

CLIMATE EXTREMES AND FIRE REGIMES IN THE PYRENEES MOUNTAINS
OF SOULE, BASQUE COUNTRY, FRANCE

by

SONRISA REED

(Under the Direction of Thomas L. Mote)

ABSTRACT

Pastoralists in Soule, France, a small province in the Basque Country, have helped to create a biodiverse landscape of grasslands and forests through thousands of years of transhumance – an ecologically sustainable form of livestock management that faces increasing ecological and social pressures. Historic and recent climate trends point to emerging challenges to the well-being of this socio-environmental system and the intertwined people, plants and animals that compose it. Soule is experiencing increased atmospheric aridity driven by rising global temperature that has outpaced gains in precipitation. The trend in atmospheric aridity, as measured by vapor pressure deficit, along with future climate projections point to a potential shift in the probability of forest fires driven by increasing VPD before the end of the century.

Keywords: climate extremes, vapor pressure deficit, fire weather, Socio-Environmental System, climate projections, écobuage, transhumance

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OF SOULE, BASQUE COUNTRY, FRANCE

by

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DEDICATION

This thesis is dedicated to Emm, who, at 8 years old, when I asked if I should bring up anything else when I went to our state capital to advocate for immigrant rights, replied in tears, “Climate change, we are not doing enough.” I realized that addressing climate change was an “all hands-on deck” issue, intertwined with everything and everyone I care about. This thesis is also dedicated to the farmers of Soule who give me hope for the future and to all who are spending their lives helping to sustain the ecosystems that sustain humanity and our future generations.

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CHAPTER 1

INTRODUCTION

1.1 Transhumance Under Climate Stress

The impact of climate change is not uniform across space and time. While some have not begun to experience climate change, others are already feeling the impact and finding ways to adapt.

Communities like the Souletine farmers in the Basque region of France are leading the way as some of the first to experience the changing climate dynamics accompanying rising temperatures and by engaging in active preparation, navigation and mitigation. The farmers in Soule practice transhumance, the seasonal movement of people and livestock, which is recognized as a form of intangible cultural heritage (UNESCO, 2025). Social environmental systems (SES) of transhumance, characterized by an inextricable interdependence among social and ecological components of the system which have sustained over millennia in Soule and across the world through historic climate and social perturbations, hold potential keys for future adaptation and may serve as models for sustainable agriculture as well as face potential risk from new climate changes (Berkes & Folke, 1998). The steep elevation gradient and climate variation in the ascent to the Pyrenees mountains shaped transhumance here. Mountainous regions across the world are important areas of study regarding a changing climate because they are poised to experience a more rapid temperature increase than many lower lying regions and may serve as refuge for plant and animal species that are not able to survive as the climate changes at lower elevations (Byrne et al., 2024).

While Soule is the center of this thesis, the analysis of climate trends expands beyond Soule to help place the changes in Soule within the context of France and Spain and to contribute knowledge that may be beneficial to the stakeholders and systems of transhumance across the broader region.

To shed light on current and potential future climate perturbations for the SES of transhumance in Soule, this thesis drew from available datasets to analyze present and future trends in key climate variables for Soule and the broader region. The selection of variables was made to meet the needs of local decision makers to define strategies and time frames for preparatory action. Analysis of the broader regions where transhumance is practiced, France, Spain, Basque Country as a whole, and the Pyrenees Mountain range helps situate the findings from Soule within a larger context. While transhumance is an important part of France and Spain, many stakeholders indirectly benefit from the system of transhumance that helped shape and sustain landscapes and culture and may also directly benefit from analysis of climate trends in France and Spain unrelated to transhumance. Impacted stakeholders who may benefit from the analysis of climate in this region include farmers and local cheese makers, and the consumers of the agricultural products that are produced. The analysis of future potential fire hazards may benefit farmers, land managers, foresters and other residents and tourists who may be endangered by wildfires. On the broadest scale would be the global population that relies on forests to act as carbon sinks, a role that reverses when a forest burns, becoming a carbon source. The subject of social environmental systems was chosen because of the importance of transhumant/livestock systems globally, and this area was selected specifically because long-term relationships with the community allowed for participatory engagement. Also, many mountainous regions are facing accelerated warming, with temperatures rising at a faster rate than other areas, so research of mountain ecosystems should be a priority. Diverse heterogeneous topography such as is found in this region also tend to have more error in reanalysis variables or downscaled data so additional research and analysis of mountainous regions is also needed for this reason. This work may help build the capacity of the local communities in Soule to advocate for policy and land management practices that will benefit this community and ecosystem now and in the future.

Fire in this region, over the course of human history, has been primarily anthropogenic and an integral part of the sustainable land management of the cycle of transhumance. Wildfires, such as ones that occurred in 2012 and 2019 in Soule (Appendix A), an emerging concern amongst farmers and local

stakeholders, have generally stopped at the edge of the moisture-rich beech forests that divide summer pasturelands.

Regulations now put limitations on prescribed fire, such as restriction to a certain portion of the year and requirements for a minimum number of attendants to monitor a prescribed burn. Newer regulations also require the clearing of brush near structures to quell the fire hazard exacerbated by land abandonment. Some regulations may foster traditional practices, while others may put unnecessary pressure on transhumant farmers already under strain from compound challenges.

This thesis attempts to help answer questions from community stakeholders on our research team regarding what future climate will look like in terms that bridge a gap between the conceptual and the concrete. The dynamic relationship with fire was chosen as an intermediary concept to help describe potential future climate scenarios and explore the nuances of that changing dynamic to help inform and empower farmers to advocate for policies that match regional and local needs.

Ecologically, fire is both a rejuvenating and destructive force. Illuminating the past, current, and potential future fire regimes in Soule within the context of local and regional changing climate variables, this thesis will hopefully serve to edify concrete notions of potential future climate impact to the SES of Soule, as well as help to bridge gaps in understanding between local experiences and needs and regulations that serve broader interests. A more nuanced understanding of potential and future fire risks may help the community arrive at land management and regulatory strategies that best serve the needs of all stakeholders.

As an extension of the ecological role of fire, fire is integral to transhumance; assessment of the changing fire regime is a paramount need considering the social and ecological interplay surrounding fire that may heat up through the impacts of and responses to climate change.

1.2 Transhumance in Soule

Transhumance in Soule has developed alongside the rich landscape of the mountains of Southwestern France in rhythm with the seasons and the natural environment. Transhumance has shaped the unique development of a biodiverse mix of flora and fauna in the Pyrenees, which in turn, helped to

shape the local social structure. Soule, or Xiberoa, in the Souletin Basque language, is a French Basque province that meets the border with Spain high in the Pyrenees mountains. Records dating back hundreds of years detail the social structure and governance of the people of Soule. Dependent upon each other, the people and the land in this social-environmental system (SES) offer lessons in how to sustain a human population in harmony and mutual beneficence with intertwined ecological systems.

In the Summer of 2024, I visited Soule and interviewed key informants to prioritize the analysis of changing climate dynamics relevant to this SES. A pressing concern among our local research partners who defined the overarching goals of the project, farmers, practitioners and land managers that was found to be echoed by historical precedent and climate projections was drought. Wet and dry days, as well as precipitation, were also analyzed to respond to their concerns regarding recent years with few consecutive dry days for hay drying. Growing from the concern regarding drought and the ability to dry hay as well as the preservation of important land management practices such as pastoral burning, analysis of atmospheric aridity projections gave insight applicable to the drying of vegetation and fire weather for the past and future. Drought impacts multiple components of this SES on multiple scales, and the community has recently faced impacts of extreme drought and water shortages. Additionally, drought conditions increase the probability of wildfire. The likelihood of controlled burns escaping also becomes higher under drought conditions. If Soule became increasingly more arid, the windows for safe burning times may become more limited, threatening the continuance of the millennia old practice of *écobuage* (pastoral burning) that is integral to this SES and helps to prevent hazardous fire.

A timeline of major seasonal activities identified by farmers and land managers helped to guide the direction of the research and selection of variables (Figure 1.1). While all aspects of transhumance in Soule are impacted by climate and climate extremes, annual controlled burns, growing seasons of various crops, and harvest seasons (particularly for hay) are most directly dependent on climate variability (Figure 1.1, highlighted in yellow).

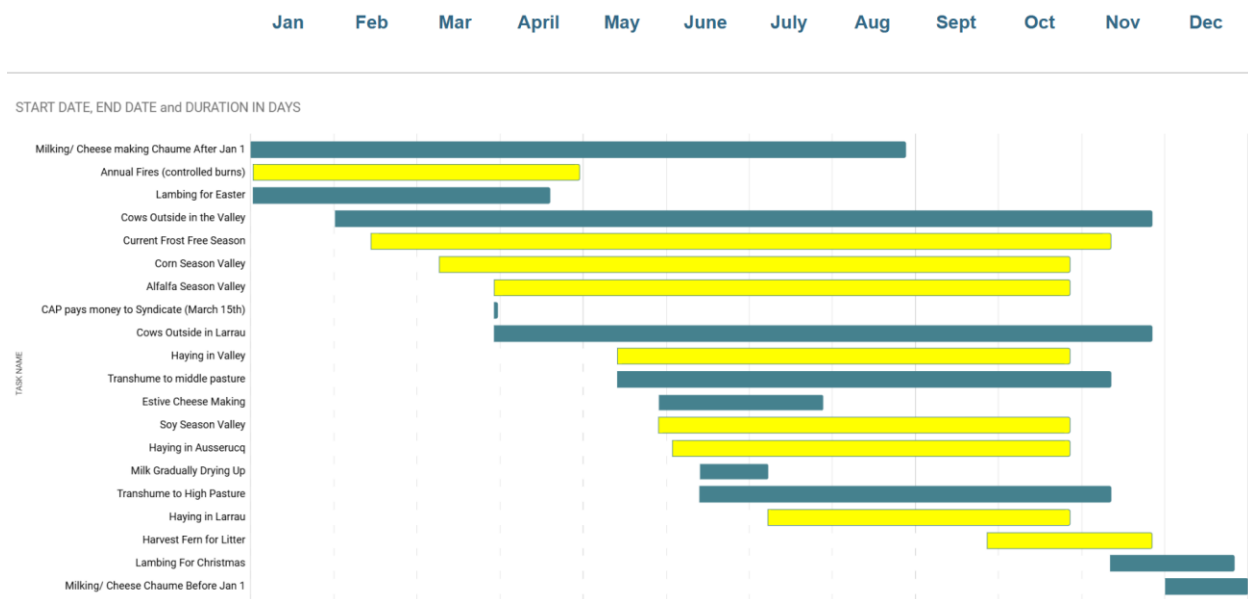


Figure 1.1. Annual timeline of seasonal activities related to transhumance January (Jan) 1– December (Dec) 31. Yellow indicates strong coupling with climate variables. (S. Maraud, personal communication, 2024).

The farmers who defined the research objectives are motivated to understand and address challenges not only to preserve their ancient lifeway of transhumance but also to mitigate other impacts of climate change such as how the land can help maximize carbon s and preserve biodiversity. The traditionally important land management practices, such as controlled pasture fires, that are integral to the SES of transhumance help to maintain a biodiverse landscape. Luza et al. (2014) highlighted the need to conserve forest-grassland mosaics to support ecological processes and biodiversity and detailed the need to maintain areas of little to no disturbance, such as patches of beech forest in Soule, for some species, while also maintaining areas of more intense disturbance, such as the grassland pastures, for other species like the diverse grasses and forbs that grow there. Overbeck et al. (2016) stressed the need for grazing and burning as part of maintaining such a biodiverse mosaic.

This analysis of the climate impacts of importance to the agro-pastoral transhumant social-ecological system (SES) of Soule, Basque Country, France, is situated within a larger, transdisciplinary,

NSF funded Dynamics of Socio-Environmental Systems (DISES) research initiative (Welch-Divine, 2024). This thesis aims to help address a primary research question defined in collaboration with indigenous farmers: “How can we expect climate to change in the next 20–50 years?”

To address this question, understanding the seasonal dynamics of the SES was necessary to identify potential climate impacts. The driving force of transhumance is climate and seasonal change. In its inception, the movement of herds to higher elevation pastures may have been partly driven by unfavorable conditions and overgrazing in the lowlands (Geddes, 1983). The adaptation to climate of rotating herds and grazing pressures with the seasons created a dynamic and diverse social environmental system that has fostered and sustained biodiversity through millennia. The lives of the farmers here follow the seasons. In January through April, after frost has browned the higher elevation pasture grasses, brambles, and ferns, fires are used to clear the brush, opening the skies for the new growth of tender grass shoots that thrive in the sun. Once the new grasses are strong enough, the mountain pastures are ready to receive sheep, cattle and horses that roam freely across the pastures and shelter in adjoining beech forests. As the animals pass through, they forage and fertilize and distribute new seeds across the landscape. Meanwhile, in the valleys, hay crops begin to come in as the herds leave for the mountains. The hay, carefully dried and stored, will be used to sustain the herds during the winter months when they return to the valley. Haying is done at intervals during the summer to ensure enough is stored for the winter. By mid-November, all the herds are back in the valleys. Milk and cheese making occurs between December and August, with special mountain cheese made from May through July. Hydroclimate variables can impact every aspect of this system directly or indirectly.

1.3 Conceptualization of climate risks.

1.3.1 Risks - Hazards, exposure and vulnerability

This thesis used the definitions of “risk,” “hazard,” “exposure,” and “vulnerability” following the IPCC framework. Within the context of the IPCC framework, “risk” specifically refers to risks to “human or ecological systems” and encompasses both adverse consequences impacting “lives, livelihoods, health and wellbeing, economic, social and cultural assets and investments, infrastructure, services (including

ecosystem services), ecosystems and species” of the changing climate and human responses to climate change (IPCC, 2020, p.1). Cardona et al. (2012) identified hazards, exposure, and vulnerability as determinants of risk (p.69). This paper used the term “hazards,” following the definition outlined by Cardona et al. within the IPPC framework, to refer to the potential occurrence of natural or anthropogenic physical events that may adversely impact vulnerable elements of the socio-environmental system of Soule. It centered the atmospheric climate hazards, found to potentially impact many aspects and processes of the SES of transhumance in Soule. The negative impact of a hazard is determined by both exposure to the hazard and “vulnerability,” or the capacity of the SES to mitigate or cope with the hazard (Cardona et al., 2012). Hazards, exposure, and vulnerability are dynamic across space and time and have many determinants that can vary with human decision (IPCC, 2020).

1.4 Study Region

1.4.1 Physical Geography and Climate of Soule

As farmers plan for their futures, the climate projection data available to them is not in terms or at a scale that has been accessible. To situate this climate analysis within the local context, it was necessary to understand the local physical geography and features that impact the local and micro-climates. To this end, mapping allowed for a spatially explicit knowledge of Soule. Mapping demonstrated the relationships between elevation, slope, and multiple climate variables. Slope plays a significant role in how and where fire will move across a landscape, with farmers describing the ease of burning on steeper slopes (S. Inda-Gallur, personal communication, 2024).

The area of Soule encompasses ~772 km² and is roughly 40km long and 20km wide. Despite Soule’s small size, elevation ranges by nearly 2000m with diverse terrain (Figures 1.1, 1.2, 1.3), which gives significant variations in climate. The mean annual climate values (Figures 1.4–1.7) in the maps below were determined from the WorldClim baseline climate analysis of the years 1970 - 2000 (Fick & Hijmans, 2017). Average annual temperatures of Soule range from 6–14° C (Figure 1.5). Annual precipitation in Soule ranges between 1000mm to over 1260 mm (Figure 1.6). Mean annual wind speed

across Soule ranges from 2.4 m/s to 4 m/s (Figure 1.7). Mean water vapor pressure within Soule ranges from 0.67 kPa to 1.2 kPa (Figure 1.8).

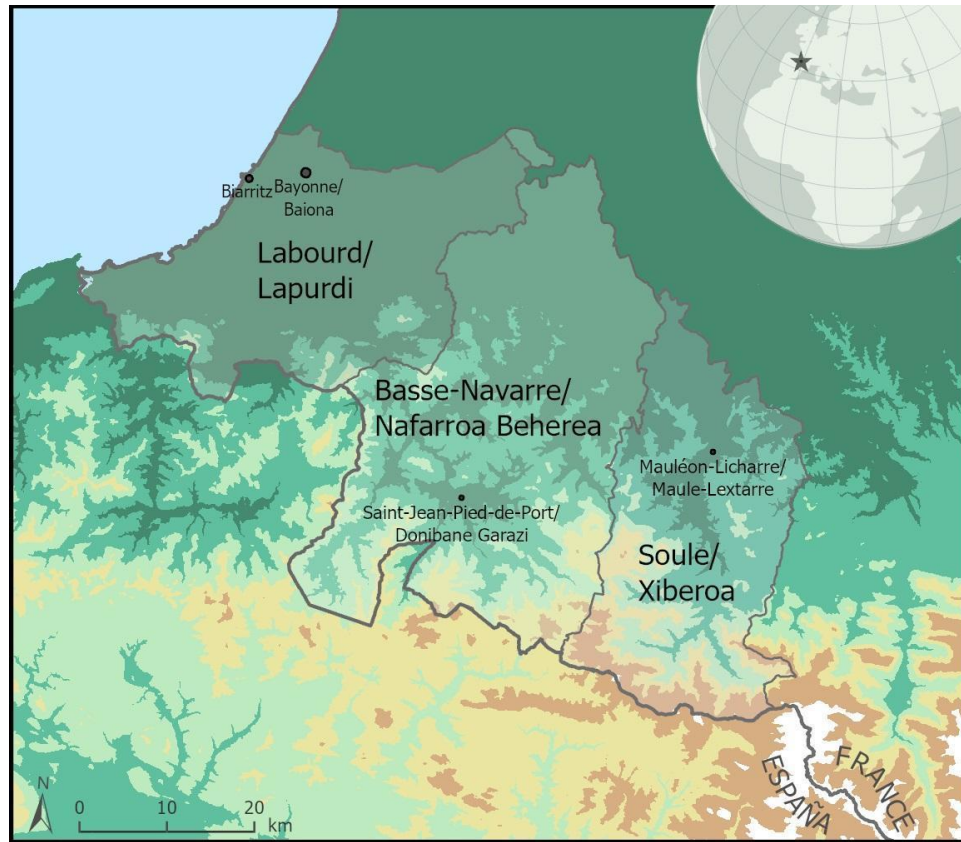


Figure 1.2. *The study region of Soule or Xiberoa showing elevation gradient and neighboring French Basque provinces to the west.*

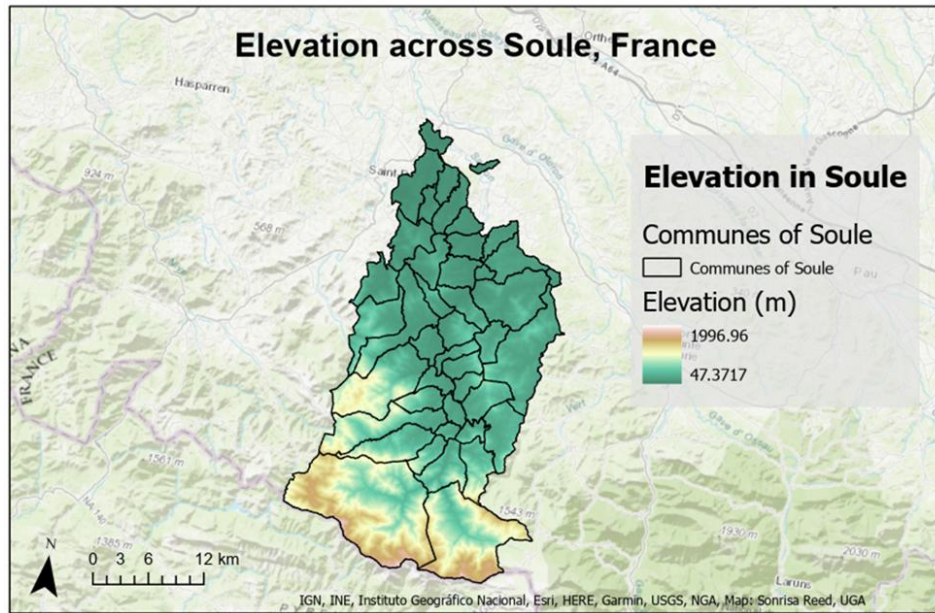


Figure 1.3. Elevation in Soule varies from 47 m in the valleys to almost 2000 m at the high peaks along the French and Spanish border.

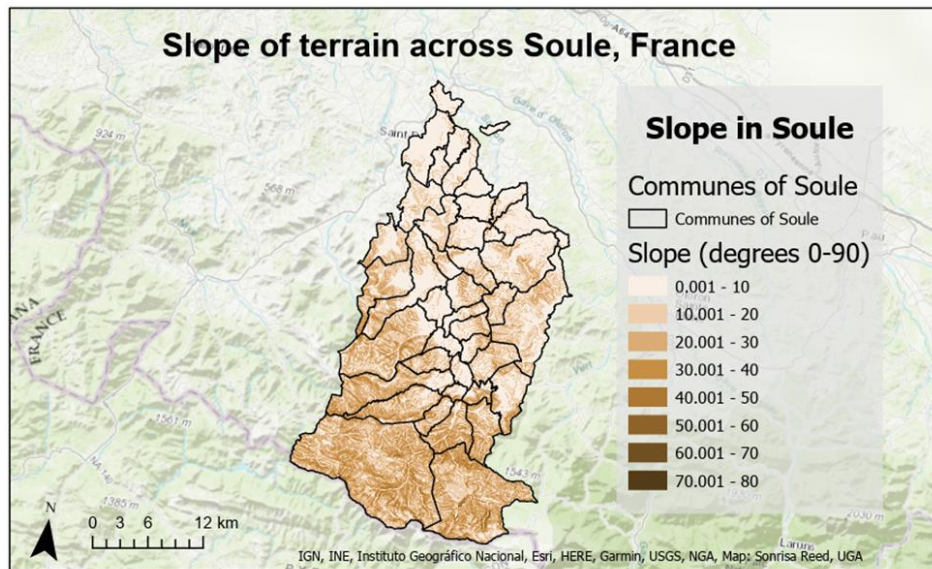


Figure 1.4. Slope varies in Soule from flat cropland and towns in the northern part of Soule to hills then to steep cliffs and mountain peaks in the South.

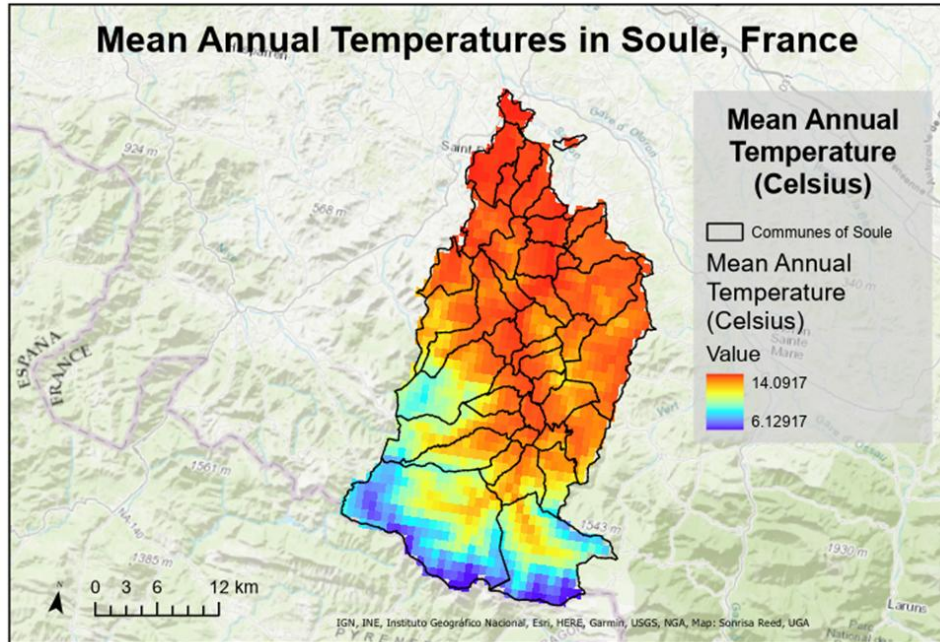


Figure 1.5. *The mean annual temperature varies considerably in a pattern matching Soule's elevation gradient. The mountain annual average in the high peaks is just over 6° C, while in the valley in the northern part of Soule, the mean annual temperature is 14° C.*

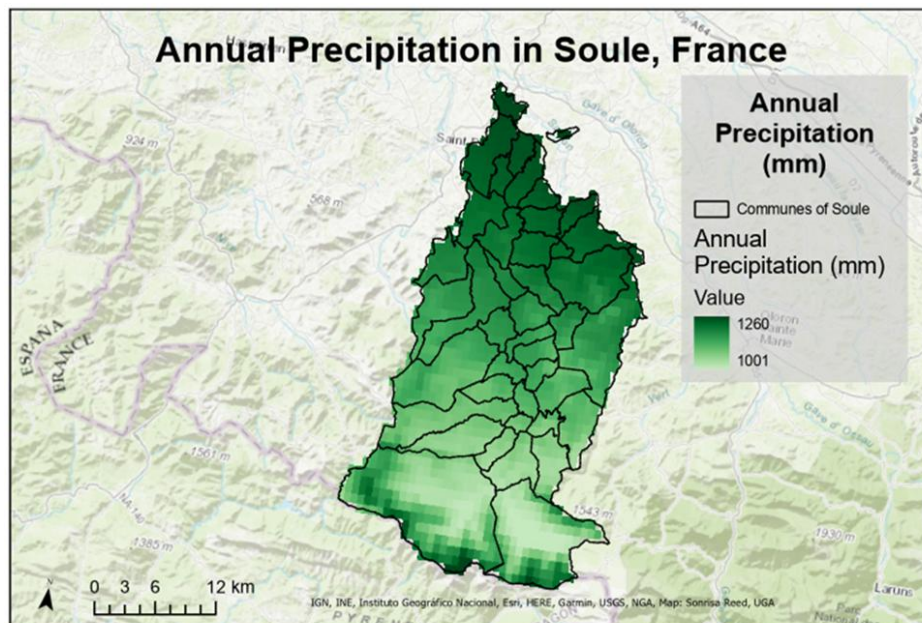


Figure 1.6. *Cumulative annual precipitation in Soule ranges from 1001 mm to 1260 mm.*

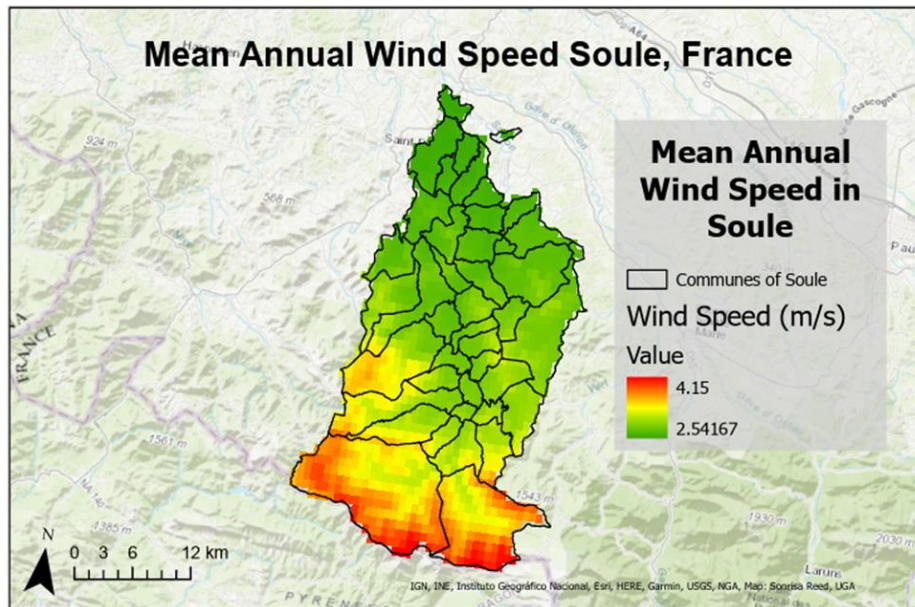


Figure 1.7. Mean Annual wind speeds in Soule range from around 2.5 ms^{-1} at lower elevations to 4 ms^{-1} at the highest elevations.

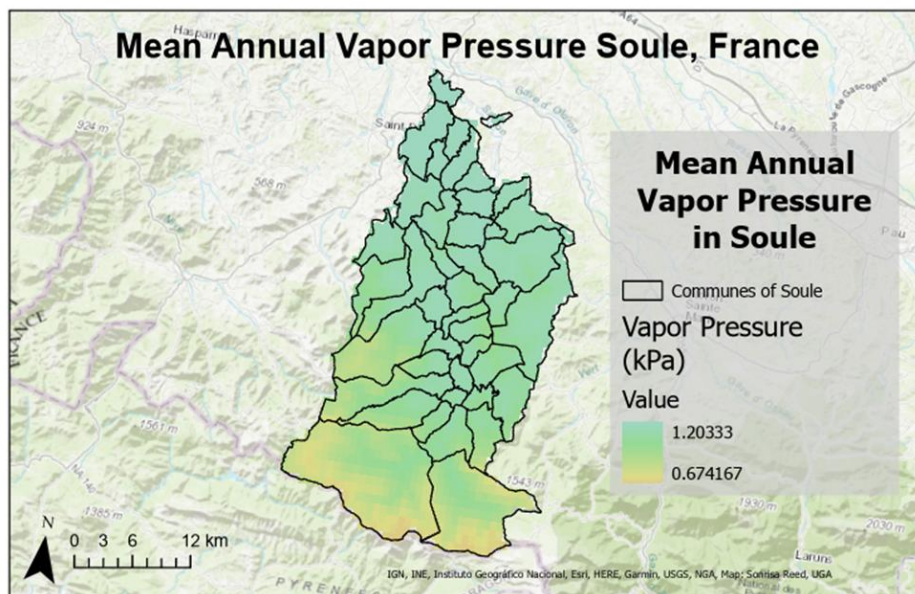


Figure 1.8. Mean annual vapor pressure ranges from 1.2 to 0.67 kPa, with generally higher vapor pressure in areas of lower elevation.

The French government meteorological service, Météo-France, described typical climate and meteorological dynamics for France as predominantly oceanic and continental with westerly winds. However, a variety of other dynamics such as polar or subtropical air, anticyclonic conditions, disturbed westerly flow, flow from south to southwest, flow from north to northwest, and return from the east, may also influence weather and climate in Soule (Les situations météo, 2025). When the Azores anticyclone shifts over France, relatively calm and warm air over the country during the summer results in occasional afternoon thunderstorms. Winter weather when the Azores anticyclone is over France is characterized by grey skies and fog or low clouds trapped in an inversion beneath warmer air of the anticyclone, and when the air is drier, such as where the climate is more continental, clear night skies result in loss of radiant heat and low temperatures (Les situations météo, 2025). When there is a south to southwest flow, subtropical, warm and humid air masses move through France, resulting in mild weather and rain in winter and strong thunderstorms in summer, and when the anticyclone shifts northwest toward Iceland, polar air may cause destabilization, showers, snow and spring downpours (Les situations météo, 2025). When the area of high pressure shifts even further north, a phenomenon more common in the winter, general atmospheric circulation may reverse and come from east to west, which results in unseasonably cool temperatures and snow especially in the southern parts of France (Les situations météo, 2025). These shifting North Atlantic atmospheric surface pressure dynamics between the Azores High and the Icelandic Low, which are quasi-permanent patterns of sea-level pressure located over the North Atlantic, characterize the North Atlantic Oscillation (NAO). The NAO has a positive index when the pressure difference is above normal and a negative index when the pressure difference is below normal. When NAO is negative in the summer, Southern Europe tends to be drier (UK Met Office, 2025; Hurrell et al., 2003). A positive phase of NAO results in the Mediterranean region experiencing major drought because of the westerlies shifting northwards, and a negative phase NAO results in humid conditions in this region from the weakening and southward shift of the westerlies toward mid-latitudes (Daniau et al., 2009).

Though influenced by these phenomenon as well as proximity to an intersection of oceanic, and an altered oceanic climate, Soule is predominantly characterized by a mountain climate with rapidly

decreasing temperature with altitude, considerable cloud cover and fog in the mountains during the summer, and significant variation in precipitation and wind (Météo-France, 2025).

Regional cities in and around Soule with meteorological data available show seasonal variation and extremes. Orbara, Mauléon-Licharre, Arette, and Saint-Jean-Pied-de-Port all fall below 800m in elevation, so they do not express the higher elevation extremes, but they lie within the grid cell analyzed for VPD.

Monthly means of high and low temperatures (Figure 1.9), chance of clear skies (Figure 1.10), average monthly rainfall (Figure 1.11), average wind speeds (Figure 1.12), and growing seasons (Figure 1.13) show typical weather for Orbara, Mauléon-Licharre, Arette, and Saint-Jean-Pied-de-Port. These figures were based on a statistical analysis of historical hourly weather reports and model reconstructions during 1980–2016 (WeatherSpark, 2025). The seasonality and variability of the climate in and around Soule help to contextualize seasonal activities related to transhumance.

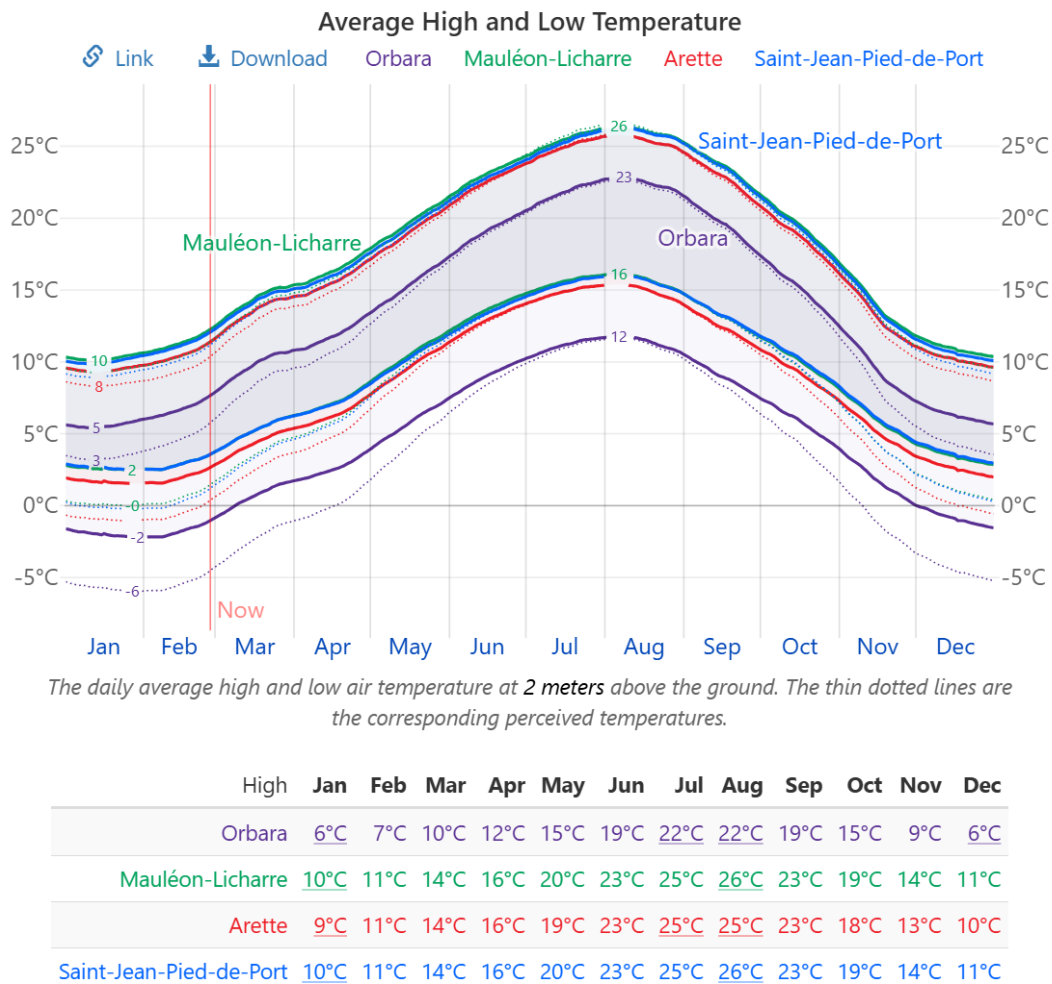
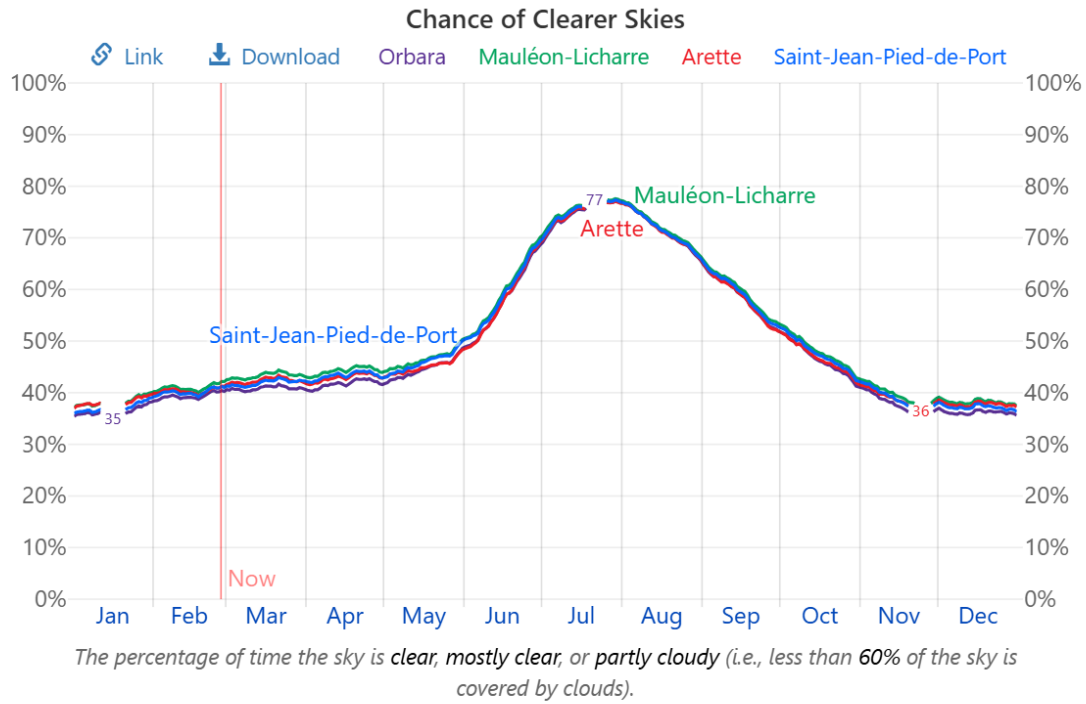


Figure 1.9. The average high and low temperatures from January through December of four towns in and around Soule, France. Notable seasonal variation and variation among the towns is evident. This graph is based on a statistical analysis of historical hourly weather reports and model reconstructions from 1 January 1980 to 31 December 2016 (WeatherSpark, 2025).



Clearer Skies	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Orbara	36%	39%	41%	42%	45%	58%	75%	71%	58%	46%	38%	36%
Mauléon-Licharre	38%	41%	43%	44%	47%	60%	76%	72%	59%	48%	39%	38%
Arette	38%	40%	42%	43%	45%	59%	75%	71%	58%	46%	39%	38%
Saint-Jean-Pied-de-Port	37%	40%	42%	43%	46%	59%	76%	71%	59%	47%	39%	37%

Figure 1.10. *The chance of clear skies throughout the year shows minimal difference between the four towns observed.*

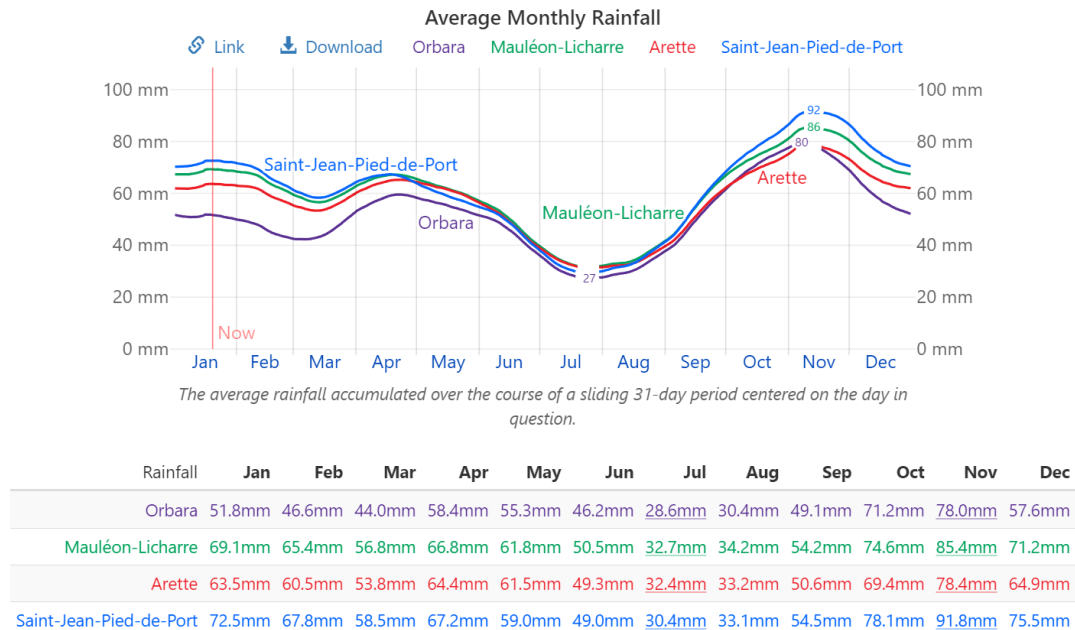


Figure 1.11. Average rainfall measured across all months for four towns in and near Soule.

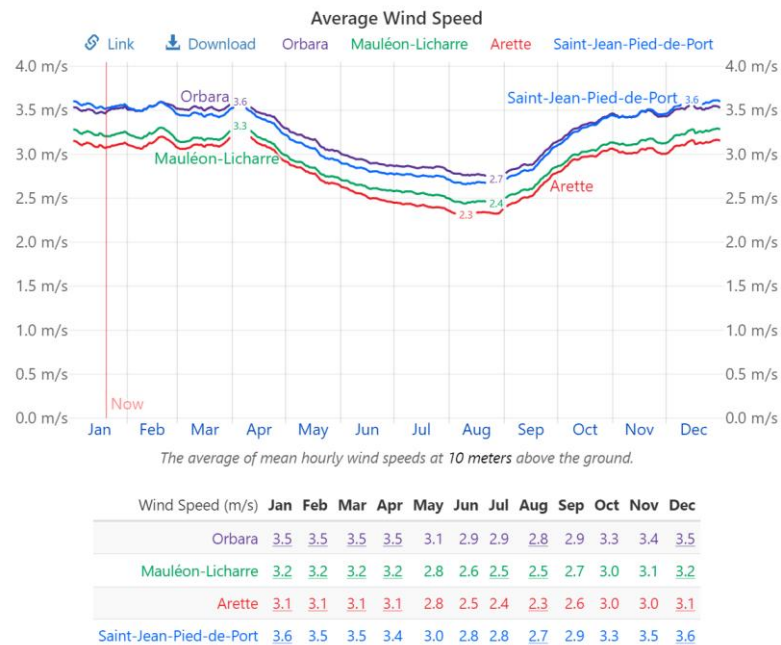


Figure 1.12. Average wind speed in four towns near the study region with consistent variation among towns throughout the year.

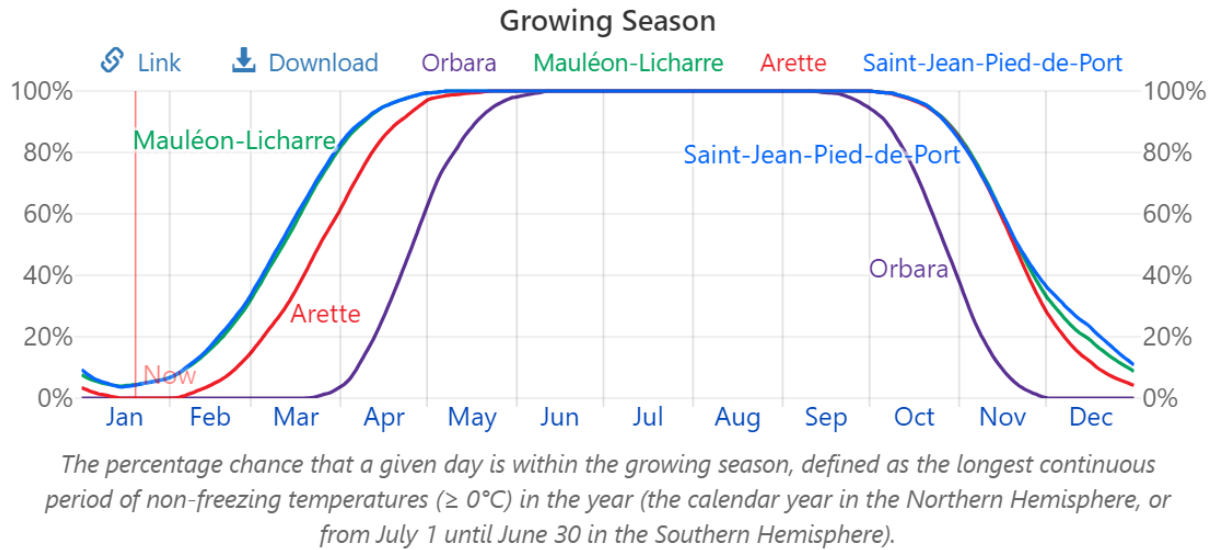


Figure 1.13. The growing seasons of four towns with data available near the study region show variation, but all have more than six months of growing season.

On a daily scale, Jiménez et al. (2014) found that the diurnal pattern of wind changes from a north wind during the day to a south wind at night on the northern slopes of the Pyrenees inclusive of Soule. This pattern is a product of cooler nocturnal downslope wind flow into the valleys, lowering the valley temperatures during the night. The winds reverse in the mornings, pushing air from the valley up the slopes (Jiménez et al., 2014).

1.4.2 Governance in Soule

The Basque province of Soule, in the southwest corner of France, nestles against the Pyrenees mountains, encompassing high mountain peaks and the fertile valley of the Saison River. Soule is in the department of the Pyrénées-Atlantiques and is divided into 35 communes, seven of which make up common-pool grazing land in summer mountain pastures, owned collectively, and managed by the Syndicate of Soule (*Xiberoa Zindikata*) (Welch-Devine, 2010). Newer regulations, such as top-down government initiatives to set aside land for preservation, do not necessarily consider the important role of farmers and transhumance in sustaining biodiversity in this landscape and may undermine the intent of these policies (Welch-Devine, 2010).

1.5 Vulnerability of Transhumance

The traditional practice of transhumance is intertwined with the land and other practices, such as prescribed pastoral burning, culture, and governance. Although it is difficult to parse the social and environmental dynamics, and arguably, that irreducible nature defines a social-environmental system such as this, climate change is already having an impact on many aspects of this SES. Precipitation extremes, rising temperature, and increasing atmospheric aridity, pose potential hazards, such as drought, floods, and heat stress, to the flora and fauna and people who compose the socio-environmental system of transhumance within Soule. The ways these climate variables change in the future may have profound implications for this SES. As the climate continues to warm and exhibit greater extremes in precipitation (IPCC, 2020), recent research has also shown that Soule is in a region of increased atmospheric aridity (Treydte et al., 2024) with decreased streamflow in recent decades (Tootle et al., 2025) and an increased ignition likelihood of large fires (Ochoa et al., 2024). This is occurring as a drying climate potentially approaches a point where the Pyrenees become more fire prone (Resco de Dios et al., 2021). How and to what extent these changes will impact farmers is uncertain and lack of actionable information impedes the ability of the community to adequately prepare for potential futures. Knowledge of climate variability and trends and the quantification of future projections in locally relevant terms at locally relevant scales is necessary not just for Soule, but for most socio-environmental systems as they find ways to help mitigate climate change related harm to human and animal health and wellbeing.

1.6 Research Questions and Significance

The primary objectives of this thesis were 1) to identify recent trends in hydroclimatology, including precipitation frequency and intensity, temperature and relative humidity and 2) to identify recent and future trends in VPD and do VPD projections indicate increased future fire hazards in Soule and the broader region in the next 20 to 50 years.

The dynamic nature of the climate in Southern France has historically exposed this landscape to a variety of hazards, including flood, storms, heat stress and drought. Guided by historical precedent, farmer concerns, and a literature review, the current trends of five key variables important to

transhumance were analyzed: precipitation, consecutive dry and wet days, temperature, humidity and vapor pressure deficit (VPD).

Table 1.1. *Key hydroclimate variables and potential points of impact.*

Variable	Description	Points of Impact to Transhumance
Precipitation	Annual and seasonal precipitation volume metrics: Total annual precipitation (TAP), mean annual precipitation (MAP), Mean seasonal precipitation (MSP)	Impacts water recharge which impacts availability of groundwater needed for trough cisterns in mountain pastures and for tree roots deep enough to tap groundwater. Annual and seasonal volumes reflect seasonal variability and shed light on potential impacts to controlled burning, transhumance and seasonal productivity of the land.
	One day event precipitation volume metrics: Days when precipitation is at least 10mm (R10mm) and Volume of precipitation in the heaviest precipitation day in a given period (Rx 1-day Max)	Used to assess trends in intensity of precipitation which may impact erosion and flood hazard.
	Consecutive dry days (CDD) and wet days (CWD)	Used to assess frequency of precipitation, meteorological drought and hay drying weather trends.

Table 1.1. Continued.

Temperature	Mean seasonal temperatures (MST)	Reflects seasonal variability which impacts season specific activities such as controlled burning, transhumance and haying.
	Warm days exceeding 90 th percentile (Tx90p) and warm nights exceeding 90 th percentile (Tn90p)	Increased number of warm days may increase heat stress.
Relative Humidity (RH)	Mean seasonal and mean annual relative humidity	Mean seasonal relative humidity reflects seasonal variability. Higher relative humidity may exacerbate heat stress.
Vapor Pressure Deficit (VPD)	Mean annual and monthly vapor pressure deficit and estimate of days/month exceeding 1.5 kPa VPD threshold (exceedance days)	VPD impacts plant growth and moisture levels of live and dead fuel, so it drives probability of fire. Monthly values allow for exploration of seasonal variability. Exceedance days give the number of days of when the VPD threshold indicates probability of fire $\geq 50\%$.

Vapor pressure deficit (VPD), an underutilized metric, was identified as a key driver of uncontrolled forest fire, a potentially severe climate-related hazard (Khadke & Ghosh, 2024; Treydte et al., 2024). Given the connection between fire and the cultural dynamics of Soule, analysis centered on VPD due both to the projected increase for this region and the association between VPD and burned area.

Prescribed fire is both an ecologically important traditional land management practice and a means of mitigating potential fire hazard. Wildfire, though limited by current moisture levels, could become a catastrophic risk to the SES of Soule if climate change drives aridity levels beyond key thresholds. Wildfire in the forests of Soule could endanger biodiverse ecosystems as well as release the carbon they store into the atmosphere as well as threatening human safety. A driving question that developed was whether moisture levels would continue to limit fire activity in Soule or would VPD reach levels that would cause the forests, currently not prone to fire, to be more vulnerable to forest fire. To address this question, data analysis for VPD was conducted at a spatial and temporal resolution as fine as the data allowed for multiple Shared Socioeconomic Pathways (SSP)/Representative Concentration

Pathways (RCP) to assess the changes in these key agro-pastoral climate variables through 2100 and compare the projected values with thresholds in VPD indicative of increased fire probability.

CHAPTER 2

LITERATURE REVIEW

2.1 Socio-Environmental System of Transhumance in Soule

The socio-environmental system of transhumance in the region of Soule has developed over thousands of years (Coughlan, 2014). High-altitude grasslands give way to mesic forest patches and lower elevation pastures in cycles of human-mediated grazing. Transhumance and traditional land management practices such as pastoral prescribed burning, or *écobuage*, have resulted in a rich diversity of plant and animal life, and a communal social and governmental structure that characterize this SES (Mazier et al., 2009; Galop et al., 2012). On the Mediterranean side of the Pyrenees, evidence points to transhumance as an adaptive strategy following aridification and ecological degradation in the lower elevations due in part to overgrazing and degradation of the lowland vegetation and soil beginning in the neolithic period around 4500 BC (Geddes, 1983).

Synonymous with social environmental system (SES) and sharing the same acronym, a social-ecological system (SES) is defined by an “intertwined nature of human and natural systems” (Biggs et al., 2022, p. 5). The SES concept was originally developed by Berkes (1989) and further developed in 1998 (Berkes & Folke, 1998). These terms acknowledge the interdependence of human systems and natural systems and the inseparable and intertwined nature of societal systems and ecosystems. SES fit within and are dependent upon the biosphere as a whole and the broader Earth system (Biggs et al., 2022). A dominant SES, pastoral systems cover more than half the global landmass and contribute to the livelihoods of as many as half a billion people, so understanding the historical and current dynamics and adaptive strategies of this system, the potential hazards, and vulnerability that help determine risk to this SES as climate changes is vital for Soule and many similar systems (Manzano et al., 2021).

2.2 Historic Fire Regimes and Role of Fire in Soule

Historically, the study area of Soule has had a dynamic relationship with fire. Daniau et al. (2009) analyzed microcharcoal in a core collected from the Biscay Bay to analyze paleoclimate fire regimes and determined that a drying trend in HE (Heinrich event) 4 and 5 in the region around Soule led to a reduced fen landscape in favor of bogs, and although fire would have been expected with that drying trend, the moisture conditions seemed to mitigate fire propagation. Heinrich events or Heinrich stadials were anomalous ice raft detritus occurrences caused by icebergs released from the Hudson Strait and the hypothesized subsequent drainage of the Laurentide ice sheet (Hemming, 2004). These extreme events in the North Atlantic correspond to fluctuations in climate documented in ice cores across the northern hemisphere (Hemming, 2004). A past regime when fire was hypothesized to be caused by increased drought could have been caused by an increased frequency of lightning storms during the atmospheric reorganization that would occur between a transition from a wet and/or cold climate to a dry and/or warm climate (Daniau et al., 2009).

Based on historical changes in fire regimes in this region, it is conceivable that with projected changing climate conditions, future fire regimes may see increased fire activity. Among other factors, increased wildfire activity may result from drought, lightning, land management practices, and/or increased woody fuel availability and decreased controlled burns.

Écobuage may be a contributing factor to the current mitigation of wildfire in Soule. However, decreasing reliance on controlled burns and decreases in resources to maintain the local knowledge needed to successfully and safely manage *écobuage*, as well as farm abandonment, which can lead to decreased forest fragmentation, may contribute to higher future wildfire prevalence in Soule (Métailié & Faerber, 2003; Venäläinen et al., 2022). Changing fire regimes, strongly influenced by both social and ecological factors, may alter the SES significantly, which places this research topic in a central position within social-ecological dynamics of this SES (Jones et al., 2022). Overarching socio-cultural dynamics related to fire in this region show the long history of fire in the French Pyrenees Mountains (Table 2.1).

Table 2.1. *Historical Socio-Cultural Dynamics of Fire from Métaillé and Faerber (2003).*

Time	Practices	Knowledge	Rules	Social actors
From Neolithic to 18th century	Building of landscape: slash and burn cultivation (<i>essarts, artigues</i>), clearing fire in forests, pastoral fire in pastures and moors	Vernacular	Local	Peasant society
19th century	Stabilization of landscape, disappearance of agricultural fire, pastoral fire exclusive	Opposition between local knowledge and scientific knowledge	Local rules vs. national rules	State engineers and administrations
20th century	Agro-pastoral crisis Fallow lands spreading Degradation of common fire practices	Crisis of local knowledge, increasing power of technical and scientific knowledge	National and European	Multiple protagonists
21st century	Use of fire for global land management Potential difficulties due to changes in local society, climate and vegetation changes?	Adaptation of local knowledge? Generalization of prescribed burning?	European?	Multiple protagonists on European scale?

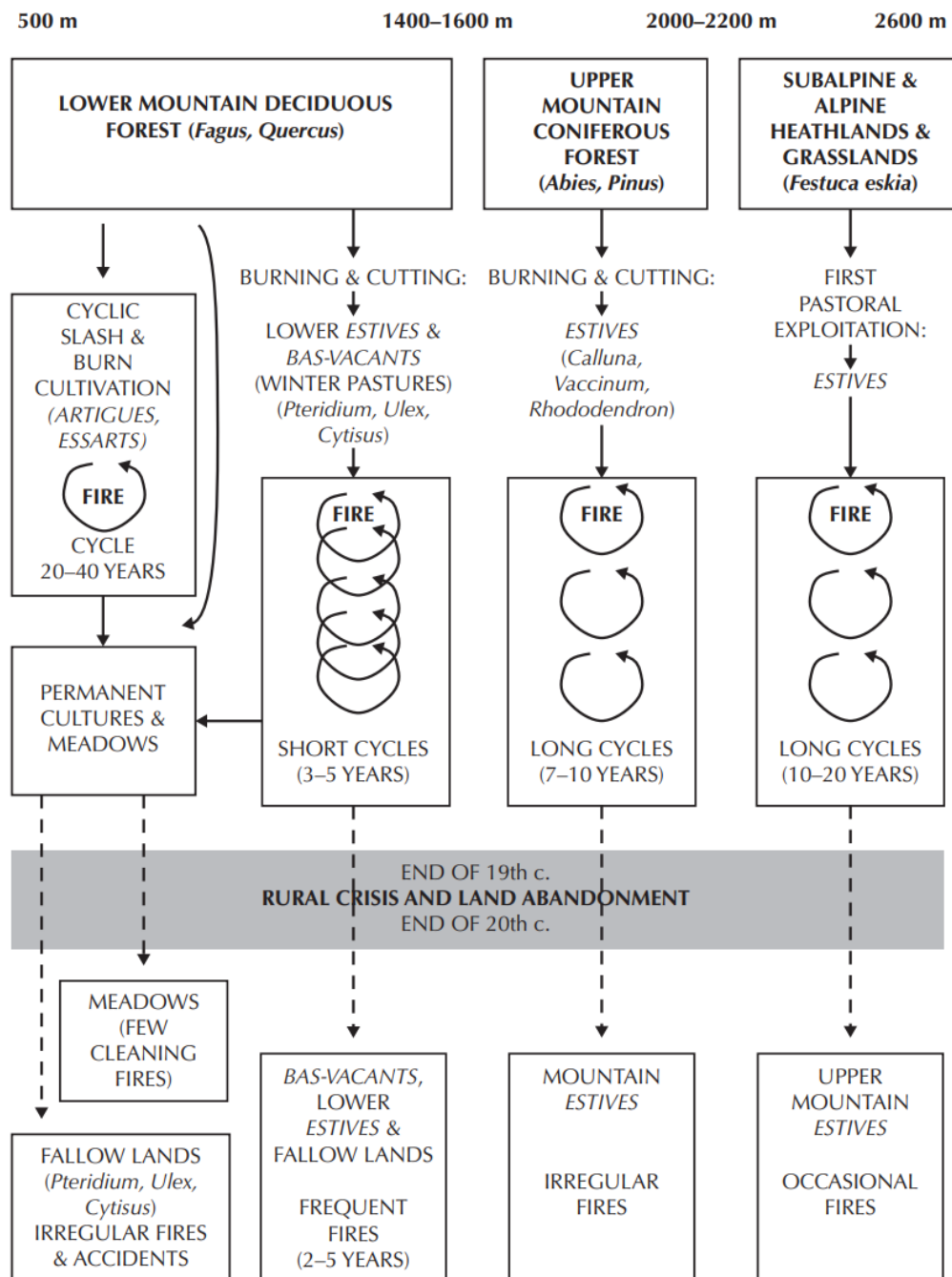


Figure 2.1. Historical uses of controlled burns across altitude and forest types from Fig. 7.2 in Métailié and Faerber (2003).

2.3 Climate Hazards Relevant to Soule

According to Ogé and Poulsen (2024), agriculture in most of the French Pyrenees region has declined as young people are not taking up traditional land management practices and with impacts of

tourism. Generally plentiful in rainfall, the mountains of Soule may face significant climatic changes that put further pressure on traditionally sustainable ways of life (Ogé & Poulsen, 2024). Additionally, farm abandonment and fewer controlled burns have resulted in new woody shrubs and resinous tree growth (Ogé & Poulsen, 2024). This, along with changes in climate and the possibility of increased droughts and atmospheric aridity, may contribute to potential fire regimes not previously known in this region (Ogé & Poulsen, 2024). The dynamic nature of the climate in Southern France has historically exposed this landscape to a variety of hazards, including flood, storms, heat stress and drought. Precipitation extremes, potentially becoming more frequent with climate change, may challenge this SES as it has in the past.

Extreme flooding and storms marked the mid-1800s in Soule and the record of this and response illustrates some of the historic impacts of climate-related phenomenon in the past. During the night on June 8th-9th of 1835, flood waters inundated Mauleon, transforming the streets to torrents that uprooted trees and destroyed houses (Hourmat, 1994, p. 302, footnote 27,). Aid after the flood was given by the soldiers of the 57th, stationed in Mauleon at the time. In 1845, just before the sowing of the corn crop, a hailstorm damaged homes and destroyed the wheat crop. The loss of wheat, after several lean years that preceded, precipitated an outbreak of violence three weeks later over a price dispute at the market in Mauleon-Licharre (the two communes had been joined in 1841). In response to the loss of crops, the municipal council requested government funds and tax relief (Hourmat, 1994).

Looking toward the future, extremes may become more frequent or even the new normal. Globally, temperature increase driven by climate change has already reached +1.1°C over the period 2011–2020 compared to the 1850–1900 pre-industrial period (IPCC, 2023). Fossil fuel use, driven by industrial demand, continued to increase after the Industrial Revolution, shifting carbon from underground reserves to the atmosphere. Increased CO₂ in the atmosphere helped the atmosphere hold more heat and raised global temperatures. For a variety of topographical and climatological reasons, some areas of the globe experience more or less warming and may face greater challenges than others. The global upward shift in temperature impacts many climate dynamics. Drought and floods, for instance, due

to shifting weather patterns and the increased demand for water from the atmosphere that accompanies higher temperatures, are expected to increase in many regions.

More research is needed to understand and assess the sustainability of socio-ecological systems. Thakur et al. (2021) highlighted the need for forest ecosystem vulnerability assessments to utilize ground-truthed data in the assessment process to provide increased accuracy in the highly variable mountain landscape as well as to create assessments that can be used reliably for regional and local decision making. Thakur et al. also reported that current modeling methods lack the spatial resolution needed to provide convincing information that would be helpful to land managers to make decisions, but downscaling to a resolution that would provide more actionable information also increases uncertainty in the models, and forest ecosystem vulnerability assessments lack knowledge of climate and other stressors, which further limits their local utility. These limitations highlighted the need for local knowledge and local collaboration as well as contextualization of the assessment within ground-truthed observations. Rising temperatures and increasing atmospheric aridity, as measured by VPD, may have significant impact on this system and the future probability of forest fire where it was not previously considered.

2.4 Heat Stress

While increasing vapor pressure deficits driven by rising temperatures may have profound consequences for the SES of transhumance in Soule, the impact of the heat itself may also have a direct impact on the wellbeing of humans and animals through increased heat stress. For instance, heat-stressed cows are more likely to become lame due to the need to remain standing to dissipate heat. The lack of rest resulting from heat stress also has a negative impact on milk production due to decreased blood circulation to udders (Ramon-Moragues et al., 2021). Rising VPD may help mitigate heat stress to some extent, but drought driven by VPD is an exacerbating factor (Heat stress, 2024).

Grass protein is expected to decrease, and woody species are expected to increase, pushing grazing animals to eat vegetation, higher in PSC, a toxic compound that when ingested can interfere with thermal regulation (Villalba et al., 2019). While it is usually not detrimental for animals to consume some

of these toxins, and often do on a regular basis, this is a potential point of vulnerability within a transhumant SES in a changing climate (Villalba et al., 2019).

Heatwaves have historically been a deadly hazard to humans in France, with death tolls ranging from the thousands to estimates in the hundreds of thousands, in the summers of 1636, 1718–1719, 1911 and in 2003, as well as 2006 (Buguet et al., 2023). The addition of warmer nights to hot days is particularly problematic. Buguet et al. (2023) found that mortality is up to 50% higher when nights are hot rather than just the days. Warmer nighttime temperatures have also been shown to increase soil microbial and fungal diversity more than both warm days and nights, warm days alone, or controls (Zhao et al., 2024).

2.5 Drought and Flash Drought

2.5.1 Drought

Mittelberger et al. (2024) placed the drought experienced across France in 2022 within the context of the historical record and more severe climate scenario, RCP8.5 (which corresponds to SSP5). This drought had significant impact on farmers in Soule in July of that year. Millelberger et al. (2024) showed that the average precipitation experienced across France in JJA of 2022 was much lower than normal for the historical record, but it aligned with the precipitation levels that would be normal in France during JJA in around 2070 if the progression of climate change follows the path of RCP 8.5/SSP5. June, July and August, 2022, were also preceded an anomalously dry year, which contributed to low groundwater reserves experienced that summer in some areas of Soule.

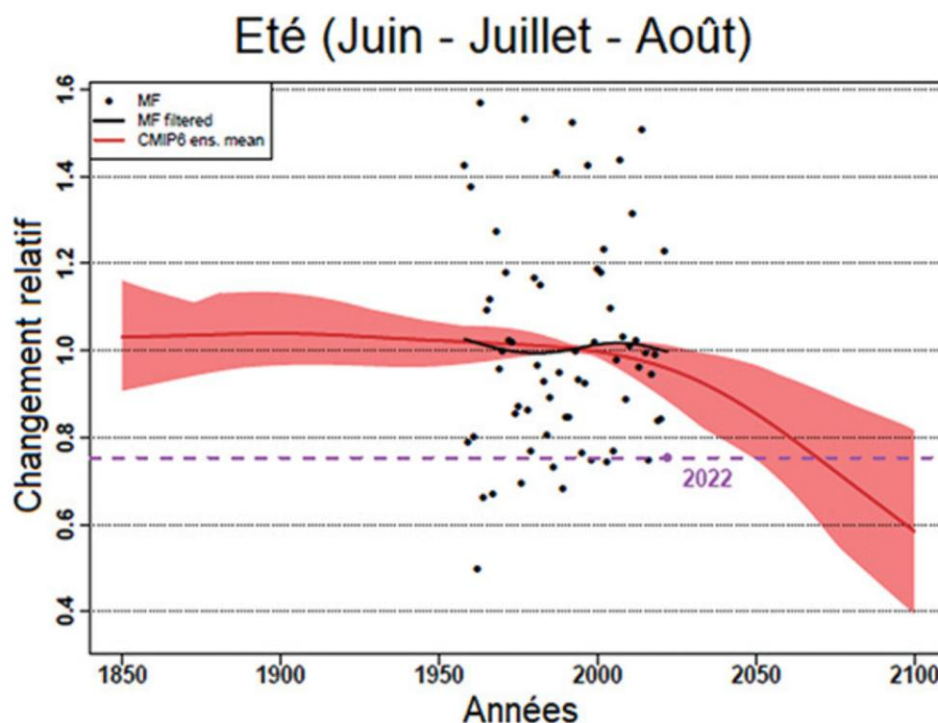


Figure 2.2. Average precipitation over France during the summer (black line) and CMIP6 simulation in SSP5-8.5 scenario in red (Mittelberger et al., 2024) is shown with black dots indicating the seasonal means for JJA. Relative differences are marked along the y-axis and years are shown on the x-axis. Mean precipitation for the summer months of the extreme drought year of 2022 is marked in purple with a dotted line.

Looking at stream flow over a 100-year observational period, the driest period in terms of streamflow occurred during 2014–2023 (Tootle et al., 2024). This same period (2014–2023) was one of the driest in the paleoclimate record spanning 2000 years (Tootle et al., 2024). This historical record of drought despite the record of precipitation trending up in Soule may be a function of increased temperatures outpacing small gains in precipitation, but further investigation should be done to interrogate the mechanisms producing these results. This illustrates the reality that precipitation is only one factor of drought and drives home the point that it is necessary to consider multiple climate drivers when assessing potential risks to an SES.

While precipitation has not shown decreasing trends, projections for soil moisture shows marked drying across the region that encompasses Soule. *Meteorological drought driven by increasing temperature and evaporative demand without precipitation deficit is beginning to be evident in Soule.* This phenomenon was described by Gebrechorkos et al. (2025) who recently found that drought severity, exacerbated by increasing atmospheric demand, has risen globally by 40% between 1901 and 2022. This increase has been accelerating over the past decade or so with expansion of global areas experiencing drought up by more than 74% over five years, 2018–2022, primarily driven by global warming and increased VPD (Douville & Willett, 2023).

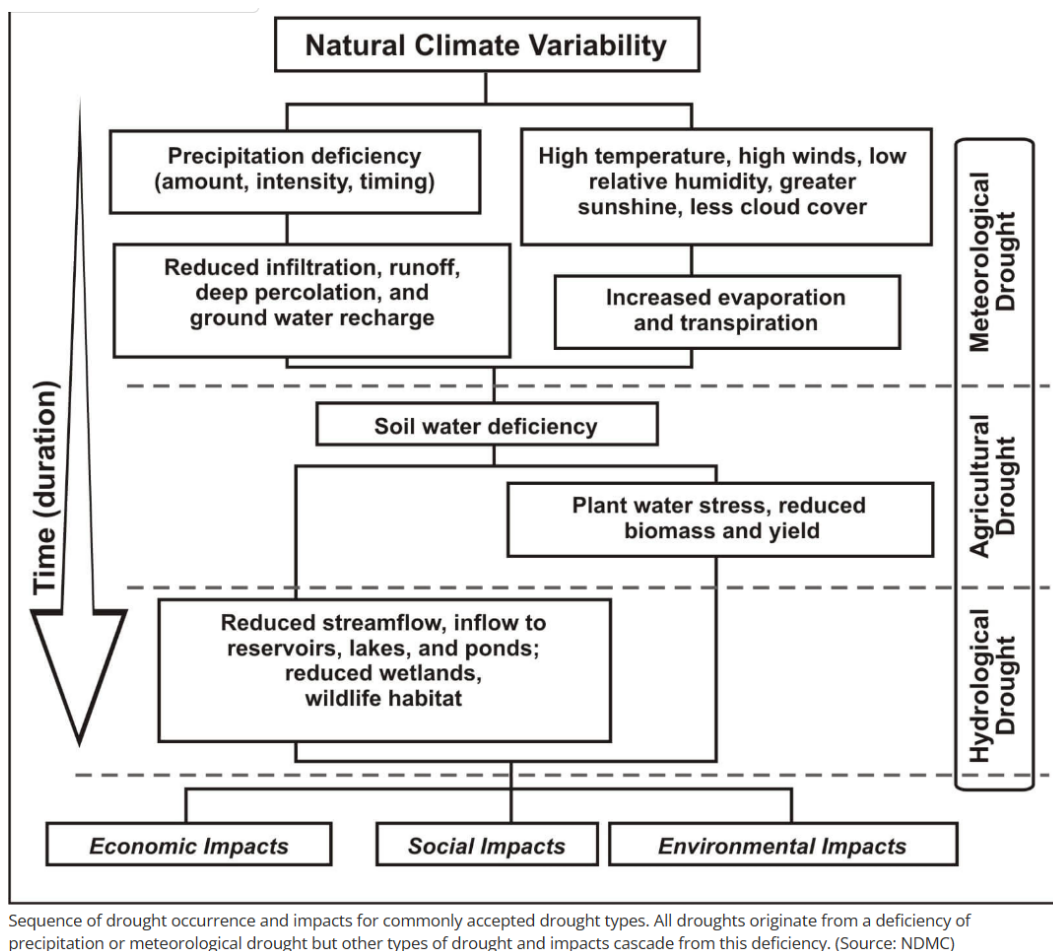


Figure 2.3. Dynamics of common drought types and sequence of progression (NDMC, 2025)

Not only does atmospheric demand for water drive drought, but it can also limit evapotranspiration to a greater extent than soil moisture in mesic forests, like the beech forests in Soule that are important to the global terrestrial carbon sink (Novick et al., 2024).

Venäläinen et al. (2022) described impacts of climate change and the management of risks related to forested landscapes in Europe. The broader region around Soule is expected to experience an increase in temperature and solar radiation, along with a decrease in precipitation and relative humidity (Venäläinen et al., 2022). These projected changes (see Figure 2.4) are based on global climate models and the amounts of change could vary significantly on smaller geographic scales. Soil moisture in our region of study is projected to decrease by 6% in the next 20 to 40 years based on analysis by Venäläinen et al. (2022). That study compared the average soil moisture during a past 30-year period (1971–2000) with a projected period (2040–2069) under RCP 4.5 (Venäläinen et al., 2022).

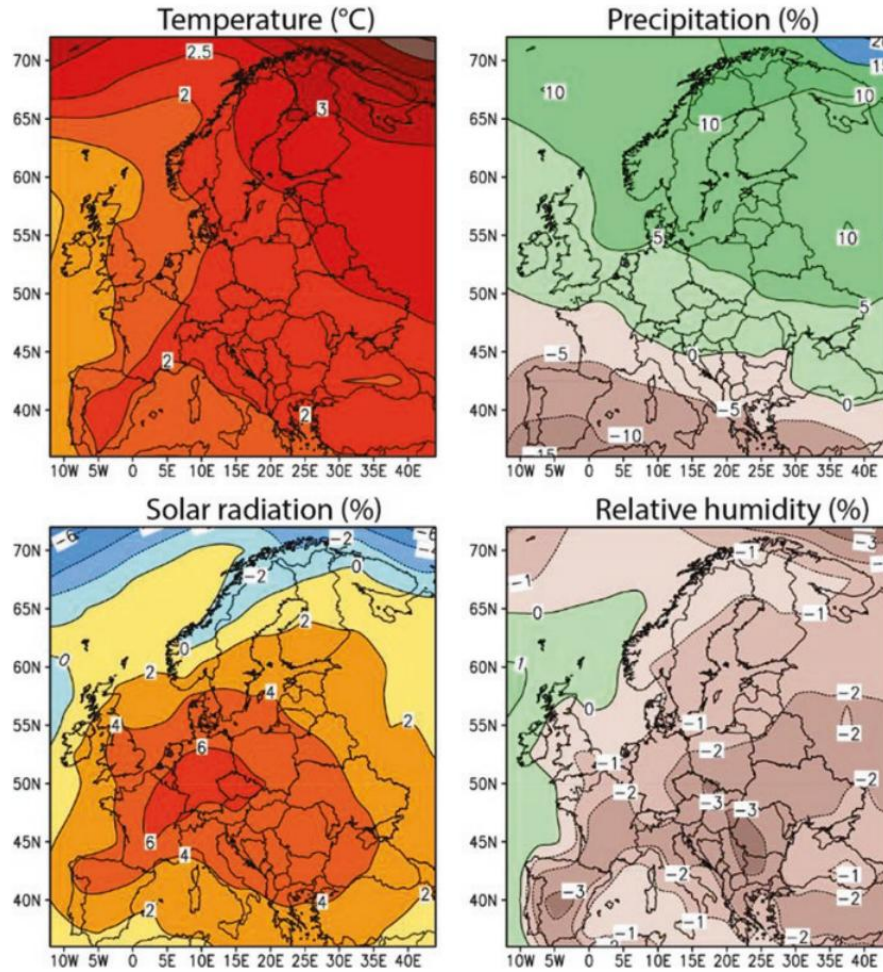


Figure 2.4. Projected climate change in mean annual temperature (°C), precipitation (%), incident solar radiation (%), and relative humidity (%) in Europe during 1971–2000 to 2040–2069 under RCP4.5. Venäläinen et al. (2022).

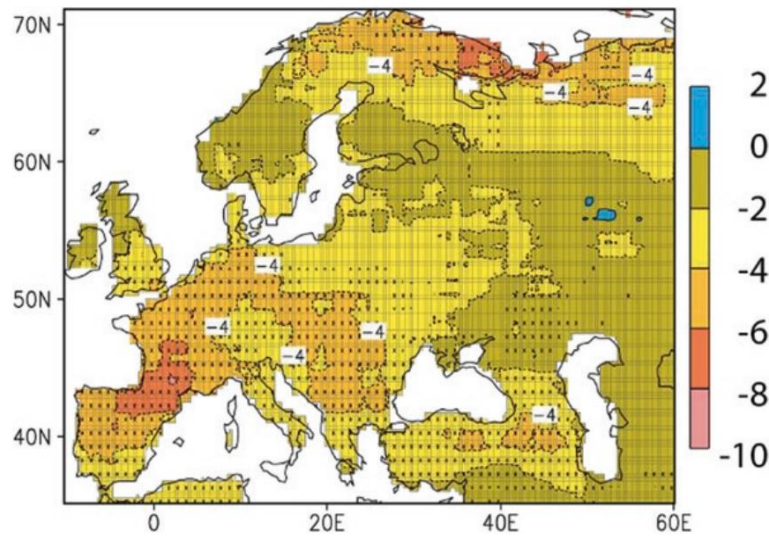


Figure 2.5. Projected change in soil moisture (%) under RCP4.5 for 2040–2069. Areas where at least 23 models agreed are stippled. From Ruosteenoja et al. (2018).

The average decrease in summer soil moisture projected for our study region in Southern France (Figure 2.5) is one of the most pronounced decreases in Europe. How this will impact the farmers at a local level is still hard to conceptualize, and what alterations in land management or transhumant practices might be needed are yet to be determined. Increases in frequency and severity of drought and flash drought possible in coming years necessitate attention to analysis and mitigation efforts to assess and prevent future hazards.

2.4.2 Flash drought

Flash droughts are a multivariable phenomenon with regional variation in drivers and are more likely to occur when drivers are compounded. Compounded drivers may involve low rainfall coupled with high temperatures, low humidity, strong winds, and clear sunny skies. Generally, these conditions involve decreased precipitation and high evaporative demand. Evaporative demand is the evaporation that would occur if moisture were unlimited. When sufficient soil moisture is present, evaporative demand and evapotranspiration increase in tandem. This is generally the dynamic in humid regions where flash droughts are more commonly identified and studied (Pendergrass et al., 2020). However, in more arid regions, where flash drought is also a concern, evaporative demand exceeds evapotranspiration, so flash

droughts are more often driven by precipitation deficits (Pendergrass et al., 2020). Anthropogenic climate change caused by greenhouse gas emissions is a significant global driver of flash drought. Climate change exacerbates many of the more regional drivers that have been implicated in flash drought. Anthropogenic climate change drives flash droughts on a global scale, interannual to decadal patterns such as ocean-atmospheric teleconnection, as well as local land atmosphere interactions also drive FD (Table 2.2).

Table 2.2. *Drivers of flash drought highlighted in a survey of the first 100 most highly cited articles found through Google Scholar grouped by their spatiotemporal scales.*

Scale	Drivers	References
Global	Anthropogenic Climate Change	(Wang et al., 2016), (Yuan et al., 2023), (Nguyen et al., 2021)
Large	Ocean-Atmospheric Teleconnections	(Yuan et al., 2023)
Interannual to Decadal	El Nino-Southern Oscillation (ENSO)	(Yuan et al., 2023), (Basara et al., 2019), (Nguyen et al., 2021), (Chen et al., 2019)
	Pacific Decadal Variability	(Yuan et al., 2023)
	Atlantic Multimodal Variability	(Yuan et al., 2023)
	Madden-Julian Oscillation	(Pendergrass et al., 2020)
	Negative Southern Annular Mode	(Nguyen et al., 2021)
	Positive Indian Ocean Dipole Mode	(Nguyen et al., 2021)
Local +	Land-Atmosphere Interactions	(Pendergrass et al., 2020)
Subseasonal to Seasonal	Precipitation Deficit	(Pendergrass et al., 2020), (Yamin et al., 2022), (Koster et al., 2019), (Parker et al., 2021),
	High Evapotranspiration	(Pendergrass et al., 2020), (Wang et al., 2016), (Chen et al., 2019), (Koster et al., 2019), (Parker et al., 2021)
	Evaporative Demand	(Pendergrass et al., 2020), (Liu et al., 2020), (Parker et al., 2021),
	Above-average Temperatures	(Pendergrass et al., 2020), (Yamin et al., 2022), (Chen et al., 2019), (Liu et al., 2020), (Koster et al., 2019), (Parker et al., 2021),
	Low Humidity	(Pendergrass et al., 2020), (Liu et al., 2020), (Parker et al., 2021),
	Strong Winds	(Pendergrass et al., 2020), (Chen et al., 2019), (Parker et al., 2021)
	Excess Insolation	(Pendergrass et al., 2020), (Chen et al., 2019), (Koster et al., 2019)
	Compound Extreme Events	(Pendergrass et al., 2020), (Yamin et al., 2022)
	Vegetation Type	(Pendergrass et al., 2020)
	Positive Geopotential Heights	(Pendergrass et al., 2020)
	Unusual Seasonal Variations	(Pendergrass et al., 2020), (Otkin et al., 2016),
	Low Soil Moisture	(Wang et al., 2016), (Parker et al., 2021)
	High Vapor Pressure Deficit	(Yamin et al., 2022)
	Runoff	(Basara et al., 2019)
	Increased Insolation	(Chen et al., 2019)

The relative impact of each driver can differ significantly by region and even by individual instances of flash drought within the same region. Some of the drivers are also indicators due to land-atmosphere interactions and positive feedback loops. For example, as soil moisture decreases, less moisture available for evaporation results in higher temperatures at the ground level, which increases evaporative demand and can intensify flash drought. The soil-moisture-precipitation feedback loop, in which dry surface conditions lead to atmospheric circulation that exacerbates dryness is another example of the interrelated nature of the drivers of flash drought (Roundy et al., 2013). Land-atmosphere interactions and energy fluxes contribute to the variability of flash drought across regions and exacerbate flash drought prediction challenges. Some of the land-atmosphere dynamics of flash drought conditions and impacts are illustrated in Figure 2.6, from Corak et al. (2023).

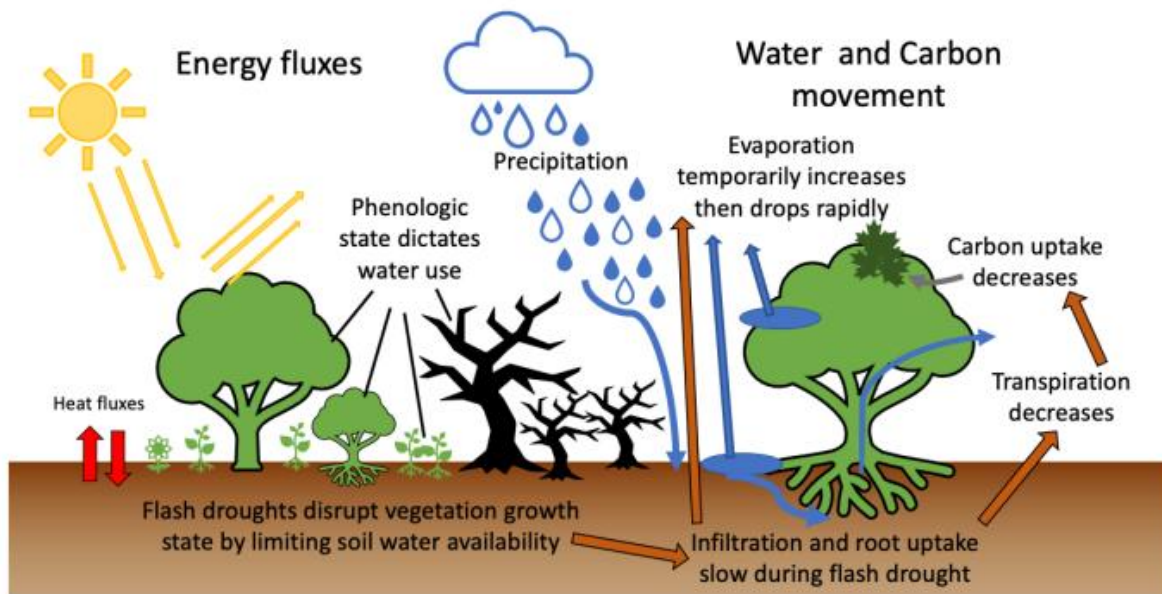


Figure 2.6. *Flash drought dynamics and hypotheses presented by Corak et al. (2023).*

The dynamics of flash drought illustrate important land-atmosphere interactions driven by VPD. Evaporation increases then ceases with lack of precipitation and elevated atmospheric demand for water (Figure 2.6). Carbon uptake declines due to decreased infiltration and root-uptake of water, and plant-atmosphere interactions are diminished along with vegetation phenological states (Figure 2.6).

Osman et al. (2021) described the complex dynamics and illustrated a simplified version of the relationships among some of the drivers, processes, and variables of flash drought (Figure 2.7). They found that important indicators of flash drought include evaporative demand (ED), vegetation health, soil moisture (SM), and evapotranspiration (ET).

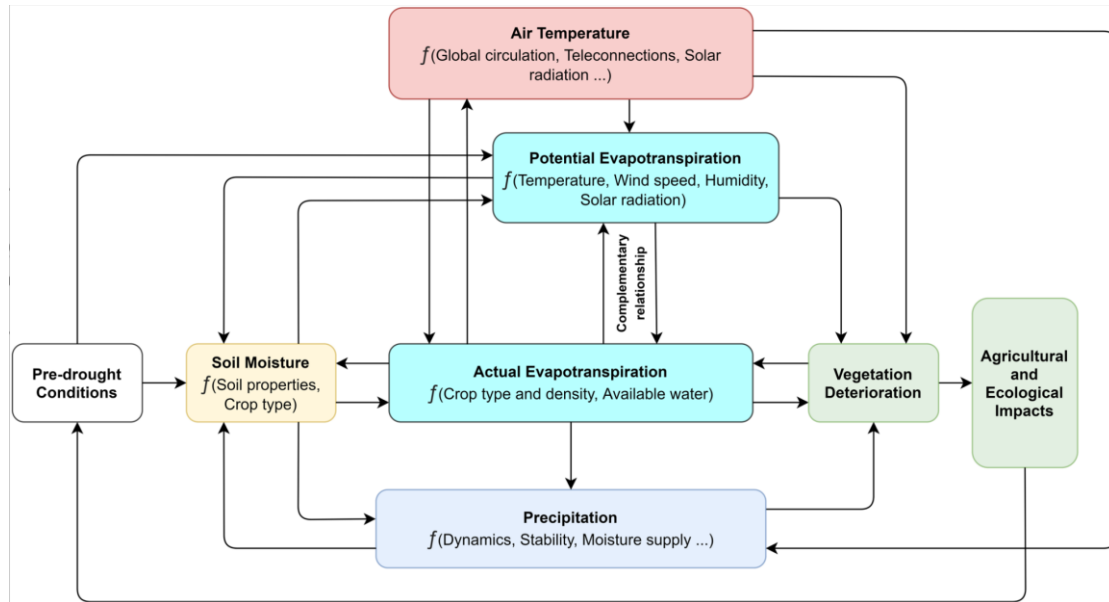


Figure 2.7. *Feedbacks (direction shown with arrows) and processes associated with the onset of flash drought. Core groups of processes, represented by color, illustrate the varying definitions of the onset of flash drought (Osman et al., 2021).*

Evapotranspiration-based indicators and soil moisture indicators are the most often utilized indicators to define flash drought (Lisonbee et al., 2021).

Flash droughts can damage ecosystems via excessive evaporative stress among other mechanisms, lower crop yields, decrease livestock production and contribute to compound extreme events such as increased likelihood of wildfire, water resource depletion, reduced air quality, and decreased food security (Christian et al., 2021; Crausbay et al., 2017).

The impacts of flash drought are often amplified due to the speed of onset and lack of warning, which leaves little time for preparation and mitigation. However, probabilistic future projections on multi-

year scales can help farmers consider the risks in their decisions, and that would be very helpful (S. Sharma, personal communication, 2023).

2.6 Rising Vapor Pressure Deficit

Rising VPD is a driver of evaporative demand, which drives extreme drought and impacts many dynamics of the SES of transhumance in Soule. VPD is also strongly correlated with wildfire extent and may drive up potential hazards according to future climate scenarios.

Globally, temperature increase driven by climate change has already reached +1.1°C over the period 2011–2020 compared to the 1850–1900 pre-industrial period (IPCC, 2023). The global upward shift in temperatures impacts many climate dynamics. Drought and floods, for instance, due to both shifting weather patterns and the increased demand for water from the atmosphere that accompanies higher temperatures are expected to increase in many regions. As temperatures rise, the demand for water from the atmosphere and power to evaporate water and desiccate vegetation increases, driving drought conditions. Along with the increased capacity of the atmosphere to evaporate and desiccate, higher VPD drives the atmosphere to hold and carry larger volumes of water and drop a greater volume of precipitation when the water vapor finally cools enough to precipitate out, which can drive flooding.

VPD was identified as an essential metric for assessing future effects of climate change on social-environmental systems, including impacts to human health, agricultural production and wildfire (Treydte et al., 2024). Treydte et al. (2024) identified unprecedented elevations in VPD across Europe attributed with more than 98% certainty to the influence of fossil fuel exploiting industry with most pronounced drying in the Alps and Pyrenees regions.

Evaporative demand, the atmosphere demand, or “thirst” for water, is an important driver of earth-atmosphere interactions and is expressed well through the measure of vapor pressure deficit (VPD) and generally has an inverse relationship with relative humidity (RH). Vapor pressure deficit is featured in this paper because it is a more accurate indicator of atmospheric demand than relative humidity.

Relative humidity is the percentage of moisture in the air relative to how much moisture the air can hold, so it only communicates the relationship of actual water vapor to maximum water vapor the air can hold.

Because it is a relative term, the same RH may occur under very different atmospheric conditions. For example, on a cold day, the air cannot hold much water, so relatively little moisture could yield a high RH percentage, but on a hot day, the air would have the capacity to hold much more water, so the same amount of moisture in the air that resulted in a high RH on the cold day could result in a low RH on a hot day. RH is not an adequate measure of atmospheric evaporative demand because it is a relative measure expressed in percentages. Vapor pressure deficit (VPD), in contrast, is an absolute measure of the difference between the maximum amount of water vapor the air can hold, i.e. Saturation Vapor Pressure (SVP), and the actual amount of water vapor the air can hold, i.e. Actual Vapor Pressure in specific values. These values are more meaningful than a relative percentage for applications to impacts on agricultural and ecological systems. It should be noted that when assessing the impact of VPD on vegetation, the type of vegetation and microclimate variables must be considered since the VPD within the boundary layer of the leaf (an area around the leaf that often has increased moisture created by the physiological processes of the leaf) and the structures of the leaf and canopy is the key VPD to consider when assessing impact of VPD on plant function.

Novick et al. (2024), summarized the impact of VPD on vegetation at different scales. The impacts of rising VPD are multifold, ranging from impacts to plant physiology and leaf-level gas exchange, increasing transpiration up to a point before rising high enough to cause the plant to close the pores or stomata on the leaf, shutting down gas exchange, and with it, photosynthesis, to conserve water within the plant. This process varies with species and even within species adapted to different areas and impacts the morbidity and mortality particularly of taller trees. With long enough time to adapt, trees can develop deeper roots and smaller canopies, allowing better survival during periods of higher VPD. More research is needed to disentangle the direct impacts of VPD and related impacts, such as decreased soil moisture, higher temperatures, and adaptive timescales. On a larger scale, rising VPD is expected to plant community composition and interactions toward more broadleaf trees and C4 grasses. Moderately wet, mesic systems are reported to be most vulnerable to rising VPD where it can significantly impact carbon cycling.

Land-atmosphere coupling strongly connects VPD and soil moisture. VPD intensifies drought conditions and is a main driver of flash drought and increases transpiration, potentially straining groundwater reserves. High VPD has been implicated in reduced crop yields across the globe. Finally, high VPD can desiccate vulnerable live and dead fuels, increasing likelihood of hazardous fire and total burned area. Prescribed fire, such as *écobuage*, can reduce the fuel load and decrease likelihood of detrimental fire (Novick et al., 2024).

2.7 Fire Hazard

Vapor pressure deficit, a dominant driver of burned area, may approach levels at the end of the century that could impact the fire regime in Soule. Treydte et al. (2024) report that while vapor pressure deficit (VPD) is increasing globally in response to anthropogenic climate change, the largest magnitude of VPD increase is in Western and Central Europe, the Alps and the Pyrenees region. Iglesias et al. (2015) pointed out that increased fire activity is associated with increased temperatures as well as changes in vegetation, land management and fuel availability. Ecoregions that generally display the most sensitivity to interannual fire weather variability are those that are not fuel limited such as most mesic forests with low to moderate fire weather frequency (Abatzoglou et al., 2018). Ecoregions lie on a spectrum from fuel limited (i.e., too little fuel to burn) to moisture limited (i.e., too wet to burn) (Jones et al., 2022). Miller et al. (2024) found in their review that the Mediterranean region (a region adjacent to the ecoregion of my study area) exhibits an “exceptionally strong” relationship between fire weather and burned area. Though a number of climate variables may help prevent damaging wildfire and forest fire in Soule, the potential impact to the SES of detrimental fire warrants close exploration.

Vapor pressure deficit, a representation of the difference between the amount of moisture in the air and the amount of moisture at saturation, is an important indicator for social-ecological systems (SES) such as the SES in Soule due to its relationship to factors contributing to ecological and human wellbeing, such as evapotranspiration, heatwaves, drought, crop yield, and forest fire (Treydte et al., 2024). Fox et al. (2018) showed a non-linear relationship between fire weather and burn area, but 97% of burned area occurred in weeks when fire weather index values were greater than 90 ($FWI > 90$).

Ochoa et al. (2024) investigated the likelihood of large fires and their drivers across Europe using a variety of social and environmental factors (Table 2.3) and reported increased probability of fire ignition according to their models near our study region of Soule (Figure 2.8, 2.9).

Table 2.3. Variables used by Ochoa et al. (2024) to predict large fire initiation in Europe.

Variables	Source	Temporal extent	Previous studies using similar variables
Distance to roads (m)	Meijer et al., 2018 (GLOBIO)	2018	(Hernandez-Leal et al., 2006 ; Martinez et al., 2009 ; Oliveira et al., 2012 ; Song et al., 2017 ; Martín et al., 2018 ; Abedi Gheshlaghi, 2019 ; Costafreda et al., 2017 ; Zhang et al., 2021)
Forest-agricultural interfaces (FAI)	From Fuel Map (Aragoneses et al., 2023)	2019	(Martinez et al., 2009 ; Martínez-Fernández et al., 2013)
Wildland-urban interfaces (WUI)	From Fuel Map (Aragoneses et al., 2023)	2022	—
Wildland-agricultural interface (WAI)	From Fuel Map (Aragoneses et al., 2023)	2019	(Martinez et al., 2009 ; Martínez-Fernández et al., 2013 ; Costafreda et al., 2017)
Wildland-forest interface (WFI)	From Fuel Map (Aragoneses et al., 2023)	2019	—
Forest-urban interfaces (FUI)	From Fuel Map (Aragoneses et al., 2023)	2019	(Costafreda et al., 2017)
Land change	Corine Land Cover	2000 & 2018	—
Cattle/km2	FAO 2014 (Robinson et al., 2014)	2010	(Martinez et al., 2009 ; Oliveira et al., 2012 ; Mancini et al., 2018)
Goats/km2	FAO 2014 (Robinson et al., 2014)	2010	(Martinez et al., 2009 ; Oliveira et al., 2012 ; Mancini et al., 2018)
Sheep/km2	FAO 2014 (Robinson et al., 2014)	2010	(Martinez et al., 2009 ; Oliveira et al., 2012 ; Mancini et al., 2018)
GDP (2011 USD, millions)	Kummu et al., 2018	2015	(Costafreda et al., 2017 ; Mancini et al., 2018)
Population > 65 years in rural areas (inhab./km2)	SEDAC-CIENSIN 2010 (Warszawski et al., 2017)	2010	—
Population density (inhab./km2)	(Eurostat JCR-GEOSTAT 2018, GISCO. (Batista e Silva et al., 2021))	2018	—
Evapotranspiration (mm)	Trabucco and Zomer, 2019 (Penman-Monteith equation)	2018	—
Aridity Index	Trabucco and Zomer, 2019 (Annual precipitation/evapotranspiration)	2018	—
Bioclimates	Metzger, 2018	2000	—
Ecozones	FAO, 2021 (Fischer et al., 2021)	2000–2010	

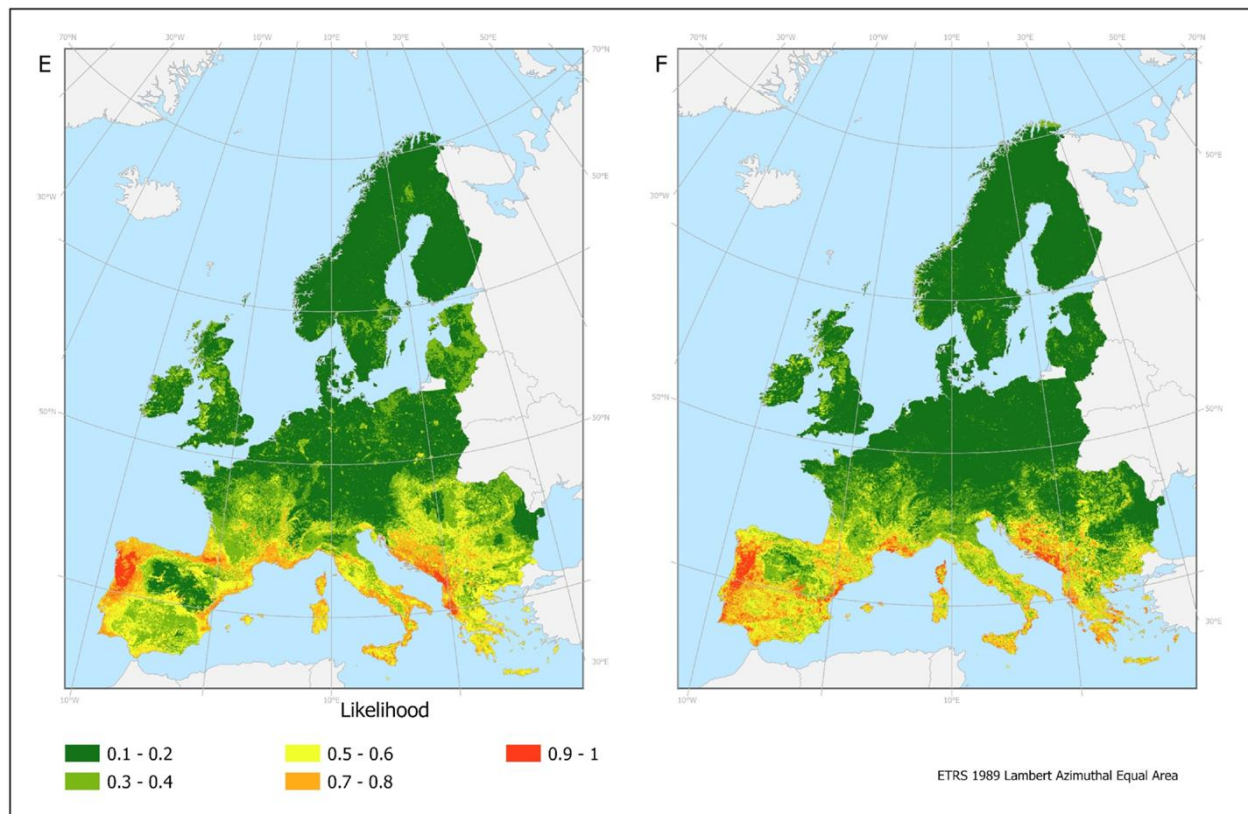


Figure 2.8. Likelihood of ignition of fires greater than 100 ha predicted by the multi variable model created by Ochoa et al. (2024). The region encompassing Soule is shown in an area of increased likelihood of large fires.

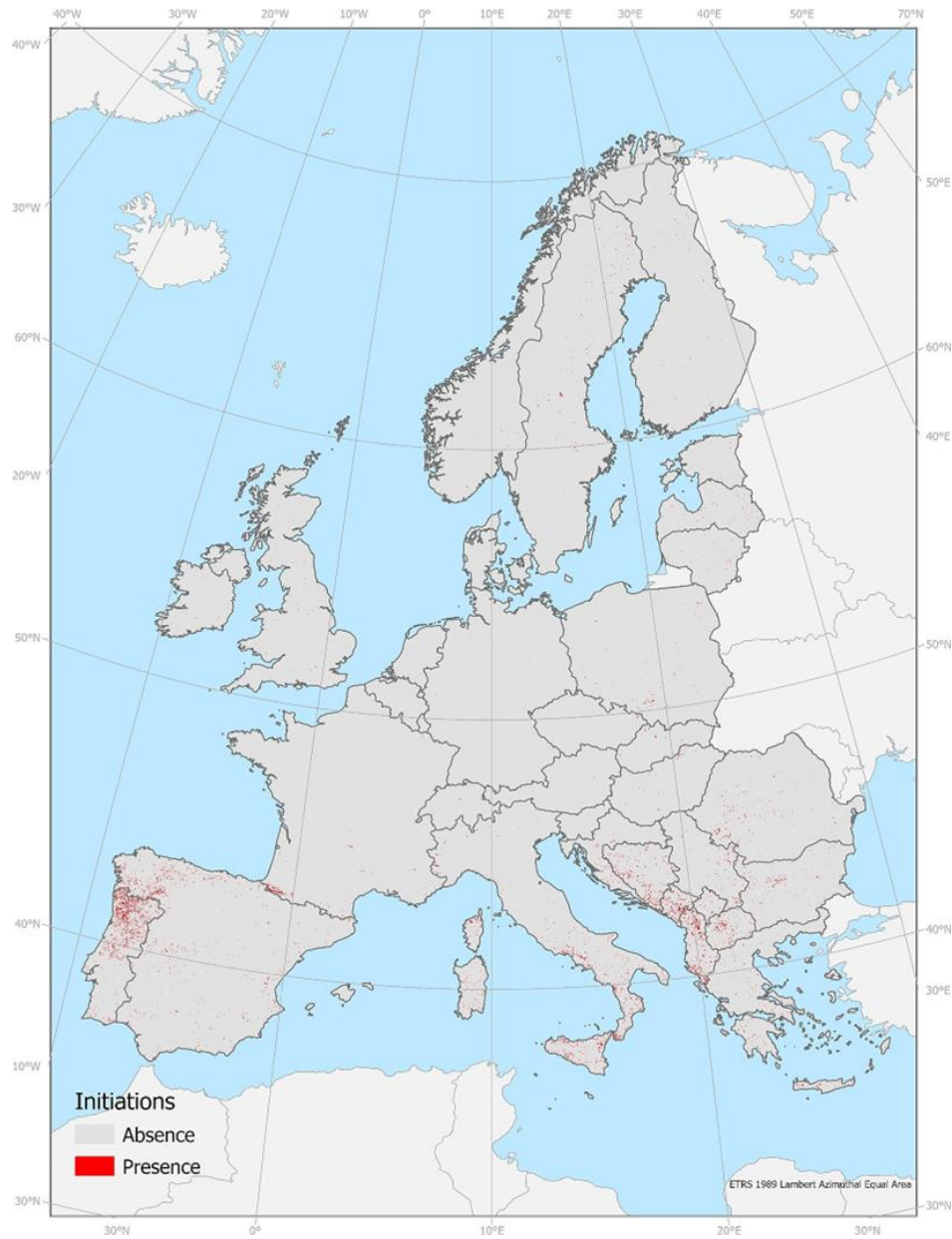


Figure 2.9. Fires larger than 100 ha (red dots) observed across Europe during 2001–2019 by Ochoa et al. (2024). A hotspot is evident in the southwestern region of France indicating elevated fire activity near Soule.

Fargeon et. al. (2020) considered future fire weather for France at an 8-km resolution using Euro-CORDEX 50km models that they downscaled to 8km. They also determined a time of emergence (TOE) when the “climate change signal exceeds internal variability” that may be beneficial to provide a possible timeline that could guide preventative action (Figure 2.10) (Fargeon et al., 2020).

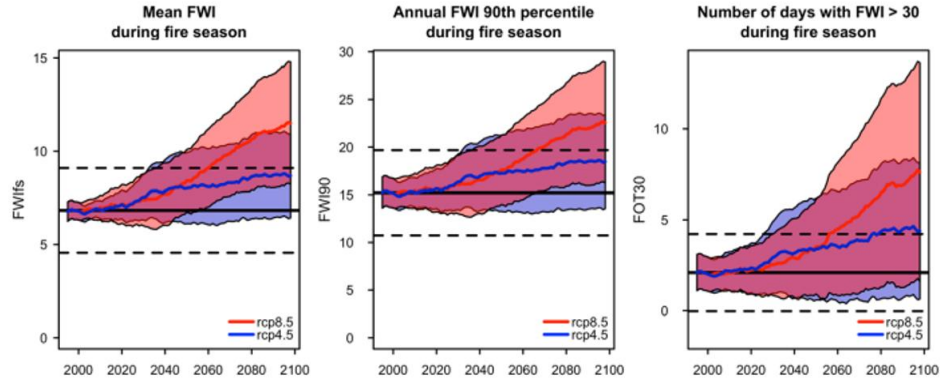


Figure 2.10. Trends in future fire weather from RCP 4.5 and RCP 8.5 as reported in Fig. 1 of Fargeon et al. (2020) show a great deal of variability in potential future FWI for the country of France.

The model and projections of Fargeon et al. (2020) do not show a pronounced hotspot in the southwestern France region which contrasts with the work of Ochoa et al. (2024), reinforcing the need for further analysis of future trends in fire weather and risk for Soule (Figure 2.11).

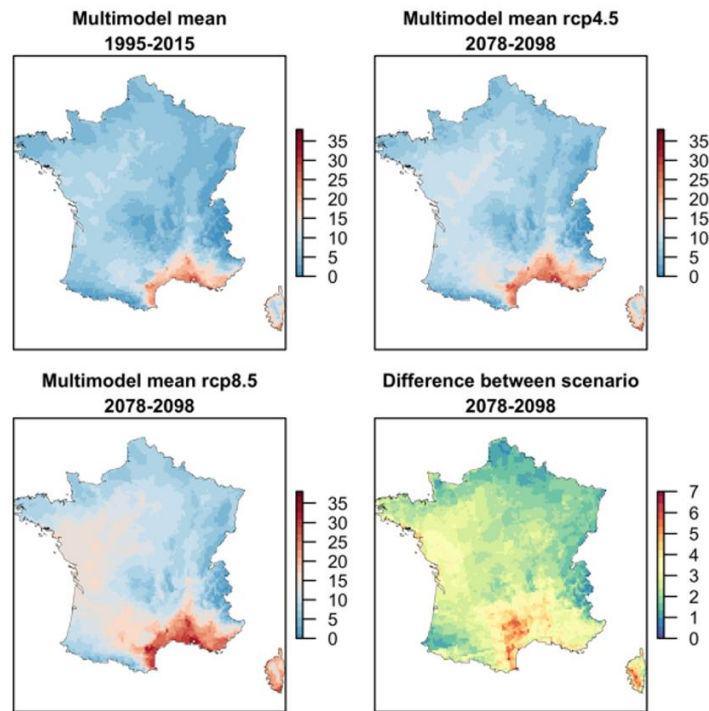


Figure 2.11. Fargeon et al. (2020) comparison of recent Fire Weather index (FWI) values with future FWI for RCP 4.5 and RCP 8.5.

Alizadeh et al. (2020) measured upslope progression of fires in recent years and estimated that climate warming trends have reduced the high-elevation mesic flammability barrier to allow fires in elevations previously protected, putting 11% more of western forests at risk of burning. Additionally, an upslope advance of high elevation fires was found to be a median cumulative advance of 252m (-107 to 656m; 95% CI) in a little over three decades (Figure 2.12). These high elevation fires were found to be strongly related to vapor pressure deficit (VPD) in the warm season. The advance of fire upslope is attributed to warming, with 60% of the increase in VPD attributed to increased air temperature.



Figure 2.12. Alizadeh et al. (2024) illustrates the movement of fires into higher elevation between 1984 and 2017.

Based on a review of the literature, while much focus on fire dynamics has been on areas where wildfires have been a frequent concern, there is little research that examines fire dynamics and hazards in areas where forest fires have not historically been a frequent issue. As traditional *écobuage* practices have declined, woody shrubs and overgrowth are encroaching on grasslands, posing fire risks to nearby structures and soil due to the increased intensity when they do burn.

Clarke et al. (2022) found that all forest biomes are sensitive to vapor pressure deficit, though the degree of sensitivity varies across regions. Maximum daily VPD more than 1.5kPa was identified by Clarke et al. as the key threshold in the region that includes Soule, beyond which fire became more likely than not, exceeding 50% probability. Clarke et al. also advised the use of VPD climatologies to predict forest fire likelihood for projected climate change. This paper assessed the historical climate trends of key variables of import to the SES of Soule (including the farmers and the social-environmental system of transhumance that structures and sustains their lifeways), and drew from a recently created global dataset of monthly VPD values to create climatologies and time series that assessed future risk of fire to the forests of Soule and if and when key threshold for increased fire probability identified by Clarke et al. might be breached.

A risk management strategy to prevent forest fires mentioned by Venäläinen et al. (2022) is a more fragmented forest landscape (p. 47). The pasturelands in our study have helped to create forest fragmentation, so farm/pasture abandonment may aid in the spread of forest fire in projected conditions conducive to a fire regime with more frequent fire activity. Pasturelands in this region have also been shown to sequester more carbon than nearby forested soils. Although the carbon in the above ground biomass of the forests may balance the equation, frequent fires would release above ground carbon quickly back into the atmosphere, erasing carbon sequestration benefits of poorly managed forest lands (Leigh et al., 2015; Venäläinen et al., 2022). Understanding climate projections for Soule in terms of fire weather and vapor pressure deficit and drought frequency may help the community maintain and incorporate land management practices that prepare for and adequately mitigate the damaging impacts of uncontrolled fire on Soule's socio-environmental systems of the future.

CHAPTER 3

DATA AND METHODS

The present study asked the following questions: What are the current trends in climate variables that impact transhumance in Soule, France? What are future trends in Vapor Pressure Deficit, and how might those impact the social-environmental system of transhumance in Soule, France? When might the VPD thresholds in Soule, France reach a threshold associated with elevated fire probability?

A high-resolution observational dataset with daily temporal resolution, E-OBS was used to extract information on climate variability during the historical period (1950–2024) for key hydroclimate variables: precipitation, relative humidity, temperature and consecutive clear days. The VPD trends from the historical period and future projections were studied from a CMIP6 GCM derived VPD dataset provided by Bjarke et al. (2023). A discussion of the construction of the various datasets used is presented in the following sections.

3.1 Datasets

3.1.1 E-OBS

E-OBS is a land-only gridded daily observational dataset in Europe (Haylock et al., 2008). This dataset is unique because of its high spatial resolution (0.10° and 0.25°) and daily resolution and is based on the observations from meteorological stations across Europe, which are provided by the National Meteorological and Hydrological Services (NMHSs) and other data holding institutes. The dataset provides primary meteorological variables, including precipitation, temperature, relative humidity, sea level pressure, global radiation from 1950 onward and wind speed from 1980 onward. The gridded dataset is calculated in a two-step process to produce daily gridded fields from the unevenly distributed station network. First, the daily values are aggregated to monthly values and fitted to a deterministic

model to estimate the long-range spatial trend in the data, then the residuals from this model are interpolated using a stochastic technique to produce the daily ensemble. Monthly values are used in the first step as it is difficult to discern the relationship between altitude and meteorological fields in daily data. The mean of ensemble members provides the “best guess”, and the ensemble spread is calculated as the difference between the 5th and 95th percentiles over the members to provide a measure of 90% uncertainty range.

Since the E-OBS dataset ensures a low degree of manipulation of the station observation data, it may be a superior data product when compared to reanalysis datasets. Extensive studies have been done to compare and validate E-OBS against other existing datasets (Van der Schrier et al., 2013; Cornes & Jones, 2013). E-OBS was initially developed to provide a validation dataset for the suite of Europe-wide model simulations but has become used more generally for monitoring climate across Europe, particularly regarding assessment of the magnitude and frequency of daily extremes.

This dataset typically undergoes major updates every 6 months. The updates are made as new station data is procured or when station data is updated locally. In this paper, for most variables we use E-OBS version v31.0e, which was released in March 2025. The previous version, E-OBSv30.0e, had one minor issue with precipitation over central Pyrenees where the period between January to June 2024 had some unrealistically high values of precipitation. This issue may have been fixed in the current version (see Figure 14 in E-OBS user guide), as the difference (v31.0e – v30.0e) between seasonal precipitation appears decreased in the central Pyrenees region. Consecutive clear days (CDD) was the only variable that used the earlier version: E-OBSv29.0e.

3.1.2 Vapor Pressure Deficit

Vapor Pressure Deficit (VPD) is a measure of the evaporative demand of the atmosphere and is a key driver and explanatory variable for hydroclimate related dynamics, such as changes in surface freshwater availability, agricultural water demand and drought (Berghuijs et al., 2017; Cook et al., 2014; Hobbins et al., 2016). Yet, there has not been an organized global dataset providing estimates of evaporative demand from the latest generation of Coupled Model Intercomparison Project (CMIP6)

general circulation models (GCMs). Thus, this study used monthly VPD from an ensemble of CMIP6 derived reference and potential evapotranspiration (Bjarke et al., 2023) that provided global monthly estimates of three crucial variables for hydroclimate risk evaluation. The dataset provided monthly estimates of evaporative demand the using two most used methods: the Priestley-Taylor evapotranspiration (ET_p) and the FAO-56 Penman-Monteith reference evapotranspiration (ET_o) for two reference vegetation land-cover. They also provide VPD, which was used in this paper since it relates to many key aspects of the SES and is commonly used to assess ecological impacts. All variables were provided for the historical simulation period (1850–2014) and four future (2015–2100) CMIP6 scenarios from the Scenario MIP. This dataset provided uniform VPD estimates from all possible CMIP6-MME. The dataset used net surface-radiation, 2-m wind-speed, vapor pressure and saturated vapor pressure from the CMIP6 GCMs to compute the evaporative demand variables for the future and historical periods. The spatial resolution of each monthly estimate of VPD is the same as that of the parent CMIP6 model (roughly 100kms, refer Bjarke et al., 2023 Table 1 for more details) and the future calculations were made for four out of five future emissions scenarios (SSPs 1-2.6, 2-4.5, 3-7.0 and 5-8.5). The dataset has been validated using observation-based historical baselines of monthly estimations of ET_p and ET_o from the Climate Research Unit (CRU) (Harris et al., 2020) dataset and ERA5-Land reanalysis (Copernicus Climate Change Service, 2019). The future projections are based on socio-economic storylines designed by IPCC’s climate modelling team, CMIP6. Thus, the next section discusses broad ideas from these storylines to put into context the uncertainty constraints on future projections of climate variables.

3.1.3 CMIP6 scenario framework

Organized under the auspices of the World Climate Research Programme (WCRP), the sixth phase of the Coupled Model Intercomparison Project (CMIP6) put forward a new Model Intercomparison Project (MIP) to understand the climate feedback from anthropogenic emissions called the Shared Socioeconomic Pathways (SSP) (Eyring et al., 2016). Results from the SSP experiments are central to the Intergovernmental Panel on Climate Change’s (IPCC) assessment reports that inform international climate and economic policies. SSPs go beyond a previously introduced MIP, Representative

Concentration Pathways (RCPs set the baseline emission scenario and subsequent global warming anticipated), as the SSPs incorporate socio-economic trajectories that have a significant impact on anthropogenic emissions on a global scale. RCPs simulate global climate change for fixed concentrations of atmospheric CO₂ that correspond to radiative imbalance (RCP 2.6, 4.5, 7.0, 8.5). SSPs are constructed as socio-economic narratives that are associated with quantitative descriptions for primary drivers of anthropogenic emissions, such as population, economic growth, urbanization, energy and land-use change (Riahi et al., 2017). The SSPs and RCPs are tied together under the scenario framework that was developed after recognizing the intrinsic link between future policy making and questions related to climate change research (Van Vuuren et al., 2014). The scenario framework essentially forms a matrix of key elements that test the effectiveness of different adaptation and mitigation strategies (in terms of their costs, risks and other consequences), possible trade-offs and synergies. Here the two primary axes of the scenario matrix are RCPs, or the radiative forcing axis, and the SSPs, or the socio-economic pathway axis (Figure 3.1).

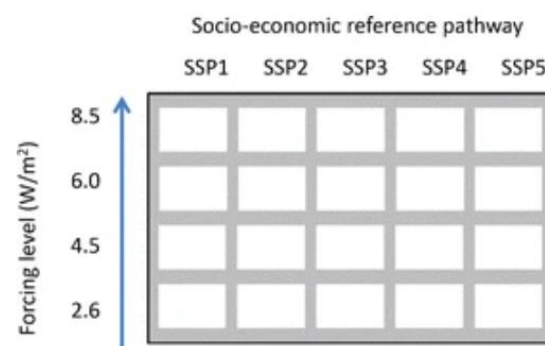


Figure 3.1. *SSP scenario matrix architecture. The architecture combines different socio-economic reference assumptions as described by SSPs with different future levels of climate forcing, reproduced from Van Vuuren et al. (2014).*

This framework streamlined several scenarios simulated by different climate modelling institutions to make future climate projections comparable. A range of uncertainty was provided based on the various implications of mitigation and adaptation to climate change. The framework is also scalable,

for example, even though the SSPs provide information at the scale of large world regions, these narratives are meant to help communicate and contextualize modelling studies for finer regional scales for both near and long-term future conditions (Van Vuuren et al., 2014). The SSP narratives can be explained through a “challenge space” with two axes – climate mitigation and adaptation (O’Neill et al., 2014, Figure 3.2). Thus, even though the development paths are separated into five narrative areas, the emission scenario would play a key role in how the challenge space changes dynamically in response to climate mitigation goals.

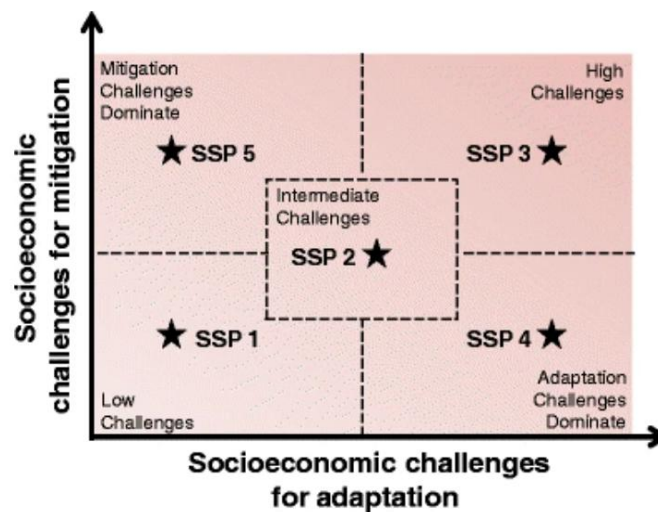


Figure 3.2. “Challenge space” spanned by the SSPs (based on Kriegler et al., 2012, Figure 3). The SSP narratives are arranged according to the level of challenges they face in mitigation and adaptation based on current climate-policy decision making framework.

The number of possible climate futures is infinite, however, marker scenarios, specific combinations of SSP and RCPs that provide robust modelling results and are consistent with other model differences were identified by Riahi et al. (2017) to enable realistic estimates of future climates. This work in SSPs has given rise to some well-established, evaluated and complete datasets for some SSPs and their associated RCP scenarios from most modelling institutions. Table 3.1 lists the main SSP scenarios and with descriptions covering socio-economic and international cooperation aspects of the narratives.

Table 3.1. *SSP narratives and primary RCP scenarios associated with each, from USDA Climate Hubs.*
(2025).

SSP	RCP(s) associated with SSP	Description
SSP1	RCP 1.9 RCP 2.6	Sustainability: The world shifts gradually, but pervasively, toward a more sustainable path, emphasizing more inclusive development that respects perceived environmental boundaries.
SSP2	RCP 4.5	Middle of the road: The world follows a path in which social, economic, and technological trends do not shift markedly from historical patterns.
SSP3	RCP 7.0	Regional rivalry: A resurgent nationalism, concerns about competitiveness and security, and regional conflicts push countries to increasingly focus on domestic or, at most, regional issues.
SSP4	RCP 3.4	Inequality: Highly unequal investments in human capital, combined with increasing disparities in economic opportunity and political power, lead to increasing inequalities and stratification both across and within countries.
SSP5	RCP 8.5	Fossil-fueled development: This world places increasing faith in competitive markets, innovation and participatory societies to produce rapid technological progress and development of human capital as the path to sustainable development. Global markets are increasingly integrated.

For the purposes of this paper, we use marker scenarios that have been evaluated and compared across different modelling institutes – SSP126, SSP245, SSP370 and SSP585. Here, the first number indicates the SSP narrative (also shown in Figure 3.2), i.e., 1, 2, 3 and 5. The last two digits correspond to the suitable radiative forcing under which a particular SSP was most likely. Thus, SSP126 stands for SSP1, RCP2.6 or SSP1 with 2.6 Wm^{-2} radiative forcing at the top of the atmosphere. These SSP scenarios encompass a wide range of variability in global climate policy and reduction in emissions, thus providing us with a wide range of uncertainty for future projections.

3.2 Methods

Time series, climatologies, and spatial distribution plots were created for the historical period 1950–2024 using the E-OBS dataset for precipitation, consecutive wet and dry days, temperature, and relative humidity. Spatial mean time series, annual and seasonal climatologies, and days of threshold exceedance for vapor pressure deficit were calculated using a global VPD dataset from Bjarke et al. (2023) spanning the historical period (1850–2014) and the future projections period (2015–2100).

3.2.1 Time series

To extract a temporal signal of climate variability from a spatially gridded dataset, spatially averaged time series for different regions were calculated. Rectangular regions defined based on latitude and longitudinal extent of the regions of interest are listed in Table 3.2. All spatial averages were computed after latitudinally weighted averages of the variables. The daily temporal resolution dataset was averaged to calculate mean annual temperature (MAT) whereas the daily data was summed to calculate total annual precipitation (TAP).

Table 3.2 *Latitude-longitude bounds defined for the regions used to calculate spatial average of climate data.*

Region	Latitude bounds	Longitude bounds
Soule	43.0 - 43.3 N	0.7 - 1.2 W
Basque Country	42.5 - 43.5 N	1 - 3.5 W
Pyrenees	42.3 - 43.2 N	-1.5 - 1.5 W
France and Spain	35.0 - 52.0 N	-6.0 - 10.0 W

Seasonal averages and totals of temperature and precipitation respectively were calculated by averaging daily values after grouping by months: December, January, February (DJF) for winter; March, April, May (MAM) for spring; June, July, August (JJA) for summer; September, October, November (SON) for fall.

3.2.2 VPD threshold exceedance days

Time series for the number of exceedance days for each of the three critical VPD thresholds (1.5, 2.0, 2.5, 3.0 kPa) was computed for each SSP scenario. To check the effect of spatial averaging on a synoptic climate signal, the spatial average of number of exceedance days were computed for nested regions- Europe, France and Spain combined, the Pyrenees, the Basque Country, and Soule. All grid cells were included that were within a defined latitude / longitude box encompassing a given region. This daily spatially averaged VPD was then checked to see if it exceeds the given threshold (e.g., 1.5, 2.0, 2.5, 3.0

kPa). The number of days per month where the regionally averaged VPD exceeds the threshold were then counted and averaged across ensemble members, giving the mean number of days per year the region exceeds the threshold. Statistical comparisons using both Welch's t-test and Mann–Whitney U tests confirm that the increases are significant ($p < 0.05$ in most scenarios), particularly in high-emissions futures. Plots include shaded ± 1 standard deviation envelopes across ensemble members.

3.2.3 Kernel density estimates

Kernel density estimates (KDE) helped in understanding the distribution of data over a dimension using probability density functions. An advantage of using KDE over normal probability density curves is that it allowed for uneven distribution of data. KDE was used to study the distribution of VPD values and to estimate the chances of surpassing critical fire thresholds of VPD. Assuming a unimodal distribution of the data, a one-dimensional Gaussian distribution curve with automatic bandwidth determination was fitted to each value of VPD in the dataset. Probability of a range around critical VPD values (1.5, 2.0, 2.5, 3.0 kPa) were estimated by calculating the area under the curve (unit area) with the desired VPD bounds. Visually, the KDE curve indicated data distribution and made differences in statistical properties like mean and skewness easily comparable among different datasets.

3.2.4 Trend analysis

Linear regression trends were calculated for the daily spatially averaged time series of TAP, RH, VPD, CDD, and maximum and minimum daily temperature variables. *Linregress* - a function from python code library SciPy was used to compute the slope of the trendlines. The code used a machine-learning algorithm that mapped the data points with their most optimized linear functions that could be used for precision on new datasets assuming a linear and stationary relationship between the input and output variable. The best-fitted line is optimized to reduce the root mean square error of each data point. The slope of the trend line indicated the amount of increase in VPD value expected per year. Spatial plots of climate variable trends were then plotted with a 95% confidence interval chosen as the statistically significant criteria.

CHAPTER 4

RESULTS AND DISCUSSION

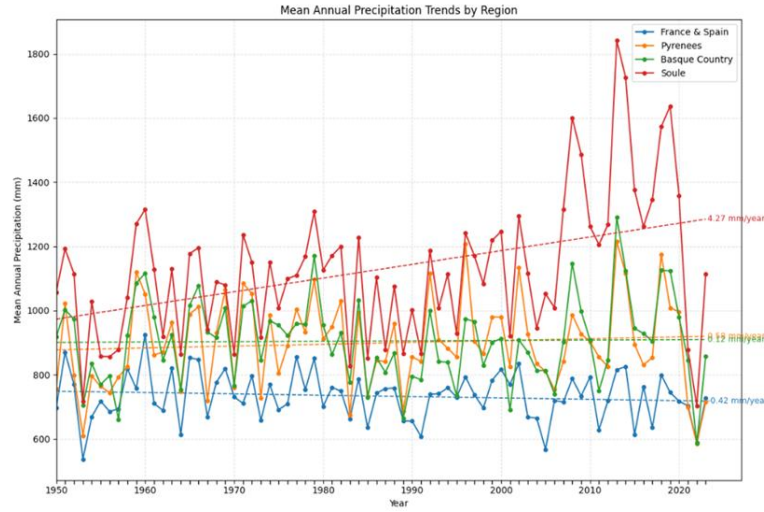
The present research was conducted within the established overarching research directive given by the transhumant farmers of Soule asking if there would be farms or farmers in Soule in 20–50 years. The research questions were designed after assessing dynamics relative to climate in the social ecological system of transhumance in Soule through literature review, site visits and key informant interviews. Key hydroclimate variables, like precipitation, consecutive dry/wet days, relative humidity, temperature and vapor pressure deficit emerged as important to this system to address current and future challenges such as finding favorable weather to dry hay and engage in traditional land management practices as well as drought and fire weather dynamics. Thus, the specific questions the study aimed to answer were 1) What are the current trends in climate variables that impact transhumance in Soule, France; 2) What are future trends in vapor pressure deficit (VPD) and how might those impact the social-environmental system of transhumance in Soule, France; and 3) When might the VPD thresholds in Soule, France reach a threshold associated with elevated fire probability?

Historical analysis using EOBS showed the trends in key hydroclimate variables that explain and validate the changes experienced in this region from 1950 to present (2024). Future projections of VPD, derived from CMIP6 GCMs by Bjarke et al. (2023) helped address whether atmospheric aridity as measured by VPD, would rise to a point that it could change the fire regime of Soule. Inclusion of the regions of France and Spain, the Pyrenees and the Basque Country serve to place Soule's climate in the context of climate in Western Europe. Finally, this chapter turns to a discussion of these results about the impact of climate change on the SES of transhumance in Soule.

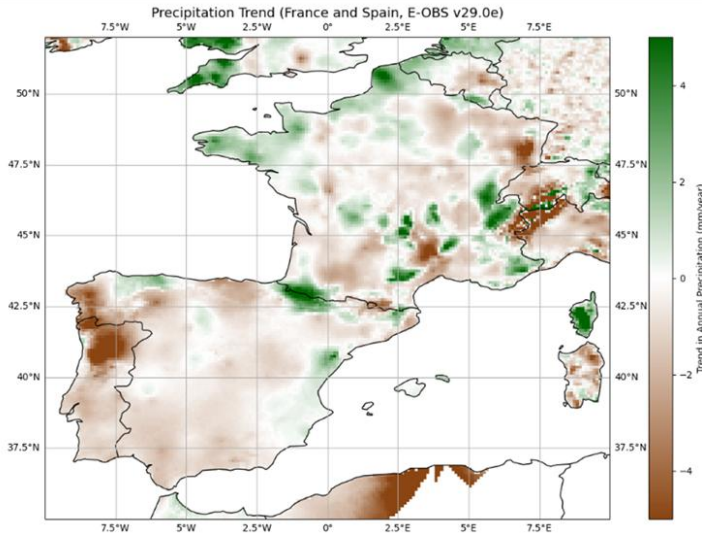
4.1 Historical hydroclimate variability and trends

4.1.1 Precipitation

Precipitation, perhaps the most important and fundamental climate variable to assess hydroclimate variability of a region, is of import to the agro-pastoral community in Soule. Total annual precipitation (TAP) (Figure 4.1a) for 1950 – 2024, plotted from the daily resolution E-OBSv29 dataset of $0.1^\circ \times 0.1^\circ$ spatial resolution showed significant interannual variability and a negative trend in TAP was shown for France and Spain as a whole, but positive trends for the Pyrenees and Basque regions, and a greater trend for Soule. The trend for Soule showed annual precipitation increasing at a rate of $4.27 \text{ mm year}^{-1}$ since 1950, so at the end of the period of record (2024), Soule had an average of $\sim 300 \text{ mm year}^{-1}$ more of precipitation than in 1950.



(a)



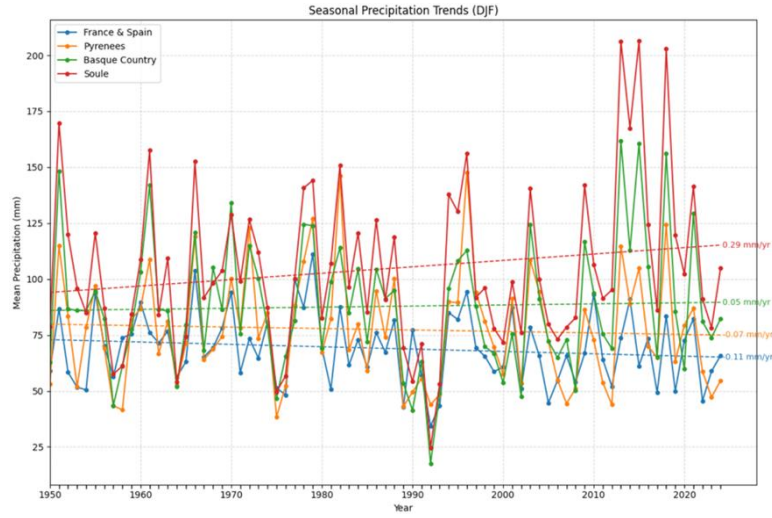
(b)

Figure 4.1. (a) Total annual precipitation (TAP) for the historical period (1950 – 2024) from E-OBSv31.0e. Region wise spatial means of TAP plotted and fitted with a trend line (b) Mean annual precipitation trend for France and Spain.

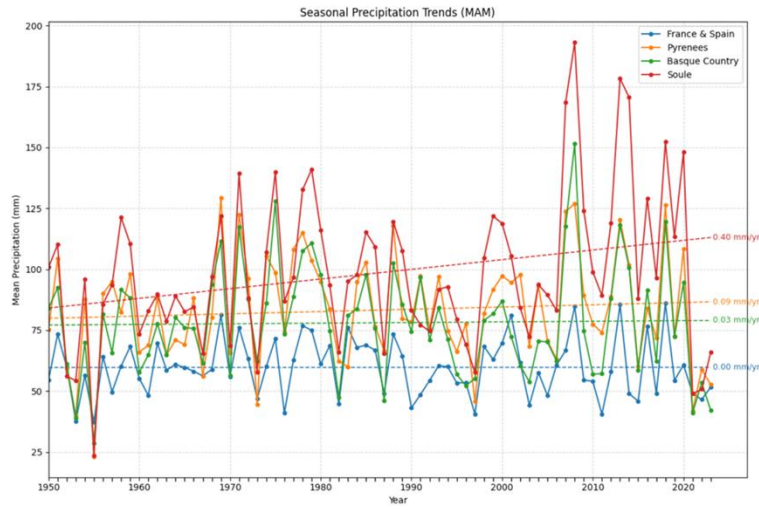
The slope of the trend line in the timeline of mean annual precipitation trends is displayed beside each line, for the largest to smallest regions, slopes were France and Spain: -0.42mm/year ; Pyrenees: 0.12 mm/year ; Basque Country: 0.58mm/year and Soule: 4.27mm/year . A large part of the Southern Pyrenees is a rain shadow region thus lowering the spatially averaged TAP for the entire Pyrenees region.

Compared to the low average precipitation of the Pyrenees and Basque regions, Soule had high TAP values as it is on the windward sides of the Pyrenees. Additionally, the steep gradient of slope in this montane region contributes to orographic enhancement in precipitation which is known to exacerbate extremes during precipitation events (Trapero et al., 2013).

The increasing TAP trend for Soule was situated within the global trend in TAP in other mid-latitude areas of the northern hemisphere (Obarein et al., 2025). Globally, precipitation is expected to increase due to the increase in atmospheric temperatures which leads to the increased capacity for the atmosphere to hold more moisture. Increased water holding capacity of the atmosphere along with increased heat resulting in higher evapotranspiration also result in increased extreme precipitation events (Obarein et al., 2025). As warm, water laden air meets the Northern facing slopes of the Western Pyrenees, it is pushed up and cools to the point of condensation, resulting in cloud formation, fog and precipitation. Figure 4.1a also shows a period of anomalously high precipitation starting from ~2007. In 2006 the mean annual precipitation was measured to be ~1000mm, but in 2007 the mean annual precipitation was above 1200mm, and it did not drop below 1200mm until 2021, when mean rainfall was less than 900mm, which helped set the stage for hydrological drought in 2022. Following 2021, 2022 also had anomalously low precipitation and was a year marked by extreme drought (Mittelberger et al., 2024). Nine of the last 20 years of the period of record (1950–2024) exceeded all the TAPs of the prior years within the period of record (1950–2024), and the anomalously dry year, 2022, had the lowest TAP (~700 mm) for the nearly 75-year time span of the period of record. The preceding year, 2021 also had a low TAP (under 900mm), which had not been seen in 30 years, occurring in 1991. Figure 4.1b shows a spatial distribution of the TAP trend for France and Spain. This figure shows wetter and drier locations across this region and illustrates that the TAP trends can be locally highly variable. Notably, this spatial distribution highlights the high rate of increase shown in dark green, corresponding to over 4.0mm/year, in TAP in the Western Pyrenees Mountains and Soule for the historical period.

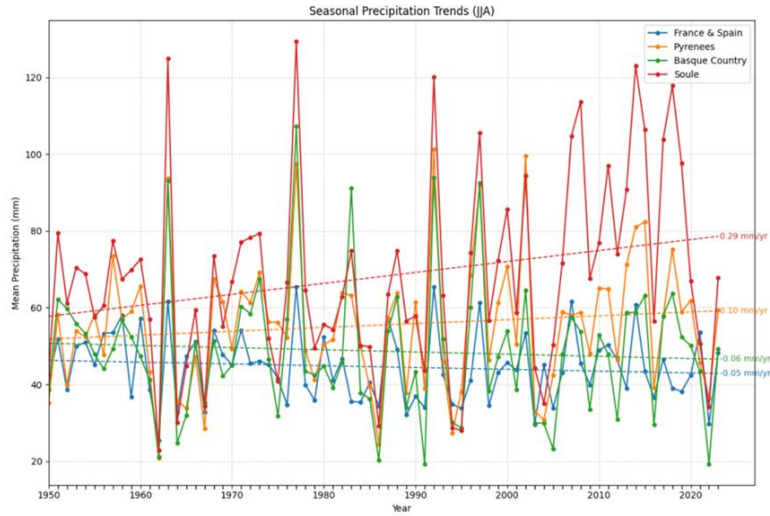


(a)

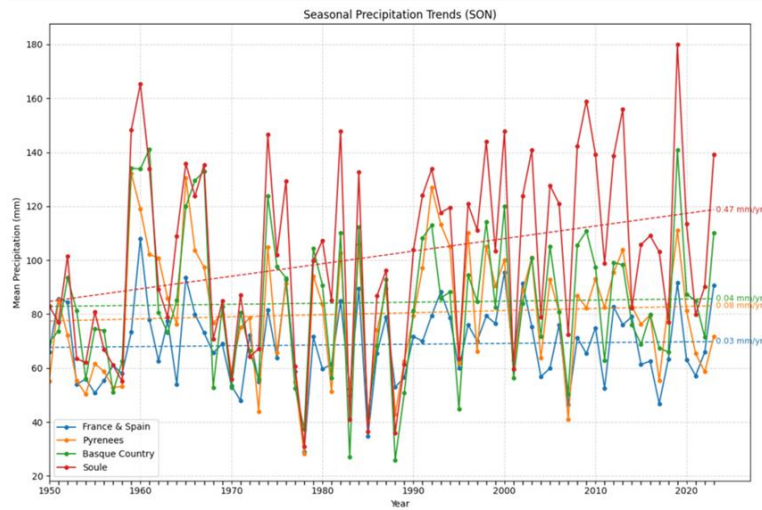


(b)

Figure 4.2. Mean seasonal precipitation (MSP) for (a) DJF, (b) MAM, (c) JJA, and (d) SON for 1950 – 2024 from E-OBSv29 with regional means of MSP for each season plotted and fitted with trend lines.



(c)



(d)

Figure 4.2. Continued.

MSP for winter (DJF) plotted for the period of record with the slope of the trend line displayed beside each line, for the largest to smallest regions slopes were as follows: France and Spain: - 0.11mm/year; Pyrenees: -0.07 mm/year; Basque Country: 0.05mm/year and Soule: 0.29mm/year (Figure 4.2a). MSP for spring (MAM) plotted for the period of record with the slope of the trend line displayed beside each line, for the largest to smallest regions, slopes were as follows: France and Spain:

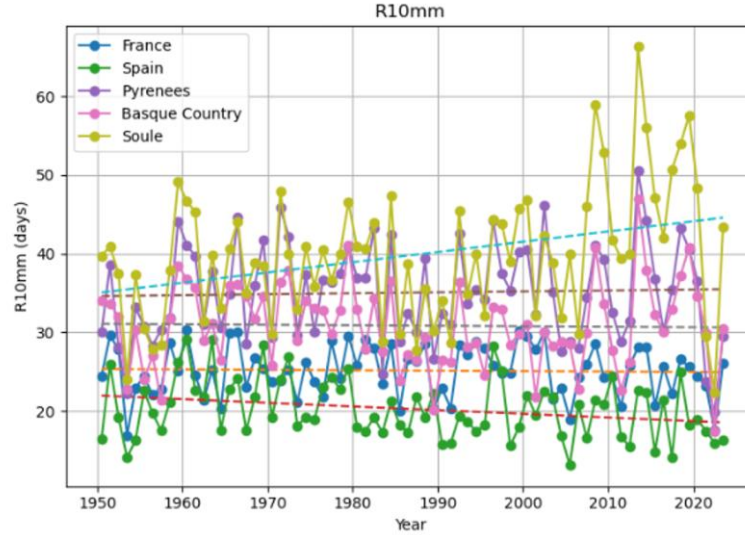
0.00mm/year; Pyrenees: 0.03 mm/year; Basque Country: 0.09mm/year and Soule: 0.40mm/year (Figure 4.2b). MSP for summer (JJA) plotted for the period of record with the slope of the trend line displayed beside each line, for the largest to smallest regions were as follows: France and Spain: -0.05mm/year; Pyrenees: -0.06 mm/year; Basque Country: 0.10mm/year and Soule: 0.29mm/year (Figure 4.2c). MSP for fall (SON) plotted for the period of record with the slope of the trend line displayed beside each line, for the largest to smallest regions were as follows: France and Spain: 0.03mm/year; Pyrenees: 0.08 mm/year; Basque Country: 0.04mm/year and Soule: 0.47mm/year (figure 4.2d).

Figure 4.2 shows significant interannual variability in MSP and a negative trend for France and Spain as well as for the Pyrenees, but a positive trend for the Basque region and Soule. The DJF MSP trend for Soule was the highest which shows MSP increasing at a rate of 0.29mm/year since 1950 when the average MSP was around 90mm to 2024 when the average MSP was just under 120mm (a difference of ~30mm) (Figure 4.2a).

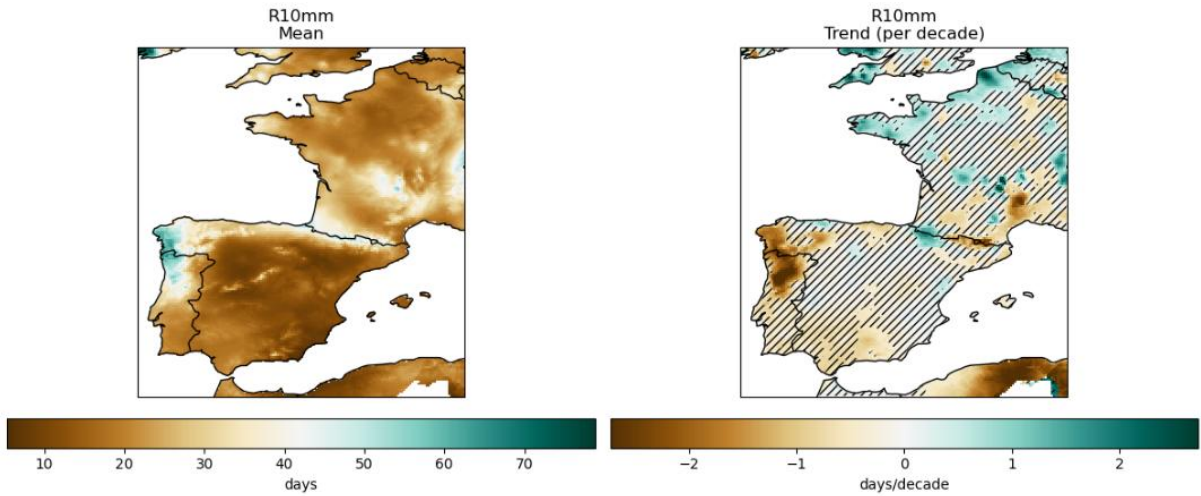
A positive trend for all regions was evident in MAM (Figure 4.2b), and the trend for Soule was the greatest (0.40 mm/year) with the average MSP for MAM beginning at around 85mm in 1950 and rising to about 115mm in 2024 (a difference of ~30mm). No trend in Spain and France was evident in JJA, but a positive trend was evident for the Pyrenees, the Basque region and Soule (Figure 4.2c). The JJA MSP trend for Soule was the highest which shows a total increase of MSP of 0.29 mm/year since 1950, rising from just under 60mm in 1950 to just under 80mm in 2024 (a difference of ~20mm).

The fall months of SON showed interannual variability in MSP for SON, and a positive trend for all regions. The SON MSP trend for Soule was the greatest with an increase of 0.47 mm/year since 1950, from around 85mm in 1950 to just less than 120mm in 2024 (a difference of ~35mm). MSP in Soule in 2022 was well below the MSP trends. For example, 2022 had the second lowest DJF MSP since 2008 (Figure 4.2a) and MAM MSP was lower than any since 1955. The JJA MSP for 2022 was less than any year since 1995 and SON MSP for 2022 with a higher MSP than 2021, but the SON MSP was still well below the MSP trend line.

These findings were notable because July 2022 had a drought with a reported 30 days of no rain that depleted the water supply to some aquifers supplying watering troughs in the mountain pastures. The drought was so severe that water was transported by truck from a river in the valley to fill cisterns for the animals (S. Inda-Gallur, personal communication, 2024). A dry JJA 2022 following a dry preceding year (Figures 4.1 and 4.2) helped to explain the exhaustion of the aquifer that occurred in July 2022.

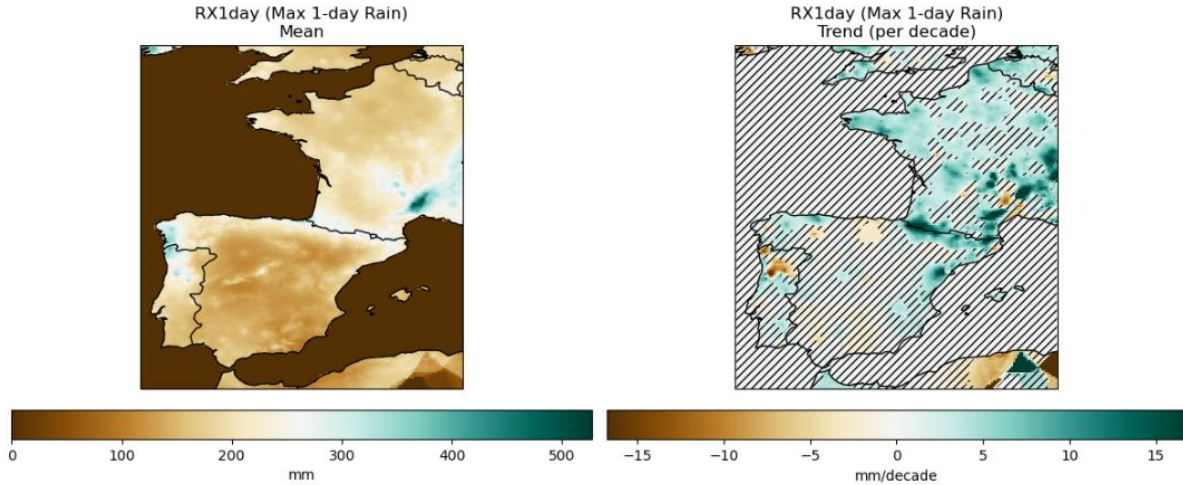


(a)



(b)

Figure 4.3. (a) Annual count of days when precipitation (PRCP) $\geq 10\text{mm}$ over the historical period of 1950–2024 in France, Spain, Pyrenees, Basque Country, and Soule, plotted with trendlines from E-OBSv31.0e. (b) Mean number of days when PRCP $\geq 10\text{mm}$ (left) and spatial distribution trend in days/decade when PRCP $\geq 10\text{mm}$ (right) for 1950–2024. (c) Maximum 1-day precipitation (left) and the trend in maximum 1-day precipitation per decade (right) for 1950–2024. Hatching indicates a lack of statistical significance.



(c)

Figure 4.3. *Continued.*

To understand trend in moderate to heavy precipitation, trends in days with $\text{PRCP} \geq 10\text{mm}$ were examined for Soule (Figure 4.3a, plotted in yellow with a dashed blue trendline). The days with mean precipitation greater than 10mm have increased at a rate of about 1.35 days/decade (Figure 4.3b (right)) over the period of record (1950–2024). In 1950, the average number of days per year in Soule with precipitation greater than 10mm was 35 days/year, by 2024, the average number of days per year with precipitation greater than 10mm had risen to 45 days/year. The spatial distributions of the mean number of days when $\text{PRCP} \geq 10\text{mm}$ over the period 1950–2024 shows that Soule averaged about 40 days/ year of rain during that time (Figure 4.3b). The spatial distribution of average maximum monthly 1-day rainfall shows Soule received 250–300mm/day on extreme precipitation days (Figure 4.3c). The decadal trend shows statistically significant ($p\text{-value } 0.05$) increase in maximum monthly 1-day precipitation (RX1day) for Soule of about 10–15mm/day of extreme precipitation per decade (Figure 4.3c).

4.1.2 Consecutive Dry Days

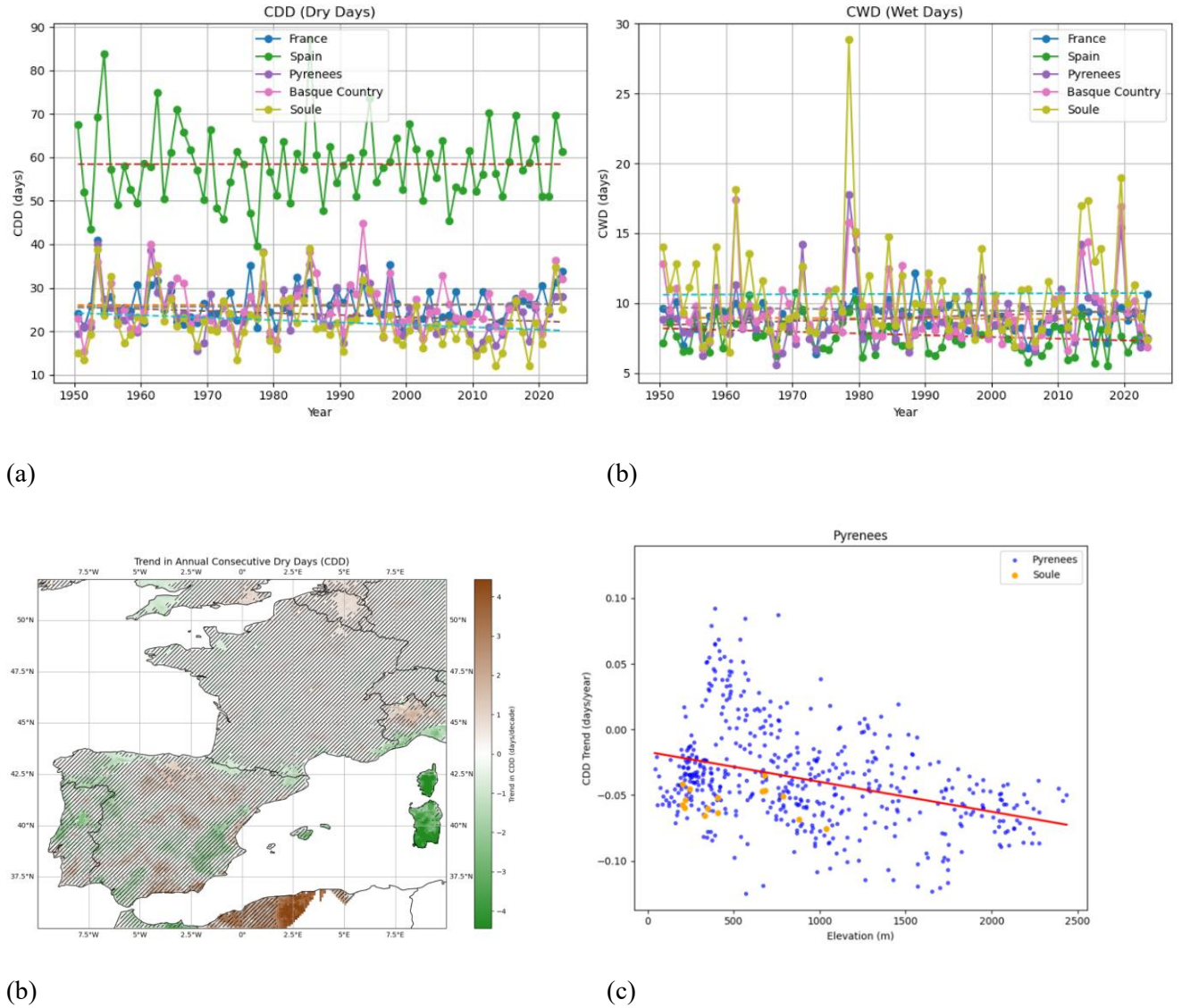


Figure 4.4. (a) Consecutive dry days (CDD) (left) and (b) consecutive wet days (CWD) during 1950–2024, plotted with trendlines from E-OBSv31.0e. (c) Trends in CDD (negative trends in green, positive in brown). Hatched areas indicate areas where change is not statistically significant ($p < 0.05$). (d) Mean CDD in the Pyrenees plotted by elevation, with locations in Soule in orange, with regression line.

Consecutive dry days (CDD) is defined as the maximum length of dry spell, i.e., the maximum number of consecutive days with daily rainfall of $< 1\text{mm}$, which is valuable for understanding drought,

agricultural stress, water availability, and ecosystem health. The inverse is consecutive wet days (CWD), defined as the maximum length of wet spell, i.e., the maximum number of consecutive days with daily rainfall ≥ 1 mm. CWD can influence soil saturation, which increases the likelihood of flooding and landslides as well as the potential for fungal root diseases.

France, Spain, the Pyrenees, Basque Country and Soule show stable CDD and CWD over the historical period (1950–2024) (Figure 4.4a). Soule (yellow) shows ~2% decrease in CDD, but the spatial distribution map indicates that this change is not statistically significant (Figure 4.4b). Areas to the southeast of Soule show a statistically significant decrease in CDD (Figure 4.4b). The trends in CDD by elevation in the Pyrenees region (inclusive of the Spanish and French regions of Basque Country) with Soule in orange dots, show that CDD decreased at a faster rate with higher elevation. The red regression line, below zero for all elevations, shows that CDDs decreased across all elevations of the Pyrenees and that the decrease in CDD has been greater at increasing elevations (Figure 4.4c). More variability in the rates and direction of the trend of CDD in the Pyrenees at lower elevations is evident by the spread of blue dots-wider at lower elevations but narrowing at higher elevations (Figure 4.4c). Above ~1500m, no areas of the Pyrenees region observed show a positive trend in CDDs (Figure 4.4c). Decreasing CDDs at higher elevations suggest few prolonged dry spells and the increase in moderate to heavy rainfall rates noted in the previous section suggest increasing rainfall extremes in the region.

4.1.3 Temperature

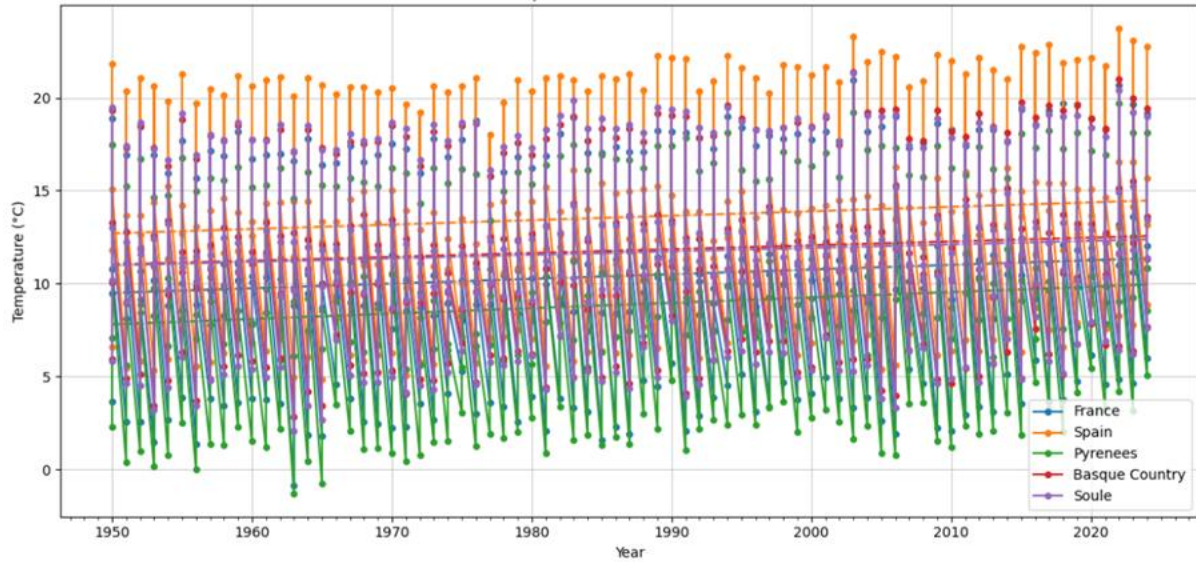
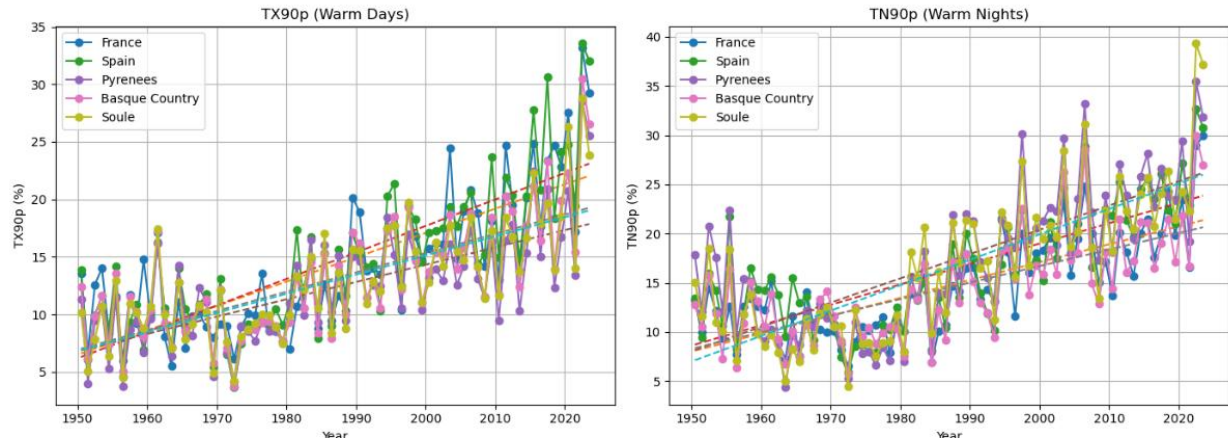
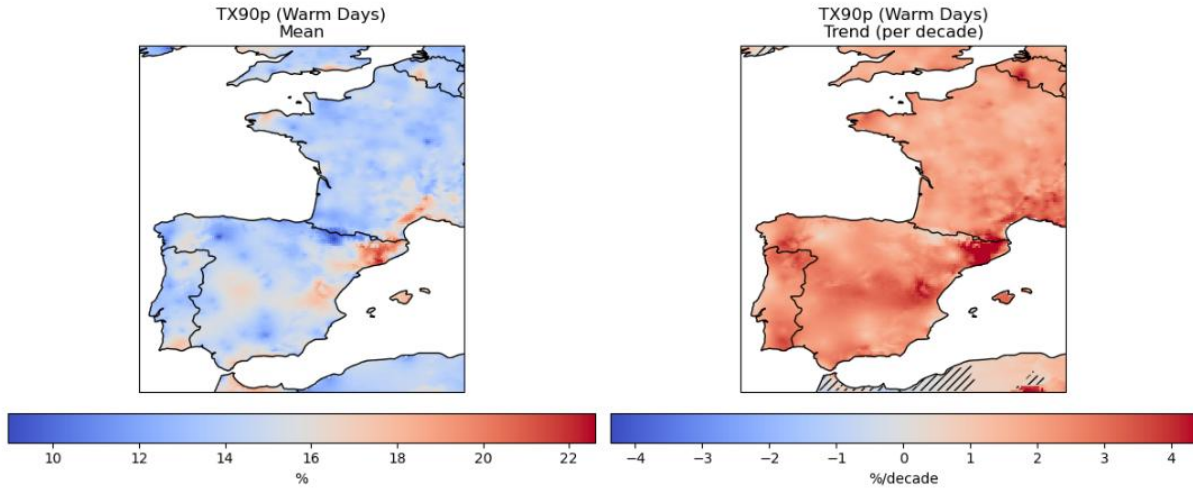


Figure 4.5. Mean seasonal temperatures of five regions (France, Spain, Pyrenees, Basque Country, and Soule) for 1950–2024, plotted with trendlines, from E-OBSv31.0e.

The mean seasonal temperature (MST) values for each season (DJF, MAM, JJA, and SON) for France, Spain, the Pyrenees, Basque Country and Soule showed an overall upward trend in MST. The range of MST values for Soule (purple) overlapped the lower MST values for Spain (orange) and the higher MST values of the Pyrenees (green) and aligned with the trend for the Basque Country (Figure 4.5). Over the historical period, the trend in Soule MST routinely went below 5 °C during DJF and was around 17 °C in JJA during 1950–1970. In contrast, during 2000–2024, MST was not less than 5 °C in DJF and exceeded 20 °C during JJA. The increase in mean seasonal temperature in Soule was ~1.5 °C since 1950 (Figure 4.5).

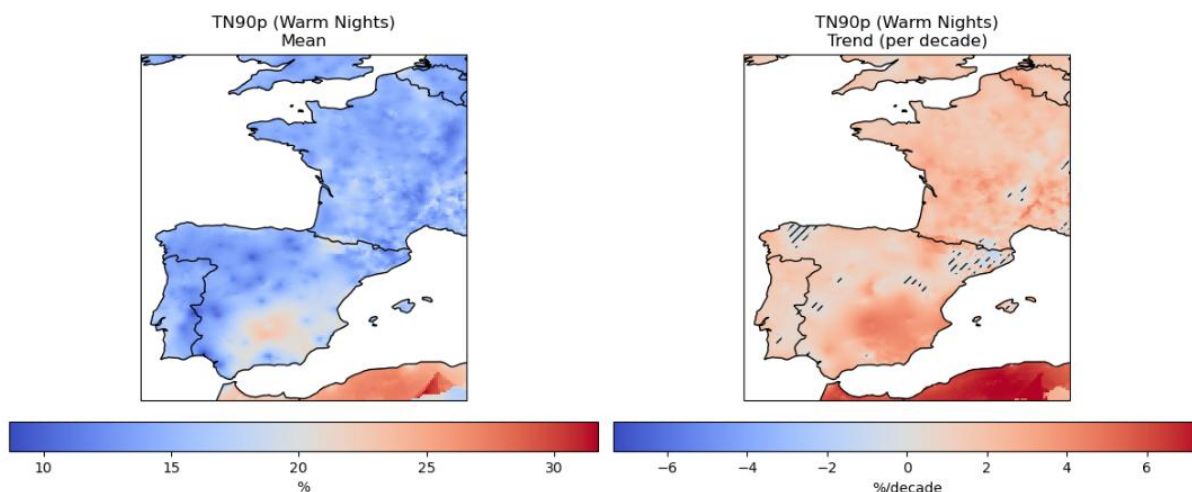


(a)



(b)

Figure 4.6. (a) Percentage of days when TX (maximum temperature, days) > 90th percentile (TX90p) (left) and the percentage of days when TN (minimum temperature, nights) > 90th percentile (TN90p) (right) for 1950–2024, plotted with trendlines, from E-OBSv31.0e. (b) Mean percentage of days when TX > 90th percentile (TX90p) (left) and trend in percentage of TX90p (days/decade, right). (c) Mean percentage of days when TN > 90th percentile (TN90p) (left) and trend in percentage of TN90p (days/decade, right). Hatching indicates not statistically significant using $p < 0.05$.



(c)

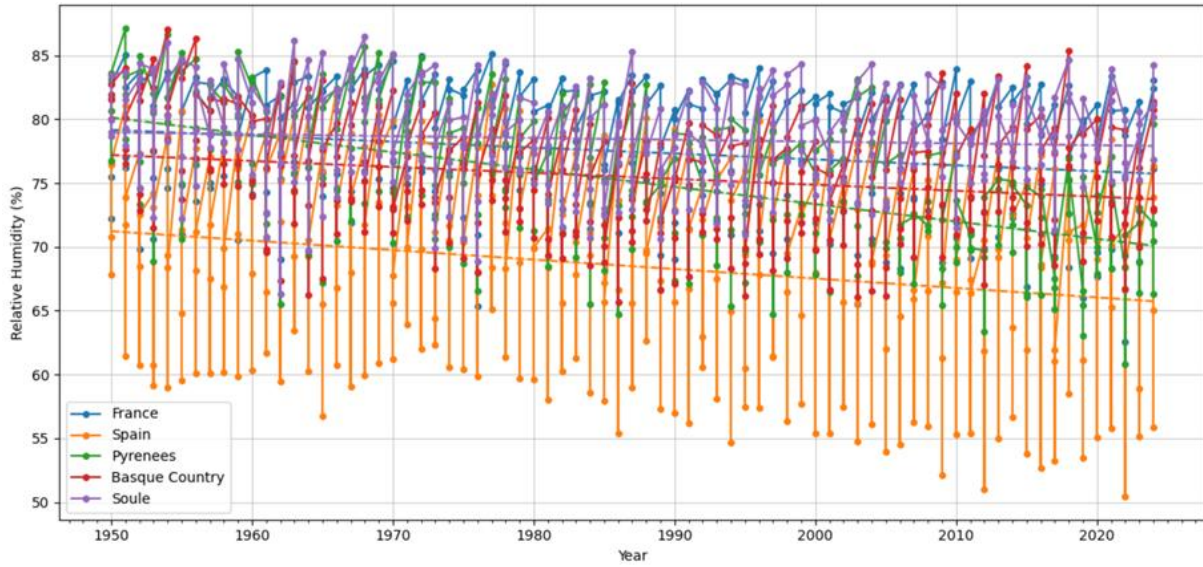
Figure 4.6. *Continued.*

Temperature extremes were examined by the percentage of days when TX (maximum temperature, days) is greater than the 90th percentile (TX90p) and the percentage of days when TN (minimum temperature, nights) is greater than 90th percentile (TN90p) from E-OBSv31.0e measured over the full period of record (1950-2024). France, Spain, the Pyrenees, Basque Country and Soule all show an overall upward trend in TX90p and TN90p. The TX90p for Soule (yellow with a dashed blue trendline) began at a mean of around 7% and rose to a mean of around 19% in 2024. Warm days increased at a rate of about 0.16% per year (Figure 4.6a). TN90p for Soule also began at a mean of ~ 7% but rose to a mean of ~ 26% in 2024. Between 1950 and 2024, warm days have increased by ~12% and warm nights have increased by ~19% (Figure 4.6b,c). During that same period, the percentage of warm nights increased in Soule at a greater rate than many other areas across France and Spain as indicated by the red shading in the western Pyrenees region that includes Soule (Figure 4.6c). The strong increase in warm nights in Soule suggests added heat stress due to increased humidity and higher cloud cover during nighttime.

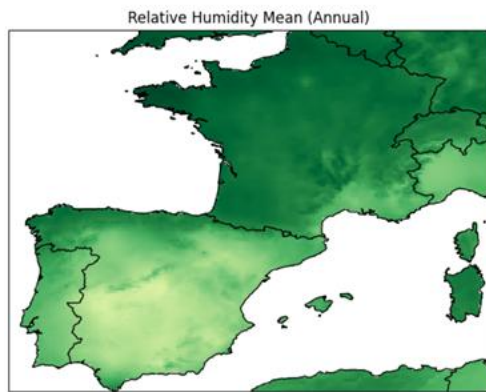
4.1.4 Relative humidity

Relative Humidity (RH) plays an important role in agriculture and human and animal health. Even without any changes in rainfall, a decrease in RH can cause faster drying of soils and plants, increasing drought and wildfire potentials and adding to plant stress. Crops may need more irrigation, and

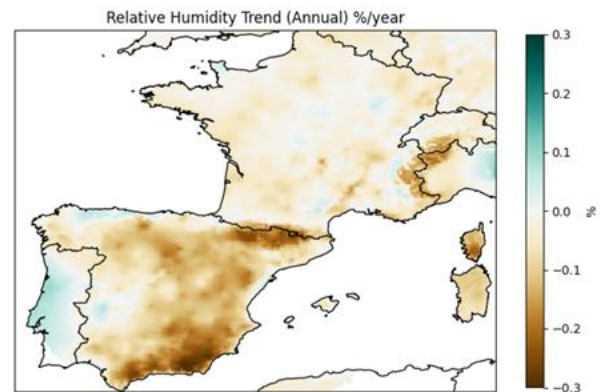
some may suffer reduced yields or increased vulnerability to pests and disease. Higher RH can promote the spread of plant diseases and reduce human comfort, making hot days feel even more oppressive by reducing the capacity for evaporative cooling.



(a)



(b)

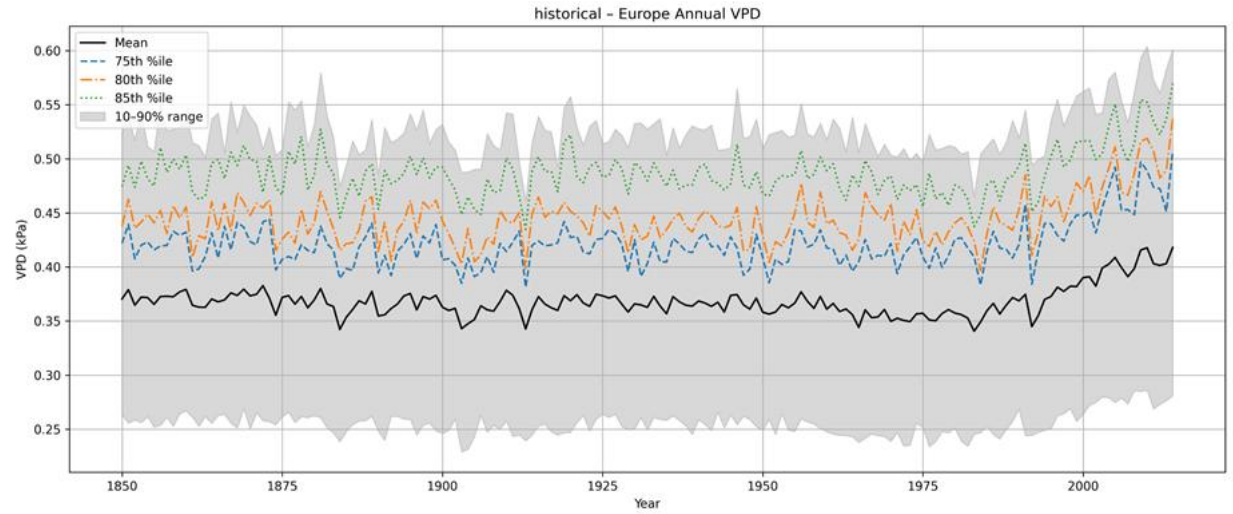


(c)

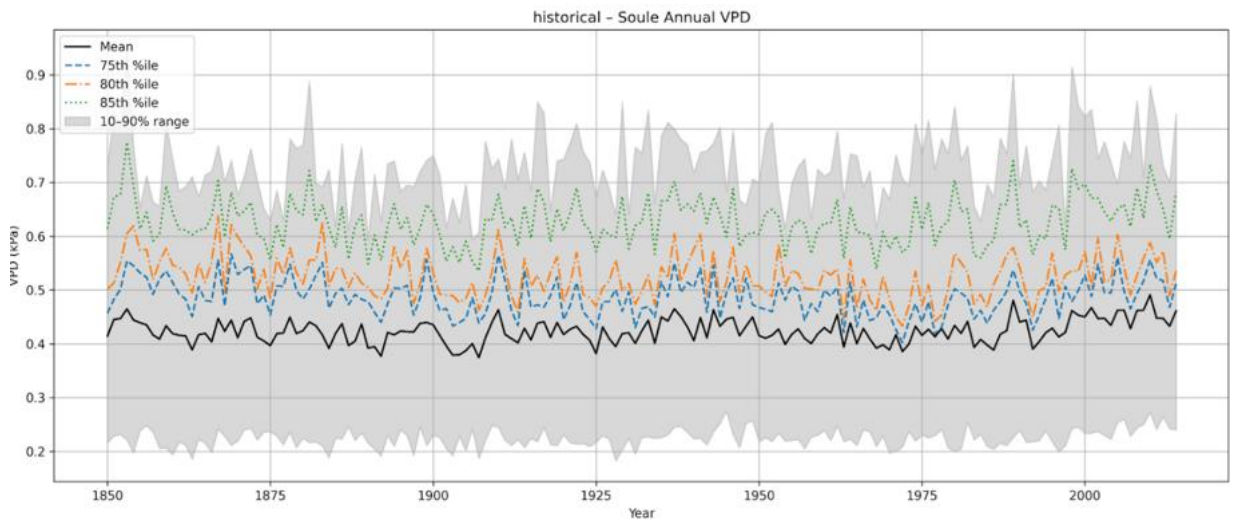
Figure 4.7. (a) Mean seasonal trends in relative humidity (RH) of France, Spain, Pyrenees, Basque Country, and Soule for 1950–2024, plotted with trendlines, from E-OBSv31.0e. (b) Mean annual RH and (c) the trend in mean annual RH.

Mean seasonal relative humidity (RH) values for each season (DJF, MAM, JJA, and SON) for 1950–2024 for France, Spain, the Pyrenees, Basque Country and Soule showed a decrease in mean seasonal RH values during the length of the period of record (Figure 4.7a). The region of the Pyrenees decreased by 10% in RH, while the other regions showed a drop of RH over the same period (1950–2024) of ~5% and the trend in mean humidity in Soule decreased by 1% over that historical period of record. The notable decrease in humidity of the Pyrenees region was also evident in the spatial distribution of the RH trends (Figure 4.7c). The Pyrenees have experienced the greatest decrease with mean seasonal RH dropping around 10% over the period of record. The trends in mean annual relative humidity are also plotted to show spatial distribution across France and Spain. The rate of annual change in mean RH across France and Spain has ranged from -0.3 to +0.3, with the Pyrenees prominently identifiable with one of the most negative trend values of the region (Figure 4.7b,c).

4.1.5 Vapor pressure deficit



(a)



(b)

Figure 4.8. Mean annual VPD (black solid line) for (a) Europe and (b) Soule and 75th, 80th, and 85th percentiles (blue, orange and green dashed lines respectively) with the 10th – 90th percentile range shaded in gray in the background for 1850– 2014 (from a monthly VPD dataset created by Bjarke et al., 2023).

Vapor Pressure Deficit (VPD) is the difference between the maximum amount of water that can exist in the atmosphere at a given temperature, i.e., saturated vapor pressure (SVP), and actual water vapor. VPD and RH both describe atmospheric moisture, but while RH shows the percentage of saturation, VPD shows physically the “drying power”. Higher temperatures increase SVP as described by the Clausius-Clapeyron relation, however, many factors impact AVP, so VPD increases non-linearly with the rising temperatures being seen with climate change (Feng et al., 2022). High VPD increases plant stress, reduces growth, and raises water demand, even with the same amount of precipitation. High VPD drives faster drying of landscapes, increasing the potential of drought and wildfires, making it a key indicator of how ecosystems respond to climate change.

Figure 4.8a,b shows the mean annual vapor pressure deficit (VPD) for Europe and for Soule for 1850 – 2014, plotted from a monthly resolution dataset created by Bjarke et al. (2023) of $1.78^{\circ} \times 2.5^{\circ}$ (lat x lon) spatial resolution. For most of the period of record (1850–2014), mean annual VPD for Soule was around 0.4kPa. VPD started to noticeably trend upward around 1990 with no mean annual VPD values less than 0.4 kPa for Soule through the end of the period of record. Blue, orange and green dashed lines show the 75th, 80th and 85th percentile indicating 25% likelihood, 20% likelihood and 15% likelihood that mean annual VPD will reach the values indicated by the respective line. The mean annual VPD for Soule has stayed below 0.5 kPa in the historical period.

As temperatures increase with climate change, VPD is expected to further increase in a greenhouse-enhanced climate, which leads to an examination here of projected changes in VPD.

4.2 Vapor Pressure Deficit Projections

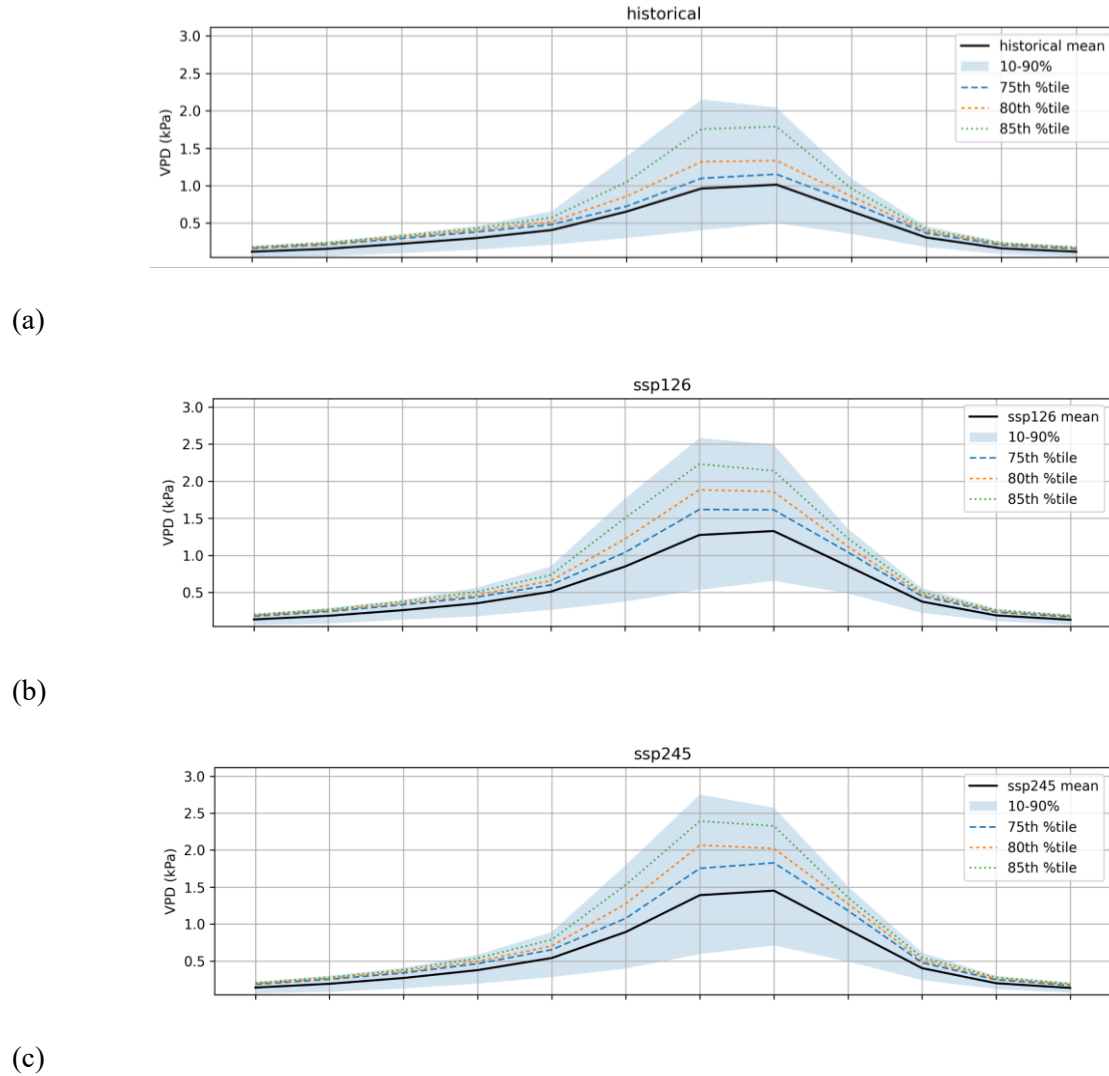
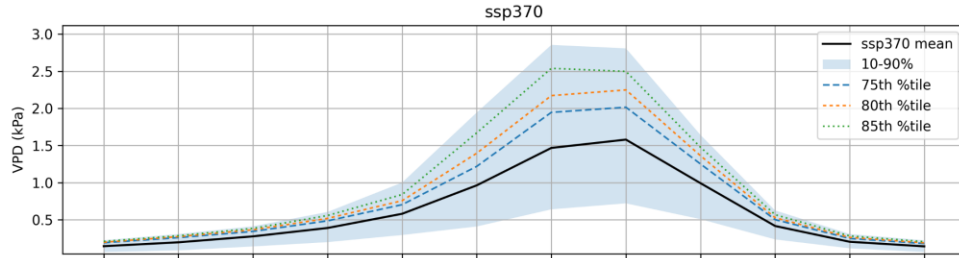
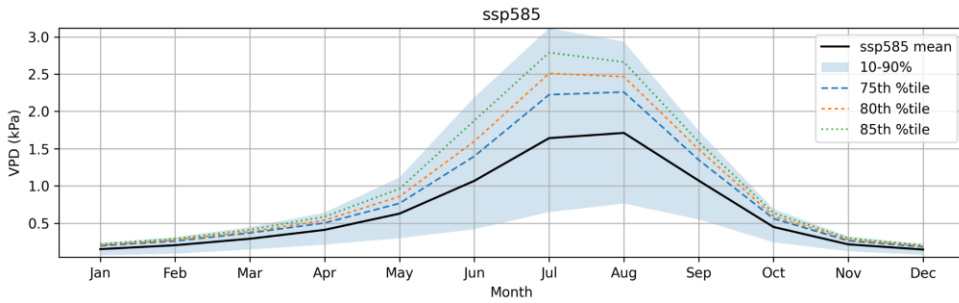


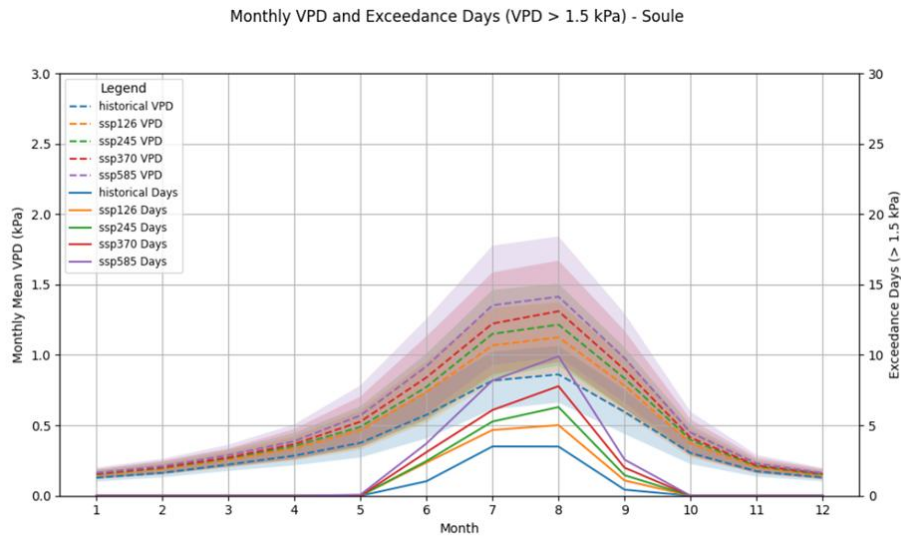
Figure 4.9. Monthly mean VPD (black line) showing 10 – 90th percentile range (shaded blue) and 75th, 80th, and 85th percentiles in (dashed blue, orange and green lines, respectively) for (a) the historical period of record (1850– 2014) (top) and (b) SSP1/RCP2.6 (126), (c) SSP2/RCP4.5 (245), (d) SSP3/RCP7.0 (370), and (e) SSP5/RCP8.5 (585) for 2014–2100. (f) Monthly VPD for Soule for 1850– 2014 (blue dashed line) and for four SSP scenarios for 2014–2100 with an estimated number of days (solid lines) each month that would exceed a 1.5 kPa threshold (from a monthly resolution dataset created Bjarke et al. (2023)).



(d)



(e)



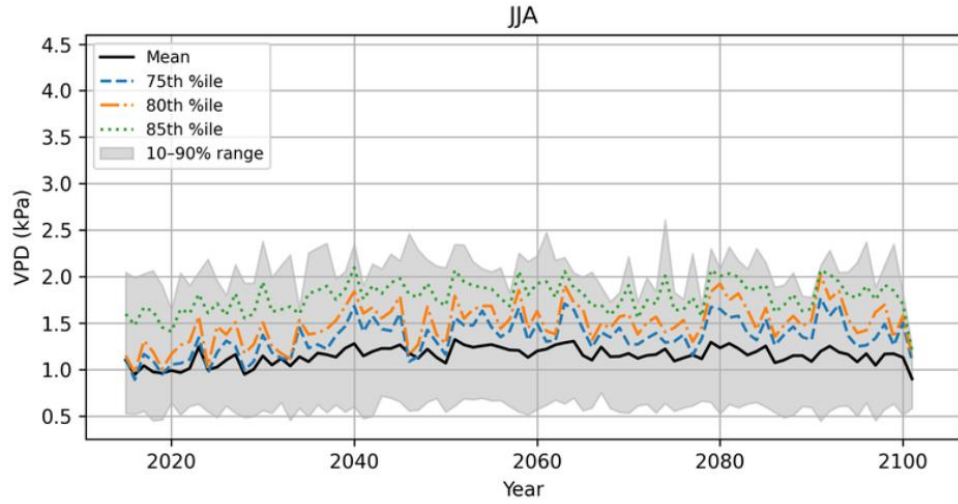
(f)

Figure 4.9. Continued.

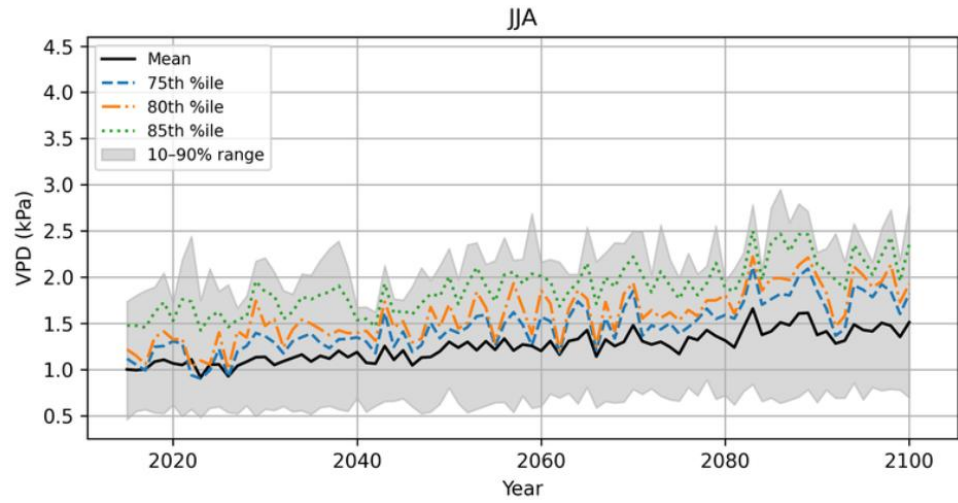
The VPD deficit projections for Soule were examined based on changes in the monthly means and simulated daily exceedances, as described in Chapter 3. Based on the projected summer VPD for Soule, a critical threshold of 1.5 kPa would be surpassed in both the SSP3 and SSP5 scenarios. There is a

25% probability that the monthly mean summer VPD could exceed the 75th percentile line (blue dashed) which breaches the threshold of 1.5 kPa VPD in all SSP scenarios. VPD values above 1.5 kPa were found by Clarke et al. (2022) to yield a probability of fire exceeding 50%, so the region that includes Soule would be more likely than not to experience forest fire during the summer for both reasonable (SSP3) and extreme (SSP5) climate change scenarios. It should be noted that there are many factors that contribute to forest fires, and one metric should not be relied on as the sole metric for the determination of wildfire probability. However, examination of monthly mean exceedance gives a conservative estimate. A month with a mean VPD value near the threshold may have multiple consecutive days that exceed the threshold.

Estimated number of days that exceed a mean VPD of 1.5 kPa per month for the historical period (1850–2014) and for each SSP scenario (Figure 5.9f) range from 0 to 10 days. The historical period (blue dashed and solid lines) had fewer than 5 days in June and July where VPD was estimated to exceed 1.5 kPa in Soule, whereas the most extreme climate scenario SSP585 (SSP5/RCP8.5) shows up to 10 consecutive days expected to surpass the 1.5 kPa threshold in Soule during the summer (Figure 5.9f).

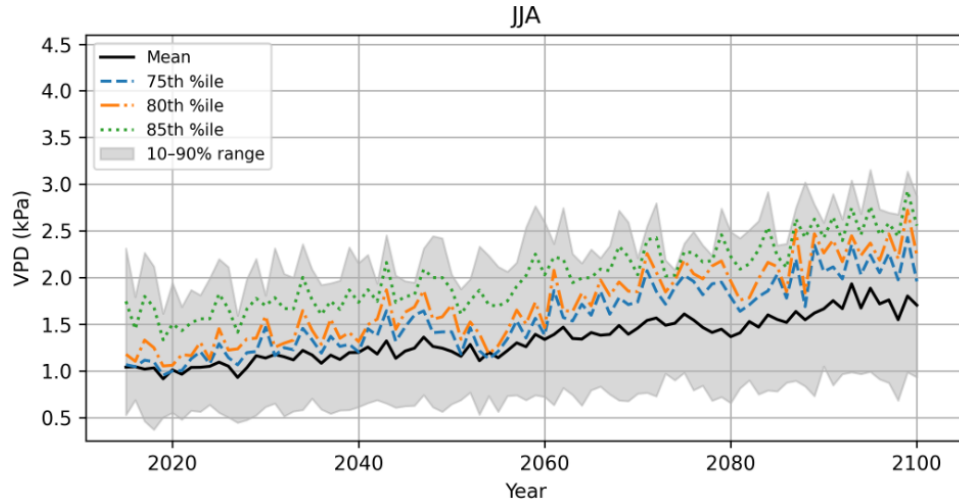


(a)

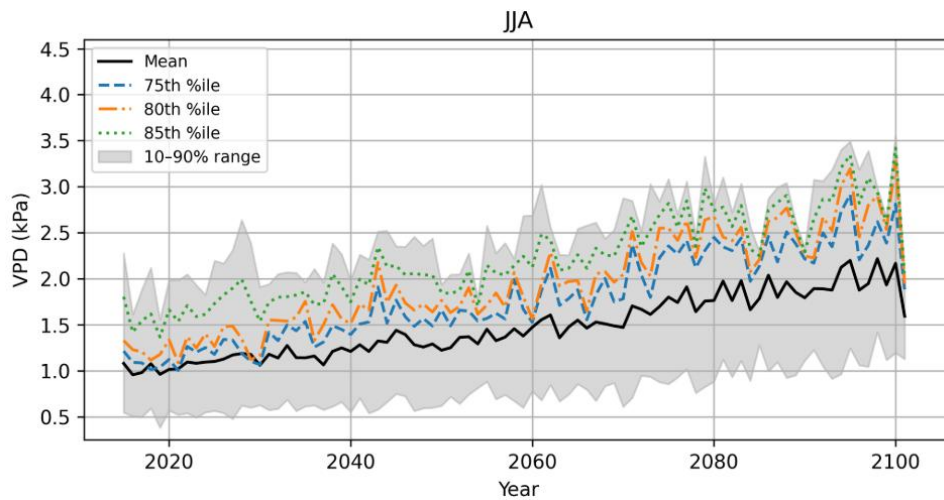


(b)

Figure 4.10. Mean seasonal VPD (solid black line) for Soule for (a) JJA for SSP1/RCP2.6, (b) JJA for SSP2/RCP4.5, (c) JJA for SSP3/RCP7.0 and (d) JJA for SSP5/RCP8.5 during 2014– 2100. The 10% – 90% percentile range (shaded gray) and 75th, 80th, and 85th percentile lines (dotted blue, orange and green respectively), are also shown, based on data from Bjarke et al. (2023).



(c)



(d)

Figure 4.10. *Continued.*

The projected seasonal mean vapor pressure deficit (VPD) for Soule for three of the four SSP/RCP scenarios show a breach of 1.5 kPa before 2100. While SSP1/RCP2.6 (Figure 4.10a) shows no breach of the 1.5kPa VPD threshold through, 2100, SSP2/RCP4.5 (Figure 4.10b) shows intermittent breeches when mean VPD exceeds 1.5 kPa after 2080. One moderate and one extreme SSP scenario will breach and maintain mean monthly VPD for JJA consistently elevated above a mean VPD of 1.5 kPa within the century. The moderate SSP3/RCP7.0 (Figure 4.10c) showed that summer mean VPD will exceed 1.5 kPa in ~2070 for the reasonably likely SSP3 scenario (Figure 4.10c) and remain consistently

elevated. The summer mean VPD will exceed 1.5 kPa 10 years earlier (~2060) for the more extreme SSP5/RCP8.5 scenario (Figure 4.10d) and continue to rise through 2100. It should be noted that with the wide range of elevation and land cover variation within Soule, large variation in mean VPD values across Soule would be expected, so some areas might see mean seasonal VPD breach the 1.5 kPa mark earlier, later, or not at all.

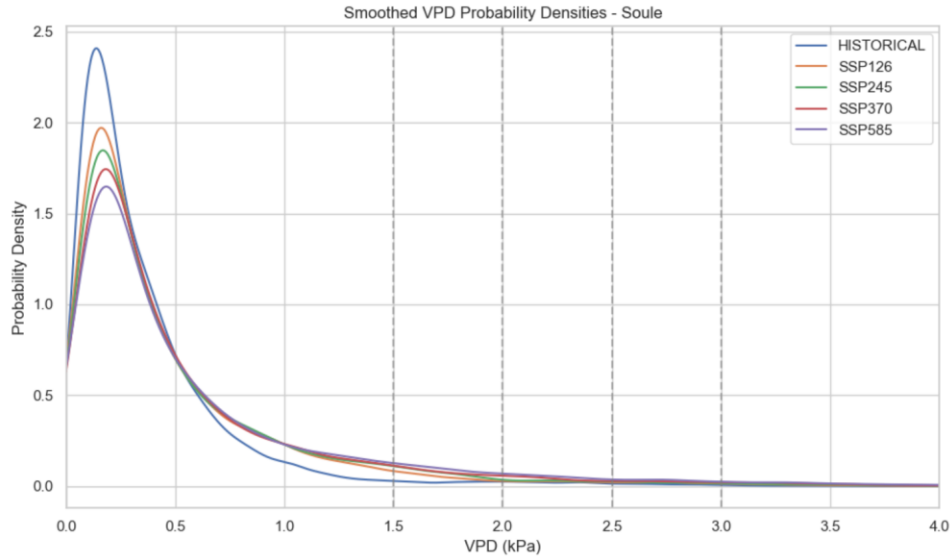


Figure 4.11. *Probability density functions of VPD projected for historical (1850–2013), and four SSPs, (2014–2100) from a dataset created by Bjarke et al. (2023).*

Finally, to understand the change in the probability of VPD, probability density functions (PDFs) were calculated from modeled daily VPD data from each future emissions scenario using kernel density estimates. Exceedance probabilities are marked by the dashed vertical lines at some critical VPD thresholds (1.5, 2.0, 2.5, 3.0 kPa) probability of the VPD values exceeding the threshold value (Figure 4.11). This probability estimate is for a single data point nearest to Soule (43.15N, 0.9 W) from the VPD dataset and shows the probability during the entire period for any specified VPD value.

Table 4.1. *VPD exceedance probability for historical period (1850–2013) and projected for four SSP scenarios (2014–2100) for the Pyrenees, Basque Country, and Soule, based on data from Bjarke et al. (2023).*

Region	Scenario	$P_{VPD} > 1.5$	$P_{VPD} > 2.0$	$P_{VPD} > 2.5$	$P_{VPD} > 3.0$
Pyrenees	Historical	0.06	0.05	0.04	0.03
	SSP126	0.10	0.07	0.06	0.05
	SSP245	0.12	0.08	0.06	0.05
	SSP370	0.14	0.10	0.08	0.06
	SSP585	0.16	0.12	0.09	0.07
Basque	Historical	0.06	0.05	0.04	0.03
	SSP126	0.10	0.07	0.06	0.05
	SSP245	0.12	0.08	0.06	0.05
	SSP370	0.14	0.10	0.07	0.06
	SSP585	0.16	0.11	0.09	0.07
Soule	Historical	0.05	0.04	0.03	0.02
	SSP126	0.08	0.06	0.05	0.04
	SSP245	0.10	0.07	0.05	0.04
	SSP370	0.12	0.08	0.06	0.05
	SSP585	0.14	0.10	0.07	0.06

Probability distribution of the historical period VPD values (blue line) shows a mean VPD of ~0.25 kPa. The distribution curves for the SSP scenarios show peaks shifted to the left of the historical peak (0.25 kPa). The historical curve decays swiftly after 0.75 kPa whereas the SSP PDFs converge at 0.75 kPa mark but decay slowly. This implies that the VPD values for future scenarios have a marked skewness towards higher VPD values, making high VPD days more likely. While all SSPs have

probability density of ~ 0.25 at the 1.0 kPa VPD, historical probability density is closer to ~ 0.15 at the 1.0kPa mark. This is very close to the probability density of SSP3 (0.12) and SSP5 (0.14) for a VPD of 1.5kPa (Table 4.1). The distribution of probability densities illustrates the variability of VPD values in Soule and suggests that critical value of 1.5 kPa VPD is as likely in future projected climate scenarios as 1.0 kPa was likely to occur in the historical period. The exceedance of 1.5 kPa is twice as likely with the more conservative SSP2/RCP4.5 as it was historically, and Soule is almost three times more likely to see VPD values of 1.5kPa in the extreme SSP5/RCP8.5 scenario as compared to the historical period (Table 4.1). These results presented above strongly suggest an increasing trend in VPD in the future scenarios implying greater atmospheric moisture demand.

4.3 Discussion

Precipitation volume in Soule has increased, however, there was not statistically significant evidence from the historical periods of record that dry days were trending in either direction. This suggests that the increased rainfall was not spread out temporally, rather the rainfall events have become more intense. Farmers in Soule have been having trouble finding enough consecutive dry days to harvest hay in the past few years (I. Elozegi, personal communication, 2024). Perhaps this is due to an anomalously higher frequency in wet days during haying season ($\sim$ May–September) (Figure 1.1.) that is not necessarily indicative of a trend. Although this analysis did not show evidence of more frequent rainfall to explain the increased annual precipitation volume, there was evidence of a trend in increased intensity of precipitation events that explained the upward trend in precipitation volume, despite stable CDD. Stable average CDDs over the historical record do not preclude anomalously long periods of dry days, such as the recent drought in July 2022, which lasted more than 30 days and occurred during a year with the lowest annual rainfall since before the beginning of the periods of record (1950) (S. Inda-Gallur, personal communication, 2024).

Soule had a rise in mean seasonal temperature with a more pronounced increase in nocturnal minimum temperatures, which may increase heat stress on farmers and livestock. A decrease in relative humidity over the same period of record indicated that increased temperatures are more than

compensating for the increased precipitation to drive a net drop in relative humidity. The decreasing RH corresponded to an increasing trend in VPD, a measure of the desiccating power of the atmosphere with a notable upward shift after 1990 for Europe and less noticeably for Soule. VPD was also found to be projected to increase under projected climate scenarios, most concerningly in the moderate to extreme SSP scenarios.

A critical threshold of 1.5 kPa of maximum daily VPD was found to be associated with a wildfire probability of more than 50% for the forests in the region of Europe that include Soule (Clarke et al., 2022). Analysis of monthly climatology of VPD in Soule showed values below the critical forest fire threshold during the historical period. This aligned with local reports that forests have not been fire prone. The mean VPD values for Soule have increased noticeably since around 1990. The degree of severity of climate change will impact how far the VPD rises. In the historical period and all SSP scenarios analyzed, the projected mean seasonal VPD for three of the four seasons (spring, fall, and winter) in Soule were well below the 1.5 kPa mark. Projected values were calculated from a dataset of mean VPD, rather than maximum VPD, so will be notably lower than the maximum expected values of VPD, especially considering the diurnal and seasonal VPD variability in Soule. The SSP mean values used here may underestimate sub-monthly periods of VPD and associated wildfire probability. SSP1/RCP1.26 did not show mean VPD reaching the critical level of 1.5 kPa before the end of the century and SSP2 did not show consistent elevation above the critical 1.5 kPa level after breaching the 1.5 kPa mark in 2080-2090 (Figure 4.10). SSP3, a currently reasonable projected pathway based on the minimal progress to date toward mitigating climate change, showed the mean summer VPD of Soule during the months of June, July, and August (JJA), breaching 1.5 kPa in 2070 – 2080 (Figure 4.10). If climate changes are more extreme, and the path looks more like the SSP5/RCP8.5 scenario, the summer season in Soule was projected to experience mean VPD exceeding the 1.5 kPa threshold by around 2060 (Figure 4.10) that would continue to rise through 2100.

Clarke et al. (2022) found that under RCP 8.5 which corresponds to SSP5, two out of three models projected an increase in western Europe, inclusive of Soule, of 45–90 days exceeding the key

daily max VPD threshold of 1.5 kPa for that region (Clarke et al., 2022). While this count of exceedance days was much higher than the analysis in this paper, this paper used the mean VPD instead of the max VPD so, the estimate in this paper is a conservative underrepresentation.

The probability of fire being more likely than not (greater than 50%) does not guarantee fire. Other factors such as precipitation, ignition source, and flammability of fuel all impact forest fire occurrence, but the rising VPD does point to increased future potential for wildfires to impact areas not previously impacted. Regional, local and micro-climate variability should be considered when assessing landscape vulnerability to wildfire. Some areas of beech forest that have not burned in the lifetime of the present trees may experience fire. Alternately, the maritime influence and moisture coming from the ocean and the nature and structure of the beech forests, particularly those mature forests on north facing slopes, may foster a protective environment that could maintain lower VPD thresholds within the forest and continue to shield the forest from fire hazard in the future, shelter livestock on dangerously hot days, and help to mitigate impacts of climate change into the future. Management practices currently in place, such as controlled burns in fields may become even more important to this SES, potentially maintaining a degree of forest fragmentation that preserves and protects the biodiverse landscape from extensive forest fire. Shifts in forest management may also become necessary in the future to preserve the structures of the forest that are conducive to maintaining lower VPD values.

The current analysis indicated intermittent increased fire potential in future years under a probable (SSP2/RCP4.5) scenario. Also, the current analysis indicated sustained increased fire potential in future years under the reasonable (SSP3/RCP7.0) and an extreme (SSP5/RCP8.5) scenario (Figure 4.10). Local variability should be further investigated to determine which areas of Soule may need special attention regarding future management practices and mitigation efforts. Recently placed temperature and humidity sensors at different elevations, aspects within Soule will record the changing temperature and moisture levels on an hourly time step within the forests and in exposed areas. This data will help gauge micro-climatic variability and the changing vapor pressure deficits in the mountain pastures of Soule.

CHAPTER 5

CONCLUSION

This thesis grew from a concern shared broadly throughout the world regarding whether our ecosystems and traditional ways of life will continue as society and the environment changes. Will our children and grandchildren know and value the ecosystems and lifeways that have sustained our ancestors? Will the land continue to sustain our descendants?

Farmers practicing transhumance in Soule, France were concerned about the future viability of their lives and the continuance of the millennia old practice of transhumance handed down through generations of the same families working with the same land and seasons. Social pressures, new regulations, and a changing climate compound to pose new challenges to this social-environmental system.

This thesis addressed the current trends in climate variables that impact transhumance in Soule, France, and it assessed future trends in Vapor Pressure Deficit and how and when those might impact the social-environmental system of transhumance in Soule, France. It also extended analysis to broader regions including France and Spain to give context and incorporate a broader audience of stakeholders.

Trends analyzed from observation datasets in the region of Soule spanning 1950–2024 helped explain recent hydroclimate dynamics. Although precipitation in Soule has been trending up, temperature and VPD are also trending up, so the resultant demand for water from the atmosphere is out-pacing modest gains in precipitation. Higher emission pathways were found to lead toward a projected breach of mean monthly VPD beyond the 1.5 kPa threshold after 2060. Among the climate data analyzed for the region of Soule and larger Pyrenees, Soule showed a strong increase in nighttime temperatures indicating increased humidity and cloud cover during the nighttime leading to increased heat-stress. The increasing atmospheric temperatures increase the moisture holding capacity of the atmosphere which leads to an

increasing trend in VPD that was identified over all regions and future emission scenarios. Specifically, the exceedance in mean monthly VPD is correlated with the probability of forest fire higher than 50% and could make wildfire in this region more likely than not on a regular basis. Increased VPD also leads to higher evaporation and saturation vapor pressure of the atmosphere. Extreme rainfall events were found to be trending up which is explained by the higher moisture holding capacity of the atmosphere thus these extremes may occur despite stability in the number of total rain days. In summary, the changes that Soule might expect due to anthropogenic emissions and the resultant elevation in global temperatures in the near future (30–50 years) include more water-stressed days, warmer days and nights, and increased extreme rainfall and higher vapor pressure deficit values. The changes in these climate variables increase the probability of climate hazards like flash floods, soil erosion and landslides due to extreme rain events. Increased VPD could result in crop stress, forest health risks and increased wildfire risks due to more intense drying.

Climate change is poised to impact many seasonal variables and potentially shift or create need for adaptation for this social environmental system. Shifts in growing season may drive changes in crops in the valley (Figure 1.1). Recently, wet summers have made the harvest and drying of hay more difficult and had raised questions regarding the potential need for hay drying barns. Windows for safe burning are impacted by weather conditions. Longer growing seasons may add to the fuel load and prime the landscape for hotter, more dangerous fires in future climate scenarios. Climate driven changes in the prevalence or frequency of controlled burns or changes in the timing of seasonal movement of animals may select for different species of fauna which may impact the system in unforeseen ways. Hotter days and nights may impact the health of humans and animals in Soule, where air-conditioning is not the norm and windows are the primary source of ventilation. This thesis did not find evidence of a change in trend of consecutive dry days, indicating that recent wet summers, as experienced by the farmers, is not indicative of a larger trend and investment in hay drying barns at this point may not be the best allocation of resources. Longer term projections of atmospheric drying and potential for decrease in groundwater recharge (Appendix B) coupled with recent experience with drought point to a need for infrastructure

interventions that prioritize water availability for the summer pastures and necessitate further interrogation of hydrological dynamics in the region.

While the results of analysis are informative and help guide research in Soule, the VPD dataset is coarse resolution so the projection may not accurately represent the VPD trends especially in a montane region with steep elevation gradient. Thus, the large spatial VPD trends need to be inferred cautiously for Soule. Spatial and temporal bias of the dataset must be verified against ground observations for the study region. Limitations in ground-observations for the region of Soule limited the capacity to validate the VPD model and E-OBS data.

Future research opportunities raised by this work include ground-truthing, exploring local and regional forest dynamics, and downscaling VPD data. Measuring hydroclimate variables in various micro-climates that are not reflected by locations of current weather stations can help shed light on the variability of these values within Soule. Investigation of the micro-climate created by the forest canopy and assessment of the well-being of the trees in extremes such as heat and high VPD, can help determine the degree of adaptive capacity of the forest of Soule. Downscaling the VPD data could reveal if all, or only parts of the larger region that include Soule, may be susceptible to VPD thresholds correlated with increased probability of fire. Ongoing collaboration with farmers to better gauge current and potential future impact of climate variability are vitally important to the development of actionable research and knowledge. New collaborations with community partners and agencies already working on climate adaptation in the Pyrenees will be invaluable to further investigation of the dynamics of the SES that sustains transhumance in Soule and to help facilitate the transdisciplinary work that is needed to chart new paths for a sustainable future.

I hope that my research will provide data for the farmers that will inform conversations amongst them and other decision makers in Soule regarding how to prevent and mitigate risks to the SES of transhumance and to the forests of Soule to aid in current efforts to maintain traditional land management practices such as *écobuage* that have helped to sustain this ecosystem and transhumance in Soule.

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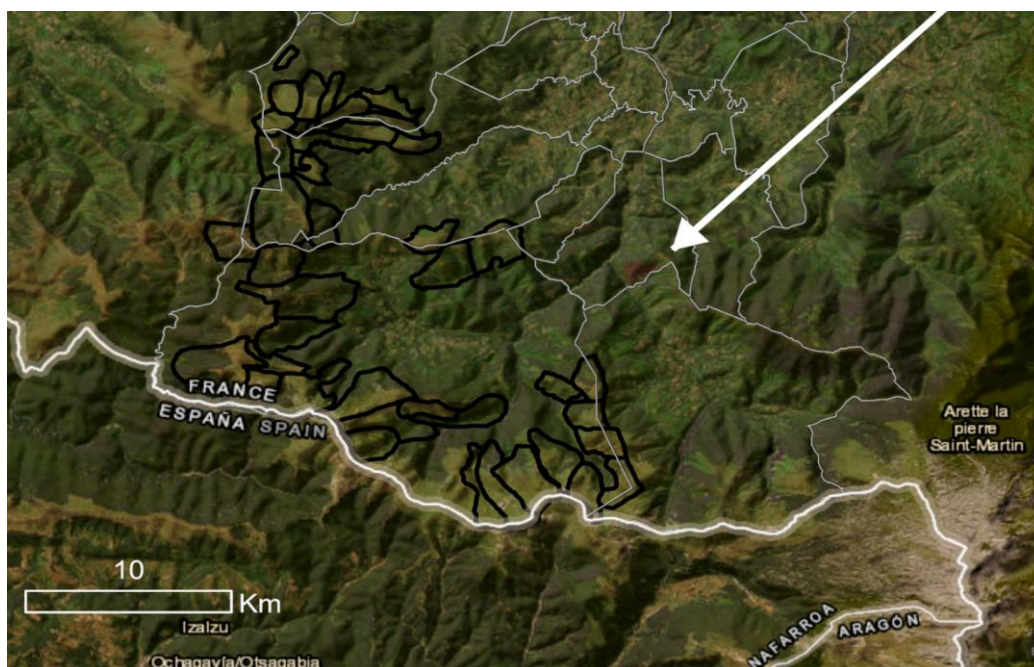
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APPENDIX A

“Mega” wildfire scar in Soule

(S. Inda-Gallur, personal communication, 2024)



APPENDIX B

Projected Groundwater Recharge for Soule based on tool from Attard et al. (2025)

