



Climate change in the Pyrenees: impacts, vulnerability and adaptation

Bases of knowledge for the future
adaptation strategy of the Pyrenees



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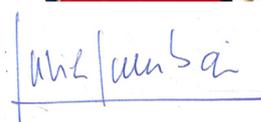
Download the full report and the executive summary in ES, FR, CAT or EN in the information portal of the Pyrenees Climate Change Observatory: <https://opcc-ctp.org/>

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Report on climate change in the Pyrenees

Since its 2010 launch under the Midi-Pyrénées presidency, the Pyrenean Climate Change Observatory of the Pyrenean Work Community (CTP) has worked to analyse the climate change vulnerability of different populations as well as natural, economic, and social sectors throughout the Pyrenean cross-border region through the development of appropriate methodologies and a collaborative perspective.

Following the Observatory's line of work, the CTP produced a report in 2018 that updates knowledge on the repercussions of climate change in the Pyrenean cross-border region. This report includes the scientific basis for the impact of climate change and its repercussions in the region, as well as an abstract of the sectoral recommendations for the subsequent adaptations proposed. These knowledge bases are essential to shape policy regarding how to most efficiently adapt to climate change, take advantage of emerging opportunities, and maximise positive synergies with other sectoral policies. Without question, its added value resides in the spirit of cooperation marked both by its conception and production. Some 100 leading experts and scientists from both sides of the Pyrenees participated in the report. They collaborated on writing the report, as well as the various review processes that provide this document with wide scientific consensus. It should be underscored that, without the long history of cooperation, work through the network, and international visibility with organisations such as the Carpathian Convention or the European Environment Agency, it would be impossible to create reference documents such as this report. The vision of this report is that of the Observatory, which sees the Pyrenees as a unique "bioregion" that does not adhere to administrative borders, and whose social, economic, and biophysical systems are particularly vulnerable to climate change. As with other studies already presented in other regions, the scientific evidence presented in this report shows that mountainous regions are experiencing temperature increases higher than those in low-lying areas, and that the impact of climate change is more intense. Specifically, impacts in the Pyrenees are already being observed in all natural and socio-economic sectors, such as the accelerated disappearance of sensitive ecosystems and iconographic elements such as glaciers; the alteration of many species' life-cycles, including certain endemic species; the influence of climate change on natural resources associated with tourism and agricultural activities, and changes observed in the water cycle. Climate change is positioning itself as an added stress factor that aggravates problems the Pyrenean region already faces, such as depopulation, changes in soil use, or a lack of generational replacement in the primary sector. The CTP understands the fight against climate change, and the need to adapt to its impacts, as transversal instruments that offer a multitude of opportunities to address challenges in the Pyrenees that are, in turn, global challenges. For this reason, through local action, the CTP is helping to achieve the UN's Agenda 2030 Sustainable Development Goal 13, Climate Action.



D. Francisco Javier Lambán Montañés
CTP President

1. Background and objectives

The Pyrenees Climate Change Observatory (OPCC) is a cross-border cooperation initiative by the Working Community of the Pyrenees (CTP) on climate change and adaptation. The purpose of the Observatory is to gain a better understanding of the phenomenon of climate change and monitor its impact on the territory in connection with global changes. With this goal, the Observatory coordinates studies and issues scientific and technical reports, to serve as the basis for identifying adaptation actions. In some cases, actions to limit the negative impact of climate change, and in others, to take advantage of emerging opportunities.

As recognised in the European Commission's EU strategy on adaptation to climate change (2013), a solid scientific basis is essential for the design and implementation of the most appropriate adaptation measures. For this reason, since it was launched in 2010, the OPCC has drafted various reports and studies on adaptation to climate change in the Pyrenees. However, every day the scientific community reveals new evidence and refines its study methods to offer new and valuable information, which must be added to our store of knowledge to facilitate decision-making on adaptation.

This new publication was prepared in the context of the OPCC2 and provides additional value to previous reports. Efforts have been focused to ensure the

participation of a large part of the scientific community of the Pyrenees and to use a common approach and agreed standards on the use of language.

This report focuses its efforts on ensuring the participation of much of the scientific community of the Pyrenees, and the use of easily understandable language without sacrificing scientific rigour.

The goals of this report are:

- Updating the bases of scientific knowledge on climate change impact and vulnerability in the Pyrenees, in the main biophysical and socio-economic sectors.
- Reaching a scientific consensus on the main challenges of climate change for the Pyrenees.
- Proposing sector-specific recommendations for adaptation to climate change in a context of global change.

It is hoped the report will be a benchmark document for the scientific community, technical and political decision-makers, the business sector, and for society in general, in the Pyrenees and beyond. For more detailed information, see the full report.

2. Methodology

The "Report on climate change in the Pyrenees: impacts, vulnerability, and adaptation" was drafted collaboratively, with the involvement of over 80 climate change experts. It is divided into three chapters:

- Past, present and future climate variability in the Pyrenees.
- Observed and projected biophysical impacts.
- Observed and projected impacts on key socio-economic sectors.

The report was coordinated by the Working Community of the Pyrenees as the OPCC2 project coordinator. The OPCC2 project partners coordinated and drafted part of the chapters.

The content was based on an exhaustive meta-analysis of the most recent scientific literature on the subject. The chapters were complemented by contributions and reviews by experts from outside the OPCC2, who voluntarily contributed to the multiple reviews of the report.

The report was also complemented by selected scientific presentations from PYRADAPT 2017, the 2nd International Colloquium on Climate Change in Mountain Areas, organised by the OPCC2 project and held in Biarritz on 7-8 November 2017.

3. The climate in the Pyrenees

Climate variability in the past

To understand current climate change and place it in a global context, we must be aware of how the climate evolved in the past. The interactions between the atmosphere, the hydrosphere and the cryosphere operate on longer time-scales than those of instrumental measurements. The study of glacial, river and lake deposits, and related studies, allows us to reconstruct how the climate of the Pyrenees changed in the past.

During the Quaternary (the last 2.6 million years), alternating glacial and interglacial periods sculpted the landscape of the Pyrenees and determined the evolution of its ecosystems, and more recently, of its human communities. Although this series of cold and warm periods affected the whole planet, the glaciers of the Pyrenees reached their maximum expansion 60,000 years ago, not 20,000 years ago as in the rest of Europe, with slight variations between valleys. This was due to the southerly location of the Pyrenean glaciers and the interaction of North Atlantic with subtropical atmospheric and oceanic processes.

Over the last deglaciation period, average temperatures changed by up to 6 °C, with periods of rapid climate change when they changed by over 1 °C in just a few decades. In the Holocene (the last 11,700 years) temperature changes were smaller, but there were many alternating wet and dry phases. In the last millennium, there was a particularly dry, warm phase (the Medieval Warm Period or Medieval Climatic Anomaly, 900 - 1,300 CE) which can be considered the most similar period to our own in terms of climate change.

The period was followed by the Little Ice Age, the last cold phase (1,300 - 1,850 CE) before the global warming we are now experiencing. Climate variability over the last 2,000 years is mainly controlled by interactions between atmospheric processes (NAO, the North Atlantic Oscillation; EA, the East Atlantic Oscillation; and SCAND, the Scandinavian Oscillation), changes in ocean currents, solar radiation and volcanic activity. These interactions can also explain regional and temporal humidity and temperature gradients. Temperatures rose more quickly during the global warming of the 20th century than in the glacial-interglacial transitions and the changes of the Holocene. To put it another way, Earth's climate is changing faster than it ever has before.

The current climate



From 1959 to 2010, the average temperature of the Pyrenees clearly rose, although the warming was neither constant nor regular. Negative anomalies predominated in the period up to 1980, with a trend towards cooler temperatures. Beginning in the 1980s this trend was reversed, with positive anomalies systematically increasing until the present day. The trend towards average annual temperature increases over the entire period analysed is positive and statistically significant, with a value of 0.2° C per decade (Figure 1).

This temperature increase over the last 50 years (1959-2010) is found throughout the Pyrenees mountain range, with little difference between the northern and southern slopes, and is more marked in summer (June, July and August).

The warmest year in the series was 1997, with a mean temperature 1.5° C higher than the average for the period 1961-1990, followed by 2003 and 2006. In contrast, 1972 was the coldest year, 0.8° C below the baseline average, followed by 1963 and 1980.



The precipitation figures mainly show decreasing annual volumes, due especially to lower precipitation in winter and summer. The climate indicator for precipitation shows a downward trend of around 2.5% per decade over the last 50 years (according to data for 1959-2010).

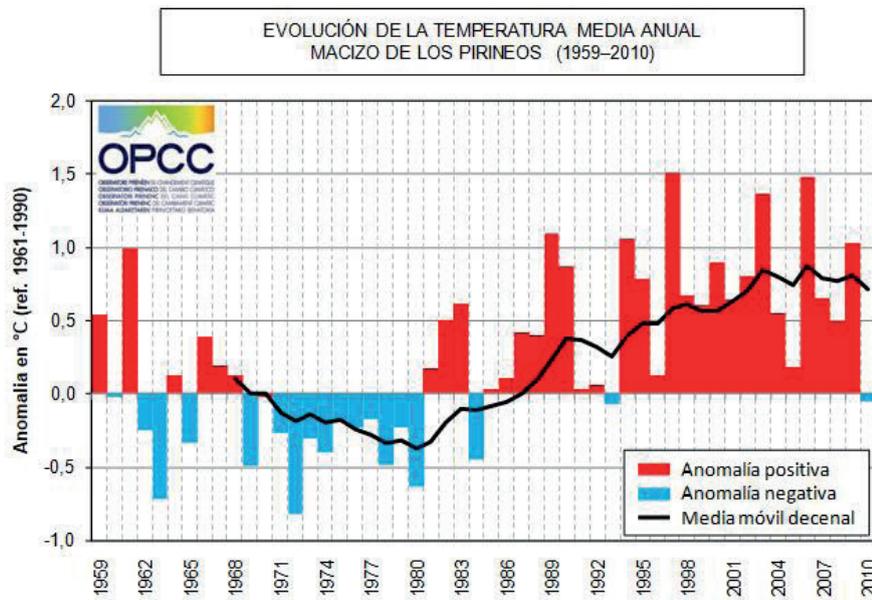


Figure 1. Average annual temperatures in the Pyrenees as a whole in the 1959-2010 period. This shows the annual anomaly in relation to the average value of the reference period 1961-1990 (in red, positive; in blue, negative) and the evolution of the moving average for a 10-year period (black line). Source: OPCC1 project

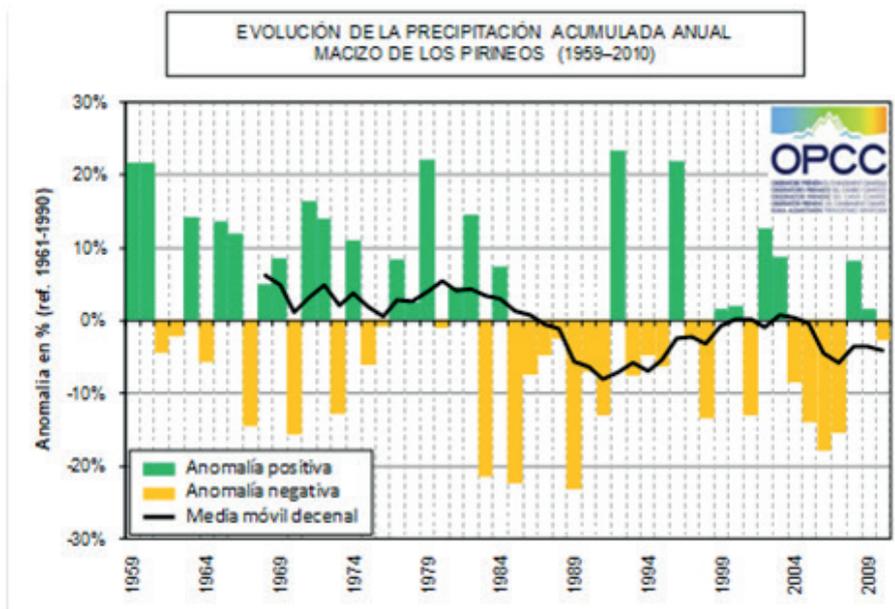


Figure 2. Average annual precipitation in the Pyrenees as a whole in the 1959-2010 period. This shows the annual anomaly in relation to the average value of the reference period 1961-1990 (in green if positive, in yellow if negative) and the evolution of the moving average for a 10-year period (black line). Source: OPCC1 project

The value of this trend varies widely from year to year, and even between decades. In general, in recent decades dry years have been predominant, with annual precipitation amounts well below the average for the reference period, but interspersed with some very rainy years, with precipitation above the average for the period. In terms of territorial differences, annual precipitation has decreased more on the southern than the northern slopes, although the contrasts are not large. Although the trend to lower precipitation does not present clearly seasonal or statistically significant behaviour, it is slightly more marked in winter and summer.



The analysis of changes in snow cover over the last half-century is difficult, given that we lack sufficiently continuous and robust historical data. This is because installing and maintaining the instruments to take the necessary measurements becomes more difficult at higher altitudes. However, the series of data from the network of beacons on the south side indicate a statistically significant decrease in snow cover in this sector from 1950 to the present (Figure 3).

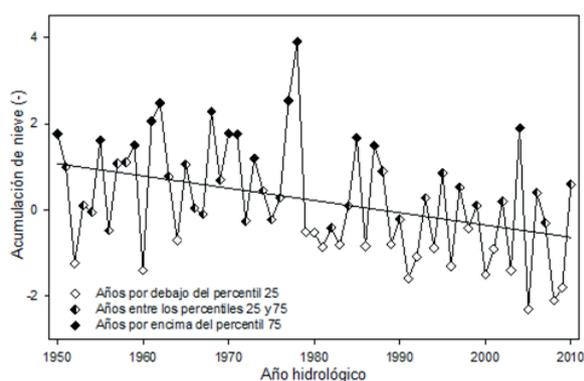


Figure 3. Evolution of the snow cover (in meters) in the month of April, between 1959 and 2010, simulated from the relationship between winter temperature and precipitation and snow accumulation in a beacon of the Izas Canal, Aragón Valley. Source: Project OPCC1

Future climate projections

Despite the uncertainties relating to future socio-economic scenarios and the limitations of the numerical models used for climate projections, the main climate models agree that global warming will intensify over the coming decades, especially in mountain areas. This may mean an intensification of climate variability and of the trends already identified in the main climate variables. If these projections are confirmed, this could lead to major effects on the climatic, hydrological, environmental and landscape characteristics of the Pyrenean bioregion.

The preliminary results of climate projections carried out in the context of the CLIMPY project (based on the data from a set of global climate models and combinations of regional climate models), considering the four global scenarios for emissions concentration RCP2.6, RCP4.5, RCP6.0, and RCP8.5 (RCP for "Representative Concentration Pathways", where RCP2.6 is the most optimistic scenario and RCP8.5 is the most pessimistic), were used for a first probabilistic approach to project future climate, summarised below:

- According to these projections, a significant rise in the daily maximum and minimum temperatures is expected throughout the 21st century, in the three emissions scenarios analysed (RCP4.5, RCP6.0 and RCP8.5) (Figure 4), in every season of the year across the entire Pyrenees area. This increase would be faster in RCP8.5, in relation to a more intense emissions scenario. The uncertainties associated with the RCP scenarios and global climate models increase over the century.
- Para el horizonte 2030, el aumento del valor medio anual de las temperaturas máximas respecto al período de referencia (1961-1990) podría estar, en promedio y para toda la zona pirenaica, entre 1° C y 2.7° C para la RCP8.5. Aumentos parecidos o ligeramente más bajos se obtienen para las temperaturas mínimas (entre 0.9° C y 2.2° C para la RCP8.5).
- For the 2030 horizon, the average annual change across the Pyrenean region in maximum temperatures compared to the reference period (1961-1990) could range from 1.0 C to 2.7 C for the RCP8.5. Similar or slightly lower increases were obtained for the minimum temperatures (0.9 C to 2.2 C for RCP8.5).
- For the 2050 horizon, warming would be somewhat higher. Increases in maximum temperatures would range from 2.0 C to 4.0 C

for RCP8.5, and 1.4o C to 3.3o C for RCP4.5, while increases in minimum temperatures would range from 1.7o C to 3.3o C and from 1.2o C to 2.8o C respectively.

- For the end of the century, the ranges of values are even wider, the changes are even larger, and the separation between the scenarios associated with the different RCPs is clearer. With RCP8.5, the average annual increase maximum temperature change over a year would be between 4.3oC and 7.1oC, while for RCP4.5 it would range from 1.9oC to 4.2oC. For

minimum temperatures, the corresponding intervals would range from 3.6 oC to 6.0 oC, in the first case, and 1.6 oC and 3.5 oC in the second.

- Future precipitations are not predicted to change significantly over the 21st century, with little influence on their evolution, at least in terms of average values (Figure 5). The number of models showing average precipitation rising is similar to the number of models showing it decreasing. The uncertainties increase as we approach the end of the century, especially in the case of RCP8.5.

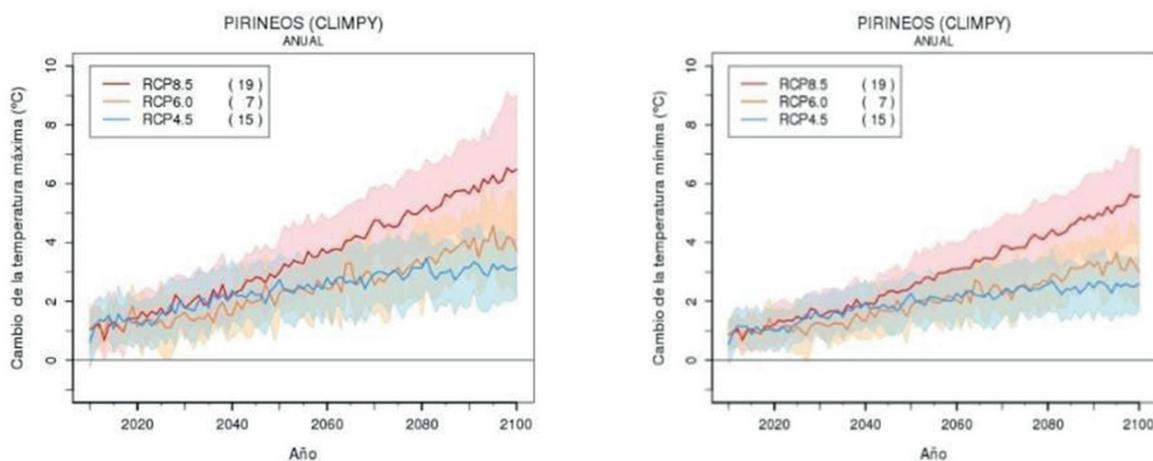
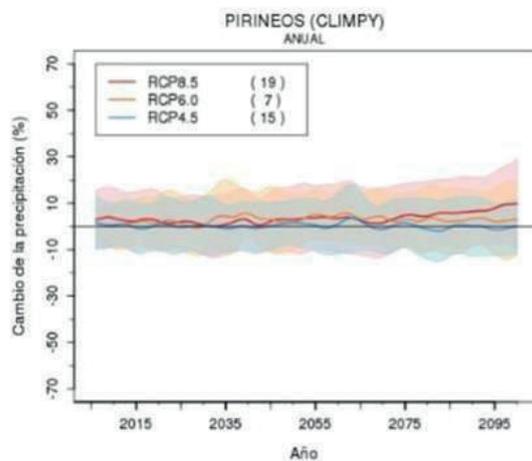


Figure 4. Evolution of the average of the maximum temperature annual anomaly (left) and minimum temperature (right) using different RCP scenarios. The numbers in brackets indicate the number of climate simulations considered for each RCP. Source: CLIMPY project



The preliminary results of the CLIMPY Project regarding the evolution of average snow depth in the Pyrenees show a significant decrease despite a marked variability between years. In the Central Pyrenees, at an altitude of 1,800 m, average snow depth could fall by half by the 2050 horizon according to the current baseline, while the period of snow cover would have fallen by more than a month.

Figure 5. Evolution of the average precipitation anomaly considering different RCP scenarios. Source: CLIMPY project

4. Climate change impacts on biophysical sectors and recommendations

4.1 Mountain biodiversity: fauna



Marmot of the Pyrenees in the Panticosa ski resort. Source: Etienne Valois

Global warming could lead to changes in the productivity and abundance of high mountain species.

Temperature changes and extreme weather events influence the most sensitive mountain species. While some species are able to adapt, the health of others may be affected, with negative effects on their productivity, and therefore on their abundance.

- The physiological state and abundance of some mountain birds, such as the rock ptarmigan, are already changing due to climate change.
- Amphibians are among the vertebrate groups most vulnerable to climate change. Considerable population loss has been observed in Pyrenean brook salamander populations, coinciding with years of extreme climate conditions such as floods and droughts.

Climate change may lead to alterations in the life cycle of different species and their interactions.



The dates of important events in animals' lives, such as reproduction, nesting, migration and hibernation, are changing because of rising temperatures.

- Migratory birds have been arriving an average of 0.16 days earlier per year since 1959.
- Some changes in birds' life cycles seem to be related to heatwaves, droughts, and intense precipitation.

- In recent decades the first sightings of many butterfly species have been getting earlier, and the rising temperatures appear to be the main cause.

Animal species often respond to global warming by changing their distribution.

Many species respond to climate change by moving to higher areas in search of the climate conditions in which they can thrive. These movements can be very negative for species at the edges of their current distribution area, as is the case for many mountain species.

- It has been estimated that in recent years European species have moved to higher altitudes by an average of 11 m per decade because of global warming.
- These upward movements are limited by the physical limits of the mountains themselves, but are also often restricted by the fragmentation of habitats and changes in land use.
- Some species may become increasingly isolated in the remaining small areas of suitable habitat, making them more vulnerable and even putting them at risk of extinction, due to a shortage of food and the gradual shrinking of their gene pools.

The combined effect of climate change impacts may negatively influence the functioning of ecosystems.

Mountain species often respond very differently to the combined actions of climate change impacts. This may lead to a loss of synchronisation between mutually dependent species, such as plants and pollinator insects, or predators and prey. If these key interactions between species are changed, this could lead to significant alterations in some processes which are fundamental to the health of mountain ecosystems.

- Climate change could be negatively affecting the ability of insect pollinators to pollinate plants, with serious repercussions on ecosystems.
- Desynchronisation is affecting migratory birds such as the cuckoo, and many butterfly species, among others.

Climate change could increase the risk of expansion of invasive species and other harmful species already present.

Climate change could increase the risk of non-native species invading and becoming established in the Pyrenees, as the new climate conditions make it easier for them to reach and settle in new areas. Meanwhile, some invasive species may be favoured by milder winters.



- Non-native species adapt better to rapid changes in climate, compared to most native species.
- Native species shifting to higher altitudes due to climate change often reduces competition, giving newly arrived species an advantage.
- Some invasive species such as the pine processionary are already proliferating more, and reaching higher altitudes, because of climate change.

The movement of animals and plants in search of suitable climate conditions may influence the connections between the natural spaces of the Pyrenees.

Some protected areas, which until now were interconnected by natural or artificial corridors, will probably become isolated for certain species which cannot tolerate the new climate conditions of the corridors.

- The effects of climate change on these interconnections may be especially notable in protected spaces with endemic species which have little ability to disperse, or which are highly specialised.
- The movement of animals and plants in search of suitable climate conditions may bring them to areas outside the present protected reserves, increasing their vulnerability to many threats.

RECOMMENDATIONS:

- Promoting new networks to observe the biodiversity of high mountain areas and incentivising their use, and ensuring the mid- and long-term maintenance of existing observation networks.
- Encouraging the inclusion of climate change adaptation in the current plans, programmes and other planning tools for the protection of biodiversity in the Pyrenees.
- Reducing the fragmentation of habitats and, as far as possible, ensuring a gradual increase in ecological connectivity among protected areas in the Pyrenees.
- Encouraging studies which combine climate factors and anthropic risks.
- Promoting collaboration and information sharing among the competent organisations in all the sectors involved.

4.2 Mountain biodiversity: flora

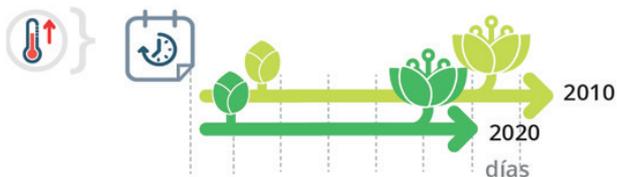
Androsace ciliata DC., an endemic plant of the Pyrenees. Source: CBNPMP/C. Bergès

Global warming alters the growth and changes the productivity of many plant species.

Changes in the different climate parameters and higher concentrations CO₂ in the atmosphere influence photosynthesis and affect the growth and development of all flora.

- The response of mountain plants to extreme conditions may lead to critical situations if these conditions are exacerbated by climate change, and also if new more competitive species arrive.
- Paradoxically, the decrease in snow cover caused by climate change reduces its insulating effect in winter, exposing high mountain flora to extreme temperatures.

Climate change alters the life cycle of many high mountain plants.



Climate change is leading to changes in the different stages of plants' life cycles, such as the earlier appearance of the first shoots in spring, or longer growing seasons.

The combined action of climate change and human activity can alter the distribution, components, and diversity of high mountain plants.



According to studies in other mountains, the combined effect of climate change and human action is causing changes in the distribution of different species, altering the characteristic flora composition of mountain communities, reducing their diversity and favouring the acceleration of the thermophilisation process.

- A general trend has been observed towards an increase in species that need warmth, and a decrease in those that need cooler conditions (a phenomenon known as thermophilisation).
- In higher-altitude areas inhabited by specialist species adapted to the cold, changes in distribution may lead to their local extinction due to the gradual disappearance of the conditions where they can thrive.

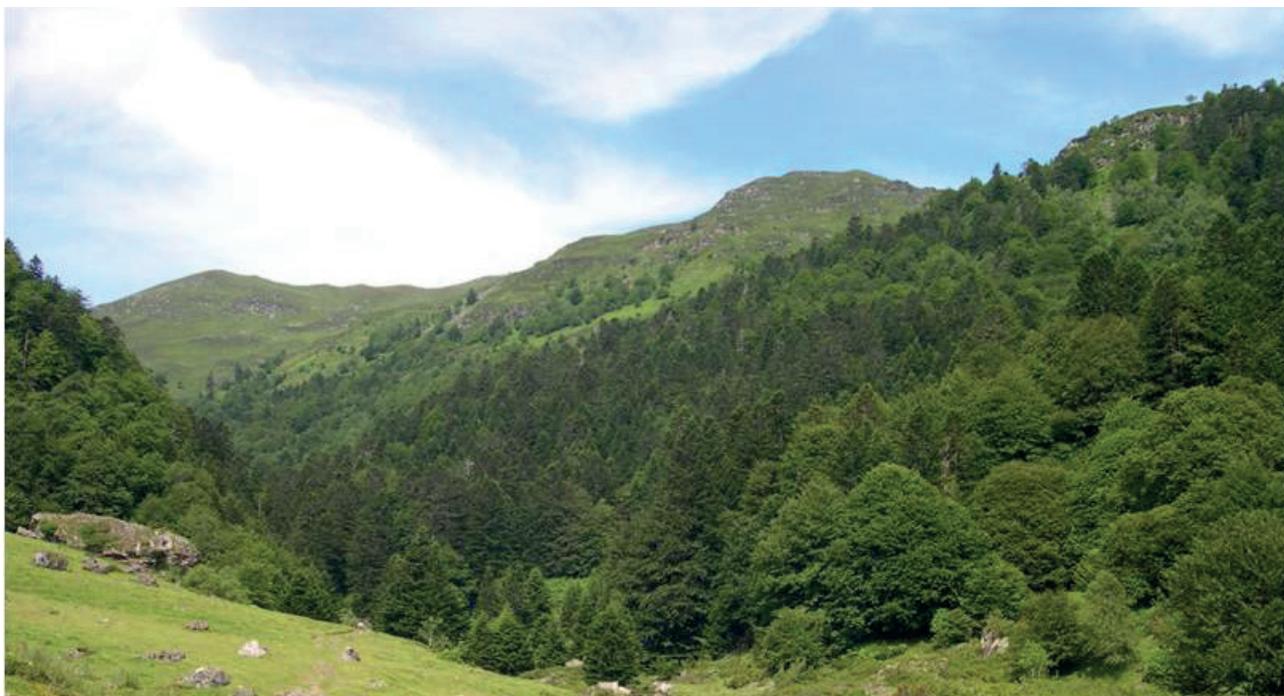
The sum of climatic and anthropic factors may lead to changes in the flora of the Pyrenees, to the point of endangering the capacity of the territory to provide important goods and services.

The alteration of the composition, life cycle and distribution of flora, combined with changes in land use and other human-caused stress factors may lead to alterations in the ecosystems, endangering key ecosystem services such as the conservation of sensitive species and ecosystems, the maintenance of ecological continuity, the educational and scientific value of typical mountain flora, and the region's attractiveness as a holiday destination.

RECOMMENDATIONS:

- Reconsidering management goals in the light of the new climatic challenges, but with the difficulty of uncertainty about future scenarios (particularly precipitation), from a pan-Pyrenean viewpoint.
- Reducing human-caused pressures at the local scale which may limit the ability of biodiversity to adapt to climate change and other changes (fragmented ecosystems, new species, genetic contamination, etc.).
- Recognising and improving the functions of protected spaces in the Pyrenees and their interconnections.
- Preserving areas identified as "reserves", with special attention to areas with populations of rare or threatened species, and areas less likely to be affected by climate change.
- Strengthening existing monitoring resources (long-term funding) and launching new ones (evolution of genetic diversity).

4.3 Forests



Pyrenean forest. Source: Forespir

Global warming and changes in land use are altering the diversity and distribution of many plant communities and forest species in the Pyrenees.



The combination of climate change and the gradual abandonment of mountain agropastoralism is altering the composition and structure of Pyrenean woodlands. However, there is a marked spatial and temporal variability in these processes, and changes do not always follow the established patterns.

- Over the last 50 years, on the southern slopes of the Pyrenees, we have seen the edge of the wooded area shift by a total of 35 metres - over half a metre per year.
- The combined effect of the gradual abandonment of mountain agropastoralism and of climate change impacts is leading to trees recolonising abandoned pastures.

Climate change may affect the productivity of forests and their ability to sequester atmospheric carbon by photosynthesis.



Rising average temperatures plus the concentration of carbon dioxide in the atmosphere have a fertilising effect on trees.

In areas of the Pyrenees where enough water is available, the productivity of woodland may increase due to climate change. However, it is probable that the increased numbers of heatwaves and droughts projected for the coming decades will limit the availability of water for plants, thus reducing the productivity and health of many Pyrenean forests. The increase in extreme phenomena (storms, wildfires, and invasive species) will also impact their ability to act as a carbon sink.

- If forests' health deteriorates, so too will their ability to grow, and consequently their ability to sequester atmospheric carbon and contribute to mitigating climate change.
- Forest management and the timber industry play a fundamental role in mitigating the effects of climate change, since they help to improve the health status of forests, thus increasing resilience to climate change.

Changes in forests health and the possible imbalance with pathogenic agents.

Extreme climatic events such as drought, heavy rainfall and heatwaves influence forest health. We must also consider the effect of pathogenic agents on these woodlands, taking into account that new invasive species are arriving and that this is expected to continue.

- Over the last 20 years there has been an increase in leaf loss and branch dieback in the top of the Pyrenees' forest canopy.
- We have also seen more pests in forests, coinciding with years when there are droughts, heatwaves, and extreme precipitation.
- The arrival of non-native pest species is expected to lead to new diseases and health problems in the Pyrenean forests.

Climate change could influence the capacity of forests to protect us from some natural hazards typical of mountain areas.

Mountain forests play a vital role in protecting the population and infrastructure from natural hazards such as floods, landslides, and avalanches. This role could be affected by climate change impacts on forests.

- Changes in the composition and structure of forests caused by climate change influence their capacity to reduce the impact of natural phenomena.
- Droughts and heatwaves, together with the expansion of some forest pests, can influence the health of forests, reducing their capacity to protect us from natural hazards exacerbated by climate change.

Climate change could increase the number and intensity of forest fires in the Pyrenees.

Rising temperatures, and especially longer and more intense droughts, could lead to a higher risk of major forest fires in the Pyrenees.

- As the availability of fuel increases (more dead wood), fires could be more intense.
- More years with high frequency heatwaves and droughts could increase the years with a high risk of forest fires, especially in summer and autumn.

RECOMMENDATIONS:

- Improving awareness throughout the Pyrenees of the effects and impacts of climate change on forests (particularly those which are more vulnerable in the mid- and short terms) and the adaptation processes (natural or anthropic).
- Maintaining and developing agriculture, grazing and forestry in mountain areas to ensure sustainable management of these environments with multiple effects: reduction of the volume and continuity of fuel for fires, a mosaic of habitats for greater overall resilience, limitation of risks, and growth of the resilience of forests to climatic or healthcare accidents.
- Encouraging the transmission of technical and scientific expertise and advances to non-specialist audiences.

4.4 Sensitive high mountain ecosystems



Acherito Mountain lake. Source: Jon Larrañaga

The projected impacts on the lakes and peat bogs of the Pyrenees due to climate variability are added to those caused by human activities (dumping heavy metals, introducing fish, adding more nutrients and sediments, hydroelectricity and grazing).

Droughts and changes in precipitation patterns can lead to alterations in the hydrological cycle, changing the amount of water available in high mountain lakes.



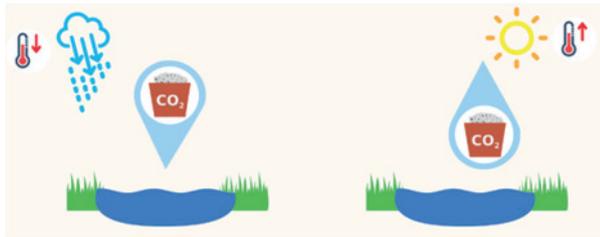
More frequent and intense droughts combined with changes in the distribution of precipitation could considerably reduce the availability of water in mountain lakes at certain times of year (especially summer and autumn).

Changes in the hydrological regime, together with rising temperatures, may change the physical and chemical conditions of lakes, with negative consequences for plant and animal communities.

Rising temperatures cause the direct warming of water in the lakes and reduces the duration of ice caps and snow cover around them.

- Deeper lakes can be expected to respond more slowly to physical, chemical and biological changes, given their greater size and thermal inertia (they warm and cool more slowly than shallower lakes).
- Rising temperatures may affect the thermal regime and dynamic of the lakes, as well as altering the chemical composition of the water (increased alkalinity), increasing the concentration of nutrients, and affecting the abundance of certain plant and animal communities typical of these environments, and often unique.

The effects of climate change could accelerate the degradation of Pyrenean peat bogs and reduce the area of wetland.



The increased variability of precipitation in the high mountains could increase the frequency and intensity of droughts and floods, with possible changes to the wetland areas of the peat bogs,

- An increase in torrential rainfall could lead to increased erosion of the peat bogs, which could be exacerbated by their drainage and the effect of over-grazing in the areas around mountain lakes.

Climate change could reverse the current role of peat bogs as carbon sinks, making them emit carbon instead of capturing it.

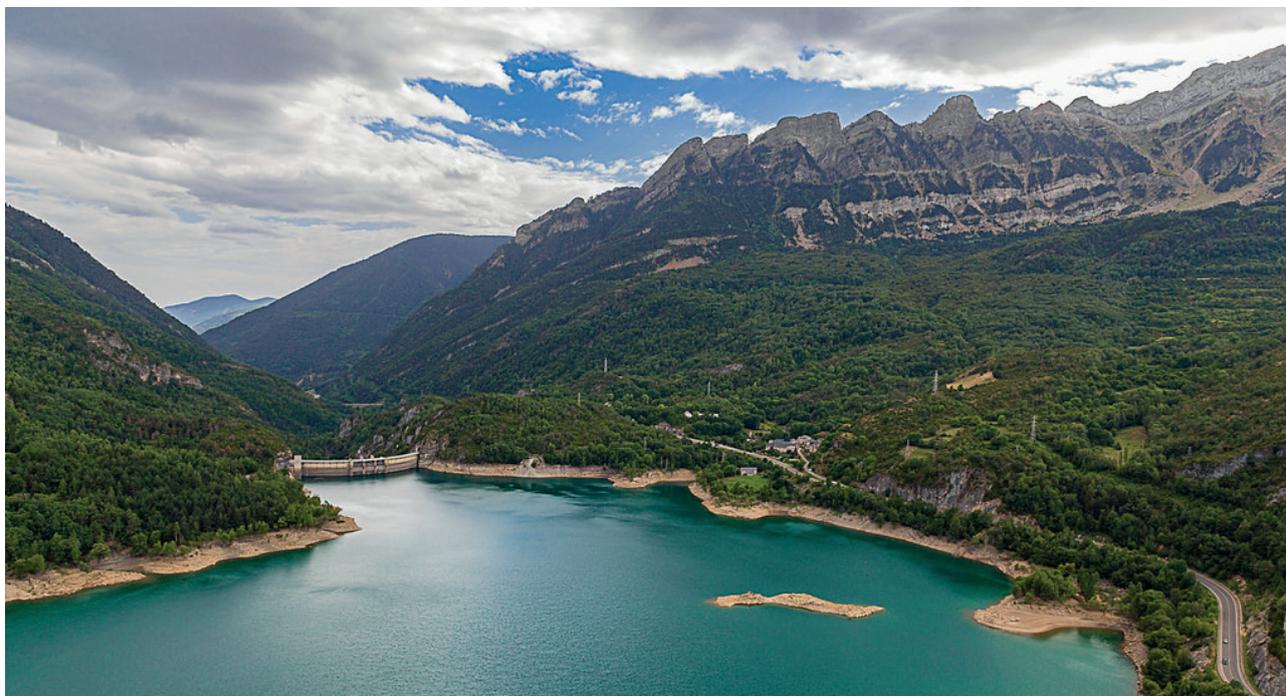
Rising temperatures and reduced wetlands could accelerate the decomposition process of peat bogs, which would increase the emissions of CH₄ and CO₂, the main greenhouse gases responsible for global warming.

- This would mean that instead of these ecosystems acting as carbon sinks as they do now, this important ecosystem service could be reversed and the peat bogs could become net carbon emitters.

RECOMMENDATIONS:

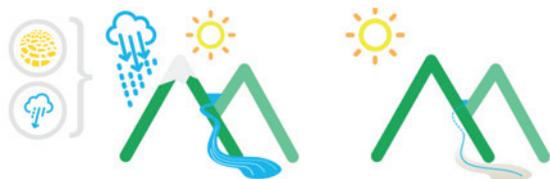
- It is important to keep analysing recent trends and future changes in high mountain lakes and peat bogs from a point of view which includes climatic and anthropic factors at the global scale (nutrient dumping, pollution) and at the local scale (specific effects on tourism in each area).
- Establishing and maintaining observation networks and detailed monitoring of these ecosystems and developing integrated projects within them with the participation of all the agents in the territory.
- Empowering eco-tourism with minimum impact on protected spaces and maximum integration of citizens in their conservation.
- Offering incentives for adapting mountain tourism companies to the goals of sustainable conservation and management of these ecosystems.

4.5 The hydrological cycle and water resources



Bubal reservoir. Source: Etienne Valois

Climate change may cause changes to the rivers and lakes of the Pyrenees, especially in the annual contribution of the rivers.



Climate change has generated changes in the average annual contributions of many rivers of the Pyrenees over recent decades. However, these changes are attributed both to climate causes and to changes in land use and plant cover, making it difficult to quantify the influence of each factor separately.

- In the Ebro basin significant decreases of more than 50% in the annual flow rate of the gauging stations studied from 1950 to 2010 have been registered.

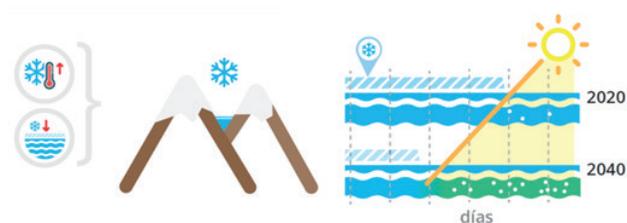
Global warming could also be leading to changes in monthly river regimes.

- The decrease in the accumulation of snow each winter due to higher temperatures and less frequent precipitation in the form of snow is leading to higher flow rates in winter.
- In contrast, more frequent and intense droughts are leading to lower river flow rates in summer and autumn.
- The accumulation of snow below 1,500 m could be reduced by 78% by the last quarter of the 21st century.

Climate change could also affect the quality and quantity of groundwater.

- Surface water and shallow aquifers are especially sensitive to changes in climate.
- The changes in the water balance mentioned above can be expected to influence the recharging and discharging of the aquifers and may cause water scarcity in areas without sufficient reservoir capacity.
- Aquifer recharging could be reduced by up to 20% in some areas of the Pyrenees by the middle of the century. This could mean a reduction of the flow rate in many springs.

Rising temperatures and changes in the water cycle caused by climate change can alter the physical and chemical characteristics of water in the Pyrenees, affecting its quality.

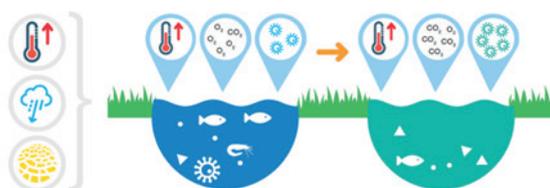


Droughts and longer periods with low water levels have a direct effect on the chemical composition of water, as the reduced amount of water increases the concentration of pollutants, lowering its quality. On the other hand, more frequent and intense floods could lead to increased inputs of nutrients and human-caused pollutant substances in rivers. This close relationship between quality (chemical and ecological) and flow rate has been fully recognised and integrated in the European Water Framework Directive.

- The combination of low flow rates and the presence of toxic substances affecting aquatic biological communities is causing structural and functional problems in river ecosystems.

The various impacts of climate change on water masses may have serious effects on their biological composition.

As rivers and streams become warmer, warmwater fish will displace coldwater fish from their habitat.



- As a consequence of climate change a widespread redistribution of different species of freshwater fish to higher altitudes has been observed.
- Climate change is also affecting algae communities, and water productivity in general, due to a greater concentration of nutrients, higher temperatures, and more hours of sunlight in the case of high mountain lakes.

RECOMMENDATIONS:

- To meet the challenges of climate change in relation to water resources, we must take a comprehensive view of management of the territory, with a new approach to the territorial distribution of water use.
- To deal with knowledge gaps, the studies of climate change impact on the hydrological cycle in the Pyrenees must be reoriented to consider the mountain range as a whole, integrating both northern and southern slopes in a single unit.
- It is also necessary to promote the development and maintenance of climate change monitoring networks, including indicators which facilitate the monitoring and characterisation of climate change impacts on the water balance.

5. Climate change impacts on socio-economic sectors and recommendations



Cross-country skiing in the Aragonese Pyrenees. Source: Mikel Ortega

5.1 Tourism

Climate change and its effects on the duration of snow cover may make some ski resorts in the Pyrenees less attractive for winter tourism.



The last few decades have seen a reduction in the number of days when skiing is possible (days with snow cover of 30 cm, enough for normal skiing at a ski resort). Also, the snow line has gradually moved higher. The large-scale production of artificial snow as an adaptation measure, apart from endangering the profitability of ski resorts, involves a series of environmental externalities which must also be considered, especially with a future scenario of relative water scarcity.

- From 1960 to 2010 the number of days a year with a layer of snow less than 30 cm deep has increased notably at all ski resorts and all altitudes, but especially at lower altitudes (from 5% to 70% in low-altitude ski resorts, and from 4% to 20% at medium altitude ski resorts).

- The start of the skiing season has also gradually become later (depending on the availability of natural snow), with delays of 5 to 55 days in low-altitude ski resorts and 5 to 30 days in medium altitude resorts.

Climate change could have irreversible effects on some iconic elements of the Pyrenean landscape.



Climate change could lead to major changes in the landscape, arising from the acceleration of the degradation process of some iconic elements of the high mountain landscape such as peat bogs, glaciers and mountain lakes.

- Changes in the composition and distribution of flora and fauna in high mountain ecosystems could contribute to reducing the beauty of the characteristic scenery of the Pyrenees.
- From 1984 to 2016, more than half the known Pyrenean glaciers recorded in 1984 disappeared, and those that remain are considerably smaller in mass and surface area, and rapidly receding.

The influence of climate change on the main natural hazards may particularly affect the integrity of tourism infrastructure and tourist safety.

The influence of climate change on hydrological and geological hazards and the risks arising from extreme climatic events appears to be an element of instability which can inflict serious damage on tourism industry infrastructure.

- Sudden floods caused by more frequent intense precipitation and landslides relating to increased freeze-thaw cycles may be the most critical elements for the sector.

Gradual warming, particularly milder temperatures in autumn and spring, may lead to a longer mountain tourism season in the Pyrenees.

Longer summers and increasingly mild spring and autumn temperatures, together with higher minimum temperatures, could mean that more people will choose tourist destinations in the mountains rather than hotter and less comfortable destinations.



RECOMMENDATIONS:

- Adjusting tourism development models to strengthen the sector's ability to recover from a probable shorter skiing season and greater environmental pressures on its activity, while enhancing emerging opportunities for nature and mountain tourism (the mountain seasons concept).
- Reducing the vulnerability of tourism infrastructure to possible increases in extreme hydrological, geological and climatic events, and ensuring tourists' safety.
- Promoting balanced management of water resources in the tourism industry, with special attention to watersheds fed by rainwater.
- Ensuring people's safety from weather and climate hazards which could be exacerbated by climate change (floods, heatwaves, poor air or water quality, and deterioration of permafrost).

5.2 Mountain agropastoralism



"Colors d'estiu" in Andorra. Source: Soraya Cristina

Climate change could have both positive and negative effects on agriculture in the Pyrenees.

A shorter frost season and increased average temperatures could favour more Mediterranean style crops. On the other hand, dry farming could be negatively affected by lower water availability.

- The number of days with frost in the Pyrenees is estimated to have fallen by around 0.3 days per decade over the period 1985 to 2014.
- Crops such as grape vines and olive trees might be able to expand to the mountains thanks to global warming.
- More frequent extreme weather events such as late frosts, heatwaves and droughts could counter some of these positive results.

It is very probable that lower availability of water, changes in the crop calendar, and the increased risk of damages due to extreme climate events will mean lower overall crop productivity.



- Climate change is considered one of the main factors associated with stagnant performance in cereal crops, despite continuous technological progress.
- The wheat flowering stage was an average of 0.3 days earlier each year from 1985 to 2014.
- The summer heatwaves of 2003 and 2010 are estimated to have caused 20% more losses than the averages of other years.

Climate change could favour the expansion of some plant pests and diseases.

Greater susceptibility to the diseases caused by climatic stress conditions could lead to variations in the patterns of distribution and dissemination of current pests and diseases, and raise the risk of expansion of new illnesses.

- The new climate conditions could create areas with the ideal climate for the expansion of invasive species already introduced in warmer areas.
- Extreme climate events can cause stress conditions in crop plants, increasing their vulnerability to pests and diseases.

The new climate conditions may influence the productivity and quality of Pyrenean pastures.

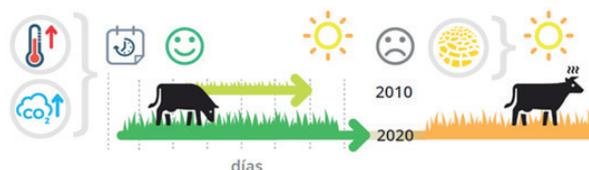
As long as the summer and autumn droughts are not severe, the higher temperatures and greater concentration of carbon in the atmospheric could have a fertilising effect on high mountain pastures, increasing their productivity. However, this phenomenon could affect the composition of fodder, and reduce its quality as feed for livestock.

- It has been shown that after very intense summer droughts, it is much more difficult for autumn pastures to recover.
- Increased concentrations of carbon in the atmosphere also has a negative effect on pastures, altering their composition. Droughts and heatwaves also have negative effects on pasture, making them less appetising and digestible for livestock.

Other consequences of climate change in pastures includes the alteration of the composition of the plant communities and diversity of species.

- Climate change is acting in synergy with the current trend towards degradation of agro-ecosystems and the gradual abandonment of high mountain agropastoralism in many areas of the Pyrenees.
- Climate change is encouraging the expansion of very competitive herbaceous plants and shrubs which displace other species, leading to a loss of plant diversity.

Rising average temperatures and heatwaves directly affect the health and well-being of animals.



High temperatures affect animals, leading them to eat less, which alters their nutrition and productive performance. This may affect the economic performance of some intensive farming ventures at the mid-mountain level.

- It is highly probable that heat stress situations for livestock will also be more frequent and intense in the Pyrenees.

The new climate conditions may increase the spread and prevalence of livestock diseases.

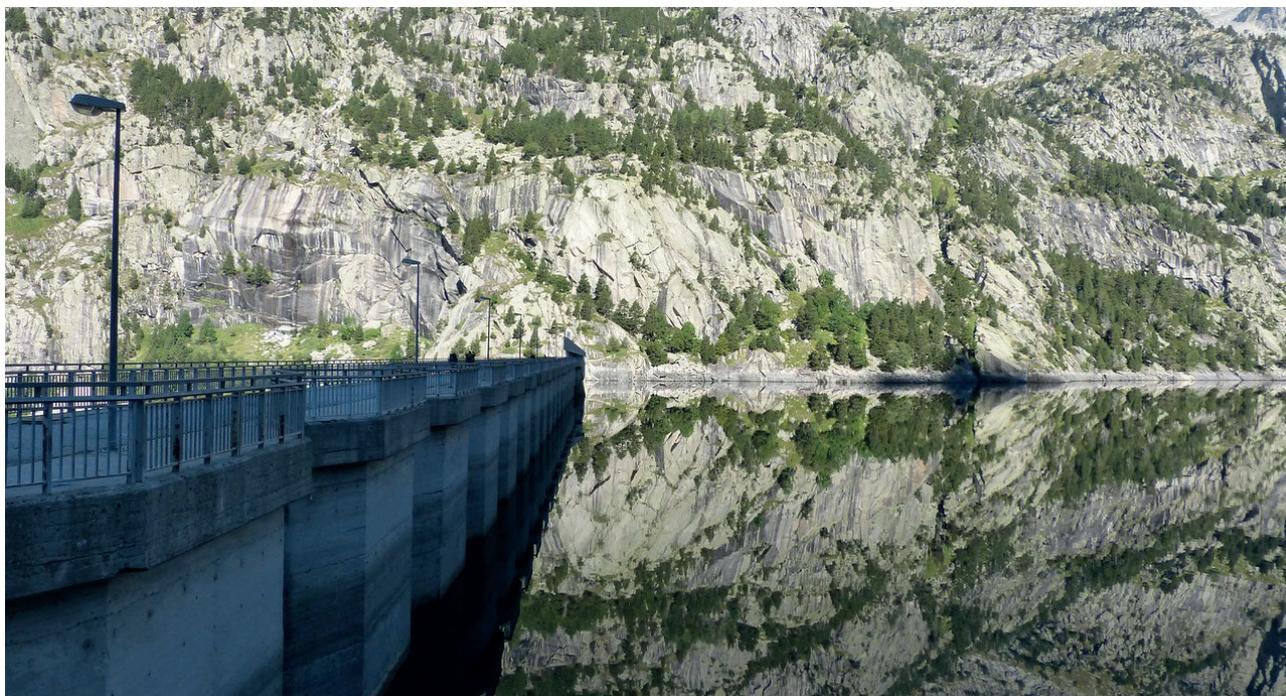
Climate change, along with greater mobility of goods and people, is the main factor involved in the more widespread appearance of livestock diseases and their vectors.

- Diseases which used to be tropical, like bluetongue, have gradually expanded along the northern slopes over recent years, partly because of climate change.

RECOMMENDATIONS:

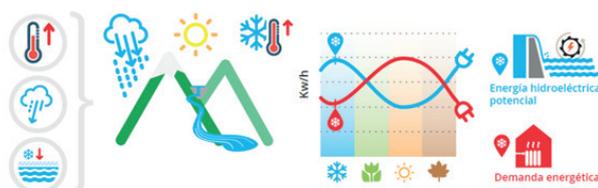
- Reducing uncertainties about the largest risks, possible negative effects and future pressure on the agropastoral ecosystems of the Pyrenees.
- Increasing the resilience of mountain agropastoral systems to climate change pressure.
- Favouring sector management measures which ensure a sustainable use of water resources in the context of comprehensive management.
- Strengthening the surveillance systems that detect emerging pathogens and diseases in livestock and crops.
- Limiting the abandonment of the sector and incentivising its diversification and modernisation in order to meet the challenges of climate change and other changes.

5.3 Energy



Estany de Cavallers Dam, Pyrenees.

The impact of climate change on the hydrological cycle may affect the capacity of hydroelectrical plants to produce power at certain times of year.



Changes in the precipitation regime and thaw dates affect the accumulation capacity of the reservoirs used to produce hydroelectricity.

- The droughts of 2003, 2005, 2007 and 2012 led to considerable reductions in hydroelectricity production in the Ebro basin and the Haute-Garonne.
- The early snow melt, caused by the high temperatures, is ahead of the spring peak flow rate of the Pyrenean rivers. This situation often means that many reservoirs fill up during rainy seasons.

Solar power production could be favoured in the future by an increase of the solar radiation index throughout the Pyrenees mountain range.

The expected changes in cloud formation and steam in the atmospheric caused by climate change may derive from an increase in total solar radiation, with positive effects on solar energy production.

- The potential production capacity of photovoltaic energy could rise by 10% in the mid-century in relation to the current capacity.
- However, this increase could be altered by the rising temperatures, which negatively affects photovoltaic systems, and by the damage caused by extreme weather events.

Wind power production could be negatively affected by climate change over the coming decades.

The changes expected in wind patterns and the reduction of their average speed at ground level (up to 9% slower) could reduce the potential production by around -1 MWh/day in relation to current values and over the course of this century.

Seasonal demand for energy is likely to vary considerably over the coming decades due to rising average temperatures and heatwaves.

Increasingly mild winters and warmer summers marked by heatwaves have led to changes in the structure of energy demand for heating and cooling.

- It is very probable that energy demand will increase in the coming years to meet the growing need for cooling in summer (peak demand).
- This increased demand could coincide with the time when the ability to generate hydroelectricity is lower due to the typical summer droughts and the growing demand for water for other uses (agriculture and human consumption).
- If heatwaves become more frequent and intense, as is predicted by the main models, peak demand periods in summer could also become more intense and create problems of supply and conflict with the agricultural sector.

Energy production and transport infrastructure could be affected by the expected increase in natural hazards.

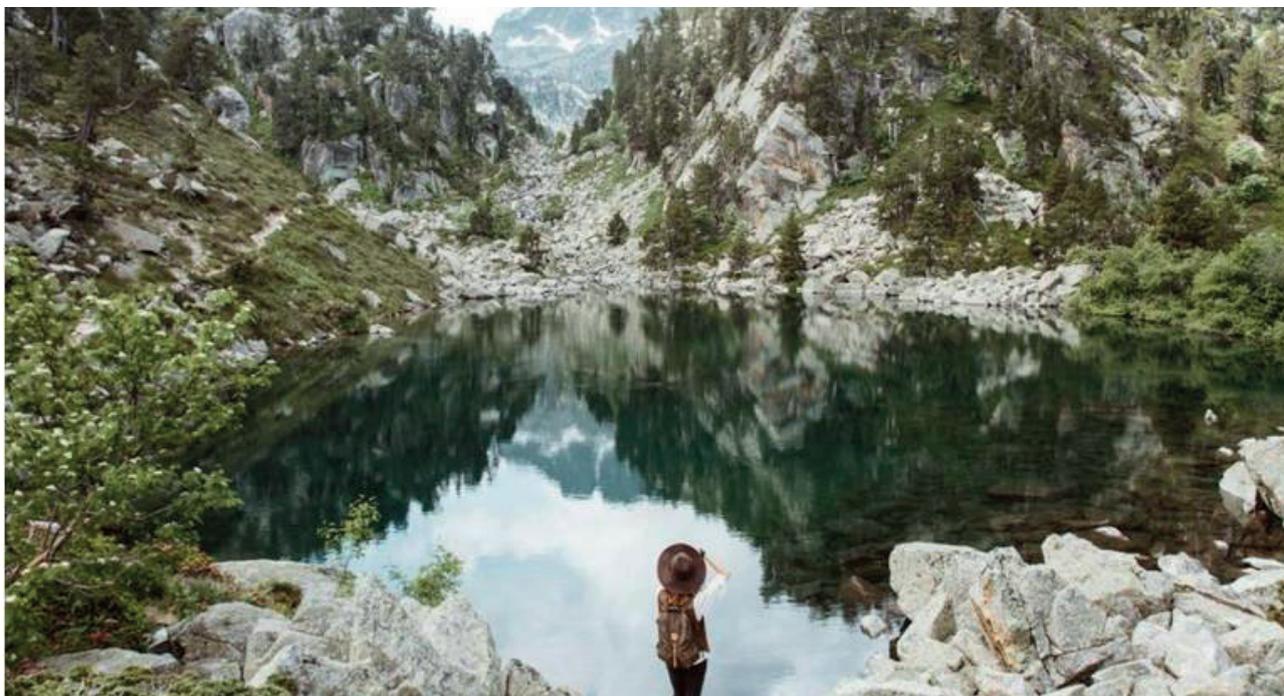


Many of the energy infrastructures and power transmission and transformation systems on both sides of the Pyrenees are particularly exposed to climatic risks and the natural hazards they cause or exacerbate.

RECOMMENDATIONS:

- Diversifying energy sources, prioritising renewable energy.
- Fomenting transition to a model of renewable energy generation and distribution, replacing the current model of centralised production.
- Optimising the use of water resources in the production of hydroelectricity and thermal energy.
- Adapting the management of the energy sector to possible variations in demand.
- Encouraging the rational use of energy in all the socio-economic sectors of the Pyrenees, especially in peak tourism periods.
- Investigate the potential limitations of the current energy system for dealing with climate challenges.
- Ensuring the distribution network has a good capacity for response and recovery in extreme climate events.

5.4 Natural hazards



Estany Gerbert Mountain Lake

It is highly probable that the Pyrenees will see an increase in extreme weather phenomena.

Although the best documented changes are in heatwaves, it is very probable that droughts, intense rainfall, and cold waves will also become more frequent and intense over the coming decades, while hailstorms will increase in intensity only.

Global warming could influence the frequency and intensity of floods.

Changes in the precipitation regime, together with earlier thaws in spring, could cause more frequent and intense flooding in the next decades. While there is no clear trend across the territory, since there are many factors in play, particularly an increase in the amount of forest and changes in land use, this trend could be masked.



- In recent decades "once in a century" floods have become more frequent in much of the Pyrenees, although they have caused less damage thanks to efforts to reduce exposure levels.
- Because of the ongoing process of rural depopulation and the increase in wooded areas, it is very probable that in the future the problem will affect certain tourist-oriented areas of the Pyrenees.

The greater climate variability arising from climate change could lead to more frequent landslides, rockfalls, avalanches and similar events.



We can expect natural events, usually triggered by weather and climatic factors (high temperatures, intense precipitation) to be more frequent in the future.

- The rising temperatures and heatwaves have led to an increase in rockfalls, landslides, mudslides, and similar phenomena.
- In some areas of the Pyrenees there has been an increase of very large mudslides in recent years.
- However, it is still difficult to define the exact relationship of the intensity of precipitations and the rising temperatures with the increase in events such as falling masonry, landslides and collapses.

Rising average temperatures can lead to an increase in the risks associated with accelerated degradation of the glaciers and frozen areas.

Global warming will probably alter the dynamic of the frozen areas and glaciers of the Pyrenees, altering their stability. This could increase the risk of more potentially dangerous episodes, such as rockfalls and landslides, especially in steeply sloping areas.

- In recent years, increased landslides have been detected on the north-west face of the Vignemale, associated with deterioration of permafrost (permanently frozen land), undoubtedly due to degradation processes caused by high temperatures.

RECOMMENDATIONS:

- Reinforcing local characterisation studies of natural hazards, including as far as possible future climate projections (e.g., replacing the current baseline values with others that include possible climate evolution in the risk calculation models).
- Prioritising the selection of robust measures, which will effectively reduce vulnerability to natural risks, whose results are positive regardless of the evolution of the climate and uncertainties (e.g., combining nature-based solutions with structural and management measures).
- Improving knowledge of climate change impacts on natural disasters, and in particular: developing an inventory of existing flood prevention measures, creating maps of natural hazards, creating tools to help the decision-making process integrating climate projections.
- Maintaining and optimising the current systems for monitoring the different natural hazards to improve monitoring in high altitude and/or difficult-to-reach areas, while also strengthening cross-border cooperation to pool resources in obtaining and processing information.

6. Conclusions: the 10 challenges of climate change in the Pyrenees

1. Preparing the preparation to deal with extreme climate events

In recent decades Europe has seen an increase in frequency and intensity of unprecedented heatwaves. Especially in cities there has been a considerable increase in mortality connected to these extreme events, due to the "heat island" effect. According to the EU, during the heatwaves of summer 2003 there were around 70,000 premature deaths in Europe associated with this heat stress. The scientific community agrees that over this century there will be an increase in climatic phenomena such as torrential rain, severe droughts, heatwaves and cold waves. While mountain areas like the Pyrenees, which are cooler and less populated, have been less affected so far, it is probable that they will be feeling the heat more often in the future. This could not only affect the health of their inhabitants, but could also impact the energy sector (peak demand for cooling), mountain agropastoralism (quality and productivity of pastures), the health of the most sensitive ecosystems, and even tourism.

2. Increasing safety precautions against natural hazards

The precipitation regime has also changed in recent decades, with increases in intense precipitation and droughts. The increase in extremely intense rain, plus the gradual shift to earlier spring thaws, could lead to a higher risk of floods and landslides, especially in late winter and early spring.

From 2010 to 2016, average annual losses were around 12.8 billion euros, representing about 83% of the monetary losses of EU member states. From 1981 to 2015 there were 77 floods in Catalonia. 23% of them were catastrophic and 51% were "extraordinary", with a total of 100 deaths. At the same time there were 97 catastrophic events from 1981 to 2010 in the Occitania and Nouvelle-Aquitaine regions, with a total of 94 deaths. There were extraordinary floods in Andorra in 1907, October 1937, and November 1982. This last one also caused deaths. Meanwhile, the acceleration of the deglaciation processes and permafrost melting could increase risk situations in the high mountains: areas which had previously been stable could become increasingly unstable and susceptible to potentially disastrous episodes such as sinkholes, collapses, mixed avalanches and landslides on the steepest slopes. These phenomena may endanger some tourist enclaves, population centres and other infrastructure (transport,

energy, or ski resorts), especially in high mountain valleys. Connected to droughts and heatwaves, the frequency and intensity of forest fires could also increase, with potential implications for health, forest ecosystems and infrastructure.

3. Support for actors in the territory in dealing with water shortages and droughts

The main climate models predict increased intensity and frequency of droughts in the coming decades. It is likely that climate change will affect the water resources of the Pyrenees, both in terms of supply (quantity and quality) and from the point of view of demand (water needs).

Significant declines in annual and seasonal flows have been detected in the Ebro and La Garona basins. On the other hand, the future recharge and discharge of aquifers could decrease slightly. These phenomena would logically affect water resources availability (surface and underground) and quality.

Water crises affect several socio-economic and biophysical sectors at the same time, causing impacts on agriculture and agropastoralism (less availability of water for irrigation, less productivity and lower quality fodder), on the production of hydroelectricity (hydroelectric dams), on tourism (water restrictions), and on the ecosystems health.

4. Guaranteeing the quality of surface water and aquifers

Climate change and changes in land use have affected and will probably continue to affect the flow rates and water quality of Pyrenean rivers. Droughts and dry periods reduce the dilution factor of the pollutants which reach the rivers, leading to a concentration of pollutants and thus to poor water quality. Meanwhile, floods tend to drag materials along and stir up pollutants in sediments. Higher temperatures, in synergy with a higher concentration of pollutants, will often alter the chemical and biological processes involved in water quality, with a negative impact on biological communities. Changes in the precipitation regime and climatic extremes can also have a negative influence on groundwater quality and the aquifer recharging process.

5. Keeping the Pyrenees attractive to tourism

Climate change could be decisive in determining what conditions are necessary for certain tourist activities in the Pyrenees. In particular, the greater variability in the depth and duration of snow cover could be a challenge for ski resorts, which must adapt to keep skiing seasons operational and ensure their businesses are sustainable. Meanwhile, climate change is altering the environment with contextual negative effects on some Pyrenean ecosystems. In particular, aspects such as the presence or absence of certain iconic species of fauna and flora, the quality of the ecosystems and the state of iconic natural formations such as glaciers could be affected by climate change, leading to a loss of tourist interest. However, the higher temperatures could have a positive effect on mountain tourism, lengthening the season and encouraging the choice of cooler mountain destinations instead of sunny beaches.

6. Dealing with changes in productivity and crop quality and leveraging emerging opportunities

The shorter frost season and higher average temperatures could favour the expansion of crops which are seldom seen in the Pyrenees, such as Mediterranean and subtropical plants. In contrast, other crops mainly used in dry farming could find their potential distribution area restricted due to greater variability in the precipitation regime and extreme temperatures.

More water stress and heat stress for crops, the loss of farming land due to increased hydrological risks, and a greater risk of pests proliferating could limit the productivity of some crops, to a greater or lesser degree depending on the areas. Elsewhere, the greater frequency and intensity of droughts and heatwaves could affect extensive livestock farming through changes to the composition and productivity of fodder, while heat stress could impact livestock health in the intensive farms at the mid-mountain level.

7. Predicting landscape irreversible changes

Climate change is accelerating the degradation process of some iconic landscapes, such as the glaciers, lakes and peat bogs of the high mountains. This and other environmental changes, such as changes in the distribution of certain animal species, forests and alpine plants, often act in synergy with human actions such as changes in land use, changing traditional Pyrenean landscapes, often irreversibly.

8. Considering possible biodiversity losses and ecosystems changes

Pyrenean ecosystems, characterised by a great wealth of native species with narrow ranges, specific habitat requirements and limited ability to disperse, are particularly vulnerable to variations in climate. Climate change favours the loss of biodiversity and the extinction of species through changes in the physiology and phenology of plants and animals, changes in the duration of the growing season, changes in population distribution, and increased risk of spreading invasive species. The combined action of anthropic impacts and climate change impacts may lead to the modification of ecological processes which are key to high mountain ecosystems, and which may limit their capacity to provide goods and services, as well as compromising their long-term survival.

9. Adapting to imbalances between energy supply and demand

Increased variability in the spatial and temporal distribution of precipitation, reduced flow rates in rivers and changes in spring thaw dates can have a negative impact on the hydroelectricity production capacity of the Pyrenees. It is likely that climate change will affect the structure of demand in every season of the year: rising temperatures could reduce demand for energy for heating in winter and autumn. However, there will probably be a significant increase in average energy demand in summer and demand peaks in response to the growing need for cooling in homes, as summers become warmer and heatwaves more frequent and intense.

10 Dealing with more widespread crop diseases, pests, and invasive species

Interactions between plants and their natural enemies are influenced by environmental conditions, and to a large extent by temperature. Any changes to the distribution areas of certain crops, and their greater sensitivity due to climatic stress, can generate changes in the distribution patterns and spread of the most common diseases, and a greater risk of expansion of new and hitherto rare diseases. Meanwhile, climate change could encourage new non-native species to become established in the Pyrenees, facilitating their transport and subsequent settlements through climate conditions which favour them. As invasive non-native species are usually opportunist and generalist, they tend to adapt better to rapid changes in climate compared to most native species. Also, rising temperatures will move climatic barriers to higher altitudes, increasing the probability of new invasions (especially by plants) and of already existing species becoming established.

Collaborators

Technical Committee and executive board



Steering committee and OPCC2 partners



Cofinancers of the OPCC2 Project



The project has been 65% cofinanced by the European Regional Development Fund (ERDF) through the Interreg V-A Spain France Andorra programme (POCTEFA 2014-2020). POCTEFA aims to reinforce the economic and social integration of the French–Spanish–Andorran border. Its support is focused on developing economic, social and environmental cross-border activities through joint strategies favouring sustainable territorial development.

