes than on N slopes, and there were also variations among substrates. It should be noted that in such extreme situations, plant water potentials of certain species, which could be measured even in autumn, could reach extremely low levels (Moreno and Cruz 2000). Recurring drought can cause an increase in standing dead matter, which would increase the hazardousness of the vegetation.

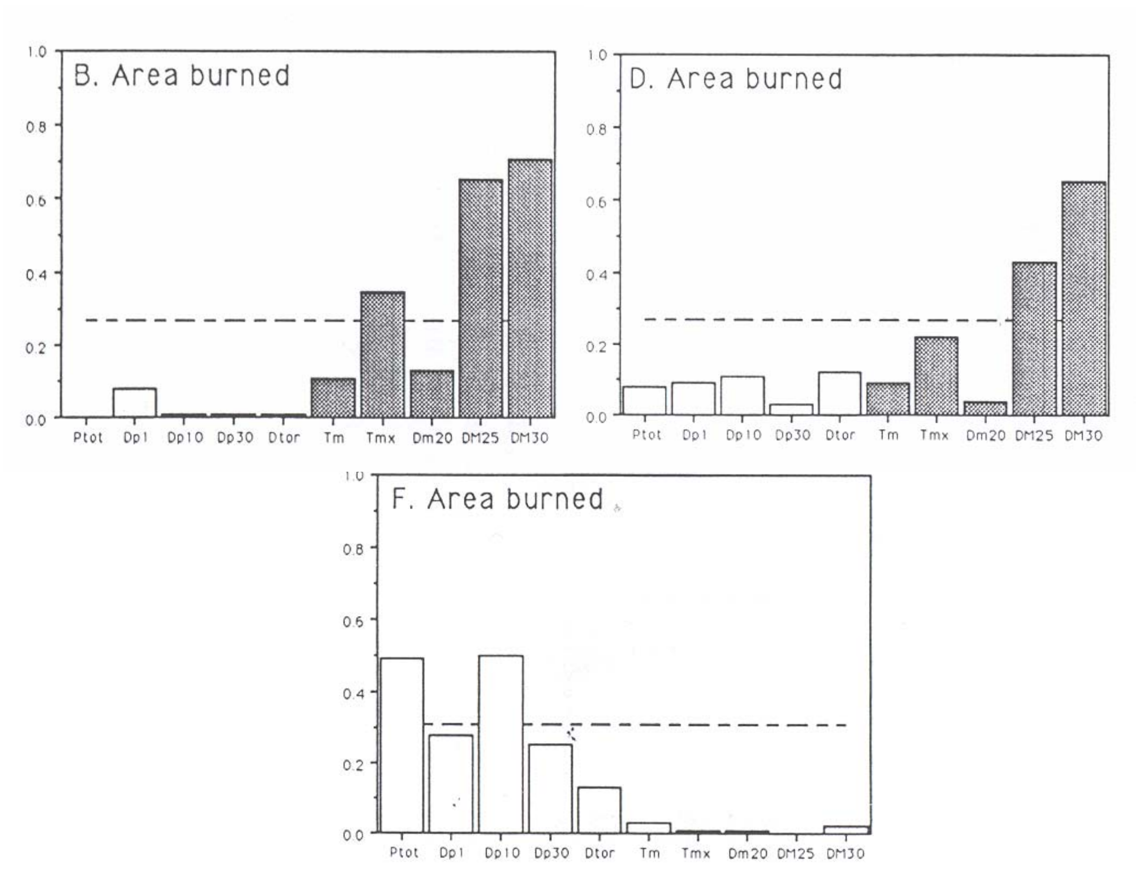

Fig. 12.C.7. *Coefficient of determination (r^2) between different annual precipitation (total rainfall [Ptot] or th rainfall equal to or greater than the values indicated in mm [Dp1, Dp10, DP30], or days with storms [Dtor], respectively) and temperature (mean [Tm], maximum [Tmx] or days with minimum [Dm] or maximum [DM] temperatures higher than the values indicated, respectively) variables and annual burnt area from 1974 to 1988 in three areas in Spain. The dense mesh indicates positive correlations, while negative correlations are shown in white. The broken line indicates the level above which the correlations are statistically significant. From: Vázquez* and *Moreno 1993.*

Wind

Average wind speed will tend to increase. This variation will be less notable in summer than in the other seasons (Chap. 1). Given the important local interactions of this meteor, it is not easy to predict the impact it will have, except that, considering the role it plays in the spread of fire, there will likely be an increase in large fires and in the difficulty involved in extinguishing these.

Vegetation and climate

As climate change materialises, the changes in vegetation it causes will become more evident (see Chapters 2 and 9). In this sense, as the more mesophytic vegetation, which is less flammable, is substituted by another more inflammable one (Peñuelas and Boada. 2003), fire hazard will increase in the areas where this occurs. The same can be said of the increment of horizontal continuity of the vegetation in areas which otherwise would hardly support the spread ofe, such as high mountain areas (Sanz-Elorza *et al*. 2003), or high plateau areas. On the other hand, the aridification of certain areas may caused a reduction in fuel quantity and continuity and thus decrease fire occurrence

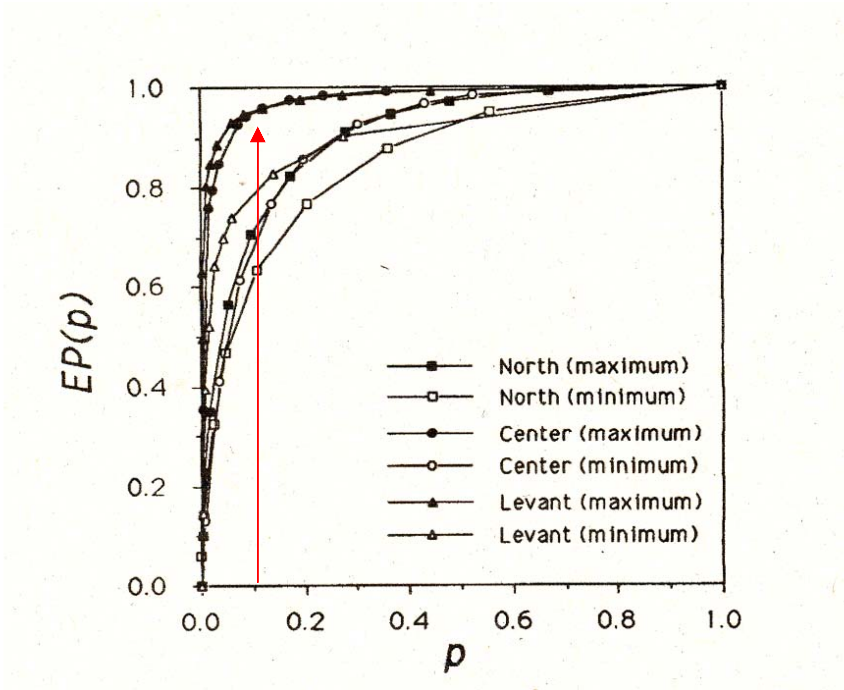

Fig. 12.C.8. *Relationship between the proportion of area burned (EP (p)) by a proportion (p) of fires in three areas of Spain from 1974 to 1988. The proportion of fires (p) is calculated cumulatively starting with the largest fires and ending with the smallest one. Hence, the arrow indicates the proportion of area burnt by the largest 10% of the fires. Please note the greater annual variability in the Levant and Centre than in the Northwest of Spain, and that in extreme years, just 10% of the fires affect over 95% of the area burnt during the year. From Vázquez* and *Moreno 1995.*

Lightning

Predictions based on GCMs indicate that the convective rain fraction will tend to increase, along with the number of lightening discharges (Price and Rind 1994). Lightening will not only be more abundant, but will spread more throughout the year, lengthening the fire season (Price and Rind 1994). Parra (1995) (taken from Rambal and Hoff 1998) demonstrated the existence of a close relationship between the surface temperature of the Mediterranean Sea (SST) and the convective rain fraction (CF) in Barcelona, (CF=4.9SST-38.7; r^2=0.93; P<0.01). The synoptic situations with the highest amount of lightening are the cyclogenic or Eastern ones (Tomas *et al*. 2004). Consequently, the number of fires caused by lightening can be expected to increase in time. The greater frequency of water deficit in the soil means that lightening discharges will become more efficient with regard to causing fires (Nash and Johnson 1996). It should be noted that in the past, most of the fires caused by lightening occurred during very few events, that is to say, consecutive days with storm-related activity (Vázquez and Moreno 1998). The persistence of these situations, resulting from the greater persistence of atmospheric conditions, may be particularly dangerous. The higher degree of abandonment that usually occurs in areas of greater elevation, where lightening is more frequent, suggests that there will be an increase in fuel accumulation, giving rise to fires caused by lightening.

12.C.3.2. Impacts on fire danger indices

As we enter the XXI century, and the predicted climate changes start to materialise, projections based on GCMs indicate a considerable increase in the mean monthly danger index (Fig. 12.C.9). These changes are generalised throughout all the months of the year and will bring the fire season forward in time, even more so as the century elapses and the bigger the change that takes place. It should be noted that all the scenarios predict a considerable increase in fire danger. Given that current fire danger indices are not the same throughout the whole country, the variations will have a greater effect on those areas which are in high danger situations for several months of the year. We can therefore expect acceleration in the number of areas included in the fire alert situations, along with a lengthening of the alert season. Similar scenarios have been described for other parts of the world, the degree of these depending on the climate change predicted (Torn and Fried 1992; Flannigan *et al*. 1998; Williams *et al*. 2001; Brown *et al*. 2004; Fried *et al*. 2004)

Furthermore, an increase in mean fire danger indices implies that, even assuming the distribution of frequencies of situations remains the same, the frequency of extreme situations will increase, but not in proportion to the increase in the average (see Schär *et al*. 2004, for the event in the summer of 2003, or Luterbacher *et al*. 2004, for the increase in the frequencies of extreme events). The duration of these may also increase as a result of the greater tendency towards atmospheric stability. It is difficult to predict the frequency and intensity of these situations, given the inaccuracies of the models. It should be noted, however, that Hulme and Carter (2000) indicate that in the 80s of the XXI century, the probability that every summer will be hotter than one among ten in the last century, is from 65% to 100%, depending on the scenarios used. In other words, every summer will be as hot as the hottest among ten in the XX century practically every year.

Although different GCMs produce different climate changes, even in the more favorable scenario we can expect increasingly frequent situations in which it will be impossible to fight fires in cases of multiple outbreaks in extreme situations. Fire fighting systems have a limited range of action, because, at the very best, they can deal with a situation that is a few times greater than a normal situation. Extreme, severe, prolonged and geographically distributed events force fire fighting services into situations that are far beyond their real capacity to handle, inevitably surpassing the maximum level of effectiveness for which they were conceived. The big fires in 1994 on the Levant or the more recent ones in Portugal in 2003 illustrate what can occur. A scenario of adverse meteorology suggests an increase in the frequency of possible situations in which it becomes tremendously difficult to combat fires.

12.C.3.3. Other impacts

Changes in land uses and in vegetation

Land use has been the most important factor related to changes in vegetation in Spain. The final decades of last century were characterised by an abandonment of the countryside, parallel to an increase in vegetation, either through forestation or due to the development of the natural vegetation (Fernández Alés *et al*. 1992; García-Ruiz *et al*. 1996; Vega García 2003; Duguy 2003; Viedma and Moreno, enviado). The tendency towards the concentration of agriculture in the more fertile areas, the reduction of extensive grazing and an increase in abandoned areas might continue to extend forest and wildland areas. However, analysis of changes in landscapes over the last few decades in certain areas shows that the biggest change might have already occurred. But changes in rainfall and temperatures will reduce the production potential in many areas, which could affect abandonment processes (see chapters 2 and 9). The loss of economic value in some woodlands due to lack of competitivenes with other areas can stimulate the abandonment process.

Other important changes will result from the vegetation that develops following fire as, in many cases, the burning of old pine forests generates shrublands or pine forests that are burnt before reaching reproductive maturity, so that it is the shrublands that emerge (Faraco *et al*. 1993; Vallejo and Alloza 1998; Valbuena *et al*. 2001; Lloret *et al*. 2003; Pérez *et al*. 2003, Rodrigo *et al*. 2004). Given that the place where fires occur does not depend on chance, but rather on specific situations, the changes in values caused by the different type of vegetation will probably involve less effort, both with regard to prevention and to alertness, which could accelerate the fire cycle (Trabaud and Galtie 1996). It has been established that in certain areas (Sierra de Gredos mountains), once pine forests have been burnt, they burn again more rapidly (Vázquez and Moreno 2001). This could lead to changes in the landscape, causing an unequal distribution of the vegetation, with areas dominated by shrublands, more susceptible to exposure to ignition sources, and other forested areas, more distant and inaccessible. Precedents of this process have already been described (Mouillot *et al*. 2003). Furthermore, simulations of increased frequency of fires as a result of climate change indicate a gradual dominance by shrublands (Pausas 1999; Mouillot *et al*. 2002).

Situations of increased frequency of fires will become possible if ecosystems are sufficiently fertile to produce the nutrients required for vegetation growth. The establishment of more favourable climatic conditions in mountains and on plateaus could increase vegetation growth, accelerating the previously described process. Imbalances, however, might be expected between nutrient inputs in the inter-fire interval and losses thereof due to fire, which would lead to decreased fertility of the system (Moreno 1999), resulting in a decrease in the generation rate of the vegetation (Díaz Delgado *et al*. 2002).

Theoretically, if the occurrence of fires is limited by fuel (Minnich 1998), we could expect this process, even in the worst possible conditions predicted, to cause a decrease in the incidence of fires, due to the lack of fuel resulting from frequent fires. Higher fire-fighting efficiency would add to this process (Piñol *et al*. 2004). The theory, however, that fires are mainly controlled by weather conditions appears to be more consistent (Moritz *et al*. 2004). In this case, and under conditions of greater danger, an increasingly negative impact of fires is to be expected in many areas, which would be subjected to fires even in early stages of regeneration (Vázquez and Moreno 2001), with the consequent risk of loss of soil fertility.

Changes in human ignition sources

We cannot establish how situations caused by climate change will affect the people deliberately causing the fires. The persistence of high risk situations will provide more opportunities for intentional fires. We cannot rule out the possibility of these people being encouraged by an occasional fire during these situations. With regard to accidental fires, that is, those whose ignition sources is the result of fortuitous human behaviour, the higher climate-related danger could raise the chances of ignition sources ending in fire. To counteract this possibility, there might be a gradual improvement in information and training for the population, as well as greater awareness of the fire problem, and ignition sources can thus be reduced.

12.C.3.4. Future fire regime and factors that could affect this.

Scenarios of the occurrence of forest fires are characterised by a generalised increase in the danger rating indices, longer duration of the fire season and greater frequency of extreme, longer-lasting situations. To this is added the tendency towards a change in vegetation, with greater abundance of shrub species, which are more sensitive to water stress. Consequently, fires can be expected to be more frequent, widespread and intense. These tendencies will vary from one area to another, but will accentuate current tendencies.

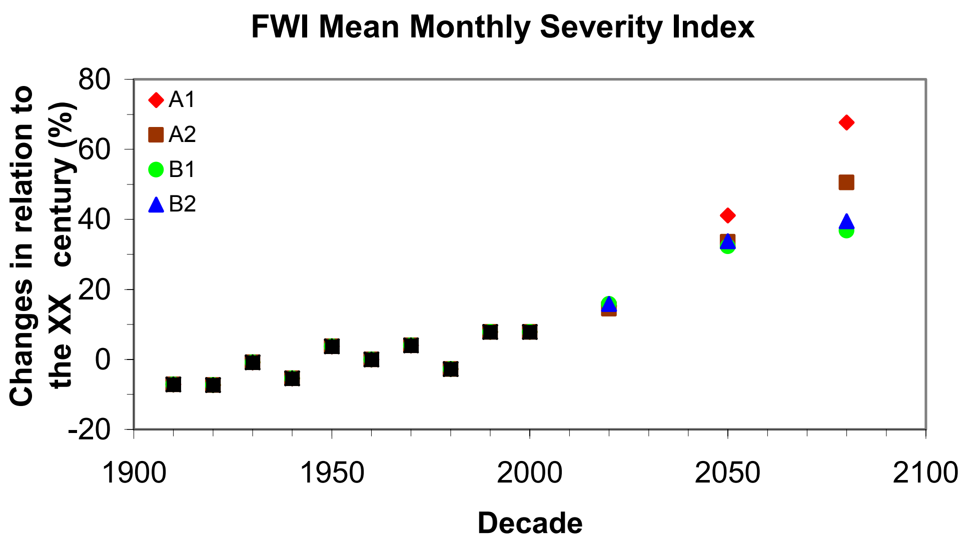

Fig. 12.C.9. *Variation (%) in the FWI mean monthly fire danger index (Canadian Fire Danger Rating System) for Mainland Spain and per decades (the datum refers to the last year thereof) in relation to the average of the XX century for two centuries. The data for the XX century were reconstructed using the ERA base and the one by New et al. (2002), adjusted with real seasonal data. The data for the XXI century are from the predictions by the HadCM3 model, from the Hadley Centre in the United Kingdom, for four emission scenarios, and rescaling according to New et al. 2002. The values of each year are calculated based on the monsths of May through October, inclusive. (Moreno et al. 2005).*

The negative projection of the occurrence of fires with climate change can be counteracted through improvements in weather forecasting, knowledge of the state of fuels, as well as surveillance and prevention strategies. Current weather forecasting enables us to establish, a few days in advance, the possible existence of danger situations. With the passing of time, improvements in forecasting systems will probably enable us to cover longer meteorological periods. Improved capacity to forecast danger could enable resources to be better planned, and, in particular, could help to implement prevention actions in the areas with highest risk levels. In this sense, the drafting of prevention plans for estates and the compulsory registering of burnt areas and associated restoration plans, such as are implemented in some Regional

Autonomies, could help to make all those involved more aware. In this sense, better knowledge of fuels could be of help, in relation either to the quantity and spatial distribution of these, or to their state of hydration and phenology (González-Alonso *et al*. 1997; Chuvieco *et al*. 2003; Riaño *et al*. 2003; Gonzalez-Alonso *et al*. 2004). Likewise, important improvements are expected as a result of the implementation of fire danger systems based on the real conditions in each area, with increasingly smaller resolutions (Carlson *et al*. 2002). This, together with improvements in the surveillance systems will enable us not only to reduce response times, but also to adjust these to the real degree of danger involved in the outbreak of a fire.

In order for the systems to be more effective, a change in fire fighting policies is needed. A policy based strictly on the exclusion of fire could be counterproductive, especially when changes are to be expected in the forest potential of many areas, and the tendency to dominate of shrubland systems becomes more widespread. This will apply more pressure to the forested areas, and defensive strategies based on these areas will therefore need to be articulated. In this sense, there is a critical need for management guidelines aimed at reducing the amount of fuel in areas with greater potential for a large-scale fire. These management guidelines should consider the use of fire as one more of many available tools. This type of strategy may not eliminate the occurrence of certain types of fires, but it only allows these to propagate out of control in extreme conditions.

The expected result is that improved prevention, danger assessment and surveillance will allow many forest fires to be contained before they reach a certain size. Eventually, only the ones occurring in very dangerous circumstances will finally prosper. Consequently, the distribution of sizes could therefore be expected to become more unequal. The recurrence of extreme situations is a clear possibility, and in these circumstances, fire fighting systems are less efficient. The tendency towards a very unequal distribution of fire sizes will therefore become consolidated, along with annual variability. With regard to the causes of fires, greater awareness and education of the population will help to reduce the fires caused by negligence, although the ones caused by lightening will persist and become bigger. Their higher concentration at certain sites and improved forecast means that these type of fires will only be able to occur in extreme situations. The incidence of deliberate fires is impossible to predict.

In short, the higher danger level may be partially counteracted by increased awareness and education. More efficient surveillance and prevention could mean that many focuses of fire are brought under control. However, we can expect those fires occurring in more adverse conditions, which will be more frequent, to prosper, both those caused by man and by lightening. Given that the area affected by a small number of fires determines the total annual burnt area, the latter can be expected to increase, in spite of the fact that few fires escape control by the fire fighting system, and that this area becomes more variable year after year. The maximum size of a fire will tend to increase throughout the whole country, and large fires may occur in places theretofore unaffected. The scenario of large fires appears to be highly likely.

12.C.4. MOST VULNERABLE AREAS

Vázquez *et al*. (2002) showed that, during the 1974-94 period, the proportion in number of big fires (>500ha) was related to high temperatures and a large number of days that had elapsed since the last rainfall. On the other hand, a high spatial and temporal frequency of fires was correlated to high relative humidity. The area affected by medium or large-sized fires, or the seasonal variability of these, was positively related to high temperatures and to the number of days that had elapsed since the last period of rainfall. To the contrary, as with the number of fires, a high proportion of areas (10000 ha squares) with high area burned (>500 ha) was correlated with high relative humidity values. These differences are a good reflection of what occurs on the gradient running from Mediterranean Spain to Atlantic Spain, particularly from the South and East to the North and Northwest of the Peninsula. In the Northwest, fires are relatively small, generalized in the country and occur under milder conditions, as they are caused by humans. In the Mediterranean, this are less frequent, but larger and occur under more extreme conditions.

Under the expected changes, the frequency of high temperatures and number of rainless days will increase, and, as the century elapses, will spread to the whole peninsula, and will become more lasting. On the other hand, it has been observed a positive relationship between the rainfall in one year and the surface burned during the next one (Pausas 2004), which indicates that the global effect of years particularly wet may not be positive. Consequently, we could expect the impact of a more extreme fire regime, subsequent to the new climatology, would be proportionally less relevant in those parts of Spain in which this pattern can already be seen, as it happens in most Mediterranean areas. Because arid areas already experience prolonged drought, it is unlikely that further increases in drought will comparatively have a large impact on fire frequency or size. To the contrary, in the areas in which the pattern of fire occurrence is very different to the one anticipated, as it happens in the peninsular North and Northwest, we could expect the capacity to withstand a new fire regime will to be lower. This is, in areas where prolonged droughts are now rare are most likely to be more sensitive to changes in fire regime. Furthermore, the high spatial distribution of fires in this part of our geography, together with the high degree of deliberateness of these, indicates that these areas are the ones with the highest levels of vulnerability. The above mentioned study demonstrates the existence of a relationship between the proportion of area burned by large fires and the proportion of fires caused by negligence or lightning. In this sense, a change in the pattern of ignition sources in the direction of becoming dominted by fires caused intentionally or by unknown causes to another dominated by fires caused by negligences could conduce to a fire regime that is typical in most Mediterranean Spain, in view of what has been observed in the two decades analysed. The greater abundance of forest in the North and Northwest of Spain permits to conjecture that fire frequency will remain high. The high primary productivity of these areas (Rodríguez Murillo 1997), and the high-stress situations they could be subjected to in the future (see Chapter 9), suggest an increase in the areas in states of regeneration following fire, resulting in greater danger. The most productive areas are the ones with the highest probability of undergoing a change in fire regime in comparison with the present one.

The vulnerable areas are also those in which fires have been relatively infrequent and which, in biogeographic terms, are areas the potential vegetation of which comprises beech forests, high plateau regions with *Juniperus* or high mountain pine and fir forests (*Pinus uncinata*, *Abies*). The increased danger, in some cases (high mountain) combined with the greater pressure upon forest areas, particularly in summer, could lead to fires of unknown frequencies or magnitudes. The lower resilience of these ecosystems to fire could hinder their regeneration after fires, with the consequent danger for the existing vegetation and a change therein. Because of their large area and importance, high plateau areas could be some of the most vulnerable ones.

Finally, the rest of Spain, which is already dominated by fire regime made up of medium to large size fires, with fires more related to negligence or lightning, and defined by high temperatures and long time periods since the last fire, will see this tendency incremented. Once again, the greater or lesser inclination of these areas to develop continuous vegetation in a short period of time, which will vary from one area to another depending on the degree to which productivity is limited by temperature, can cause the spread of these situations, the present pattern becoming more evident. The tendency towards more widespread and intense fires will therefore increase, as will frequency, due to the higher probability of a fire being caused through negligence.

12.C.5. MAIN ADAPTIVE OPTIONS

12.C.5.1. Fire fighting and prevention strategies

The option of fighting all fires in an environment of danger and increasing risk might simply be technically impossible and economically unfeasible. Furthermore, from the ecosystem management point of view, some of these could be managed taking fire into consideration, that is to say, by periodically incorporating fire into management schemes. In this sense, it appears to be necessary to determine where and when a fire is unacceptable at any cost and where or when it can be tolerated or even desirable, albeit in order to minimise the risk of an uncontrolled fire. This can be dome by implementing forest management systems that contemplate the use of prescribed burning (Rodríguez Silva 1998 2004). This is done at present, but will be even more necessary in the future. The concept is that fire can be used to control the types and amounts of fuels. It is generally true (but with noteworthy exceptions) that an area that is burned is highly unlikely to burn for some years. This offers the possibility of using management burns to create zones through which fires will not spread. This is suggested, for example, as a means of protecting areas of economic value and that are sensitive to fire from wildfire, such as young tree planatations, or buildings adjacent to wild areas, etc.. But fire management is not without risks. Anytime fire is set, there is some probability of escapte outside the designated boundaries. Therefore, its use must be made cautiously.

Given the large amount of resources used in combating and preventing fire, and the limited effectiveness that can be expected, in view of the results of cost-benefit analyses (which means to say, investing more resources does not necessarily lead to greater effectiveness (Martell 2001)), there appears to be a need to revise fire fighting policies, fundamentally through changes in prevention strategies, because technical advances in the capacity to fight fire once this has started and been detected seem to be limited. In this sense, fuel management techniques (whether these involve clearing, prescribed burning, the use of herbivores or others) should advance through knowledge of plant species and ecosystems, in order to allow for the integrated management thereof, and should contemplate, apart from fire prevention, the conservation of biodiversity, carbon fixation and the fight against desertification.

Table 12.C.1. *Summary of the main impacts of climate change on fire regime and occurrence in Spain (Scale of 1 to 5).*

Variables related to the occurrence of fires	Change	Certainty
Danger of fire	Increase	*****
Frequency of fires	Increase	****
Maximum size of fires	Increase	*****
Intensity	Increase	*****
Danger zones	Increase	*****
Fire season	Increase	*****
Annual variability	Increase	*****
Fires caused through negligence	Increase	****
Deliberate fires	Increase	**
Fires caused by lightening	Increase	****

12.C.5.2. Silviculture and land uses

Past studies show that, although in the country as a whole, the type of plant cover does not seem to be determinant in the occurrence of fires (Vázquez *et al*. 2002), in certain areas, the fires have been selective, which means to say, they did not affect all the vegetation in the same way (Viedma and Moreno, submitted). Furthermore, it is not easy to make predictions in relation to the commercial values of forest plantations in the near future. If we consider, however, that in the past a considerable amount of plantations were burnt down at early ages (Moreno *et al*. 1998), then we can expect the same to occur in the future. The occurrence of fires in forests with undeveloped soils, which predominate in Mediterranean forests and wildlands, could imply a highly negative impact on edaphic resources, due to the loss of nutrients and soils involved (Soto and Díaz-Fierros 1998; Bautista *et al*. 1996; Andreu *et al*. 1996). The scenario involving rain concentrated in time suggests that the negative effects will tend to increase (De Luis *et al*. 2003). The greater frequency of droughts might be doubly negative, as this limits the development of the vegetation in early stages. Consequently, forest management strategies in the different territories of Spain, including reforestation species, in particular those with a high forest potentiality, should consider the possibility of frequent fires (Pausas *et al*. 2004). The risk associated with soil loss should be calculated in order to verify the suitability of the different land uses.

12.C.5.3. Recreational uses of forest and wildlands

The tendency towards population increase, socioeconomic improvements and the growing interest in remaining in contact with nature suggests that the demand for use of forests and wildlands will increase. Improved education will probably lead to greater sensitivity to risk and less dangerous practices. More intense recreational use of forests and wildlands, however, together with longer periods of activity due to the milder temperatures, could give rise to serious risk factors, although it is impossible to quantify this. We should also consider fire risk in town planning, so that any reclassification of lands for development will take fire into consideration. Furthermore, legislation ought to be reinforced in relation to fire protection in the urban-forest interphase, and measurements designed to implement this.

12.C.5.4. Surveillance and warning systems

Improvements in the surveillance systems, favoured by technological development, will facilitate widespread application, shortening detection and response times, which will constitute a great backup for the fire fighting systems. Furthermore, the possibility of availing of fuel maps with high spatial resolutions, showing the condition of the fuel (moisture content) and adjusted to meteorology, together with the integration in SIG of all the existing information and with the application of fire spread models in the event of an incipient fire, will facilitate rapid and opportune response. Likewise, the availability of *in situ* information provided by remote communication systems and computerisation, will constitute powerful tools for the forest manager for better gauging the imminent danger and improving fire fighting. The capacity for medium-term prediction, with approximate simulations of the worst possible conditions, can allow for better campaign planning. All of this suggests that the capacity to fight fire is increasing, especially in the early stages of a fire.

12.C.6. IMPLICATIONS FOR OTHER SECTORS OR AREAS

12.C.6.1. Forestry sector

Timber and fibre production may be altered by climate change and by increased fire danger. Variations in climate will mean that currently productive areas will cease to be so, and vice versa. These changes will be too rapid and unstable, however, to take advantage of them and to plant forest plantations, given their cycles, which can last up to tens of years. The possibility of forest fires will have to be included as a negative element when dealing with these actions. It is also likely that a growing number of forest plantations will be affected by fire before reaching commercial value. This could reduce the sector's production capacity.

The increased risk of fire predicted is a factor that must be included in any forest management plan. Furthermore, the scenarios upon which some of the present plans have been based, in relation to situations of risk, may become worse. This means that the barriers designed to stop fires, along with the associated fire fighting techniques, may not be as effective as was originally thought. Consequently, forest management plans ought to contemplate a range of future scenarios, including the worst ones, within the temporal framework for which determined planning is designed. This planning ought to take into account the vegetation dynamics resulting from fire, along with the associated risks, under scenarios of increasing danger. In prevention actions, the dimension of the defence elements should be considered in view of the increasing linear intensities of the fire fronts. Given the current and growing importance of CO_2 emissions into the atmosphere, and the role that fires can play in relation to the capacity of forest systems to act as carbon sinks (Rodríguez Murillo 1997), there appears to be a need to predict the feasibility and shortcomings of fire management plans from this perspective, especially with regard to those that could be included within the framework of emissions and sinks of the Kyoto Protocol, and in future agreements.

12.C.6.2. Soil conservation

Frequent drought scenarios, rain concentrated in time and increased fire danger make soil conservation of vital importance, considering that, soil fertility permitting, vegetation can be expected to develop in few years, becoming very dangerous and increasing the occurrence of fires. Consequently, in areas with greater danger of erosion, reforestation plans should be a priority, because in the event of a fire, these allow for sufficient recovery of plant cover to reduce risk. Considering that certain forest species negatively affect some resprouting species (Bellot *et al*. 2004), there is a need for techniques that allow for the presence of these species so that, following a fire, they can produce minimum plant cover (Vallejo and Alloza 1998; Maestre *et al*. 2001) thus increasing resistance to fire.

12.C.6.3. Recreational use

The capacity of forests and wildlands to accommodate visitors, and therefore for recreational use, could be affected. Increased risk of fire and the spread of this throughout the year could lead to restrictions in the use of forests and wildlands aimed at avoiding greater danger, as is already being implemented in some parts of Spain. This, together with the greater demand for available open spaces, could give rise to conflicts, which will need to be solved with the use of appropriate information and education. The areas with the biggest influxes of visitors will require more active and permanent surveillance.

12.C.6.4. Plant and animal biodiversity

A possible increase in the occurrence of fires could lead to the dominance of pioneer vegetation, consequently reducing plant diversity. More frequent droughts, before and after fire, could bring about more widespread and intense fires, hindering the colonisation of species, either because it is more difficult for seeds to be transported from outside the fire zone (Rodrigo *et al*. 2004), or because it is impossible for the species to become established in the temporal window that limits some of these (Quintana *et al*. 2003), which can lead to local extinction. The homogenization of areas recurrently burned will decrease animal biodiversity and can alter the interactions among species (Moreira *et al*. 2001; Torre and Díaz 2004). Fires can therefore cause habitat and species loss. In this sense, the vulnerability of protected terrestrial areas should be considered in view of the growing danger of fire.

12.C.7. MAIN UNCERTAINTIES AND KNOWLEDGE GAPS

12.C.7.1. Relationship between risk and occurrence of fires

As the vast majority of fires are deliberate, the main uncertainty is related to how future conditions can affect human behaviour patterns in relation to causing more or less fires. We could expect people to become more aware of risk, in view of recurring devastating fires, caused by negligence or by high-risk situations, with the consequent reduction of the causes of fire through negligence.

12.C.7.2. Changes in the landscape and occurrence of fires

One of the foundations of fire fighting involves the importance of landscape structure in determining the spread of fire (Minnich 1983; Green *et al*. 1990). Consequently, in some countries, actions have been implemented aimed at favouring the diversity of the landscape mosaic. However, in the environments dominated by crown fires, whether these be in shrublands or in forests with complex structures, it seems that landscape structure plays a less important role, with regard to stopping fire, in extreme conditions (Johnson *et al*. 2001; Keeley and Fotheringham 2001). Although we know that spatial heterogeneity at the very least helps in management and extinction work, it is undoubtedly one of the most unknown elements in forest planning. Until we have made a better appraisal of how landscape structure conditions the spread of fires in different risk situations, the land planning applied or any real assessment of danger in a given area will continue to be uncertain.

12.C.7.3. Interactions with other impacts

There is a clear possibility that prolonged droughts will affect vast areas, thus causing the generalised or selective death of certain species and brusquely influencing the danger status of a territory (Peñuelas *et al*. 2001). There will also be interactions with certain pathogenic agents which will cause the death of their hosts (Hodar *et al*. 2003), thus increasing dead biomass. This will influence the hazardousness of the system for a long time, due to the deposit of dead material which can remain standing, without decomposing, for years.

12.C.7.4. Changes in the use patterns of forests and wildlands

It is likely that changes in the use patterns of forests and wildlands will constitute one of the most relevant alterations to be expected. On the one hand, due to the greater demand for recreation; on the other, because of increased residential use. We can only expect an increase in the dangers posed by these uses with regard to ignition sources or to the damage that could be caused in the event of a fire. The tendency towards residential use of forests and wildlands or of forest habitats, which is already occurring in many places (the coast, the vicinity of big towns), involves pressure with the associated and growing risk which is difficult to quantify.

12.C.8. DETECTING THE CHANGE

Detection of change in the occurrence of forest fires in Spain is difficult because of the lack of historic data covering the XX century, with the exception of the final part. Fortunately, the EGIF database of the General Direction for Biodiversity (MIMAM) is sufficiently complete to appraise possible tendencies. Analysis of this type is hindered by the fact that, parallel to the collection of data, there have been socioeconomic, demographic and landscape changes, while forest management policies have been modified and a high level of fire fighting capacity has been reached. Consequently, the climate factor is one more of those affecting the phenomenon of fires, but it is not the only one.

Given the close relationship between fire danger rating indices and the climatic variables determining these (temperature, humidity, rainfall and wind), we can expect the changes detected to have influenced the fire danger rating indices, as available data appear to indicate (Fig. 12.C.9). The identification of possible tendencies in the occurrence of fires is even more complicated if we consider the huge annual fluctuations (Fig. 12.C.1). The instability of the landscapes and of the fire fighting or prevention policies hinders the availability of reliable indices for the detection of change. Among the possible indices parameters could be considered which are based on the distribution of sizes (Vázquez and Moreno 1995; Duguy 2003), either for the whole of Spain, or, preferably, for ecologically similar zones. Other possible indicators could be those related to the effective duration of the fire season, or to the temporal variability in the occurrence of the fires, based on use of accidental ones. An increase in danger level could be expected to cause the earlier appearance of more regular fires.

The biggest problem with regard to determining possible changes in the occurrence of fires is the lack of capacity to predict the number of ignitions, their temporal and spatial distribution and thus their propagation potencial to develop a fire. Unlike fires caused by man, the characteristics of those started by lightening can be established with certain accuracy. Consequently, it would be possible to appraise tendencies in the occurrence of fires by considering the number of discharges and the magnitude, type and location of these.

12.C.9. IMPLICATIONS FOR POLICIES

12.C.9.1. Fire fighting

Climate change and the possible effects of this on fire danger will inevitably affect fire fighting and prevention policies. These policies should focus on managing complex systems, such as forests, that is to say, ecosystems in which fire will be unavoidable when all is said and done. We must therefore decide how these ecosystems are managed and what role, if any, is to be given to fire. Thus, consideration should be given to whether fire is excluded at any cost, or whether it can be accepted under certain circumstances. And, if this were to be the case, where and when will be acceptable that a fire may be the result of clearly established management objectives. In some cases the decision will involve extinguishing the fire, and in others, when the values at stake are not very high, or less important than the resources needed to stop the fire, or if the greater danger is minimised, the fire may be tolerated. It may even be necessary to consider introducing fire under controlled conditions. There is no single recipe for all forest ecosystems in Spain, or for all the situations that can arise. A flexible management system should therefore be implemented, with clear objectives aimed at protecting all the values at stake, firstly people's property and lives, but also the ecological sustainability of the system. In scenarios of greater danger, the policy involving the total elimination of the fire may simply be unfeasible, or undesirable due to the amount of resources required to attain certain levels of efficiency which, in the end, will never quite reach the objectives established (Piñol *et al.* 2004). Climate change should therefore evoke debate on fire fighting and prevention policies.

12.C.9.2. Conservation of biodiversity

At present, conservation policies rarely include fire as an element of the management of protected areas. Besides, no models have been applied to the ecosystems protected, aimed at predicting the impact of a fire. Neither are there any predictions of the impact of conservation management itself, and even less so in relation to how climate change will interact with fire. Consequently, there is a need for models adjusted to the ecosystems subjected to protection, that consider the eventuality not of a fire in itself, but rather of risk situations that increase the frequency, intensity or magnitude of fires. There is a pressing need for appraisal of the vulnerability to fire of the ecosystems and of the protected species.

12.C.9.3. Combating desertification

Part of Spain’s territory, particularly the East of the Peninsula, is affected by desertification processes (Puigdefábregas and Mendizábal 1998). Furthermore, forest fires are a recognised cause of desertification. The fight against desertification, especially in areas with less plant cover, now involves a difficult choice. On one hand, a lack of vegetation cover causes soil loss, and on the other, abundant plant cover increases the risk of fire. With regard to this dilemma, the worst possible scenario is one of frequent fires, because the transitory elimination of plant cover can cause increasing loss of soil and nutrients. In scenarios of increased danger, it is therefore necessary to develop models that simulate the processes involved and serve as guidelines for the management of these territories.

12.C.9.4. Land planning in areas subjected to fire risk

Increased afluence in the last few decades, along with the new tendency to develop part of the forest and wildlands for residential use, have given rise to a new situation in our environment. This tendency can be expected to grow, especially in those areas where there is limited land available for development, such as the coast and residential areas in the mountains. Increased risk of fire in the future can seriously endanger residential areas which were previously safer. Planning of these areas should therefore take into account fire danger and the possible scenarios of climate change.

12.C.10. MAIN RESEARCH NEEDS

There is a need to refine our knowledge of the synoptic conditions that correlate with high fire danger. This requires study of long-term meteorlogical records. With such refined knowledge it will be possible to place fire suppression teams on alert in advance of probable fire incidents

Monitoring data that track the amount, nature, and condition of fuels is needed for all areas susceptible to wildfire. These data need to be translated into a format that allows fire suppression teams and land managers to assess the times and places where fires pose the greatest risks. There must be annual updating to record areas burned. We need to evaluate what is burnt, where this occurs and with what frequency, to evaluate the risk of recurring fires, in order to maintain the integrity of the ecosystem. The risks of “worst scenario possible” type situations should be quantified in order to get a better idea of the budding risk.

The projections by the GCMs are not spatially or temporally precise enough to be of practical use in fire management and suppression. Progress must therefore be made in projections by the GCMs at the required spatial and temporal scale. There is also a need for socioeconomic scenarios adapted to the reality of Spain.

We need to understand fire in a landscape context . We must improve our understanding of how management actions affect the fire susceptibility of landscapes. Careful thought must be given to the need to protect certain landscape elements. Advances need to be made in relation to knowledge of the interaction between fires and landscape, as this is the basis of forest planning. There ought to be studies aimed at verifying to what degree risk conditions make the landscape more or less relevant in relation to fire. Research and development of techniques for the management of ecosystems threatened by fire should progress and be based on multifunctional management of our forests and wildlands, in order to respond to multiple threats and objectives.

There is still a need for study of the impact of forest fires on the capacity of ecosystems to fix or release Carbon. Direct measurements of C flows in different ecosystems are needed, and of the factors controlling these and their interaction with fire.

Adverse climatology, specifically drought, not only increases danger, it also can have other adverse effects. For example, the soil moisture levels will affect germinatioin and establishment and by determining the level of plant hydration, may control the capacity of plants to resprout after fire or other disturbances (Cruz *et al*. 2002; Quintana *et al*. 2004). More detailed knowledge is needed of how response by plants varies in extreme situations, particularly in drought. Given that the temporal window for the establishment of certain species is limited, periods of no rain may be more relevant that how much it rains, if there is no rainfall at the right time. Experimental simulations in different ecosystems could indicate what is to be expected in the eventuality of extreme droughts.

Assessment of the state of fuels, of their biomass and moisture, in relation to climate, and at temporal and spatial scales of detail, is vital in the prediction of situations of maximum danger in time and in space.

Further work must be done on the social aspects of fire. Because the actions of humans are so important in all aspects of fire, it is necessary to understand to what degree changes public attitudes and private actions can ameliorate or exacerbate changes in the fire regime due to climate change.

Finally, scenarios of climate change and danger and impact of fires need to be applied in protected areas, in order to assess the vulnerability of these to the growing risk of fires.

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